ENGINEERING DESIGN CYCLE

AT A GLANCE

Students will learn the steps of the engineering design cycle by designing and building an airbag system that can safely land an egg dropped on the floor.

OBJECTIVES

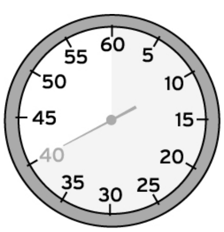
Students will:

- Engage in the engineering design cycle to solve an engineering challenge
- Evaluate competing design solutions using criteria and constraints
- Develop a model to test and gather data.
- Analyze data from tests to revise and refine design solutions
- Communicate design and process with others

KEY VOCABULARY
design, engineering design cycle, criteria, constraint,

SUGGESTED GRADE LEVELS: 4—8

PACE YOURSELF
THREE 40 MINUTES PERIODS



LEARNING STANDARDS

ILLINOIS STATE LEARNING GOALS

Late Elementary: 3: A, B; 4: A, B; 5: C; 9: A; 10: A, B; 11: A, B; 13: B
Middle/Junior High: 3: A, B; 4: A, B; 10: B; 11: A, B; 13: B

NEXT GENERATION SCIENCE STANDARDS

Science & Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
• Asking Questions and Defining Problems • Planning and Carrying Out Investigations • Analyzing and Interpreting Data • Developing and Using Models • Constructing Explanations and Designing Solutions • Engaging in Argument from Evidence • Using Mathematical and Computational Thinking • Obtaining, Evaluating, and Communicating Information	• ETS1: Engineering Design • ETS2: Links Among Engineering, Technology, Science, and Society • PS2.A: Forces and Motion • PS2.B: Types of Interactions	• Cause and Effect: Mechanisms and Explanation • Systems and System Models • Energy and Matter: Flows, Cycles, and Conservation • Structure and Function

ADVANCE PREPARATION

1. This lesson is most effective when taught in conjunction with the *Engineering and Technology* lesson.
2. Plan to have 2 eggs per student group, plus a few extra on hand in case of accidents.
3. Find the Opportunity Rover video in the videos folder of this lesson.
4. Decide how to divide students into groups of 3-4.
5. Make copies of the student worksheet.

MATERIALS

Per Class:
Materials available for student groups to purchase: string, rubber

bands, craft sticks, cotton balls, masking tape, balloons, binder clips, small paper cups, etc.

Per Group:
1 egg
1 small Ziploc bag
1 pair of scissors

WHAT YOU NEED TO KNOW

Engineering starts with a challenge: something we want or need to do. The challenge may be as simple as "How can we attach three pieces of paper together?" Or it can be as complicated as "How can we safely land a one-ton robotic laboratory on Mars?" **Design** is the act of conceiving and planning a solution to a challenge. More specifically, the **engineering design cycle** is a process that engineers use to create solutions to a human need or want. After identifying a challenge, engineers need two key pieces of information to guide the design process: criteria and constraints. **Criteria** are the set of attributes that a solution must have in order to be deemed successful. **Constraints** define the limits of what engineers can do to meet the criteria. For a more in-depth discussion of criteria and constraints, see the *Engineering and Technology* lesson.

There are different ways to describe the engineering design cycle; the following five-step process is adapted from Engineering is Elementary (http://www.eie.org/) at the Museum of Science in Boston:

- **Ask**—Engineers ask wondering questions. What is the problem? How have others approached it? What are the criteria for a successful solution? What constraints are on the design?
- **Imagine**—Engineers play with possibilities. Think of as many different solutions as possible. Brainstorm ideas. Every idea is awesome!
- **Plan**—Engineers build on knowledge and experience. Decide as a group what the best idea is within the constraints. Put it on paper. Draw a sketch. List the materials you need.
- **Create**—Engineers solve problems systematically. Build your solution and test it out.
- **Improve**—Engineers look for patterns, trends, and surprises. They make arguments based on evidence. Find out what worked and what didn't. Modify your design to make it better. Test it again. There may be a new problem that was revealed in the process. If so, start the engineering design cycle again.

Because it is a cycle, there is no official starting or ending point. It is possible to begin anywhere, focus on a few of the steps, move back and forth between steps, or repeat the cycle as many times as possible. For example, with very complex projects, engineers often work on just one or two of the steps and pass on their work to another team of engineers.

Students should experience all five steps of the cycle to learn the process. At each step, teachers should facilitate the process without prescribing solutions. Each step presents a unique challenge for students and teachers alike. The following are examples of what teachers as facilitators can do at each step to help their students navigate through these challenges:

- In the ask step, teachers should set the criteria and constraints for the problem and make sure that all students understand them.
- In the imagine step, teachers should make sure that every voice is heard. Furthermore, no ideas should be rejected at this point in the process.

- In the plan step, teachers should help students come to consensus on a design. Also, teachers should make sure that students carefully describe their design, including the reasoning behind their choices, on paper before building it.
- In the create step, teachers should give every student a chance to test their design three to five times before making any changes to the design. Also, teachers should make sure students are making measurements (against the criteria) so that they have evidence about how their designs are working.
- In the improve step, teachers should make sure that students make a log of the changes they make to their design, including the reasoning behind these changes. Also, teachers should emphasize improvement over competition.

Most importantly, the five steps of the engineering design cycle can serve as a framework for any lesson in engineering. A common misconception about teaching engineering is that lessons must never be teacher-directed. Engineering lessons, however, should not be completely unstructured. By making intentional choices about how to guide students in each step of the cycle, teachers will structure students' experiences with engineering in a way that builds their design skills.

Although the goal of engineering design is to create something that meets the challenge defined by the criteria and constraints, success can be measured by more than just the performance of the end product. Both teachers and students need to understand not to judge work solely based on the success of the final product. Reaching the end product usually includes stopping and starting; following dead-ends and retracing steps; and improving designs that don't initially work. Rarely do engineers solve a problem on the first try, and neither should students. If students succeed too easily, then the problem might not have been challenging enough for them. Being a successful engineer includes learning at every step of the process, understanding what worked and what didn't work, and more importantly, why.

The knowledge and skills required in the engineering design cycle will be unfamiliar to many students. Some students will thrive; others will become frustrated. Thus, it is important that teachers reinforce the idea that students can be successful even if their design doesn't work as well as they planned. Teachers should set an expectation that students will be assessed on their level of engagement in the entire process. Assessing learning at every step of the cycle helps students become better engineers. The *Engineering Design Cycle Assessment Rubric* is a way for teachers and students alike to evaluate work done during each of the steps of the cycle. With guidance, students can learn metacognitive skills that will help them think critically about their own work.

The best way to become a better engineer is to practice. Give students the opportunity to experiment, fail, and succeed, and ultimately they will become better engineers.

WARM UP

1. Ask students if they think people have ever been to Mars. Allow them to share their answers, and then explain that people have actually never been to Mars, even though many space agencies around the world are working very hard to make this a reality. Sending people that far away is a tremendously difficult task, so in the meantime NASA has sent unmanned missions to land on and orbit the planet.
2. Tell students that they will now watch a short video showing how the Mars Exploration Rover Mission got the Opportunity Rover from Earth all the way to Mars. Show the *Getting to Mars: Opportunity Rover* video.
3. Encourage students to ask any questions they may have about what they saw in the video, allowing their curiosity to guide the questions while guiding the discussion to the mechanics of launching from

Earth and landing on Mars.

4. Show the video one more time and tell students to focus on two aspects: how the rover launches from the Earth, and how it lands on Mars.
5. When they have finished watching, ask students how the rover is launched. Ask why it needed a rocket to start its journey. Answers will vary, but students will likely point out that the rover needed a way to move away from Earth, and that the rocket was a means to get the rover going. If it is not brought up, mention that the rocket provided the thrust to move towards Mars and away from the Earth's gravitational pull.
6. Now ask students to describe how the rover landed. Ask why it needed to slow down as it approached the surface of Mars. Answers will vary, but students will likely say that if it had not slowed down, the rover would have crashed onto the surface and been destroyed. If it is not brought up, mention that the rover needed to decrease its momentum—the quantity of motion it had—in order to land safely.
7. Point out that, even though its velocity was greatly decreased, the rover was still moving quickly as it hit the surface. Ask students why the rover did not break on impact with the surface?
8. Explain that the airbags of the rover work a lot like airbags in cars, or bubble wrap in packages—they absorb the shock of impact, and so they work to protect the item inside.
9. Tell students that designing landing systems, like Opportunity Rover's airbag system, is the job of engineers. In this lesson, they will work as engineers do, using the engineering design cycle to develop a landing system for a raw egg.

ACTIVITY

Ask

1. Tell students that today they will work as engineers to design an egg landing system. They will carry out this challenge in teams, and will use the engineering design cycle to guide their work.
2. Distribute the *Egg Landing System Design* worksheets and explain that they will use the worksheets to guide them through the engineering design cycle.
3. Explain that an essential part of this cycle involves defining the criteria and constraints of the project. The criteria are the goals that must be satisfied to achieve success. For this challenge, students' designs must meet the following criteria:
    - The egg can be dropped from a 2-meter height onto a hard floor without breaking.
    - The egg can be rolled across the floor for at least 2 meters without breaking.
4. Tell students that the constraints of a challenge are the factors that limit how you can solve the problem. For this activity the constraints are:
    - Each team will have a $100 budget to purchase materials.
    - Only purchased materials can be used to construct a landing system.
    - Student teams must show a detailed sketch of the planned landing system to the teacher before purchasing the materials to build their model.
5. Show students the materials they can choose from, and provide a couple of examples of how the materials can be used together to construct a landing system. For example, show students how to

use binder clips to connect craft sticks, or rubber bands to tie balloons to one another. Direct students to the price list in their student worksheet that shows the cost of each material.

6. Tell students that engineers rely on criteria and constraints throughout the design process. In the beginning, the criteria and constraints allow engineers to define and understand the problem, and to know how to work within the parameters of what is acceptable.

Imagine

1. Explain that once engineers understand the criteria and constraints of the challenge, they engage in the brainstorming process. This is a time for the team to generate multiple solutions and ideas, to be creative and inventive, and to be open-minded in considering a wide variety of solutions.
2. Direct student groups to work to come up with at least 3 different ideas of how to design a landing system for an egg, making sure to use their student worksheets to describe, sketch, and label each possible solution.
3. Tell students that, while they should consider the criteria and constraints of the challenge, they should try to stay away from evaluating the suitability of an idea at this point, so as to allow for a wide variety of ideas to be explored.
4. Since this is likely the first time many students will have engaged in this process, students may struggle to generate ideas, especially if they feel there is a clear solution to the challenge or, alternatively, if they feel there is not a solution at all. Encourage student groups to share ideas and guide this process by asking questions such as: What will your design have to accomplish? What has been done in the past to solve this problem? What type of material can help prevent eggs from breaking? How are you going to build a frame around the egg to prevent it from breaking?
5. The brainstorming process can be frustrating to some students who would prefer to begin building straight away, without systematically considering different possible designs. Do not allow students to skip this step, however, even if they have come up with what they consider a perfect design.

Plan

1. Once each student group has generated at least 3 unique design ideas, they are ready for the next step of the process: the planning. Tell students that during this stage they will evaluate each of their ideas against the set of criteria and constraints, and select a design to build and test.
2. Direct students to the criteria and constraints table in the *Plan* section of their student worksheet, and ask them to complete the table with descriptions of how each of the criteria and constraints will be met by each of the 3 ideas they developed during the brainstorming section.
3. Once the table is complete, instruct students to discuss which idea is best suited to meet the criteria and constraints, and select a design to build and test.

Create

1. Ask each student team to use the detailed description and sketch of their selected design to complete the materials purchasing form in the *Create* section of their student worksheet.
2. Direct each group to show you their detailed sketch and description, as well as their materials purchasing form before allowing them to get the materials and proceed to the building of their model.
3. Instruct student teams to build their prototype according to the plan. If changes are made to the design during the building process, students must create a new description and sketch to reflect these changes. Remind students to keep all records of previous designs; they should neither erase nor de-

stroy descriptions and sketches they have already made.

4. Once their prototype is built, direct student groups toward the testing station to test their models. Students must perform first the dropping and then the rolling test while collecting data in the student worksheet.
5. During testing, make sure students are making careful observations about how their model worked. If either the egg or parts of their structure broke, they should look for where, how, and when the parts broke. This will help them answer the questions in the *Improve* section of the student worksheet.

Improve

1. Ask student groups who have finished their testing to complete the *Improve* section of the student worksheet. Tell students to thoughtfully answer each of the questions, considering what aspects of their design worked well, and what aspects can be improved.
2. Come together as a class and have each student group share their results. Direct students to take notice of design ideas other teams came up with, and the parts of those ideas that worked well.
3. Have student teams gather back together and use what they learned from testing their own design, as well as what they heard from other student teams to look at their design and determine what aspects can be changed in order to improve the way their landing system works.
4. Tell students to describe and sketch their revised design, paying close attention to describing the changes they made, as well as the reasons for those changes. Explain that each student team will have an additional $___ in their budgets to purchase materials their revised design may require.
5. Check students' revised designs before allowing them to gather their new materials and begin the physical revision to their prototype.
6. Have student groups re-test their designs, gather data from the tests, and revise their design as many times as possible, given the time and material constraints in your classroom.
7. Have each student group present their final design to the class. This presentation should include the design sketches and descriptions, test results, and an explanation of how the final design meets the criteria and constraints of the challenge.

Assessment (optional)

1. Once students have completed this engineering challenge, give each student a copy of the *Engineering Design Cycle Assessment Rubric* and ask them to complete the "Self Evaluation" column of the form. Ask students to be honest and fair assessors of their work, emphasizing that this process can serve as a tool to understand their areas of strength, as well as the areas that need improvement. Tell them you will not be using this as a mathematical way of determining their grade for this assignment.
2. Ask students to exchange their rubric with another person in their team, and have the second student complete the "Peer Evaluation" column of the rubric. You may choose to assign who completes the peer review section of the rubric rather than let your students choose for themselves.
3. Collect all rubrics and complete the "Teacher Evaluation" column of the rubric. In cases where the self or peer evaluations are very different from your own, you might choose to discuss these differences with the students involved. Convey to students that the role of these evaluations is to help them grow as learners by identifying strengths and areas of improvement.
4. Once students are more familiar with the engineering design cycle and the assessment rubric, you

can provide a copy of the rubric at the beginning of an engineering lesson to help guide their design process.

CHECK FOR UNDERSTANDING

1. What is the engineering design cycle? *The engineering design cycle is a process that engineers use to create solutions to a human need or want. Through this process, engineers identify problems, determine parameters for a successful solution, brainstorm ideas and research past solutions, and go through an iterative process of testing proposed solutions to find a solution that best fits the criteria and constraints.*
2. Why do engineers need criteria? *Engineers need criteria in order to find design solutions that meet all the requirements of the problem. In the case of this challenge, engineers needed to know that a solution would be successful if the egg did not break when dropped or rolled.*
3. Why do engineers need constraints? *Engineers need constraints so that they know what the limits are on the solutions they can design. In this challenge, the main limit was on materials because engineers had a limited budget that they could use to purchase materials to build their launcher.*
4. Why do you think it is important to brainstorm many ideas when beginning to explore the solution to a problem? *Answers will vary, but students should point out that engaging in a brainstorm session allows for more inventive and creative ideas to be shared by a group of people with varied perspectives and experiences.*
5. How are criteria useful in the planning portion of the engineering design cycle? *Once a set of possible designs have been brainstormed, each design can be evaluated against the criteria and constraints of the project. This allows the team to determine which solution best suits the criteria and constraints.*
6. What was the constraint that you found most difficult to meet in your design? Why was it difficult? *Answers will vary, but since material availability is the main constraint in this challenge, students are likely to mention that as the most difficult constraint.*
7. If you could continue to refine the design of your egg landing system, what would you modify and test? *Answers will vary.*
8. If you could have one material that was not included in the materials list, what would it be? How would it help you improve your design? *Answers will vary, but students will likely mention materials that help with shock absorption.*
9. How were the egg landing systems other teams designed similar to yours? How were they different? *Answers will vary, but students should be able to identify commonalities and differences in designs.*
10. Was there one correct solution to this challenge? Why do you think that is? *No, there was not one correct solution to this challenge. As long as the design solution met the criteria and constraints, it was considered a successful solution.*

WHAT'S HAPPENING?

Students are engaging in an engineering challenge that is commonly used as an introduction to the process of designing an engineering solution to a problem. Working in teams, students explore each step in the engineering design cycle:

- **Ask**: They begin with the process of gaining a meaningful understanding of the criteria and constraints of the challenge.

- **Imagine**: Once they understand the criteria and constraints, students move on to the brainstorming portion of the challenge, where they are asked to be creative, inventive, and open minded as they share ideas to solve the challenge.
- **Plan**: In this step, students compare the generated ideas to the criteria and constraints to select the idea they want to build and test.
- **Create**: Using a limited budget, students purchase building materials and create a prototype of their idea. They test their prototypes. During testing, students gather observational data about what worked and what did not work in their design.
- **Improve**: Using both what they learned in the testing phase and what worked well for other teams, students engage in an iterative cycle of refining and retesting of the prototype, until they reach a result that best meets the criteria and constraints set forth at the start.

Through this activity, students gain a first hand understanding of what the engineering design cycle process steps are, and how each step builds upon the previous ones to help engineers design solutions to problems. Additionally, students see that what determines their success is not getting "the right answer", but rather engaging meaningfully in the process, creating a product that meets a set of criteria and constraints, and communicating both the process and the result to others.

DIFFERENTIATED INSTRUCTION

- Assign student group roles to facilitate the work flow and to ensure that every student is actively engaged in the process. The *Small Group Self-Managing Roles* document describes four key roles that can be used in small group work.
- Model each step of the cycle in more detail, guiding students more closely as they explore brainstorming, planning, creating and testing, and revising and improving. If students are struggling with a certain aspect of the cycle, carry out the step as a class and model a couple of examples so that students can develop their own skills. Avoid eliminating cycle steps, as each component is an essential part of the whole.
- Have students present their final products to other classes to showcase their work and practice communicating their work to audiences who are not familiar with the challenge.
- Consider different ways to manage the materials budget. For example, you might give an incentive for students to come under budget.

EXTENSIONS

LANGUAGE ARTS

- Research a famous engineer, like Leonardo daVinci, Robert Goddard, or Grace Murray Hopper, and learn about their work, their contributions to a field, and the challenges they faced. Describe how this person used any part of the engineering design cycle, and how using that part of the cycle helped them design an object, tool, or process more effectively.
- Arrange for students to meet and interview a school engineer or someone whose job it is to solve problems and design engineering solutions at the school (for example, HVAC, IT, electrical, transportation, food service, traffic, etc.). Your assistant principal or a director of operations could recommend someone. Ideally, this is someone students are already familiar with.
- Write about a situation where students used a process similar to the engineering design cycle in sub-

jects other than engineering—any time they had to come up with a creative solution to a problem or challenge.

MATH

When designing rovers, NASA engineers try to maximize the amount of instruments a rover can carry while minimizing the cost. Simulate this process by looking back at your egg landing system and attempting to make it as heavy as possible while staying within the original budget. Remember that the landing system still has to work—the egg cannot break while landing or rolling.

DIGITAL RESOURCES

- Engineering is Elementary:
  http://www.eie.org/
- The American Society for Engineering Education:
  http://www.egfi-k12.org/
- NASA's BEST (Beginning Engineering, Science, and Technology) Students
  http://www.nasa.gov/audience/foreducators/best/
- Discovery Channel's *The Big Brain Theory* engineering competition
  http://www.discovery.com/tv-shows/the-big-brain-theory
- Cartoon Network's *Destroy Build Destroy*: Teams of kids compete to build something out of wreckage
  http://www.cartoonnetwork.com/tv_shows/dbd/

RELATED EXHIBITS

- *Fast Forward*
- *U-505 Submarine:* Moving the U-505 movie
- *Coal Mine:* coal excavation and extraction tools
- *Science Storms*: Storm chasing technologies, Tsunami buoy
- *Transportation Gallery*: Wright Flyer, Boeing 727
- *You! The Experience*: Biomedical Engineering
- *Henry Crown Space Center*: Mercury, Gemini, Apollo programs, rocket technologies