Introduction to Engineering Methods

A knowledge based product development (KBPD) approach to developing individual student projects

Engineering Grade 11

This unit is intended for use for at the beginning of an engineering course, an individual research project, or a science fair unit. Students will be introduced to basic engineering concepts and current industry techniques. At the end of the unit, students will have developed a procedure and a timeline for a personal STEM project. The lessons in this unit focus on providing a brief overview of the engineering process, useful brainstorming techniques, Root Cause Analysis, knowledge gaps analysis, and timeline development. This unit will teach students how to think through problems with an engineering mindset, help students develop personal research plans, and expose students to engineering jargon.

This curriculum was developed through the Cape Cod STEM Network Teacher in Residence program which partnered Siobhan Curran of the Massachusetts Academy of Math and Science with Bob Melvin of Teledyne Benthos/Teledyne Marine.

This material is based upon work supported by the National Science Foundation under Grant No. 1347610. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Background Information

1. Who helped to create this unit?

Names	School (Grade/course taught)
Siobhan Curran	Massachusetts Academy of Math and Science at WPI, 11th grade STEM teacher

2. What were some sources of inspiration for this unit?

Some of the major components of this unit were drawn from Bob Melvin's book Knowledge Based Product Development: A Practical Guide. Bob hosted me at Teledyne Marine as part of the Teacher in Residence program through the Cape Cod Regional Stem Network. At Teledyne, I had the chance to see how KBPD principles were implemented in a real-world engineering environment. For example, I attended trainings and meetings focused on project tracking techniques, Root Cause Analysis, the 5-Whys, and Set Based Design. These practices help engineers improve their projects, so it makes sense to apply these tools and approaches to student research.

The other main inspiration for this unit was my belief that students should be able to participate in every stage of project development. Although students who are given projects can learn many useful techniques, students who design their own projects are more invested and engaged in the process. All students, regardless of future career choices, will deal with problems, problem solving, and projects. By encouraging student driven research, this unit should help students acquire new tools for dealing with such challenges in new environments.

3. In your own words, what are you hoping students learn—big picture—through this unit?

I want students to learn to think like engineers. They should be able to see that problems can have many causes and many solutions. Students should appreciate how much planning precedes a successful project. I also hope that students gain an understanding of how engineering really happens.

4. What might students find exciting in this unit?

This unit addresses the perennial question, "why is this important?" Students love to see how classroom activities relate to the wider world. This unit not only applies classroom ideas to real world examples, but also helps students learn to think like engineers. As students develop personal research plans, they will get to see how their interests intersect with engineering and research principles. Students might also be motivated by the idea that good projects can continue to science fairs, journals, or patentable devices.

5. What science standards or real-world content did you strive to emphasize?

This unit emphasizes process: How do you identify, research, and solve problems? Towards this end, these lessons integrate real-world engineering *process and jargon with the Engineering Design Cycle published in the 2016 Massachusetts Science and Technology/Engineering Curriculum Framework.*

6. How would you say that this unit "matters" to the STEM community? Or to our community on Cape Cod? Or to the larger community?

For students considering careers in STEM, it is important to see what real engineering entails. Exposing students to the correct jargon and tools will also help prepare them for a future in engineering. Students interested in alternative career paths will gain transferable problem-solving skills. High school students are capable of inventing amazing things. By helping students learn how engineering happens, this unit will set them up for successful projects. Many students focus on products that will help the wider world. In my classroom, students must develop assistive devices for individuals with special needs. By following the appropriate engineering process, students will be able to provide robust devices for their clients.

7. What's the most important lesson you learned as you created this?

It can be challenging to help students generate a project timeline. Student timelines often emphasize long periods of time devoted to complicated processes. When they are faced with large tasks and far off deadlines, it is easy to be distracted by tangential problems or procrastination. My work with Bob Melvin and the Cape Cod STEM Network helped me learn more about different project tracking methods. I have found these methods to be useful in many projects (not just those covered in this unit).

8. **Anything else you would like fellow teachers or others to know about this unit?**

Although this unit focuses on engineering standards, project planning principles apply to all STEM fields. STEM projects start with observation, brainstorming, background reading, and planning. Many schools incorporate experimental design in the Biology curriculum. Lessons from this unit can be adapted to that classroom environment.

This unit only covers the beginning of an individual project. Good follow-up lessons would focus on:

- *Data: How to collect it, how to use it, and how to avoid misusing it.*
- *Matrices: How to transfer what students have learned about decision matrices to raw data matrices, how to develop more advanced scoring systems.*
- *Logbooks: Expectations for how data will be recorded.*
- *Presenting personal results: How to develop a poster, paper, or talk for different intended audiences.*

If you are considering a group engineering project, Knowledge-briefs (K-briefs) and other KBPD practices can help keep the project focused and on track. Consider checking out some KBPD, Agile, Lean, or Six Sigma resources for additional project management ideas. The Project Management Institute (PMI) also has excellent information on best practices in this field.

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Stage 1 Desired Results

MA STE Standards ● HS-ETS1-1 ● HS-ETS1-2 ● HS-ETS-3	**ESSENTIAL QUESTIONS** ***EQ1. What can be learned from previous projects?*** ***EQ2. What should a student consider when developing a project?*** ***EQ3. How can engineering principles be applied to student projects?*** ***EQ4. What are effective techniques for brainstorming and problem solving?***
	UNDERSTANDINGS ● *Students will understand that a good project has clear goals and scope. Students will also understand that gathering background information is an essential part of a project. Additionally, students will know that science and engineering can overlap with any other field.* ● *Students will be skilled at generating ideas, determining project criteria, and building a knowledge-driven project.*
	TRANSFER *Students will be able to develop personal research plans. Students will also be able to use the 5-Whys and fishbone diagrams to problem solve. Students should be able to think about problems with an engineering mindset.*
	CROSS-CURRICULAR CONNECTIONS *Examples in this unit encourage students to think of the intersection between engineering and a variety of other disciplines including English, history, music, art, science, and community service.*

Stage 2 Evidence

Formative Assessment Ideas:

- **Homework**: Homework worksheets have been developed to check for understanding/introduce new ideas
- **Research into the existing body of knowledge**: Notes file
- **Knowledge gaps**: Notes file
- **Project updates**: Each iteration of project brainstorming (pie diagrams, mapping, mixing pie diagrams and mapping, notecard, fishbone diagream), Logbook
- **For project management:** Developing and updating the Kanban

Summative Assessment Ideas:

- **For the unit:** Brainstorming ideas should be transferred to student logbooks. The evolution of these ideas can be assessed. The research proposal can be analyzed for completeness, uniqueness, feasibility, and connection to existing literature. The notes file can be used as evidence of background research. The predicted knowledge gaps in the notes file can be used to support the analysis of the procedure.
- **For the project:** The notes file can be used to understand what background research contributed to the project and what sub-projects the student pursued (see the knowledge gap table). The knowledge gap notes should help identify the location of associated information. The logbook will also provide good long-term evidence of research. Logbooks should include schedules, procedural notes, Final student projects can be presented in class, at a conference, at a STEM fair, or in a journal article.

Stage 3 Learning Plan

Summary of Key Learning Events and Instruction

- Introduce and analyze previous engineering projects.
- Groups develop engineering plans.
- Students learn how to improve engineering plans using decision matrices, the Voice of the Customer (VOC), Set Based Design, and knowledge gap analysis.
- Students brainstorm for individual projects.
- Students learn how to perform Root Cause Analysis.
- Students plan a project procedure and timeline.

Introductory Lesson	**Constructing Lesson**	**Practice Lesson**	**Assessment Lesson**
Lesson that introduces the content. More teacher directed	Lessons that engage students in building and linking together understanding. Guided/collaborative. Student/teacher or partners/small group	Lessons or activities that students can complete relatively independently	Formative: Check-ins along the way to see if students "get it" Summative: Students showing what they know, when you feel they are ready

Stage 3 Learning Plan

Summary of Key Learning Events and Instruction

Lesson Name	**Type** (Introductory, Constructing, Practice, and Assessment)	**Content Addressed**	**Standards Included (by number)**
Lesson 1: Introduction to the Engineering Process	Constructing Lesson	Review a recent engineering project, groups develop a project to address a similar issue, groups present engineering plans	HS-ETS1-1, HS-ETS1-2
Lesson 2: Criteria and Decision Matrices (2 classes)	Introductory Lesson	Introduce the idea of criteria, discuss the proper use of decision matrices, students use decision matrices, students develop a decision matrix for beached whale removal	HS-ETS1-1, HS-ETS1-2, HS-ETS-3
Lesson 3: Using matrices	Practice Lesson	Set Based Design case studies, how to develop a decision matrix in Excel, project brainstorming (pie diagrams)	HS-ETS1-1, HS-ETS1-2, HS-ETS-3
Lesson 4: Brainstorming for projects of interest (mind mapping)	Practice Lesson	Mind mapping, content areas for projects	HS-ETS1-2
Lesson 5: Brainstorming for projects of interest (fishbone diagrams, VOC, 5-Whys)	Constructing Lesson	Fishbone diagrams, Root Cause Analysis, Voice of the Customer, asking effective questions, problem solving, project selection, project cycle	HS-ETS1-2, HS-ETS-3
Lesson 6: Moving from idea to procedure	Introductory Lesson	Importance of reading, notes file, knowledge gaps, narrowing project options	HS-ETS1-2

Lesson 7: Research and timeline planning	Introductory Lesson	Procedure clarification, project tracking methods, breaking the project into manageable parts	HS-ETS1-2

Lesson 1: Introduction to the Engineering Process

Overview of the Lesson: What will students be doing?

Students will read about the process implemented by the Gravity Light Foundation. They will then participate in a guided discussion on the engineering process. Special attention will be paid to Set Based Design and the iterative nature of engineering. Small groups of students will then develop and present engineering plans.

Time (minutes): 60

Standard(s): What standards will be the focus of the lesson?

- HS-ETS1-1. Analyze a major global challenge to specify a design problem that can be improved. Determine necessary qualitative and quantitative criteria and constraints for solutions, including any requirements set by society.
  - Clarification Statement: Examples of societal requirements can include risk mitigation, aesthetics, ethical considerations, and long-term maintenance costs.
- HS-ETS1-2. Break a complex real-world problem into smaller, more manageable problems that each can be solved using scientific and engineering principles

Essential Question(s): What essential questions will be addressed in this lesson?

- How do engineers approach a problem?
- How can global problems be broken down into smaller more manageable parts?
- What should students consider when developing a project?

Science Objectives

- Students will read about an engineering project, analyze the information, and communicate their thoughts.
- Students will gain exposure to key terms they will explore later in the course (Set Based Design, Root Cause Analysis, Voice of the Customer).
- Students will gain experience brainstorming solutions to complicated problems.

Language Objectives and/or Targeted Academic Language

- Set Based Design, iterative process, root cause, generator, developing country, subsidize, scope, scope creep

What students should know/be able to do before this lesson

- Students should have read the following article and written a brief reflection on the information provided in the **Gravity Light Handout:**

  Kerbel, N. (2014, Feb 17). Gravity-Powered Light 'To Help Millions' Sky News. Retrieved from http://news.sky.com/story/gravity-powered-light-to-help-millions-10417046

- If homework is not feasible/desired, a video from the GravityLight Foundation would work: https://gravitylight.org/

Anticipated Student Pre-conceptions/Misconceptions

- The first functional idea is the best idea. If a device functions, the project is done.
- Engineers build first and test later.
- Good products are expensive.
- To be successful, a project must solve every aspect of the problem.
- Every problem has one solution.

Instructional Materials/Resources/Tools

- Student pre-reading: **Gravity Light Handout**. The article is also available at http://news.sky.com/story/gravity-powered-light-to-help-millions-10417046
- **Presentation Rubric**
- **Establishing Criteria Worksheet**
- Optional teacher pre-reading:
  - Information the environmental problems faced by developing countries from the World Health Organization: http://www.who.int/heli/risks/ehindevcoun/en/
  - Information on the Gravity Light
    - from the Gravity Light Foundation: https://gravitylight.org/
    - from Deciwatt: http://deciwatt.global/
  - Information on Set Based Design from Scaled Agile: http://www.scaledagileframework.com/set-based-design/
    - "Set Based Design is a practice that keeps requirements and design options flexible for as long as possible during the development process. Instead of teams choosing a single "point" solution upfront, Set Based Design identifies and simultaneously explores multiple options and eliminate poorer choices over time. It enhances flexibility in the design process, commits to technical solutions only after validating assumptions, and produces better economic outcomes."
    - Request permission to use text and graphics: http://www.scaledagile.com/permissions-form/
  - Information on Set Based Design and project planning from Velopi: http://www.velopi.com/news/pmi-pmp-free-project-management-resource-set-based-design
    - "Project managers are supposed to plan their work and then work their plan"

Assessment: How will you know that the students got it?

- Informally assess participation in group discussions. Stop by each group and have them address 5-Whys, have students justify decisions with respect to scope.
- Presentation rubric (could also substitute a school presentation rubric)

Science and Engineering Practices included (put the included ones in bold):

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 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**

Opening/Engagement: Summarizing and discussing the reading
Time (minutes): 20

1. **Engage students with a quick interest poll** [a thumb-scale is a good option here because it is quick and engages all students]
   - *Who liked the reading?*
   - *Who was surprised at the length of time it has taken this product to get to market? [note: the project was requested by the charity SolarAid in 2009, the product launch occurred in 2017]*
   - *Based on what you read, do you think this product is a feasible alternative to kerosene lights?*
   - *How would you rate their approach? [this question can be good to kick off the discussion because you can follow up with why/why not]*
2. **Switch to a more open discussion. For large classes, you may want to switch these to small group discussions so that all students get a chance to participate. Group discussions may go in different directions. Some guided questions are below.**
   - *Who is the target customer?*
   - *What criteria did the team take into consideration during the engineering process?*
   - *What data did the group need to collect in order to design this product?*
   - *Why did they avoid common clean energy sources (wind, solar)?*
   - *If they had been unable to use gravity in this way, what would they have used instead? [with this part of the discussion, introduce the phrase 'Set Based Design']*
     - Briefly discuss the importance of having alternative design options. Writing a procedure, doesn't mean it will work. Highlight the fact that this surprises many students over the course of Science Fair projects.
     - If the discussion does not naturally trend in this direction, make sure to insert it yourself.
   - Try to integrate the target vocabulary in responses to student commentary:
     - Set Based Design, iterative process, root cause, generator, developing country, subsidize, scope, scope creep

During the Lesson: Engineering proposal
Time (minutes): 20

3. **Relate the following information to students:**
   - *Developing countries face many problems. The Gravity Light is one team's effort to address the pollution, danger, and cost associated with the kerosene lights used in many areas of the world. According to the World Health Organization, indoor smoke from cooking and heating is responsible for 1.5-1.6 million cases of fatal respiratory disease every year [note: this number is higher than that reported in the homework* ***Gravity Light*** *article]. The students at your table are tasked with designing a way to reduce indoor smoke. There is no way for you to solve every aspect of the problem. See if you can take on a small piece of the problem. For example, the Gravity Light addressed the lamps used for light in the evening. Light, heat, and cooking are all areas you can consider. Define your scope first; focus on one particular area quickly so you have more time to work on your specific problem. One of the biggest problems faced by engineers is called "****scope creep****." Your product can't be all things for all people. To develop a successful product, you need to focus in on one particular aspect of this problem. In 20 minutes, your group will have to present your idea to the class.*
   - *Provide large papers to students so that they can develop a visual model of their idea and/or record information about their process.*
4. **Remember to give students a few warnings:**
   - 10 minute warning about scope.
   - 5 minute warning before the presentation phase.

Lesson Closing: Proposal presentations
Time (minutes): 20

5. Inform students that each person needs to participate during the presentation. Have students write down questions during the presentations. Encourage the listening students to probe for specificity at the end of the presentation. Each group only has five minutes, so there may not be enough time for all questions to be answered. The class will revisit the projects in the next class, so the students can ask their questions then.
6. Assign the **Establishing Criteria Worksheet** as homework.

Instructional Tips/Strategies/Suggestions for Teacher: What other ideas would you like to highlight? What grouping strategies are important? What are adjustments for struggling learners, enrichment, or for students who are English Learners?

- Depending on the topics you want to emphasize, you may not have time to introduce each of the vocab words/concepts for this lesson. This unit integrates these ideas repeatedly. The main purpose of this lesson is twofold: To get students into the mindset needed for idea generation and to expose them to *some* engineering concepts. Emphasize whatever is most needed in your class. Jargon can easily be introduced in later lessons where you can connect new ideas to this previous experience.

- In facilitating group discussion, make sure to ask questions that force students to clearly define scope. Follow up with questions relating to why the design required certain elements. If you are not stressing jargon in this class, these clarifying questions are especially important in focusing discussion.
- One way to engage students who don't see themselves as engineers is to pull in criteria design examples that are related to other classes. The cross-curricular nature of the homework can be easily targeted towards lessons running concurrently in other classes at your school. For example, you could change the Thoreau question to relate to a book that students read at your school.
- For struggling learners, the homework might be better (at least partially) as an in-class activity. For struggling learners, discussions of multiple weighting systems might be confusing; there are several different ways of ranking/weighting criteria in the homework. If you are working with college prep/lower level students, consider changing these to a single ranking system.
- It is important to keep groups small enough to allow everyone to participate. If it is not possible to fit discussion in for all groups there are two possibilities:
    - Have groups send a 'foreign exchange student' to other groups. This way, each student gets to present the whole project to a smaller group. The drawback to this approach is that students don't get the chance to work on public speaking in front of a crowd.
    - Have groups present at the beginning of the next class. The drawback to this option is that students will have forgotten some important aspects of their design. However, this approach may provide a good springboard into the next lesson.
    - Split the class in two and have students present to half the class. This method can get noisy and unwieldy if you don't have a secondary location to send students and a second teacher (or aid) in the classroom.

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Lesson 2: Criteria and Decision Matrices

Overview of the Lesson: What will students be doing?
Students will revisit the engineering plans developed for Lesson 1. Groups will discuss and refine the criteria used during the development process. Groups will design a weighted decision matrix to compare the initial and revised plan.

Time (minutes):60 x 2

Standard(s): What standards will be the focus of the lesson?

- HS-ETS1-1. Analyze a major global challenge to specify a design problem that can be improved. Determine necessary qualitative and quantitative criteria and constraints for solutions, including any requirements set by society.
    - Clarification Statement: Examples of societal requirements can include risk mitigation, aesthetics, ethical considerations, and long-term maintenance costs.
- HS-ETS1-2. Break a complex real-world problem into smaller, more manageable problems that each can be solved using scientific and engineering principles.
- HS-ETS1-3. Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, aesthetics, and maintenance, as well as social, cultural, and environmental impacts.

Essential Question(s): What essential questions will be addressed in this lesson?

- How are criteria designed?
- How are decision matrices generated and used?
- What is Knowledge Based Product Development (KBPD)?
- What is a knowledge gap?
- What are technical specifications and when are they identified?

Science Objectives

- Students will be able to design criteria and develop decision matrices.
- Students will be able to use the 5-Whys method to revise engineering plans.
- Students will be able to identify knowledge gaps.

Language Objectives and/or Targeted Academic Language

• Voice of the Customer, criteria, decision matrix, knowledge gap, weighted contribution
Anticipated Student Pre-conceptions/Misconceptions • All design is knowledge based. • Just because a solution works, doesn't mean a project is done. • A product needs to be built before testing can be performed. • As soon as you have an idea you can start building. • You only have to consider one solution to a problem.

Instructional Materials/Resources/Tools
• **IntroEngineering PowerPoint**
• **Decision Matrices Worksheet**
• **Empty Matrix Worksheet**
• Information on testing and further development of the GravityLight
  ○ https://gravitylight.org/gravitylight-blog/2016/5/23/bead-cord-issue
• Technical specifications of the GravityLight were obtained directly from the GravityLight Foundation. They are available with this lesson plan (**TechSpec1, TechSpec2, TechSpec3**), or from the organization:
  ○ TechSpec1—The GLO2: https://static1.squarespace.com/static/552aca94e4b0c75f5b87b0fe/t/57b5d54dff7c506aed7189eb/1471534417333/GL02+Technical+Specification.pdf
  ○ TechSpec2—The GLO2 Home System: https://static1.squarespace.com/static/552aca94e4b0c75f5b87b0fe/t/57b5d513ebbd1ad66b10d3c8/1471534360241/GL02+Home+System+Technical+Specification.pdf
  ○ TechSpec3—The SatLight Accessory Pack: https://static1.squarespace.com/static/552aca94e4b0c75f5b87b0fe/t/57b5d582ff7c506aed718c79/1471534473771/SAP+Technical+Specification.pdf
• Exploding whale video: https://www.youtube.com/watch?annotation_id=annotation_696072&feature=iv&src_vid=xBgThvB_IDQ&v=uD5sPgV61bw#t=43s

Assessment: How will you know that the students got it? Teachers can assess student understanding by checking homework, taking notes during class discussion, considering contributions to group participation, or checking the decision matrix for the whale problem.
Science and Engineering Practices included (put the included ones in bold): **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 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**

Day 1: Intro to the Decision Matrix

Opening/Engagement: Homework and Voice of the Customer discussion
Time (minutes): 25

1. **Review some parts of the homework. During the discussion, the main focus should be on writing good criteria and capturing the Voice of the Customer.**
    - Question 1 is particularly important for discussing good criteria.
        - Take an informal poll to see what students selected for each of the bicycle criteria. Have students provide examples of improved criteria. *(5 minutes)*
        - During your discussion of criteria, give students 30 seconds for a quick look at each of the specifications for the GravityLight. Three options are provided. Leave one open during the discussion. Ask students if they think the customers requested a specific voltage, beam angle, or product weight. During your brief discussion highlight the fact that a customer won't give you product specifications; if you are thinking of criteria, think in broad terms. Specifications, like the requirements in the product sheets, come later. This discussion can lead to the Voice of the Customer (VOC) discussion. Tell students that some testing may be required to determine exact specifications later in the project. *(10 minutes)*
    - Question 2 will be used during group meetings later in the class.
    - Questions 3 and 4 (to a lesser extent question 5) can help focus on the VOC. Focus on the following points *(10 minutes)*:
        - What did you believe the term "relative importance" meant? [rank vs weight; how is clarity of expression important?]
        - Who was the "customer" or end user in question 3?
        - Who were the "customers" or end users in question 4?
        - You were not given much information about your goals. What assumptions did you make? Were they the same as those made by your neighbor (this would be a good small group discussion point). After students discuss this concept, highlight the fact that engineers often make assumption about needs and wants. Have students propose three or four places they can look to ensure they are addressing a real need.

During the Lesson: Using the decision matrix
Time (minutes):22

2. **Introduce the decision matrix**. *(3 minutes)*
    - Walk the students through the layout of the **Empty Matrix Worksheet**. Tell them that they will be focusing on the first two columns for now. Indicate that there are several systems that can be used to weight the data in a matrix. Let them know that we will be using one style today, but they may see (or choose) others in the future. The homework had several options (see which they like, could mention a few pros/cons)
3. **Have the groups from lesson 1 reconvene. Task the groups with determining criteria important for their projects and generating consensus on the relative importance of each feature. Students should have completed the first two columns of the decision matrix by the end of this activity.** *(8 minutes)*
4. **Draw attention to the top of the decision matrix. Make sure to highlight that products or options belong at the top (ex. Iterations for CS projects, different proposals for projects, existing solutions, later in a project could have prototypes). Highlight that this system should compare the proposed project to the alternatives. Have students fill in their project at the top of column 1.** *(4 minutes)*
5. **Introduce the idea of ranking in the decision matrix. Relate the following information, then have students rank their project for each of the criteria**:
    - *Determining ranks for a decision matrix can be tricky. Let's say you are an engineer in a group meeting discussing a proposed product. One of your criteria is high durability. You are trying to rate the durability of your design on a 1-10 scale. You think the product will be durable, but you aren't sure if it deserves a 9 or a 9.5. As you can imagine, this situation could lead to a lot of debate; what earns a product a 9 for durability? In situations where chief engineers want to cut down on that debate, and get to the heart of the matter quickly, they sometimes use more extreme gaps. If you have three choices (1, 3, or 9), the choice is much easier. If a product is pretty durable, it would earn the maximum score of 9. We are just starting out, and we haven't captured the background knowledge needed to develop a well-defined scale for each criteria. Therefore we will be using this 1-3-9 scoring system. (7 minutes)*
        - *Notes:*
            - *This scoring system weights confident answers (1, 9) heavily; a -1, 0, 1 system may be easier if you have time to do more background investigations into your maybe/middle answers. The -1, 0, 1 system also lends itself well to mental math.*
            - *Students may remember the 1, 3, 9 method when you try to transition to a more complicated scoring system later in the year (bins, equations, educated scores, scoring matrices). You may want to insert a lesson on more complicated scoring systems immediately after this lesson to eliminate this future issue.*

Lesson Closing: How to use the matrix, homework introduction
Time (minutes): 10

6. **Project the matrix demo file. Explain how a weighted score works.**
    - *Although you may not know it, you have been exposed to weighted scores for years. If a teacher says, homework is worth 10% of the grade, tests are worth 60%, and quizzes are worth 30 %, how is that score calculated? Imagine you are taking a class where there are three tests. The test average will account for 60% of the course grade. There are 15 quizzes and they are worth 40 % of the course grade. How would you calculate your grade?*

    - *For visual students, or students who struggle with math, a comparative example is provided in the* ***IntroEngineering PowerPoint****. When information is put in the context of school grades, most students understand the idea of weighting more easily.*
    - *For advanced math students, those slides are unnecessary.*
  - *In the case of a decision matrix, you aren't dealing with tests or quizzes; you are dealing with criteria. You get to decide how much each criterion is "worth" by assigning it a weight. When you use a matrix to make a decision, you need to consider the relative importance of each criterion.*
  - For stronger classes, hand out the worksheet now; work through one column in question 2 together. For classes needing more support, work through the ***IntroEngineering*** PowerPoint together.
  - Identify the **Decision Matrices Worksheet** as homework. We will review the worksheet portion at the beginning of the next class and the reading at the beginning of the next class. Assign different readings to different students. Make sure students record which selection they are required to read.

DAY 2: Practice with decision matrices

Opening/Engagement: Homework and confusion elimination
Time (minutes): 5

- Review how to build a decision matrix
- Discuss common decision matrix misconceptions

During the Lesson: Using the decision matrix
Time (minutes): 40

- Pose the following problem: A whale has washed up on the beach. Your group (groups of approximately 3-4 students) must get rid of this whale. Come up with at least five different criteria for this project. Weight the criteria. Then, develop at least three different ways to solve this problem. Fill in the decision matrix to determine how you would address this problem.
- Give students a timeline for completion (for students who struggle, they may need to complete the matrix for homework; advanced students may complete the matrix in time for the lesson closing).

Lesson Closing: How to use the matrix, homework introduction
Time (minutes): 15

- Ask each group to identify one criteria used (workshop as needed so that criteria are concise, directional, and clear).
- Ask each group to identify the "winning" project.
- Ask groups to score "eating the whale" as a possible approach. Discuss the fact that poorly constructed criteria could lead someone to select this option. Could also clarify that something that is particularly important (like safety) should have a built-in system where you CANNOT do a project that earns below a certain score in a certain category.
- In the last five minutes of class, watch the following video (do not load it early or kids will add exploding whale to the decision matrices):

https://www.youtube.com/watch?annotation_id=annotation_696072&feature=iv&src_vid=xBgThvB_IDQ&v=uD5sPgV61bw#t=43s

- Homework should be continued to next class. Ask students to go back and check over answers/complete the readings.

Instructional Tips/Strategies/Suggestions for Teacher: What other ideas would you like to highlight? What grouping strategies are important? What are adjustments for struggling learners, enrichment, or for students who are English Learners?

- The first two lessons in this unit are introductory ideas; capturing the Voice of the Customer requires research. The point of introducing the terminology now is to help students understand that they will need to be goal oriented in designing their products. This discussion foreshadows a more in-depth discussion in later lessons (especially Lesson 5).
- It is important to introduce the idea that you won't know specifications (like luminous efficiency) before you gather some information. Students can get nervous about 'not knowing enough' to do a project. This lesson helps them see that it is normal to have knowledge gaps. This lesson (especially the homework) helps students see how data can be used to close knowledge gaps, make decisions, and lead to success.
- When students work through a decision matrix, they often find the first decision/option/product easy to calculate. However, multiplying two columns that are not next to one another can cause confusion. If you work through an entire device together, try choosing Proposed device 2 or 3 so that they have a chance to do a trickier column. Have students use a finger to track which weight you are working with. Alternatively, you could hand out paper strips to block the columns they are currently ignoring.
- If you are using this lesson for a class geared towards STEM work, make sure to highlight how decisions are important in scientific research as well. Many of these techniques can be applied to science projects (especially in the design phase).
- If you have extra time, you could have students compare their solutions to those proposed by other groups or to the GravityLight.
- For students who struggle with weighted averages, an unweighted system can be used.

Lesson 3: Using matrices

Overview of the Lesson: What will students be doing?
Students will discuss the case studies they read for homework. They will then work on generating decision matrices using basic Excel skills. Students will also work on brainstorming for their own projects.

Time (minutes): 60

Standard(s): What standards will be the focus of the lesson?

- HS-ETS1-1. Analyze a major global challenge to specify a design problem that can be improved. Determine necessary qualitative and quantitative criteria and constraints for solutions, including any requirements set by society.
  - Clarification Statement: Examples of societal requirements can include risk mitigation, aesthetics, ethical considerations, and long-term maintenance costs.
- HS-ETS1-2. Break a complex real-world problem into smaller, more manageable problems that each can be solved using scientific and engineering principles.
- HS-ETS1-3. Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, aesthetics, and maintenance, as well as social, cultural, and environmental impacts.

Essential Question(s): What essential questions will be addressed in this lesson?

- How does planning ahead prevent project failure? (case study discussion)
- How are decision matrices used?
- How do you develop a project?

Science Objectives

- Students should learn how to use a spreadsheet to speed up calculations and develop dynamic self-updating equations.
- Students should begin to think about the Voice of the Customer, Set Based Design, and knowledge gaps.
- Students should begin to brainstorm for their own projects.

Language Objectives and/or Targeted Academic Language

- Voice of the Customer (VOC), translation document, knowledge gap, ad hoc, post hoc, Set Based Design

Anticipated Student Pre-conceptions/Misconceptions

- You need to update their calculations every time a change is made (if you use equations in Excel, the calculations update automatically).
- Everything a professional engineer or researcher does is successful.

Instructional Materials/Resources/Tools

- Homework due: **Decision Matrices Worksheet**
- **IntroEngineering Powerpoint (see folder for lesson 2)**
- **Decision Matrix Demo** Excel file
- **Decision Matrix Decoded Worksheet**
- **Brainstorming Exercise Worksheet**
- Students will need access to a computer or tablet with Google Sheets or Excel.

Assessment: How will you know that the students got it?

- Students will be able to contribute to discussions about the case studies in the homework.
- Students will have a functional decision matrix in Google Sheets or Excel.
- Students will brainstorm possible areas of interest.

Science and Engineering Practices included (put the included ones in bold):

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 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**

Opening/Engagement: Homework reading selection review
Time (minutes): 15

1. Have students sit with people who had different reading assignments from the **Decision Matrices Worksheet**. Ask them to summarize their reading and highlight any useful information. If students seem to be drifting off task, provide some structured questions like the following:
    - What was the main point of the selection?
    - What was the main problem described in the selection?
    - How was Set Based Design implemented in this reading?
    - How could the process described be improved?
    - Did you learn anything new about the engineering process?
2. Ask students for a couple quick ideas for how Set Based Design could be employed in a science or math project.

During the Lesson: How to make a matrix easy to use
Time (minutes): 40

3. Discuss how forgetting to weight your scores could lead to problems (the matrices from the homework are available in the Homework matrix tab in the **Decision Matrix Demo**)
4. Run through an example (15 minutes)
   - Open the **Decision Matrix Demo** file. Tell students you will be provide a quick demonstration, then you will be working through it slowly along with them.
   - Have students take out the decision matrix they developed in the last class.
     1. Request some criteria and weights from the class, insert it into the student criteria tab. The other tabs should automatically update with this information.
   - Walk students around the decision matrix. Click on a few boxes and show students where they can see/edit equations (in the cell, in the header).
   - Select the **Data** tab at the top of the file. Then click on any box in the table. Next click **Sort**. Show students where to find the different options. Sort the data by weight—values—largest to smallest.
     1. Point out what happened to the numbering system.
   - Delete the currently misnumbered criteria. Write a number 1 in box **A2.** Demonstrate how to fill a series.
     1. Now is a good point to talk about sorting techniques: today students are sorting based on relative importance. Are there any other systems that are common (or even acceptable) in your program? In other source material you use?
   - Next, click on the total for the Competitor device.
     1. Point out the = sign in the equation
     2. Point out the $ in the equation
     3. Point out the : in the equation
     4. Have students identify any known parts of the equation and predict what the role of the equation was
     5. Drag the equation across the bottom of the table. Then choose the box in the bottom right. Select **fill without formatting**.
   - Move over to the Matrix Sum tab. This example HAS BEEN DONE INCORRECTLY. The simple sums have been calculated. See if students can draw connections with the homework questions.
5. Discuss formatting options with your students. Use real examples. The **IntroEngineering** PowerPoint provides several common designs. (10 minutes)
6. Give students the **Decision Matrix Decoded** worksheet. Remind students that if they put their matrices in Excel, they have saved time for report writing, decreased calculation time/make-work, and (if they give each decision a different tab in the same spreadsheet) helped organize their research. Have students build a matrix with their own information. (15 minutes)

Lesson Closing
Time (minutes): 5

7. Convey the following homework information to the students.

- *Until this point, we have been working on theoretical projects. However, you will be starting your own project soon. While you brainstorm try to keep some of these ideas in mind:*
  1. *You don't have to solve every problem in the world; you can take on a small part of a big problem.*
  2. *As you develop your ideas, keep in mind that your first idea may not be your final idea. (If you have a class of engineers, you can ask who is familiar with WD-40. It got its name because it was the 40th attempt.)*
  3. *Every one of you is a complex person with many interests. The GravityLight combined public health, physics, and engineering. There might be a project at the intersection of your interests.*
  4. *If you are passionate about a topic, there is a project there. When you work on a project, you think about it for hours, you read about it, you work on it, you think about it some more, you revise it, you write about it, you talk about it… Look for an area of sincere interest.*

I understand that it can be tough to figure out what to do your project on. You are not alone; we will be brainstorming for the next few classes. You might also have to read up on your topic of interest. It can be difficult to narrow down your field without some preliminary knowledge—you can fill those knowledge gaps by reading background information. Your homework will help you start the brainstorming process. There are two parts to the homework:

1. *The notecard: carry this with you for the next week. On one side, write down complaints or annoyances. What problems or frustrations are you facing? On the other side of the card, you should note down any patterns you observe. It is hard to think of a pattern off the top of your head. But there are patterns everywhere. The point of this exercise is to generate ideas. Patterns can be turned into math, statistics, or computer science projects. Complaints or annoyances can reveal problems. An engineering project could solve that problem. Additionally, if you aren't sure of the root cause of the problem, you might be able to find a science project in there. Don't worry if a project isn't apparent from the complaint. Right now, we are focused on generating a lot of options. Project proposals are still a long way off.*
2. *Complete the* ***Brainstorming Exercise*** *worksheet (top of the page says Brainstorming is as easy as pie).*

Instructional Tips/Strategies/Suggestions for Teacher: What other ideas would you like to highlight? What grouping strategies are important? What are adjustments for struggling learners, enrichment, or for students who are English Learners?

- It may be helpful to provide examples of patterns; students often think they need to have pie-in-the-sky perfect mathematical patterns. This idea provides unnecessary stress and results in fewer students completing the exercise. To address this problem, you could
  - provide local sports examples
  - talk about the movement of people or animals
  - ask students about situations where the word frequently could be used
  - discuss sickweather.com or other live pattern tracking sites (selecting one that they might have seen in another class can help build cross-curricular connections)
  - mention daily schedules
  - identify specific criminal behavior as a pattern
  - reference a recent pattern revealed in the news

- During brainstorming, students (especially perfectionists and high performers) get discouraged when they can't think of the *perfect* idea. Make sure to stress the idea that we are doing high throughput brainstorming—if you have 100 possible topics, you will like one. The important thing to remember is quantity. If students develop ideas in general fields of interest, they will be able to narrow their ideas later. They may just notice a particular subcategory they want to read up on. This is very early in the process.
- Students interested in specialty areas (ex. genetics), might not be able to narrow their focus without some background reading. The brainstorming process is still important because it will help them focus the areas they have to read about.
- If you want students to see the how to update the matrix, you could task students with adding ratings for projects by other groups. They will easily be able to see how reactive the table is. If you have students add in comparisons, highlight the fact that criteria are set before building and decision making begins; decisions are fit to the data.
- If you have some students who struggle with Excel, and some who excel with Excel, you can have some students:
    - Start homework
    - Set up a matrix for later use
- Students should be clear that if they are planning an engineering project, they will need at least one decision matrix.
- Feel free to modify the example table to stress points that are confusing in your specific classroom; not every group gets stuck on the same ideas.

Lesson 4: Brainstorming for projects of interest (mind mapping)

Overview of the Lesson: What will students be doing? *Students will begin to brainstorm ideas for their own projects using mind mapping. They will learn how good ideas can come from the intersection of related information.* **Time (minutes): 60**
Standard(s): What standards will be the focus of the lesson? • HS-ETS1-2. Break a complex real-world problem into smaller, more manageable problems that each can be solved using scientific and engineering principles.
Essential Question(s): What essential questions will be addressed in this lesson? • How do you move from a field of interest to a project? • What topics can projects focus on?
Science Objectives • Students will develop a list of possible projects. • Students will see how different perspectives can lead to interesting ideas. • Students will begin to clarify their interests.
Language Objectives and/or Targeted Academic Language • High throughput screening, knowledge gap, mind mapping
Anticipated Student Pre-conceptions/Misconceptions • All of the important problems in the world have been solved. • Students can't solve important problems. • Ideas are linear. • The right project will come to you immediately. • Students need a teacher, parent, or mentor to provide a project idea.
Instructional Materials/Resources/Tools • **Targeted Brainstorming Worksheet** • **IntroEngineering Powerpoint (see folder for Lesson 2)**

- Optional extra teacher reading
  - Information on how to make a mind map by mindmapping.com: http://www.mindmapping.com/
- Recommended Teacher Pre-reading
  - Preventing car-reindeer collisions in Finland (in lesson)

Assessment: How will you know that the students got it?

- Students will be able to develop a list of mind mapping requirements.
- Students will be able to contribute ideas to mind maps for peer projects.
- Students will be able to combine pie diagrams and mind mapping (homework).

Science and Engineering Practices included (put the included ones in bold):

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 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

Opening/Engagement: Introduction to brainstorming
Time (minutes): 10

1. **Make sure that every student has some ideas of interest—ask for a few examples.**
2. **Discuss the idea of high throughput screening. Use topics they are familiar with (ex. taking hundreds of photos and posting two). Then mention that this technique can be used for drug discovery: by testing thousands of samples, you increase your chance of finding something interesting. Let students know we will be generating *a lot* of ideas (high throughput idea generation) so that each person can find one to pursue. Make sure to highlight the following:**
   - *You don't have to love every idea.*
   - *An idea you don't want to pursue may lead you to think about a related topic that you do want to pursue.*
   - *You can't solve every problem and answer every question. If a topic seems giant and daunting, pause and look for a small piece you can take on.*
   - *You may not know enough about your topic to frame a question right now. That is okay. Developing a good project requires a lot of background reading [you might want to ask students why this is].*
   - *Remember that this class will use Set Based Design. When you put together your procedure, you will need to think about alternatives for each possible roadblock. If a bunch of related ideas occur to you, write them all down! You will be saving these ideas, and they may come in handy later in your project.*
   - *When you help your peers brainstorm, imagine what feedback you would want if it were your project.*

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During the Lesson: Mind mapping
Time (minutes): 40

3. **An introduction to mind mapping can be found in the IntroEngineering PowerPoint. Work through the reindeer example. Ask students what else they could add to this map. Then, have them come up with a list of guidelines for building a mind map.** *(10 minutes)*
    - **Background on preventing car-reindeer collisions in Finland:** There are approximately 300,000 reindeer that roam around the wilderness in the Lapland region of Finland. There are an estimated 4,000 reindeer road deaths. These accidents also pose a risk for drivers and passengers involved in collisions. Multiple attempts have been made to increase safety. For example, one group tried putting reflectors on the reindeer. According to the Finnish Reindeer Herders' Association, Anne Ollila, "Drivers often mistook reindeer with reflectors for people in the dark, thinking they wouldn't run into the middle of the road when they saw car headlights approaching… and the deer would tear the reflectors off." Reindeer warning signs were frequently stolen by tourists. In 2014, a new approach was tried: coating the reindeer's antlers with fluorescent paint. There were many problems associated with this approach including the need to capture and release individual reindeer. Furthermore, the reindeer would scrape the paint off. In 2016, the Finns began a new pilot project: a reindeer locator app. A thousand drivers were given handsets to identify reindeer. The app would then warn drivers if reindeer had been reported in the area. Animal-vehicle collisions are a problem all over the world. This particular example was chosen because it is unlikely that a student is brainstorming a reindeer-related project.

Source (note: the Huuhlanen article was available through the AP; it is present on a lot of different websites with slightly different pictures).

Huuhlanen, M. (2016, June 8). *Glowing antlers failed, so Finns try app to save reindeer.* AP News. Retrieved from: https://apnews.com/801aa30308b24b459251c60d569df33c/reindeer-herders-finland-launch-app-reduce-road-kills

- **What should you look for in the list of mind map guidelines?**

1. This technique will help you narrow your focus
2. Ideas are not necessarily linear; ideas flow from one to another
3. You can build on anything on the page
4. You can keep going indefinitely
5. Some ideas are very specific, others are very vague
6. You can both ask and answer questions
7. If you can't think of a solution, ask a question, identify a knowledge gap, suggest materials, or list possible resources
8. There is no wrong answer
9. They should take this seriously; joke ideas don't give you a lot to work with [this one may not come up during this exercise, but it may during mapping itself]

4. **Trying an example mind map: there are several good approaches. The goal of this exercise is to have students practice mind mapping. They should get a sense of the pace, type of ideas, and general process.** *(7 minutes)*
   - Have the class choose one of these topics, put it on the board, and build a mind map together.
   - Have tables take a paper with one of these ideas. Have groups build a mind map together.
   - Have groups stand at the board (space permitting) and work through a few of these topics. Rotate students after a few minutes (or set up a rotation pattern: add an idea to one, move to the next).
   - Set up groups of 3-4 students. Give them a large paper. Have each student write an idea in one quadrant of the page. Have the group rotate the paper. Each student will have to contribute ideas for each quadrant.
5. **Mapping student ideas** *(10 minutes)*
   - On a large paper, have students start write down 2-4 of their topics of interest. If students just write the main idea (ex. Security), they may get upset when the topics do not match what they are really interested in. Encourage students to include 2-3 subcategories around the main area of interest. [note: have them write their names too!]
   - Have students pass (or rotate) the papers. Every student should be getting feedback from peers.
6. **Mapping check-in** *(13 minutes)*
   - Get the maps back to the original authors. Allow authors a few minutes to read through the commentary.
   - Give authors the chance to add to their own mind maps. Let them know that they can add requests for more information. For example:
     1. Where can I find materials for this?
     2. Do you know of anyone working in this area?
     3. What problems could occur in this field?
     4. How could I collect data?
     5. What data would I need to gather?
   - Have students pass the maps around again.

Lesson Closing: Mapping with discussion
Time (minutes): 10

7. **Give students back their maps. Have the students sit in groups of 3-4 students each. Ask students to discuss their ideas as they continue mapping.**
8. **Homework**
    - Have students collect the **Targeted Brainstorming** as they leave the class.

Instructional Tips/Strategies/Suggestions for Teacher: What other ideas would you like to highlight? What grouping strategies are important? What are adjustments for struggling learners, enrichment, or for students who are English Learners?

- Students often want to try techniques they have read about online. It is not always possible for students to get access to the cutting-edge tools they are interested in (like CRISPR). It can also be challenging for students to understand how long projects take; papers make research sound easy, but some papers take years to produce. Encourage Set Based Design. If students use Set Based Design, they can easily transition from an idea that is not working to an alternative option. Developing a set of ideas also helps prevent students from stopping at the first semi-viable idea. Later in the project, when students get stuck, ask them to reference the set of alternatives.
- At the earliest stages, most projects will need to work on scope (reading and timeline planning will help with this). See the example below:
    - Student plan: I would like to do CRISPR to see what would happen to adult flies who experience this mutation.
    - Ask the student if it is the tool they are interested in OR the outcome for the flies. Have they thought about alternatives that could answer their questions (or tangential questions)? Ask the student to brainstorm possible roadblocks and alternatives that would bypass those roadblocks.
        - Secondary plan: I will check fly libraries for existing mutants and use these flies in my experiment.
        - Tertiary plan: I will use BLAST to determine if any organisms already have this mutation. I will use a computer program to model how this mutation would be perpetuated through a target population.
        - If the student starts working on one idea, set a time to check in and shift to another idea if needed.
- If students know they are interested in a tool rather than a question (ex. artificial neural networks), it will be very difficult to brainstorm. Encourage these students to identify other interests and look for ways their tool of interest overlap with this topic. Projects require a lot of time; students who have more connections to their project tend to enjoy the process more.
- Using markers or colored pencils during mapping helps students track down individuals for follow up questions—ex. what does this mean? It will also help you if you need to identify who wrote an off-topic comment. A different way of tracking ideas is to use the website www.coggle.it. Coggle is a free mind mapping program that you can access through google. You can comment on different pieces of information, add pictures, and share with friends. You could have students share within a group. This tool can also be used later in the year if students want to communicate work flow in other projects.
- Some students identify the discussion as the most helpful part of this exercise. It is particularly helpful for students whose interests are nebulous, auditory learners, and for students whose mapping prompt was confusing to their peers.
- For students who want to work on a high-level project, caution them against writing a jargon heavy prompt. Some students think if a peer can't understand it in advanced words, that peer has nothing worthwhile to offer. Remind students that part of receiving good feedback is asking good questions. Have them write in simple terms. I often tell kids, anyone who picked up

that paper should be able to contribute. If we were to grab a random person walking through the hall, they should be able to write a useable idea.

- Mapping can sometimes spread over several classes—students often refocus ideas after they get the first round of feedback. On the second day of mapping, provide more structured ideas for contributions:
  - Have students take a minute to write down 1-4 new questions, directions, or topics for a mapping activity. These topics can be from the pie diagrams, the mapping exercise, the hybrid pie diagram-mapping homework, the notecard, or something totally new. If a topic is the same as the previous class, have the student add some sub-topics or possible directions they would like feedback on.
  - Ask students to imagine each one of these maps is for their own project. Ask them to think about how to make that idea into a project. What would they need to know? What pathways are possible?
- Students are sometimes self-conscious at the beginning of this exercise. Make sure to highlight that even if students are not contributing the exact idea that someone will pursue, they may start a chain of thoughts that lead to the final project.
- Some students come into a brainstorming exercise with a clear view of what they want to do. The students with a clear path should be encouraged to add to their own initial ideas so that they request additional information. For example, if someone is set on doing a project with molecular modeling a particular protein, that student might feel that no one in the class has ideas to offer. Encourage that student to (1) not use jargon on the mind map (2) highlight a specific area to learn more about (3) highlight a problem that needs to be solved (4) ask students to identify helpful resources (5) ask students to predict roadblocks.

Lesson 5: Brainstorming for projects of interest (fishbone diagrams, VOC, 5-Whys)

Overview of the Lesson: What will students be doing?

Students will learn how to use a common problem identification and Root Cause Analysis tool (the fishbone diagram). Students will also learn how to use the LAMDA cycle to perform investigations. As part of the LAMDA discussion, students will learn how to ask questions that can capture the Voice of the Customer. Students will also use a script to model the 5-Whys, and discuss two main uses of this technique (finding specific causes, obtaining diverse background information).

Time (minutes): 60

Standard(s): What standards will be the focus of the lesson?

- HS-ETS1-2. Break a complex real-world problem into smaller, more manageable problems that each can be solved using scientific and engineering principles.
- HS-ETS1-3. Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, aesthetics, and maintenance, as well as social, cultural, and environmental impacts.

Essential Question(s): What essential questions will be addressed in this lesson?

- How do you narrow the scope of your project?
- How do you solve problems?
- How do you find the root cause of a problem or failure?
- How do you use fishbone diagrams?
- How do you use the 5-Whys to gather information?
- How are priorities used to direct a project?
- What is a project charter?

Science Objectives

- Students should see observed problems as symptoms of the root cause.
- Students should be able to design a fishbone diagram and use the 5-Whys to look for root causes.
- Students should see how a successful project can focus on one aspect of a problem; they don’t need to solve every related issue or answer every related question.
- Students should see how STEM projects can arise from the cross section of interests.
- Students should understand that clear goals, technical specifications, focus, and scope are essential for a successful project.

• Students should understand the importance of testing subsystems before completing a project.
Language Objectives and/or Targeted Academic Language • Fishbone diagram, 5-Whys, Voice of the Customer (VOC), Root Cause Analysis, LAMDA, subsystems
Anticipated Student Pre-conceptions/Misconceptions • It is impossible for a student to identify or fix a major problem. • There is only one way to solve a problem. • There is only one cause of a problem. • When you are trying to problem solve, the first thing you test will work. • Schedule is not important in project design. • You can only test a completed device.

Instructional Materials/Resources/Tools
• **5Whys script**
• **Fishbone Diagram Worksheet**
• **IntroEngineering PowerPoint (see folder for Lesson 2)**
• Optional teacher pre-reading:
  o Information on using a fishbone correctly from ASQ: http://asq.org/learn-about-quality/cause-analysis-tools/overview/fishbone.html
  o Information on fishbone diagrams from MoreSteam: https://www.moresteam.com/toolbox/fishbone-diagram.cfm
  o Comprehensive information on the 5-Whys method from Buffer**: https://open.buffer.com/5-Whys-process/**
  o Information on the 5-Whys (and how they relate to fishbone diagrams) from iSixSigma: https://www.isixsigma.com/tools-templates/cause-effect/determine-root-cause-5-Whys/
• Recommended teacher pre-reading:
  o This lesson plan contains teacher background information on fishbone diagrams, the 5-Whys, LAMDA, and the reasons the Vasa sank. This information will be helpful for lesson preparation.

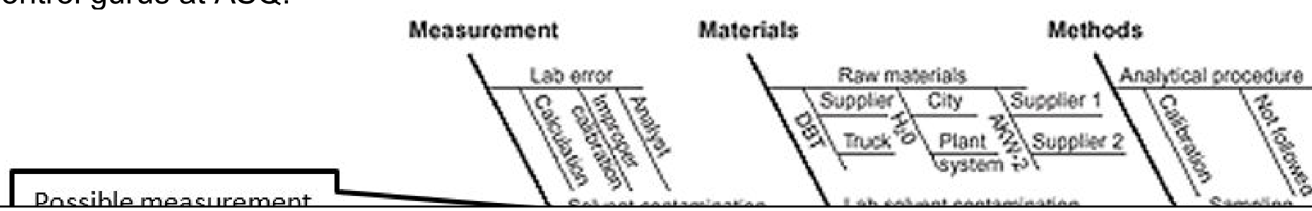
Assessment: How will you know that the students got it? • Students will be able to contribute to fishbone discussions. • Students will be able to populate fishbone diagrams. • Students will be able to extrapolate from fishbone diagrams to possible project ideas.
Science and Engineering Practices included (put the included ones in bold): **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 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**
Day 1

Opening/Engagement: Check in and quick idea capture
Time (minutes):20

1. **Inform students that you will be moving on to a new brainstorming technique called the fishbone diagram. Open the IntroEngineering PowerPoint to the appropriate location and introduce the topic.** *(5 minutes)*
    - **Background information:** The fishbone (or Ishikawa) diagram was invented by a Japanese man (Kaoru Ishikawa) interested in quality control. A wide variety of fields currently use this tool to identify possible causes for problems. Brainstorming with a fishbone diagram is particularly helpful for teams who tend to get stuck on one idea. The observed problem is placed at one side of the chart. This problem is considered the symptom of the real problem. It is generated by some unknown cause. Most people talk about fishbones in terms of cause and effect. An arrow leads to the effect. The group will brainstorm possible causes and place them along the arrow. In general, problems fall into the 6 Ms:
        1. Measurement
        2. Materials
        3. Method
        4. Man (or Manpower or People)
        5. Machine
        6. Mother Nature (or Environment)

If you think of a problem, the cause is generally in at least one of these categories. Using a fishbone diagram forces individuals and groups to consider causes that might have been outside of their initial focus. For example, a group might be stuck reworking a procedure they "know" is not working. The real problems might not be related to method. If the group builds a fishbone diagram, they are forced to think outside the box. As the group begins to fill in the fishbone, they may develop ideas related to contamination, moisture, or imprecise measurements. These possible causes can inspire new ideas. For example, if one person suggests that the problem came from a metal plate in a device, another person might suggest that the metal plate was too thin, composed of the wrong metal, or corroded. These ideas can be included in the fishbone diagram too—they branch off the cause they are associated with. Here is an example fishbone diagram prepared by the quality control gurus at ASQ:



This tool is generally used as part of a process called Root Cause Analysis. For school projects, fishbone diagrams are particularly good at pushing students to think of multiple possible causes. For science fair projects, you can use this technique for a secondary purpose: topic selection. If a student is interested in a topic, problem, or question, they should use the 6 Ms in a fishbone diagram to diversify the causes they consider. The other brainstorming techniques we have tried focus on developing a wide range of ideas. Fishbone diagrams produce a range of ideas, but topic generation is more focused. Students are forced to think about topics in terms of real-world considerations (ex. in what ways does the environment influence this topic?).

Students (and engineers) often have trouble with scope. A student who is planning a giant project can use this tool to identify one or two possible causes to investigate. Remember, we follow Set Based Design principles. A student can establish the minimum viable product—for example, they can decide a successful project will address one possible cause. They can choose two or three additional causes to investigate *if they have time*. Keep in mind that this tool was not initially made for science fair project selection. Students might get an inkling of an idea from this tool and then revisit one of the other brainstorming techniques and the available literature to really nail down a topic.

Source:
Fishbone (Ishikawa) diagram. ASQ. Retrieved from http://asq.org/learn-about-quality/cause-analysis-tools/overview/fishbone.html

2. Building a fishbone: On the board, assemble a fishbone diagram for untuned bagpipes. Have the class contribute ideas for the diagram. Then take a look at the fishbone provided. Highlight how this information could be used to move a project forward. A student project can't fix every possible problem, but it could certainly take on one or two possible causes. The projects that come out of a fishbone could involve researching possible cause-effect relationships (a science project), or solving a related problem (an engineering project)

During the Lesson: Introducing the Vasa
Time (minutes): 25

3. **Introduce the problem of the Vasa**
   - Discuss the idea of a project charter (use the design slide). Highlight the problem statement, engineering goals, and priorities. The problem statement should NOT mention a solution. It merely conveys the problem. The Engineering goal is where the general approach to solving the problem is specified. Highlight that, in this case, cost was not a priority; time and power were the main priorities. Let students know that keeping a list of top priorities will help make decisions easier. For their project proposals, they should have to provide a ranked list of priorities. Priorities are not the same thing as project specifications. Priorities are what is important to you, specifications detail measurements and counts.
     1. Note: Project charters often include scope (what is included in the project and what is excluded). This charter presented here is a simplistic version intended for this introductory exercise.

Give students 10 minutes to generate a fishbone diagram of possible causes for the sinking of the Vasa.

Lesson Closing: The Vasa
Time (minutes): 15

4. **Ask students to identify possible causes.**
5. **Discuss why the Vasa actually sank and brainstorm a list of lessons for the future.**

ckground information—There are many factors that contributed to the Vasa disaster. Here are some of the main problems:

- Specifications for the Vasa were unclear and frequently changed. The building process was funded by the Swedish king Gustav II Adolf. He was off fighting a war in Poland. Whenever an idea would occur to him, he would send the ship builders requests for additions and changes. Major changes continued to be made even after building began. One major change required the 111-ft version of the Vasa to be scaled up to 135-feet. Because construction had already begun, the shipbuilders just added to the existing profile. The keel for this longer boat was too thin for such a large boat. In fact, the keel was so thin, additional support beams were added inside of the hold. The change in length elevated the center of gravity because the keel was neither deep enough nor heavy enough for such a large ship. Boats are extremely sensitive to the location of the center of gravity. If the boat is too top heavy, it will heel (tip) over. The problem with the Vasa's high center of gravity was exacerbated by the fact that the timbers used to brace the keel blocked some space normally occupied by ballast. Ballast is the additional heavy material added to a boat the help lower the center of gravity and thereby stabilize the boat. Another change requested during the build required the boat to be wider; this change was made after the bottom of the boat was built, so the additional width was only applied to the top of the boat. This unique profile contributed to the top heavy nature of the design. Ballast would normally be used to bring the center of gravity down, but the bottom of the boat was too narrow to accommodate extra ballast. Yet another request further elevated the center of gravity: the king heard that the Danish navy had a boat with an innovative new design including two enclosed gun decks, he decided that the Vasa should have the same. The shipwright, Henrik Hybertsson, had never built a ship with two enclosed gun decks before. Hybertsson made the decks extra heavy to help support the weight of the guns. The weight of the decks (and the additional guns) further elevated the Vasa's center of gravity. The top of the boat was made even heavier when the king requested ornate wooden sculptures be added to the boat. The choices made during the design of the Vasa culminated in an exceptionally high center of gravity. Less than a mile from the dock, a slight wind caused the boat to heel over. Analysis done after the Vasa was recovered in 1961 indicated that the high center of gravity was one of the main causes of the disaster.

When a boat is built today, many subsystem tests are performed. Calculations are done to identify the center of gravity and predict the relative stability of the boat. At the time when the Vasa was built, such calculations and tests did not exist. Many boats heeled over and sank in the 17th and 18th centuries because of this cross-your-fingers-and-hope approach. Although no one tested the seaworthiness of the Vasa before the build was complete, we know that concerns about the stability of the ship were clear before the boat set sail. The captain of the ship (Söfring Hansson) called Vice Admiral Klas Fleming to the Vasa prior to the launch date. The captain asked 30 men to run across the deck so that the Vice Admiral could see how dramatically the boat swayed. The men ran across the deck three times. They were asked to stop because of fears that the boat would capsize. The king was in Poland fighting the war, and Fleming didn't want to tell him that the most expensive ship of its time was not seaworthy. He ordered the launch to continue as planned.

Additional project management failures existed during the building of the Vasa. The original shipwright (Henrik Hybertsson) died during the course of construction and his assistant (Hein Jakobsson) took on the project; there were no written plans to follow. During Hybertsson's illness, communication was poor, so division of labor, schedule, and requirements were unclear. There were four hundred people split into five main groups who were working on the hull with little oversight. An archaeologist, Fred Hocker, found four different rulers used on the boat: two rulers used Swedish feet (12 inches), two rulers used Amsterdam feet (11 inches). Because different systems of measurement were used by different carpenters, the boat was asymmetrical. The port (left) side of the boat was heavier than the starboard (right) side. When it sank, the Vasa tipped towards the heavier side.

- Lessons from the Vasa that can be applied to student projects
    1. Write clear goals before starting a project
    2. Write clear technical specifications
    3. If the focus of the project changes, review scope changes with a teacher/mentor
    4. Test parts and subsystems before assembling the whole project
    5. Periodically step back and evaluate where you are in relation to your overall goals; it is very easy to get stuck in day-to-day tasks and lose sight of big objectives

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6. **Homework:** Hand out the **Fishbone Diagram** worksheet. Students should fill in three fishbone diagrams for possible projects of interest. They should further identify 3 possible projects from each of those diagrams. Provide students with an example (ex. if you were considering the Vasa, a project could involve investigating keel designs on scale models, or computer modeling to find out which design choices had the greatest impact on seaworthiness).

CAPE COD REGIONAL STEM NETWORK

Day 2

Opening/Engagement: Check in and quick idea capture
Time (minutes): 10

7. **Have students take out the notecard from Lesson 3. Ask students to share one pattern and two annoyances with a neighbor. Ask the class if any interesting topics came from the notecard**.

During the Lesson: Moving towards projects
Time (minutes): 40

8. **Have students develop a fishbone with at least 5 possible causes for one of the topics on the notecard. Have a random problem for students who forget their notecards.**
9. **Introduce the idea that asking questions can help resolve some of the unknowns and lead to possible projects. Use the Vasa as a model. Generate at least four feasible Vasa-related project ideas. Then try brainstorming projects from the bagpipe example.**
    - This topic was selected for several reasons: it is a problem that can be quickly understood, it is unlikely to be a topic students are considering for their own projects, and students will be exposed to the idea that you have to do some background research before a project can begin.
    - When you work through the first problem (bagpipes are frequently out of tune), ask students what they would do if it were their project. Get students to come around to the idea that if in order to solve a problem, they need to understand it. They need to talk to people who deal with the problem, and observe it happening.
    - In Engineering, this investigative process is called capturing customer interest or capturing the Voice of the Customer (VOC). The customer may be an individual (if the product is for one person or animal), or a group of people (or animals). Capturing the VOC helps identify areas of concern and set important criteria. For science projects, you can also talk about the VOC. The terminology changes a little bit for scientists. However, students who do science projects are often asked why they chose the project. Why should we care? What is important about this work? Who would be influenced by these findings? For students interested in science projects, they may need to define their VOC from existing literature rather than interviews and discussions. However, all STEM projects begin with this general concern. Make sure to ask students why they chose a particular project. The answers should include an element of initial interest, but the specific focus should be driven by some data or observations (the VOC).
    - LAMDA: This technique is used by many engineering companies. Having a poster of these stages is a nice addition to a classroom. The class can reference the part of the process they are engaging in at any given time.
        1. **L**ook: Practice first-hand observation
        2. **A**sk: pose probing questions to get to the heart of the issue (ask why 5 times, check existing literature)
        3. **M**odel: Use engineering analysis, simulation, or prototypes to predict expected performance
        4. **D**iscuss: Talk about observations, models, and hypotheses
            - Mention the written and verbal components of the project

5. **A**ct: Take action to validate what you have learned
    - Let students know that you will discuss validation later but that it should involve some form of mathematical/statistical proof of success

- **The 5-Whys:** Have students model appropriate and inappropriate use of the 5-Whys. The appropriate use of the 5-Whys requires you to use information from each answer in asking your next question. Have two volunteers model both interactions. Use the famous example by Taiichi Ohno, former executive vice president of Toyota Motor Corporation, the bagpipe related example provided in the **5whys script**, or an example that is pertinent to the class. If the script is used, do a quick follow up activity with a major world issue (ex. people are dying of respiratory disease). See if students can use the 5-Whys to collect a bunch of possible causes. Then act as a specific patient with respiratory disease. See if students apply the 5-Whys differently.

Background information: Many industry professionals believe that for every problem, you should ask why five times. This process will help you work backwards from the initial complaint/observation to the actual cause of the problem. If you can figure out the actual root cause, you can work on that topic rather than some downstream observation. Sometimes students (and engineers) are skeptical of the usefulness of this tool. If the 5-Whys is applied incorrectly, it can lead to a toddler-esque interaction where the investigator repeatedly asks ‘but why’ when faced with a simple statement. For the 5-Whys to work, the investigator needs to clothe the question in context. The investigator should note key words from each answer to see if they can follow up on particular nuggets of information.

For student projects, there are two main places that the 5-Whys can be applied. The way this tool is used is slightly different in both scenarios.

1. Collecting information about a diverse group of problems. In this scenario, the student is using the 5-Whys to gather as much information as possible about a broad problem. This approach can be especially helpful for brainstorming and capturing the VOC.
    - For students doing science projects, this process focuses heavily on existing literature; they need to determine what is currently known, what gaps in knowledge exist, and why it is important to fill these gaps. These students can also focus the 5-Why approach on model systems. They should ask why a model system is good and why it is preferred over the alternatives. For these students the ‘customer’ may be difficult to define; have them focus on why the world should care. By focusing on a specific area, the student will be able to clarify the impetus for their work. If these projects will go to a science fair, determining why the world should care helps students structure their posters and talks.
    - For students doing engineering projects, this process focuses heavily on existing problems. These students need to identify problems to solve. They need to determine if they are genuinely solving a problem or addressing a tangential issue. If the project is intended for a specific group of people, consider surveys, in-person interactions, and emails. If the project is meant to address a large group of people (ex. a project working on image compression), students will have to look at a wide range of contributing factors. Some students may use surveys to collect some background information. Remember that surveys for science fair

projects must be approved by the IRB and the SRC. The engineers will also need to do background reading to understand the underlying information and work in their field of interest.

- Encourage students to begin asking/answering the 5-Whys with existing literature. As part of this process, consider adding a class on how to contact corresponding authors, patent holders, or individuals in the target field.

2. Solving a problem mid-project: in this scenario, a student has hit a roadblock. The cause of the problem needs to be understood before it can be resolved. The student should ask why the problem occurred in the first place. Merely thinking about the problem is not working. The student should identify where the process broke down. By asking why five times, the student should be able to work back to the root cause of the problem. Rather than creating a work around, the student should try to fix the real problem. If the student is too focused on one possible contributing factor, encourage the use of a fishbone diagram. By encouraging the student to think of the different categories (Man, Machine, Mother Nature, Method, Materials, Measurement), you could help identify the real root cause(s).

Sources

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- 5-Why examples:
  a. Taiichi Ohno Example taken verbatim from Ohno, 2006.

He used the example of a welding robot stopping in the middle of its operation to demonstrate the usefulness of his method, finally arriving at the root cause of the problem through persistent enquiry:

i. **"Why did the robot stop?"** The circuit has overloaded, causing a fuse to blow.
ii. **"Why is the circuit overloaded?"** There was insufficient lubrication on the bearings, so they locked up.
iii. **"Why was there insufficient lubrication on the bearings?"** The oil pump on the robot is not circulating sufficient oil.
iv. **"Why is the pump not circulating sufficient oil?"** The pump intake is clogged with metal shavings.
v. **"Why is the intake clogged with metal shavings?"** Because there is no filter on the pump.

b. Bagpipes examples (Example 1: incorrect use of method, Example 2: Broad information gathering, Example 3: Specific root cause identification) [NOTE: If you want to print these scripts for use in class, use the **5whys script** file]

i. Using the 5-Whys incorrectly: Model 1

When you lead discussion, make sure that students grasp the importance of rephrasing the "why" as a targeted question. Consider drawing parallels to babysitting young kids—students should be able to see how this approach could lead to the customer equivalent of "because I said so."

i. Using the 5-Whys for general information gathering (early in the VOC capture, for a large group of possible customers, or if scope is not yet determined): Model 2 When you lead discussion, make sure that students grasp how the 5-Whys can be used to fish for more information. This approach is especially helpful at the start of the project, or when a student is facing a problem that completely new. ii. Using the 5-Whys to identify the specific cause for a specific problem: Model 3 If a student is working on a narrow problem (a specific failure point in a procedure, a product for a specific customer), the 5-Whys can help the student discover the specific root cause for the specific problem.
Instructional Tips/Strategies/Suggestions for Teacher: What other ideas would you like to highlight? What grouping strategies are important? What are adjustments for struggling learners, enrichment, or for students who are English Learners? ● Fishbone diagrams can also be helpful in planning for English and History papers. This diagram can be used to capture the evidence before students construct an argument. Students can use the fishbone to develop a thesis and select supporting information. If you find this diagram helpful, talk to a colleague in the humanities to see if it can be used there as well. Another way for English teachers to use this tool is for brainstorming for narrative essays (like the college essay); it can help students contextualize an experience they want to describe. Using the same tool in different subjects may be especially helpful for struggling learners. ● Struggling learners may need several additional examples for how to move from a fishbone diagram to a project. ● Some students get stuck if they try to identify a cause from each of the six categories. For advanced students, encourage them to get at least one thing for each branch of the fishbone. However, for struggling learners, merely sorting ideas may be a helpful use of this tool. ● Another way to help struggling learners is to change the bagpipe example; use something they are familiar with. As a class, you can choose a topic of interest.

Lesson 6: Moving from idea to procedure

Overview of the Lesson: What will students be doing? *Students will learn how to begin a project. They will begin by extracting project planning lessons from the Vasa disaster. The class will then focus on knowledge gaps in planning a project. Students will gain an appreciation for the importance of existing literature. The notes file is presented as a way for tracking information acquired over the course of the project. Individuals will narrow possible projects to three ideas.*

CAPE COD REGIONAL STEM NETWORK

Time (minutes): 60
Standard(s): What standards will be the focus of the lesson? • HS-ETS1-2. Break a complex real-world problem into smaller, more manageable problems that each can be solved using scientific and engineering principles.
Essential Question(s): What essential questions will be addressed in this lesson? • What lessons can be learned from a failed project? • How should information be preserved so that it is searchable, editable, and clear? • What should you think about as you hone in on your project idea?
Science Objectives • Students should understand common project roadblocks. • Students should understand what knowledge gaps are and what resources are appropriate for filling those gaps. • Students should understand that the main ideas for the project should come from within; asking for help with a knowledge gap is different than asking someone to design an entire product or experiment. • Students should understand that they need to pre-read or pre-test before searching for a subject matter expert; they should talk to the expert with a list of logical questions. • Students should collect data on possible projects to make an informed decision about which project to pursue. • Students should start thinking of data analysis as an important part of the engineering and research process.
Language Objectives and/or Targeted Academic Language • Project proposal, knowledge gaps, subject matter expert (SME), patent
Anticipated Student Pre-conceptions/Misconceptions • After they choose a project, someone will give them a procedure. • Engineers go directly from ideas to prototyping. • It is better to prioritize ease of project over interest in project.
Instructional Materials/Resources/Tools • Homework due: **Fishbone Diagram Worksheet** • **Preplanning Worksheet** • **Initial Plan Worksheet** • **Project Notes Demo** • **IntroEngineering PowerPoint (see folder for Lesson 2)**

Assessment: How will you know that the students got it? ● Students will develop a rough proposal for their projects. ● Students will create a notes file to track reading, information gathered, and problems solved.
Science and Engineering Practices included (put the included ones in bold): **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 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**
Opening/Engagement: Discuss proper project approaches **Time (minutes): 10** **1. Revisit the story of why the Vasa actually sank. Background information is available in Lesson 5.** **2. Review or generate a list of lessons to be learned from the Vasa disaster. The following are good examples:** ▪ Write clear goals before starting a project. ▪ Write clear technical specifications. ▪ If the focus of the project changes, review scope changes with a teacher/mentor. ▪ Test parts and subsystems before assembling the whole project. ▪ Periodically step back and evaluate where you are in relation to your overall goals; it is very easy to get stuck in day-to-day tasks and lose sight of big objectives. ▪ Don’t take on a project that is too large.
During the Lesson: Narrowing project focus **Time (minutes): 47** **3. Work through the pre-proposal planning worksheet together.** ○ Have students fill in questions 1-3 (so that their goals start become clearer) (*7 minutes)* ○ Have students fill in the general topic and possible projects for three different possible projects *(5 minutes)* **4. Discuss what knowledge gaps are, how to identify them, and how to fill them** *(10 minutes)* ○ This discussion can be a simple conversation, or the **IntroEngineering** PowerPoint can be used to highlight specific areas. Students often think that experimentation is the only way to fill a knowledge gap; information can be obtained from a variety of sources. If a PowerPoint-free discussion is selected, make sure to highlight different ways to fill knowledge gaps:

- **Reading—**highlight the need for technical articles, patents, common databases, and records of what was read
- **Subject matter experts (SMEs)—**you can contact authors, people in your field, teachers, students who did similar projects in past years (ex. fly care is always the same even if you are asking a different question using your flies)
  - Make sure to clarify the border between asking targeted questions and asking someone to design too much.
- **Practice—**you can use this to develop a 'check sheet' of common problems
- **Testing—**you need statistical proof for any claims

- Remind students that their research needs to contribute something new to the existing body of knowledge; they cannot repeat a previous experiment

5. **How to keep a record of sources and knowledge gaps** *(12 minutes)*
   - Introduce the notes file as a way to track what you have learned. Highlight that a typed file will be good for several reasons.
     - First, a file is easily searchable. To make it even easier to find what you are looking for, add keywords you want associated with each source.
     - Second, you will have everything at your fingertips when you write up your project. Adding the knowledge gaps section will make reviewing for the project even easier.
     - Third, it is harder to lose than a paper.
   - Warnings about the notes file:
     - Clearly identify any quotes (that will help you avoid plagiarism if you write from the notes later)
     - Including a citation section for each topic will make writing up much easier. There might be resistance to doing this as the project proceeds.
     - If students use any fields (ex. Table of Contents), they will need to update the field before printing or electronically submitting work.
     - Students do not usually see the usefulness of generating the list of search terms. Highlight this as a good practice. Use review articles and meta-analysis as evidence.
   - Show students the example notes file. Let them know when they will be expected to develop one of their own.
   - Warning about knowledge gaps: asking someone to read over a procedure is different than asking them to write a procedure. Students are expected to design and perform their own tests. Make sure to model a few quick examples of correct/incorrect use of resources
     - Asking an engineer to help brainstorm possible causes of a problem (correct—if you first research the problem and later credit the engineer in your notes, papers, and presentation)
     - Asking an engineer how to build your device (incorrect)
       - It is better to talk to this subject matter expert with notes in hand—ex. a draft of the circuit you plan to use, a list of safety considerations, an analysis of the materials you have, a scaled drawing of your intended device, a list of priorities, a project charter, a decision matrix
       - Consider asking them for good resources for problem solving in the field.
6. **Have students complete the Preplanning worksheet.** *(13 minutes)*

Lesson Closing: New homework

Time (minutes): 3 **7. Give students the <u>Initial Plan</u> worksheet for homework. Ask them to look over the <u>Preplanning</u> worksheet. They may have to fill a few knowledge gaps before committing to a particular project.**

Instructional Tips/Strategies/Suggestions for Teacher: What other ideas would you like to highlight? What grouping strategies are important? What are adjustments for struggling learners, enrichment, or for students who are English Learners?
● Consider asking students who had successful projects in previous years to serve as subject matter experts for the incoming class. This can help students find materials and resources more quickly and help them identify common misconceptions.
● Students will probably need more than one night to narrow down project ideas from three to one.
● Consider having a ‘check sheet’ check-in halfway through the project. Have students working with similar models compare common mistakes and set up ‘check sheets’
    ○ For problem solving when they are stuck
    ○ For common mistakes
This peer-driven check sheet meeting will allow students to problem solve with peers.

Lesson 7: Research and timeline planning

Overview of the Lesson: What will students be doing? Students will make more concrete plans for their own research. They will be reminded that mathematical analysis is part of any good project. They will also be introduced to two different project tracking techniques: the Gantt chart and the Kanban method. They will learn that the Gantt chart will help them understand the major portions of their timeline and the Kanban will help them plan for smaller "sprints." **Time (minutes): 60**
Standard(s): What standards will be the focus of the lesson? • HS-ETS1-2. Break a complex real-world problem into smaller, more manageable problems that each can be solved using scientific and engineering principles.
Essential Question(s): What essential questions will be addressed in this lesson? • How do you break a project into manageable parts? • How do you develop a timeline? • How do you track a project? • How do you employ Set Based Design in a project?
Science Objectives • Students will be able to break a large project down into smaller solvable problems or tasks. • Students will learn how to develop contingency plans before a project begins. • Students will learn that analysis should be planned before building or experimentation begins.
Language Objectives and/or Targeted Academic Language • Set Based Design, Gantt chart, Kanban method, ANOVA, T-test, scope creep
Anticipated Student Pre-conceptions/Misconceptions • A functional device is good enough (all claims need to be substantiated with proof). • A good project can be finished in a weekend (good projects require background reading, multiple trials or iterations, and analysis). • A project is ready to begin as soon as you have an idea (you need paperwork, safety analysis, and a detailed plan).
Instructional Materials/Resources/Tools • **Initial Plan Worksheet**

- **Schedule Example** Excel sheet
- **Scheduling and Planning Worksheet**
- Optional teacher pre-reading:
  - Information on Set Based Design from Scaled Agile: http://www.scaledagileframework.com/set-based-design/
    - "Set Based Design is a practice that keeps requirements and design options flexible for as long as possible during the development process. Instead of teams choosing a single "point" solution upfront, Set Based Design identifies and simultaneously explores multiple options and eliminate poorer choices over time. It enhances flexibility in the design process, commits to technical solutions only after validating assumptions, and produces better economic outcomes."
    - Request permission to use text and graphics: http://www.scaledagile.com/permissions-form/
  - Information on Set Based Design and project planning from Velopi: http://www.velopi.com/news/pmi-pmp-free-project-management-resource-set-based-design
    - "Project managers are supposed to plan their work and then work their plan"
  - Information on Gantt charts from Six Sigma Material: http://www.six-sigma-material.com/Gantt-Chart.html
  - Information on Kanban from Lean Kit: https://leankit.com/learn/kanban/what-is-kanban/
    - Core elements of Kanban: (1) visualize work (2) limit work in progress (3) focus on flow (4) continuous improvement
  - Information on Kanban from the Modus Institute: https://www.youtube.com/watch?v=ZYzRHH-fdf8
    - This video calls the "to do" column "options"
    - This video uses post-it notes, this lesson plan uses Excel/Google sheet
    - This video provides a nice breakdown of why you develop a Kanban and what you are thinking about as you develop the Kanban
  - Kanban note: Although this lesson calls for Kanban boards, it also employs some of the scheduling focus and "sprint" approach you would find in a different management technique (scrum). However, since scrum requires frequent project check-in meetings, and teachers are not always able to do that with all students, this lesson relies on the term Kanban. If you would like to learn more about the difference between Kanban and scrum, CPrime has a good resource: https://www.cprime.com/2015/02/3-differences-between-scrum-and-kanban-you-need-to-know/
  - Funny scrum video (good for communicating how it works to students): https://www.youtube.com/watch?v=DYMR-4nlwqU
- Optional statistics resources:
  - Types of data: http://blog.minitab.com/blog/understanding-statistics/understanding-qualitative-quantitative-attribute-discrete-and-continuous-data-types
  - ANOVA post hoc tests: http://astatsa.com/OneWay_Anova_with_TukeyHSD/
  - Poisson test online: http://stattrek.com/online-calculator/poisson.aspx

- Types of T-tests: http://support.minitab.com/en-us/minitab/17/topic-library/basic-statistics-and-graphs/hypothesis-tests/tests-of-means/types-of-t-tests/
- Correlation vs. causation: http://www.tylervigen.com/spurious-correlations

- Note for teachers: It was difficult to write this lesson because scheduling for projects can be very specific to your course and your students. In some classes all of these techniques are appropriate, in others they become unwieldy. If you are having difficulty using these techniques, consider switching to a simpler Work Breakdown Structure (WBS). Have students add their estimates for high, low, and likely time required for each item on the WBS. When they add up those numbers, they will have an idea of what is reasonable/not reasonable for a project. The author typically picks different techniques depending on the project requirements.

Assessment: How will you know that the students got it?

- Students will have logical sets of options for three major design choices.
- Students will have individual research plans.

Science and Engineering Practices included (put the included ones in bold):

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 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

Opening/Engagement: Quick check-in
Time (minutes): 5

1. **Ask students to share a brief (two sentence) project overview with their neighbors**

During the Lesson: Developing a Research Plan from the preliminary procedure plan
Time (minutes): 41

2. **Introduce the point of converting the preliminary procedure to a full-fledged Research Plan. (1) Students will gain a clear understanding of every step they will undertake (2) Students will have a written plan that can be used for Science Fair forms** *(4 minutes)*
   - Ask students to take out the **Initial Plan** worksheet and ask them to open to the procedure outline.
   - If the project is intended for entry in a science fair, this procedure can be further developed for use as the Research Plan. In Massachusetts, this plan accompanies Form 1A.

- Ask for students working with chemicals to raise their hands—tell them to circle every chemical in the outline. They will need to read the MSDS for this chemical. They need to know (1) what to do if it spills (2) what to do if it gets on their skin (3) what personal protective equipment (PPE) is required for handling each material (4) how to store the material (5) what the waste disposal procedure will be
- Ask for students who will need a space to set up their projects to raise their hands—let them know when this issue needs to be resolved by. Let these students know they will need a backup plan if this problem cannot be resolved by the target date.

3. **Set Based Design activity** *(15 minutes)*
   - Students who need space (like a lab) are not the only students who will need backup plans. In industry, professionals follow a procedure called Set Based Design. This idea was introduced in previous lessons. It is now time to apply it to specific projects.
   - Ask students to look at their preliminary procedure plan (question 5 on the **Initial Plan** homework). Have them identify three important choices they already made in the procedure or will have to make over the course of the project.
   - Give students the **Scheduling and Planning** worksheet.
   - Have students add a brief description of each choice to the worksheet (ex. sensor location).
   - Have students add three options they considered (or would consider) to the left side of the figure.
     - If students need to do some testing to make the decision, have them identify the choice with (KG) for knowledge gap.
     - If students have already made a choice, have them star the option they selected.
   - Have students narrow down the options to the two safer choices (the most likely to work). The safer choices might be less preferable for a variety of reasons (ex. the sensor costs $5 more).
   - Next, identify the safest option. This option, in your opinion, is most likely to succeed.
   - Ask students to hold on to this sheet (or transcribe it into their logbooks) and reference it when they run across roadblocks. This exercise was just an activity, but students should start to think of each choice as a branching point with multiple options. Encourage them to jot down ideas of alternatives. These ideas should go in their logbooks so that a record is preserved. Highlight the usefulness of this approach: if the project hits a wall later, some of these alternative approaches may provide the solution.
4. **Gantt chart overview** *(7 minutes)*
   - Open the **Schedule Example** Excel sheet, select the Gantt-phases tab.
   - Talk about how this scheduling format provides a clear overview of the project.
   - Mention that Gantt charts can be used to visualize items that occur concurrently and items that begin at different times.
   - Talk about backwards planning; students should look at the last date they can run experiments, give themselves a two-three week buffer, then start placing important features of the project.
   - Look at the colors used in the example:
     - **Gray**: before experimentation/building starts
     - **Red**: paperwork—remind students that paperwork will probably need to go through revisions; they may need to allot extra time (especially for behavioral/survey or chemistry projects)
     - **Blue**: phase 1--ant care
     - **Green**: phase 2—baseline behavior

        - **Orange**: phase 3—choice chamber
    - It is easiest to start by breaking a project into major phases. It helps build a global view of what needs to happen. However, it can be difficult to figure out how long to allot for a phase like 'build the prototype.' By having students break down 'build the prototype' to manageable chunks of activity, students will be better able to estimate times. The smaller chunks of activity are called "sprints."
5. **Kanban overview** *(15 minutes)*
    - Background from the scheduling handout:

The Kanban method is helpful for planning day-to-day tasks. When you think of a large-scale project, it is easy to take on 20 different tasks and accomplish none of them. If you are taking on a long-term project, you might procrastinate or feel overwhelmed. The Kanban method helps break your project up into small manageable parts.

Every project has multiple little pieces. You will have to cluster your tasks into sprints. A sprint is cohesive group of tasks (ex. learning to assemble your apparatus for a biology experiment, programming one sensor, or trouble shooting your first iteration of a program). These tasks need to be feasible within 1-2 weeks. If you think you might need three weeks for a procedure, break it into two sprints.

You will need to develop a list of the tasks needed to accomplish each sprint. The Gantt chart helps you track long term goals (like major shifts in the project). The Kanban chart helps you see what you have to do, are doing, or have done for the piece of the project you are working on.

    - Open the Kanban tab in the **Schedule Example** sheet. Highlight the following features
        - The sprint you are working on is in the first column.
        - The Kanban chart is the To do-doing-done portion of the file. At the beginning of one sprint, you put the associated tasks in the "to do" column. When you are working on one of the items, move it to the "doing" column. The "doing" column contains work in progress. If you try to take on too much, you get nothing done. The maximum number of tasks you can put in that column is three. When you finish a task, move it over to the done column.
            - Note: some people refer to the limitations on the 'doing' column as WIP Limits (work in progress limits). If you read up on this technique, include that phrase in your searches.
    - Model what happens when you move from one task to another.
        - Sometimes this chart is just updated for specific dates or meetings (ex. daily, weekly, or biweekly). A teacher can easily track student progress if it is recorded in a shared google doc, or a submitted Excel sheet.
        - Let students know what the expectation is for updating the Kanban document, meetings, and in-person updates.
    - Show students the different phases and example sprints. Ask them if they think the time allotted is reasonable. Highlight that this project tracking method is used in industry—tell them to look up Lean engineering. Students are less hesitant to use a process if it is from the 'real world.'
    - Remind students to save time for analysis. Every claim should be backed up with quantitative evidence.
        - If a plan calls for qualitative observations (like color) challenge students to come up with a scale or some other means to convert the data to a numeric value. Then, they should see if any observations are significant. Common tests for student data include: paired T-tests, Two-sample T-tests, ANOVA (don't forget the post hoc test—ANOVAs

just let you know that something was different, the post hoc test lets you know what was different), Poisson tests, and binomial distributions.

- Stress that students need to be able to justify any claims they make. They have nothing unless they have proof. They need to plan ahead to make the arguments they want to make. They should plan for future analysis now. That way, they won't need to repeat parts of their projects later.
  - Note: some engineering students have trouble with this idea. Use examples from previous years or from industry. How reliable is the device? Is it better than similar devices on the market today? How did they choose materials/lengths/layouts?
- Remind students that they need to be clear about the scope of their project before they come up with a timeline. They can avoid **scope creep** by being clear about minimum project requirements. Any possible additions are only undertaken once the initial requirements are met. Students should know what happens if they try to do too much all at once—highlight the dangers of that approach and contrast it with the Kanban sprint method.
- Remind students that it can be difficult to jump into the middle of a new field. They should intentionally schedule some time to play around with any new systems.

Lesson Closing: Generate a schedule file for personal projects
Time (minutes): 14

6. **Students schedule their projects**
   - Decide on 3-6 major project phases.
   - Put together the sprints required to make each phase a reality.
   - Build a Gantt chart with each of the sprints accounted for.
   - Remind students to leave a two-week buffer in the Gantt chart.
   - Remind students that projects approval takes longer if the committees need to consider possible health hazards (surveys, chemicals, living organisms). Students should plan to begin the paperwork as early as possible. They may want to schedule overlap with their background reading and procedure development.
7. **Homework: If students have not finished their schedule, have them finish it for homework.**
   - Let students know this file will be helpful for more than project tracking; it can be transformed into a Research Plan for science fair paperwork.

Instructional Tips/Strategies/Suggestions for Teacher: What other ideas would you like to highlight? What grouping strategies are important? What are adjustments for struggling learners, enrichment, or for students who are English Learners?

- The short-term sprint method is particularly effective for students who struggle with executive function. However, some of the high achievers might have trouble with the limitations to the work in progress portion of the Kanban method. Consider developing different rules for college prep and honors level students.
- Some students will object to scheduling. One of the most common complaints is that they can't schedule because their project hasn't been done before, so it is impossible to know how long anything will take. These students will have the

hardest time developing sprints. These students should be encouraged to practice Set Based Design—what alternatives exist? When will they shift gears to the alternative option? They could also be asked to break things down to smaller pieces—what is a reasonable amount of time to allot to sensor integration? Another extremely important consideration is how detailed the sprints are. The early sprints should have lots of detail. The later ones might branch based on observation (ex. if a student makes one particular design choice, they may switch to a different path).

- Scheduling is a challenge for programming projects. How do you figure out how long things like debugging and testing will take? These students should be encouraged to develop a clear workflow. Have them write out the three-five functions their project needs to have to be successful. These features represent the minimum viable product (MVP). They can then assign a lot of time for each of the major features. Everything else is a delighter. Projects where planning is difficult should also give themselves a larger buffer. It might be helpful for the programming students to talk to people who did similar projects in previous years. These mentors (or subject matter experts) may have good insight about time management and common roadblocks.
- If it is possible for you to meet with students about their projects, try holding the meeting with the Kanban open. Have the students explain what they are working on. Ask them if there are any roadblocks in their way. Make sure they are spreading out what they need to do. If you hold these meetings regularly, procrastination becomes less of a problem. Before you leave, the last thing to do is to glance at the Gantt chart. See if they are on track. If they aren't, identify a date by which direction change choices should be made. This approach helps students balance day-to-day and global requirements. If you do not have time to hold these meetings for every student, consider running them for struggling learners.
- Some students vastly underestimate how long certain steps will take. Read over plans to make sure that time estimates are logical.
- If you have not done much statistical analysis, check with the stats teacher (or another math teacher) at your school to see if you can include some good cross curricular content. Alternatively, you could see if AP Stats students would serve as subject matter experts; maybe they could chat with your students about choosing the right tests.
- If you have students identify their data analysis strategy from the beginning, they will have less stress at the end of the project. Using your class to highlight the concept that claims should always be justified with data will also help students more fully engage in the design process. Have your students devote a page in their logbooks to planning for the type of data they are collecting (continuous, ordinal, categorical), if the data is paired or unpaired, how many groups they are using, and what tests they are considering. Have them look up appropriate ways to perform analysis for the questions they want to ask. Make sure students clearly define any assumptions a chosen test makes. At the end of the project, have them revisit that list of assumptions and confirm that the test was appropriate for the situation.
- If your school has access to Microsoft Project, consider using it to track student projects. It combines both the global and day-to-day tracking that this lesson puts into spreadsheet form. Microsoft Project is used in a wide range of engineering workplaces and has been built specifically for project tracking.