# BEYOND THE EGG DROP

## Infusing Engineering Into High School Physics

Arthur Eisenkraft
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Editors

NSTA press
National Science Teachers Association

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# Preface

ARTHUR EISENKRAFT

The "egg drop" is certainly a fun activity. Students are charged with designing packaging for an egg that will allow it to be dropped from a height of five meters onto a concrete floor without being damaged. The drop is even more fun—and messy—if students forget to first wrap the egg in a plastic bag. But, is this science? Is it engineering? The project is used in science classes and asks for an engineering design. But is that enough to qualify it as engineering?

The egg drop project can be given to engineers. The engineers will certainly use physics principles in solving this design challenge. They will bring to this problem an understanding of materials, design, and analysis. They may build prototypes and test them as part of their work. How do we assess students along the lines of how engineers would address this challenge? As teachers, how can we clarify our directions and alter our expectations so that the high school engineering students become student engineers? How can we interweave opportunities to learn engineering concepts and skills in an already packed science curriculum?

Using engineering design principles and engineering terminology (e.g., the following boldface terms) can move this activity closer to meeting the criteria for an exemplary engineering lesson. In the challenge to **design** packaging for an egg, we can include additional **constraints** to the given **criterion** of surviving the impact of the concrete floor from a drop height of five meters. For example, we can limit the packaging material to one piece of paper and one meter of masking tape. We can require the students to come up with three possible designs, and then choose their **optimum** design and provide **justification** for their choices. We can allow them multiple **iterations** of their design after **testing** from a height of one meter, requiring them to record in their **engineering notebook** their **analysis** of the present design and the reason for each **modification**. We can insist that they include the relevant **physics principles** such as impulse, force, time, and change in momentum and how their design takes these physics principles into account. But even this is not enough.

Engineering is defined in *A Framework for K–12 Science Education* (the *Framework;* NRC 2012, p. 11) as "any engagement in a systematic practice of design to achieve solutions to particular human problems." In asking the students to design packaging for an egg, the teacher should provide a rationale for the request. The rationale for an engineering design project is crucial. Who wants to protect this egg? Why is anyone dropping eggs onto concrete from five meters up? What is the human problem we are trying to solve? Are we really concerned that people are dropping eggs from five-meter heights onto concrete and the eggs are breaking? Of course not! However, we do know that when we buy a carton of eggs at the market, one or more eggs may be cracked or broken. The safe transportation of eggs is a problem and we have to decide how to test packaging. Packaging eggs for safe transport is one valid rationale. But the rationale for our engineering design may not be about eggs at all. We may be devising an improved safety device for a car. When testing this device, we can use the egg as a model for the human skull. If we can keep the egg safe, then we can assume that the human skull would also be safe. This, of course, depends on whether an egg is a useful **model** for a skull. Exemplary engineering projects are not contrived situations, and with a bit of effort, teachers and students can create the rationale for why students are engaging in the design challenge.

The *Framework* and the *Next Generation Science Standards* (*NGSS;* NGSS 2013) demand that engineering be a part of a student's education. One solution to this requirement is to adopt or create engineering courses in high schools. Some schools have been inventing or adopting a number of curricula. These courses require students to find room in their programs to enroll in such a course for a semester or more. Some of the curricula available are quite engaging and comprehensive. Given the staffing constraints in many schools and the impossibility of adding another course to some students' schedules, we advocate for a different model—infusion of engineering into all science courses.

Adopting the engineering infusion model implies that all students enrolled in science courses will get exposure to engineering and a sense of the interplay between science and engineering. Science and engineering coexist in our culture. We need engineers to help invent technologies to allow science to proceed. We need scientists to uncover new areas of knowledge and to develop new theories so that engineers can invent new technologies to solve problems. Too often in school instruction, engineering and technology are either ignored in the curriculum or seen as the handmaiden of science. The infusion model addresses this problem and brings out the rich relationship between the two subjects.

This book explores the model of infusing engineering into high school physics or physical science courses. Most of the book provides lessons that can be incorporated throughout the school year. The lessons vary in length. Some require only a part of a class period, while others require a full class period. Some are longer projects that go on for days or weeks. Sometimes those lessons are activators and are best used before any discussion of physics principles. Others are capstones and are best used after the physics lessons have been completed. These lessons have all been tested and are accompanied by artifacts of student work so that other teachers can get a better sense of student expectations.

The *Framework* and *NGSS* reference engineering design. Research shows that engineers have reached a consensus on the most important features of engineering. We will use those four features—design, analysis, modeling, and systems—to help frame engineering lessons. All science teachers will recognize that these same four terms are used throughout science instruction. Teachers and students should be able to distinguish between the uses of these terms in their different contexts. The following are examples:

- How are engineering models similar to and different from scientific models? An engineering model of an airplane is quite different from the scientific atomic model. The models also serve different purposes.
- How does one compare and contrast engineering systems and systems in biology or physics? In designing a new sound system, one engineer may focus on the electrical system, another may focus on the mechanical system, and a third may focus on the safety system. Biologists invent systems to help them understand the human body. They define the digestive system and the endocrine system but do not define the "left leg" system. Physicists use isolated systems to simplify the problem.
- Engineers design a product (e.g., a safety device for a car) that must meet certain constraints. Physicists design an experiment to find the relationship between variables (e.g., how does the stopping distance of a car relate to its speed?).
- Analysis is an important component of both engineering and physics. Engineers will use analysis to determine the type of fastener to use for a given situation. Physicists will use analysis of Newton's laws to determine the stability of an object on a ramp.

All of these are important distinctions that teachers should be able to articulate for students to understand these overlapping engineering and science concepts.

Through the lessons presented in this book, we articulate the use and examples of the terms—*design, analysis, models,* and *systems*. Among the lessons are "anchor activities" that can be used to provide a foundational understanding of these terms in engineering. Each anchor activity provides a memorable example of design, analysis, models, or systems. Each engineering-infused activity in the book includes a chart that will show the unique use of each of these terms.

Presenting engineering-infused lessons in not enough. Assessment must play a central role in the infusion of engineering into physics. The larger issue of assessment has three facets, which are all considered in this book: assessment of lessons, assessment of teaching and assessment of student learning. Each affects the others but uses a unique rubric.

Assessment of lessons has to do with the quality of the engineering activities. How does a teacher decide whether a lesson found on the internet in which students drop an egg onto concrete represents a high-quality engineering activity? What criteria should be reviewed? How can teachers modify and improve what they find? Rubrics are provided in this book to help guide teachers in the adoption of engineering-infused activities.

Assessment of teaching focuses on teacher practices. How should a teacher introduce an engineering design challenge? How much time should a teacher allocate to engineering principles? Should the engineering infusion activity be positioned before the science, during the science or after the science? How much help should a teacher provide students? At what point during the student design work should teachers make suggestions? How much time should students be provided to complete a design challenge? These questions are discussed here in general and then articulated through the sample lessons that follow.

We discuss assessment of student learning, as well as the difficulties inherent in any such an evaluation. For example, do we want to assess the product that the students submit or are we more interested in the process that got them to the product? If one student group converges on a single design, executes it, and has a product that meets the criteria, what grade does it get? If another student group looks at multiple solutions, chooses the best one (and defines why it is best), and pursues this through a number of iterations but fails to have a final product that meets the criteria, what grade does it get?

We begin the book with an example of an exemplary infusion of engineering and contrast it with a lower-quality infusion. We then discuss the role of engineering in the *Framework* and *NGSS*, and make distinctions between engineering and trial and error. Then we introduce approaches to engineering infusion. We discuss the themes of design, models, systems, and analysis and make distinctions between how these terms are used in science and in engineering. Finally, we introduce the three facets of assessment.

The major focus of the book is the classroom-tested engineering-infused lessons. Along with each lesson, we provide a detailed description of why teachers should consider adding the lesson to their science curriculum. We then present examples of student work to illustrate the demands the different lessons make on high school students at different times. The lesson plans are presented in the major content areas of physics and those given in the *Framework* and *NGSS*.

We close with suggestions to readers for how they can involve other teachers and students in the infusion of engineering into high school physics and physical science courses.

As teachers, we must take many things into consideration as we develop our curriculum. Every day, there is more science in the news that we could use to engage students. We must decide which current events to bring into the classroom or whether to debate a scientific controversy. Some may ask whether engineering infusion will push out some of the physics or physical science curriculum. No science teacher wants to give up valuable lessons just to include another topic in their curriculum. We think that engineering infusion is different in that instead of taking away from time on a subject, it will enhance the science we get to present and provide students with additional understanding of science concepts. This book is our attempt to find out if we are on the right track.

## REFERENCES

National Research Council (NRC). 2012. *A framework for K–12 science education: Practices, crosscutting concepts, and core ideas.* Washington, DC: National Academies Press.

NGSS Lead States. 2013. *Next Generation Science Standards: For states, by states.* Washington, DC: National Academies Press. *www.nextgenscience.org/next-generation-science-standards.*

# Summary of Contents by Chapter

The egg drop activity is a classic physics classroom experience that is specifically mentioned in the *Next Generation Science Standards* (*NGSS*). However, with simple shifts in focus, it can also incorporate elements of engineering concepts and skills that are typically not addressed in a traditional physics classroom.

### Chapter I: Justification

Teachers from the Greater Boston area share experiences of their own with infusing engineering, discuss some of the lessons learned, and offer some rationales for continuing to add engineering components to their classroom.

### Chapter 2: Design, Analysis, Models, and Systems: Core Concepts for Engineering Infusion

Project Infuse focuses on four core concepts in engineering. Teachers can articulate different aspects and components in engineering practices that go beyond the general engineering design process.

### Chapter 3: Implementation

Different experiences and methods have been developed by Project Infuse teachers. How can engineering be infused using the core concepts and engineering process in both larger project-based challenges and in smaller-scale anchor activities and case studies? The chapter ends with suggestions for timing, grouping, and structuring the classroom to make it more design-centered.

### Chapter 4: Assessments

Engineering should be assessed alongside the science content. Teachers use rubrics to assess the quality of an engineering activity and the number of engineering concepts addressed and to self-assess the implementation of these engineering activities. This chapter explores the types of assessment for students and ways to support student success through a balance of assessing engineering process versus designed product.

### Chapter 5: Engineering Infusion Using Anchor Activities

Brief activities that address specific engineering core concepts that can be used throughout the academic year.

### Chapter 6: Engineering Infusion With Mechanics

Engineering-infused physics lessons that can be used throughout the mechanics unit. These address topics of forces, kinematics, and linear momentum and impulse.

### Chapter 7: Engineering Infusion With Energy

Engineering-infused physics lessons that can be used throughout the energy unit. These address topics of mechanical energy, energy conservation, and thermal energy.

### Chapter 8: Engineering Infusion With Waves

Engineering-infused physics lessons that can be used throughout the waves unit. These address topics of sound, light, reflection, and refraction.

### Chapter 9: Engineering Infusion With Electricity and Magnetism

Engineering-infused physics lessons that can be used throughout the electromagnetism unit. These address topics of current electricity, electrical components, and magnetism.

### Chapter 10: Professional Development and Growth in Engineering Infusion

The history of Project Infuse and how it supports professional development opportunities for groups of teachers to implement engineering concepts into the classroom.

# About the Editors

**Arthur Eisenkraft, PhD,** is the distinguished professor of science education, professor of physics, and director of the Center of Science and Mathematics in Context at the University of Massachusetts (UMass) Boston. He is past president of the National Science Teachers Association (NSTA) and is past chair of the Science Academic Advisory Committee of the College Board. Eisenkraft is also project director of the National Science Foundation (NSF)–supported *Active Physics* and *Active Chemistry* curriculum projects, which introduce high-quality, project-based science to *all* students. In addition, he is chair and co-creator of the Toshiba/NSTA ExploraVision Awards, involving 15,000 students annually. Eisenkraft also leads the Wipro Science Education Fellowship program, which is bringing sustainable change to 20 school districts in Massachusetts, New Jersey, New York, and Texas, and he has recently been supporting novel educational initiatives in Thailand and India.

His current research projects include investigating the efficacy of a second-generation model of distance learning for professional development—a study of professional development choices that teachers make when facing a large-scale curriculum change—and assessing the technological literacy of K–12 students.

He has received numerous awards recognizing his teaching and related work, including the National Public Service Award, the Presidential Award for Excellence in Mathematics and Science Teaching, the American Association of Physics Teachers Millikan Medal, the Disney Corporation's Science Teacher of the Year, and the NSTA Robert H. Carleton Award. He is a fellow of the American Association for the Advancement of Science, holds a patent for a laser vision testing system, and was awarded an honorary doctorate from Rensselaer Polytechnic Institute.

**Shu-Yee Chen Freake** has taught physics and biology at Newton North High School (NNHS) in Newton, Massachusetts, since 2005. She has a BS in biology, with minors in physics and education, from Brandeis University. She also holds an MEd from Northeastern University. At NNHS, she has taught a wide range of levels in both physics and biology. As a secondary educator, she is constantly looking for ways to engage students, focusing mainly on scaffolding learning experiences that promote student science and engineering skills that are necessary to solve problems in novel situations. She field-tested the NSF-funded Energizing Physics curriculum, which led to her interest in incorporating engineering pieces into the physics curriculum. In 2014, she was part of a team that developed videos to demonstrate reflective teaching through a grant funded by the Massachusetts Department of Elementary and Secondary Education. In this project, she taught and revised a physics and engineering lesson as part of a professional learning community. Since 2012, she has been involved in the Project Infuse program as a participant for the first cohort and then a co-trainer for the second cohort. She has presented at NSTA conferences, and helped in the planning and writing of this book.

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*See the "More About the Contributors" section (p. 457) for additional information about some of the individuals listed above.*

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# Justification

**Arthur Eisenkraft**

One Project Infuse teacher, Alex, found that year after year her students struggled with the concepts of electricity and electromagnetic induction. She didn't blame; after all, we cannot see either the charged particles associated with electrical current or the magnetic field. So it was really a stretch for her students to not only conceptualize but also understand the relationship between these two "invisible" concepts. To help make these concepts more visible for her students, she incorporated a variety of demonstrations of Faraday's law and electromagnetic induction. However, despite her efforts, her students did not improve in their assessments. Something was missing.

During the 2014–2015 academic year, Alex tried an engineering design challenge to introduce students to the concepts of how a moving magnetic field can induce a current in a conductor and how the same effect can be achieved by a moving coil in the presence of a magnetic field. After the usual demos, she introduced the challenge to her students—to build a wind-powered turbine that would allow a coil of current to rotate in the presence of a magnetic field and thus induce an electromagnetic field (emf). She gave certain constraints for the project and set criteria for the best wind turbine. The challenge proved to be a motivator to all students, who were highly engaged during the entire building process.

Although the students initially could not grasp how a change in magnetic flux induced an emf in the coil (as this was still a "black box" mechanism for them), after testing the wind turbines, every student knew that their moving coils had an induced emf. Later, when they talked about the process of electromagnetic induction, all of the students could relate these concepts to how their wind turbines worked. This was a great vehicle for introducing not only the current unit's concept of electromagnetic induction, but also the concepts of friction, rotation, and motion explored in an upcoming unit. Incorporating the engineering design challenge had not only increased her students' engagement level, but also led to her students earning a better score than previous years' students on the assessment associated with this topic.

This is what every educator strives for, greater engagement and better comprehension of the material. Infusing engineering in this particular unit seemed to have solved the problems Alex had struggled with over 10 years. As she gets ready for the new school year, Alex is hopeful that she can see similar results as she further incorporates infused lessons.

Alex's story is not unique. The 30 physics teachers who collaborated in Project Infuse all found ways to introduce engineering into their existing physics curriculum. These ranged from small insertions into one lesson to design challenges, and some infusions of engineering were more successful than others. The consensus among the teachers was that engineering could be infused in meaningful ways into physics courses, that engineering was one way to increase student understanding of science, and that there is more to engineering than merely having students use a trial-and-error approach in designing something or follow the step-by-step do-it-yourself instructions from maker websites, which have become increasingly popular.

Another Project Infuse teacher, Julie, found that the engineering projects she infused into her class are worthwhile for several reasons, including an increase in student skills. Julie's reflections both affirm the value of infusing engineering and respond to concerns some physics teachers harbor. She says, "Infusing engineering into a physics classroom can be a daunting task, and some teachers may be wondering whether it is even a worthwhile endeavor. Teachers may wonder whether teaching physics through the use of engineering design projects leads to an increase student understanding of the physics over more traditional methods or even over inquiry-based methods. Also, teachers may wonder whether the time needed to infuse 'extra' engineering projects is worth the loss of 'physics teaching' time. As an experienced physics teacher who has spent some time infusing physics and engineering together, I can say that engineering infusion is a worthwhile tool for teaching physics and that often students gain a deeper understanding of the physics concepts than they can gain through a more traditional classroom setting."

Julie believes that one of the first aspects of teaching engineering versus traditional physics that a teacher will need to understand is that the results, student solutions, and artifacts from an engineering project will be quite different from those from a traditional physics activity. Engineering projects usually start with some problem presented to the students for which there could be multiple solutions. In an engineering design project, each student can present a viable solution that has sound reasoning behind it and that can look nothing like anyone else's. This is different from a physics problem or activity, which has a much narrower solution set, possibly consisting of only one correct solution or method.

For example, during a recent school year, Julie removed a more traditional Archimedes' principle lab from her curriculum and replaced it with a culminating engineering design challenge for a unit on static fluids. For that Archimedes's principle engineering challenge, students were asked to design and build a vessel that can hold the most amount of weight without sinking. Students were only given dimensional constraints for the vessel. Because there clearly would be a winner in this challenge, students were motivated to be successful. In a design project such as this, there could be as many solutions to the problem as there are students in the classroom (which is what happened in Julie's class).

This multiple-solution result is much different from the result from students being asked to perform the more traditional Archimedes's principle lab in which they predetermine how much weight a given vessel can hold before sinking and then test the prediction. In that more traditional case, there is only one right answer and all students are expected to reach close to the same conclusion, assuming they are using proper measurement and math analysis techniques.

In summary, physics problems (traditional labs or inquiry-based activities) tend to be narrower in their solution set and serve the purpose of trying to show, use, demonstrate, or prove some sort of physical knowledge of how the world works. In contrast, engineering problems require students to use their prior knowledge or learned physics knowledge to create a solution, and one that could be quite different than any other, depending on which aspect of the constraints students focus on. Engineering projects invite and celebrate creative ways of solving the problem.

So, the question remains: Which is better, traditional physics or engineering infusion? Julie would argue that, in many cases, teaching and reinforcing the physics concepts through engineering design projects can deepen students' understanding of the physics behind the problem and often indirectly teaches important design and analysis skills that are not typically taught or reinforced in a traditional physics confirmation lab. If we explore the Archimedes's principle engineering challenge more deeply and think about what knowledge and skills students need to to develop a successful solution, we find that teaching physics through engineering yields great benefits beyond a deeper understanding of the physics. Here is a (noncomprehensive) list of the skills and knowledge that students need to be successful in the Archimedes's principle engineering challenge:

- Develop, nurture, and apply a true understanding of the ideas behind Archimedes's principle and of how the vessel's size, shape, and weight affect its behavior when in a fluid.
- Analyze different materials that can be used to determine which material might be optimal, then run materials analysis tests before deciding what materials to use.
- Determine the best method for putting together the chosen materials.
- Explore how the vessel will hold the weight and determine and understand the role of weight placement within the vessel.
- Develop (after much debate) a fair and balanced testing method for the vessel so that the results are authentic.
- Complete a failure versus success analysis of what went wrong and what went right with the vessel (including math calculations to compare the weight it actually held with what weight it theoretically should have held).
- Provide evidence-based reasoning for their decisions.

This noncomprehensive list far outweighs the skills needed to perform the more traditional Archimedes's principle lab that Julie used to have students perform. In the traditional lab, students need to do the following:

- Understand how Archimedes' principle works (at least know the formula and what each variable represents).
- Correctly measure and calculate the volume of the vessel.
- Gather the needed data for plugging into the Archimedes's formula to predict the mass the vessel will hold.
- Test their prediction and perform an error analysis to explain why the results did not match the prediction.

The list for the traditional lab consists of a solid set of skills but seems lacking when compared to the list for the engineering design challenge. As someone who has spent time infusing engineering into many different units for a variety of levels of physics instruction, Julie realizes that the results she gets continually demonstrate a deeper understanding by students when they are asked to solve a problem using what they have learned. The engineering-infused approach also improves students' ability to apply learned physics concepts to other situations. Being a student engineer uses more of the 21st-century skills that we want students to learn through the context of our classroom and subject matter.

Project Infuse teacher Blair has come to know that not all engineering design projects are equally successful. Blair has found that his former engineering projects were lacking in some aspects. He may also have discovered that sometimes less is more.

For years, Blair did what he called engineering challenges in his physics classroom; however, he began to realize that he was really only doing building projects. He believed that in their designs the students were using the physics concepts he was teaching, but did not require students to make direct, explicit connections between the physics and the project. He also encouraged his students to go through a design cycle, but often did not follow up on this either.

Through learning more about engineering himself, Blair has realized how to truly infuse it into his classroom for his students. One difference between what Blair did for years and what he is doing now and going forward is the strength of the connections between physics content and engineering. Blair explains, "In my new projects I am focused on the students using physics concepts in their designs. I do not believe that any [engineering] project that does not enhance the physics has as much value in the classroom. The use of the projects to just teach engineering concepts is something I am attempting to avoid." For example, Blair does a project involving bungee jumping that is focused heavily on the energy involved in the bungee jump. In evaluating the project, a major point he considers is whether the students used energy concepts to inform their design. Any revisions he makes to the project will focus on bringing the use of physics more to the forefront.

Another difference in Blair's classroom now is the length of the projects. Traditionally, building projects take a long time and involve work outside of class, with the longest project taking a whole semester. He has started to use shorter projects. Doing a design challenge in one period is a great way to start infusing engineering into the classroom. The key that Blair has found is to stop thinking that every project has to involve a building component. He understands that designing is more than just making something and that not all projects need to involve every aspect of engineering. For example, an optics project that Blair uses in his classroom is only one class period long and involves students designing the final product but not building it. Blair extends the project to have students look at materials that night as homework. Shorter projects such as this can be used as an activator or a quick check of understanding.

Another aspect of engineering that Blair tries to use in his classroom now is a method of design that does not rely on trial and error. Too many times in the past, Blair allowed students to base everything they did in their design project on trial and error. Now the students' approach for their design process includes more thoughtful, data-driven design. Blair believes this enables better designs and makes stronger connections between physics and engineering in his classroom. His students also learn science laboratory skills while performing tests related to their engineering designs.

## AT WHAT COST?

Alex's main concern when she first learned about infusing engineering in her classroom was whether it was possible to teach engineering without cutting into the demands of the existing physics curriculum. However, after some guidance and practice, she discovered that engineering can add tremendous value to the physics curriculum. Infusing engineering in physics provides students with realistic, meaningful, and applicable context and purpose for learning the physics content. Certain aspects of engineering can also bring a level of excitement that is often lacking in a traditional classroom (Weiss et al. 2003). Some students cannot be engaged in learning unless they find a personal connection with the material. Engineering provides a human connection that is straightforward and immediate.

Another Project Infuse teacher, Gita, shares the concern of time constraints but has still made the decision to proceed with engineering infusion. Gita shares her thoughts:

> *I still have the same number of days of school and hours in the day. If I do engineering projects, doesn't that mean I will have to give up something else out of my curriculum? Yes, of course it does. But don't we do that all the time as teachers? You*

*might read about or hear of a new lab or activity at a conference and say, "I can use that in place of this other lab that I do." You decide to replace one lab or activity with another because you believe it will better serve your curricular goals. The same thing is true of engineering activities. You might find that they better serve your curricular goals in physics. One classic example is the egg drop. Many physics teachers have done that challenge for years. They see it as a way to solidify students' understanding of impulse, momentum, and energy. Little tweaks on that activity and it becomes a robust example of engineering design as well: explain the engineering process using the egg drop as an example; have students keep engineering notebooks as they work through the project; give students opportunities to analyze and modify their designs. All of these tweaks turn the project from simply a demonstration of understanding of physics principles into an engineering project.*

Julie has found ways that she can rationalize the time for engineering infusion. She explains,

*One of the big pushbacks I receive when I mention engineering infusion to other science teachers is the time factor. Teachers want to know whether the engineering-infused lessons take more time and if so, whether that extra time is worth spending. The answers to those two questions are "quite possibly yes" and "yes." It is true that, in general, the engineering-infused lessons can take a bit more time, particularly if you do not change anything else about the way you teach and you insist on keeping every other activity in your curriculum.*

*My findings have been that I can alleviate some of the time issue by making some changes to how I teach and some thoughtful decisions about which activities and labs I continue to ask students to perform. I have found that a thoughtfully developed engineering-infused lesson can have the same or similar physics objectives as a more traditional lesson and also tends to have additional objectives that would not be in the traditional lesson. Because of this, I have found that I am comfortable in some cases with replacing my more traditional physics activities and labs with engineering activities, in order to aid in time management.*

*For example, this past year, I asked students to complete a mousetrap car engineering challenge as part of my motion unit. The students brainstormed ideas in class, but the majority of the build process was completed outside of the classroom so that precious class time was not spent waiting for glue to dry or cutting up cardboard. The testing* *and analysis of the cars was done in class and students were required to complete a quantitative analysis using the formulas we had been working on in class.*

*This engineering design challenge took the place of several more traditional speed and acceleration labs that I would typically have the students perform. I found that students could still complete the math calculations that would have been an objective in the traditional lab while also gaining greater insight into additional factors that affect the speed and acceleration of an object—leading to a deeper understanding of the relationships among friction, acceleration, distance, time, and speed. I also found students much more engaged in the learning process than what I usually see with the traditional labs.*

Julie also notes that engineering infusion has another advantage that alleviates the time crunch—students do more of the physics learning themselves through the discovery process. She explains,

*Often, with the well-developed engineering challenge, students can "discover" some of the physics and make the connections for themselves, with less guidance and input from me. When I teach physics topics with more traditional methods, I feel the need to spell out everything and make all the connections for the students—or at least to plan out special activities for students to perform so that they can make the connections I want them to make.*

*For example, to begin my unit on forces this past year, I used a quick one-day engineering challenge for creating a "hovercraft" device that can hover at rest in a vertical wind tube. Students had to work with the given materials and used iterative design, testing, and analysis to try to come to an optimal solution. Although each group was not completely successful in the short time allotted, each group was able to improve its design from beginning to end, and in each class, there was at least one successful group, so students were able to see the device hovering. The behavior of the hovercraft led to a great discussion about equilibrium and the conditions necessary for an object to be in equilibrium.*

*This challenge was something concrete that I referred to throughout the forces unit. Since the students were really motivated by the challenge, they seemed to take more ownership of the topics and were very willing to discuss and explore successful solutions. Furthermore, I found that students had a greater understanding (than in previous years) of the concepts of balanced versus unbalanced forces and how objects* *behave in each case. Throughout the unit and then into subsequent units, students were better able to answer both qualitative and quantitative questions even when equilibrium was applied to other systems (cars moving down the road, charged objects near other charged objects, and so on). Because of this, I didn't have to spend as much traditional teaching time on this topic and I didn't have to repeatedly make the connection between the net force on an object and its motion.*

*This benefit of the engineering infusion (particularly in activator activities) is something I saw through many of the units I taught. The gain in knowledge from the engineering design projects allows me to decrease the amount of traditional "note-giving" time in many cases.*

## RETRIEVING KNOWLEDGE

When students learn about a new concept in isolation, chances are that they will walk away with only a vague understanding of the concept presented to them. Without extended, meaningful exposure, the knowledge that students initially understand might fade and disappear over time.

To be readily accessible, a memory needs to have multiple, relevant retrieval cues. Retention begins to take place when students can compare a current stimulus to something sensed in the past. To retain the information presented to them, students need multiple exposures to new knowledge in tangible, meaningful contexts. Infusing engineering allows educators to provide students with creative, relevant context and instructional techniques and assignments that appeal to a wide range of learning styles, backgrounds, and skill levels, which in turn can improve students' chances of retaining the knowledge.

Project Infuse teacher Danielle expands on this by placing the retrieval of knowledge in the larger context of brain-targeted teaching (Hardiman 2012) and meeting the needs of students' knowledge retention so that they can access it throughout their lives and apply it in problem solving. Danielle justifies teaching engineering from a neuroscience standpoint and sees infusing engineering as supporting student retention of knowledge by

- Emphasizing the importance of creativity and innovation in education
- Valuing divergent thinking over convergent thinking
- Distinguishing between creativity and intelligence
- Affirming that creativity can be taught and fostered and is not innate
- Emphasizing 21st-century skills
- Providing opportunities to be inventive in the classroom

- Encouraing the teaching and performing of creative tasks that not only enhance cognitive functions but also modify brain structure
- Promoting highly creative thinking that is different and nonconventional
- Having students conduct multipart tasks in groups and single tasks that are better completed individually

## INCREASING STUDENT INTEREST IN SCIENCE

Our economy is driven by elements that require advanced problem-solving skills and processing of complex knowledge. As the world around us becomes increasingly complex, we should anticipate a concomitant increase in the demand for people with these advanced skills. These observations suggest that the number of jobs in the United States that require science and engineering training will grow. However, not enough young people are interested in studying science and technology in the United States, so involving students in science and engineering skills is vital for being able to meet future workforce demands.

Gita, a physics teacher, has found that engineering challenges are more engaging than science laboratory experiments. In her teaching, she has seen that when students are given a design challenge, they become very engaged, and certainly much more engaged than they are in more traditional lab activities. Simply taking pictures using their phones and adding these visuals as supporting documents in their engineering notebooks seems to keep students engaged. Gita's students like activities for which there is more than one right answer or more than one way to find a solution. Some also like to compete against one another, although she rarely makes the challenge a competition with other students. Of course, although the activity must be engaging, it also must teach or reinforce important concepts we want students to know and skills we want them to develop.

## ENGINEERING IS MORE THAN BUILDING A PROTOTYPE

When we think of ways to infuse engineering lessons in the classroom, the first thing that comes to mind is a design or building challenge. Just like their educators, many students' views on engineering consist of the development of solutions to technical problems. This limited conceptualization of what engineering entails may be a demonstration of the limited exposure students have had to authentic engineering tasks in the science curriculum.

Although many engineers do develop new products, the development process integrates many components to produce the final design. Some aspects of the design process that are often hidden from students include the following:

- Testing of materials to determine the causes of component failure

- Computer analysis to simulate and test how a machine, structure, or system operates
- Development of models (not limited to science and math) to provide a representation of how a system or combination of systems will work
- The interaction of systems or subsystems to achieve a task
- Designer communication during the design process

Project Infuse teacher Nora recalls the first time she did the mousetrap cars activity in her classroom as the culminating project in the energy unit. She had no idea what to expect. She had made mousetrap cars in elementary school and had witnessed middle school students assemble balloon-powered cars easily. She figured that her 11th and 12th grade students in an urban public school would build the cars without many problems. She had assumed that the problems would be in measurement of the efficiency, the second part of the project. She did not expect that the student who had struggled in her honors class all year and often seemed unengaged would be the first to build a working car—and one of the better-working cars at that. She did not expect the English language learner (ELL) student in her college preparatory class, who barely ever spoke in class, to come in the next day with a beautifully made car that he had made at home—the best car she has seen to date. She also did not expect the "A" students who had aced the test on the work, potential energy, and kinetic energy concepts to struggle so much. She had one student who made one attempt at making a car and then turned to her and said, "I tried—now how do I do it?"

After that first project, Nora became convinced of the value of doing engineering in her classroom. It made her students who usually struggle shine, and it challenged other students in a way that is unusual for them in a traditional school assessment. Nora has had students who are extremely afraid of trying something new because of a paralyzing fear of failure after 12 years in a standardized testing environment. For some students, Nora's projects can be the way they learn what it means to fail and try again.

This is a lesson that Nora thinks students can take beyond her classroom. Nora worries about whether her high-achieving students will have the resilience to keep going as they move on to college if they do not immediately do well academically. She uses the mousetrap cars project as a way to have conversations with students about the complex problem-solving skills they will need outside the classroom, when it is not enough to do the worksheet or answer all of the questions on the test.

In Nora's second year of teaching engineering, she had an ELL student who struggled in her class. His employment required him to work every day from 3:00 p.m. until 1:00 a.m., and he could not stay after school for help or to do his homework. When it came time in the year to make mousetrap cars, he found a plastic cover from a toy car that someone from another class had discarded in the classroom. She recounts his excitement as he picked it up and named it Carrito (In Spanish, *carrito* means "little car.") "He would move it back and forth on the table like a little kid playing with a toy car. Eventually, he added cardboard wheels supported by pen axles and a cardboard bottom. He was very excited to show me his car, saying *'Mira, mi carrito'* ("Look, my car"). I pointed out that it needed to move with a mousetrap. He added a mousetrap to the top of the car and immediately tried to figure out how to make the car move. Eventually, he and his partner got the car to jolt by releasing the mousetrap. Excitedly, he called me over, but to his dismay, the car had to go one meter. Once again, he and his partner, another student who was often disengaged in my class, started working furiously to make the car move one meter. Finally, after school one day, they got Carrito to move a full meter."

Seeing this as a critical moment to motivate her students, Nora then explained to them that they still had to calculate the efficiency of the car and write some reports. They all did so, and that was the first time this student turned in a project of this size and the first time he passed a quarter. The student went into the next quarter determined to do better. He was still unable to do homework because of how much he worked in his job, and he still could not work late after school, but he no longer was disengaged during class and he started to improve.

This story is not unique. Nora has had other students who have risen to the challenge and embraced engineering. She has had students stay after school, sometimes for hours, trying to refine their designs to make the car as successful as possible. Those students became leaders in the classroom, often helping groups who were struggling. Other students would often turn to them for suggestions or lessons on how to solder. Engineering projects help students value each other's skills and learn from each other.

During an electronics project, when Nora was teaching a student to solder, the student told Nora that her father solders as part of his job. Nora asked her what her father did, and she said that he worked as a mechanic. Nora encouraged her to tell her father that she learned how to solder today. Her response was to ask how to say *solder* in Spanish (it is *soldar*). This reminded Nora that for many of her students, communicating what that they are learning in school to their parents is difficult. Engineering projects can help such students to explain the physics they are learning and bridge the gap between school and home.

Nora does engineering projects in her class because she believes that students should be exposed to what engineering is. She believes that engineering teaches students to problem solve in a way that they are not often exposed to in school and that can be transferred to other parts of their lives.

Nora has students engage in engineering projects because students care a lot more about circuit diagrams when they are using them to figure out how to combine multiple light-emitting diodes in a complex circuit to build a sign that lights up. They care more about projectile motion when they are trying to figure out how fast their catapult can fling a table tennis ball across the table. They care more about work and kinetic energy when it means finding the efficiency of their own Carrito.

## REFERENCES

Hardiman, M. 2012. Informing pedagogy through the brain-targeted teaching model. *Journal of Microbiology and Biology Education* 13 (1): 11–16.

Weiss, I. R., J. D. Pasley, P. S. Smith, E. R. Banilower, and D. J. Heck. 2003. Looking inside the classroom: A study of K–12 mathematics and science education in the United States. Chapel Hill, NC: Horizon Research.

2

# Design, Analysis, Models, and Systems

## Core Concepts for Engineering Infusion

**Kristen Wendell**

Despite the testimonies of our team of teachers provided in Chapter 1, you might be wondering at this point how the vast world of engineering—which, truth be told, consists of dozens of different fields of study and practice—can be added meaningfully to an already jam-packed course of high school physics. Given that engineering is a huge multidisciplinary enterprise, that's an important and insightful question. Just as we expect students to understand what constitutes science and what does not, we seek general principles of engineering that can help students distinguish between engineering and uninformed trial and error.

We focus our high school engineering infusion efforts on four key themes that are common across nearly all major engineering endeavors. We call these themes—design, analysis, models, and systems—the four *core concepts* for engineering infusion. In this chapter, we will define these four principles of engineering and give you a first taste of what they look like in high school physics classrooms. We also will show how they relate to *A Framework for K–12 Science Education* (*Framework;* NRC 2012) and the *Next Generation Science Standards* (*NGSS;* NGSS Lead States 2013) and will compare and contrast them with four elements of science that use identical terms.

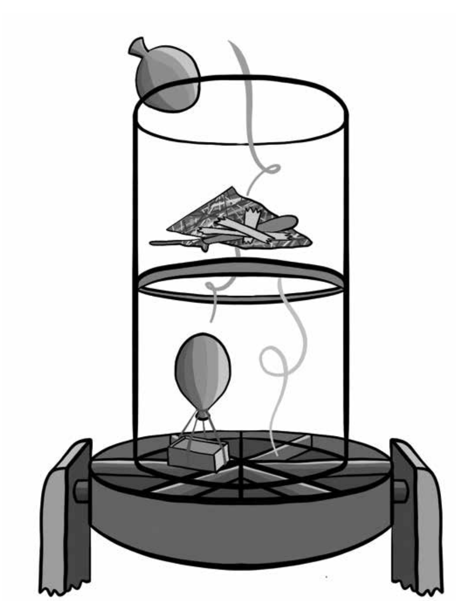
The guidance offered in this book stems from the work of 30 high school physics teachers who gathered as two groups over the course of four years to explore and learn together how to incorporate engineering into their physics classrooms. These teachers took up two important, related goals: (1) to generate and enact engineering-infused physics lessons that worked for their students and (2) to identify a repeatable approach that other educators could adopt to bring engineering to their physics students. To make the most of the impressive knowledge, experience, and wisdom of 30 physics teachers from different schools and districts, it was important to have a shared language for talking about what engineering is and what it looks like when supporting physics learning. It would be easy for that many teachers over that many years to lose cohesion and diverge into several groups, each with a different image of engineering! Thankfully, the leaders of the engineering infusion project suggested that we keep four major aspects of the engineering enterprise in the fronts of our minds. Design, analysis, models, and systems were the four key concepts that were identified as cutting across the many distinct domains of engineering.

## OVERVIEW OF THE FOUR CORE CONCEPTS

For a quick overview of the four core concepts, let's consider one of our favorite physics-related engineering challenges: the vertical wind tube challenge. In Chapter 1 (p. 1), we mentioned how Project Infuse teacher Julie used it at the beginning of her unit on forces. The setup for the wind tube challenge is a clear tube, about 14 inches in diameter and four feet tall, set on top of a circular fan that is pointed toward the ceiling (see Figure 2.1 and Wilkerson and Petrich 2007). The task is to use common household and office supplies (e.g., bags, cups, tape, paper clips, string, and coffee filters) to create something that will hover in the wind tube for 10 seconds without flying out of the top of the tube and without falling down to the surface of the fan.

Depending on how the task is facilitated and what learning the teacher hopes it will foster, the wind tube challenge can provide a context for each of the four core concepts. Students can iterate on hovercraft **designs,** conduct **analysis** of successful and unsuccessful prototypes, propose **models** of the dominant features and factors that determine success or failure, or make sense of the **systems** interactions among the fan, tube, and hovering objects. Throughout this chapter we will return to the wind tube challenge as we say more about each of the four core concepts.

**FIGURE 2.1. Sketch of the Wind Tube Challenge**



(image credit: Steven Andrews / used with permission)

The wind tube for the challenge uses an upward-blowing fan, an air channel (tube), and a hovercraft for the challenge attempt.

## ORIGIN OF THE DESIGN, ANALYSIS, MODELS, AND SYSTEMS FRAMEWORK

How did the leaders of the Project Infuse decide on using the design, analysis, models, and systems (DAMS) framework? First, they followed the results of a Delphi study, which is a classic technique for achieving consensus of experts' opinions. In a Delphi study, experts on a particular subject are asked to list the most important elements of that subject. Then they are shown other experts' lists and asked to rerank the most important elements across the list. The elements with the lowest average ranking are removed from consideration, and the cycle of independent ranking, shared review, and reranking is repeated until the group of experts agrees that a stable list of important elements has been achieved. When a panel of professional engineers, college engineering faculty, and high school teachers of engineering and technology followed the Delphi process regarding the key concepts important for all engineering learners, 13 concepts rose to the top out of 100 themes they considered (Custer, Daugherty, and Meyer 2010). Design, analysis, models, and systems were among those 13.

The engineering-into-physics infusion project began just as the public draft of the *Framework* was being released. The project leaders chose to focus on design, analysis, models, and systems because they were the four concepts that had emerged as important in the Delphi study that were also emphasized in the disciplinary core ideas, science and engineering practices, and crosscutting concepts of the *Framework.* Because it helped lead to the identification of the DAMS framework, the Delphi study was very helpful in grounding and guiding the first year of work by the original group of teachers. Guided by the four-part framework, the group saw clearly that engineering infusion was going to involve more than just posing a few design challenges. We needed to connect students' physics thinking and learning to aspects of engineers' work beyond designing physical contraptions.

## ROLE OF THE FOUR CORE CONCEPTS IN LEARNING TO INFUSE ENGINEERING

The DAMS framework has been helpful to our group of teachers in several ways. First, it serves as a check on whether we are offering a broad enough view of engineering to our students. DAMS reminds us that engineering is more than designing physical devices—its framework helps us share with our students a fuller picture of the kinds of thinking that engineers do and the ways they make use of and contribute to physics and mathematics. Second, the DAMS framework offers alternatives when we find a phenomenon in physics that is difficult to consider within an engineering design challenge. If we can't infuse engineering into a physics unit with a **design** task, we can usually find a way to connect the physical phenomenon to an **analysis** of the trade-offs between two potential designs, a **model** of an existing technology, or a consideration of the components of a complex engineering **system**. The third way that DAMS supports our group of teachers is by providing a shared language that we can use to classify different kinds of engineering-infused physics lessons. When we say to one another, "this lesson is more analysis than it is design," we know that means that the lesson probably asks students to collect data about an existing engineering technology and mathematize that data set, rather than asking students to tackle a challenge to design a new technology. Finally, the DAMS framework grounds our discussions about the overlaps and distinctions between engineering and science. Of course, design, analysis, models, and systems are terms used to describe key elements of science endeavors as well. At the end of the chapter, we will return to this point and compare and contrast the use of the terms in engineering and science.

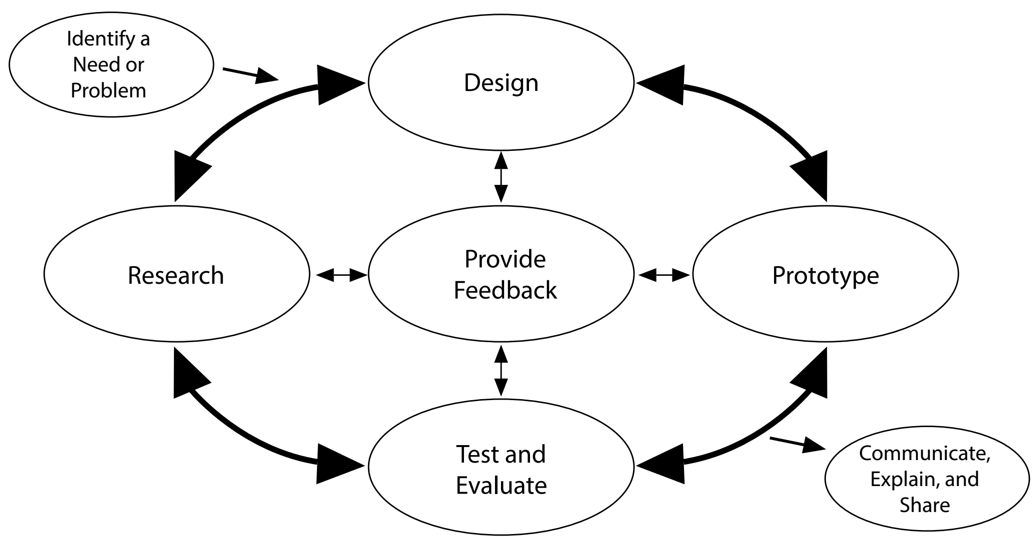
## Design

Henry Petroski—an engineer, historian, professor, and prolific author of books about how engineers do their work—writes in one of his titles that design is how engineers get from thought to thing (Petroski 1996). In fact, design itself is a common human activity that extends well beyond the purview of engineers: the word *design* can be used to describe what all humans do when they make and implement an intentional plan to change some current state of affairs. However, in the context of engineering, design is an iterative process conducted within specific constraints to develop products or systems to satisfy needs and wants. Typically, an engineering design process (EDP) includes problem definition, conceptual planning, modeling of possible solutions, analysis of data, and prototyping and refinement of solutions. Design in engineering requires making trade-offs between the advantages and disadvantages of different possible solutions. The work of coming as close as possible to all desired criteria while staying within the limits of all constraints is called *design optimization*.

One way to learn more about engineering design is to study different depictions of it. Figure 2.2 shows the design process diagram used in the 2016 Massachusetts science and technology/engineering standards for K–12 students. While no two engineering teams follow exactly the same procedure, there are enough commonalities across different engineering design efforts that scholars have been able to create descriptive representation of the phases of design. It is important to understand that these diagrams are *descriptive*, not *prescriptive*. That means that they should not be interpreted as a step-by-step recipe that all engineering designers follow. Instead, they are meant to help us understand the general flow of their work. Just as scientists do not rigidly follow a "scientific method," engineers do not strictly follow the "design process" at the cost of creativity and insights. For example, an engineering team may go from planning to prototyping to testing and then return to planning.

One principle that all EDP diagrams convey is the important role of iteration in design. When designing, engineers repeat the actions of creating a prototype (or other testable model), evaluating, learning from failure, and redesigning over and over again. Iteration should be a key component of engineering design in a physics classroom.

**FIGURE 2.2. Diagram of the EDP used in the 2016 Massachusetts Science and Technology/Education Curriculum Framework**




*Source:* Adapted from Massachusetts Department of Elementary and Secondary Education, *2016 Massachusetts science and technology/engineering curriculum framework. www.doe.mass.edu/frameworks/scitech/2016-04.pdf.*

It will be valuable for students to search the internet for different engineering design cycles and discuss their similarities and differences. Depictions of engineering design are available in ethnographies and histories of design as well as in think-aloud protocols (studies of engineers "thinking aloud" as they work to solve design problems). (In addition to Petroski's volumes, we recommend Bucciarelli 1994, Cross 2011, and Madhavan 2015.) Some researchers have compared the design processes of novice, experienced, and expert engineers (see Atman et al. 2007; Cardella, Atman, Turns, and Adams 2008; and Crismond and Adams 2012). Through these efforts of engineers and social scientists, a great deal of information is available to the general public about how professional engineers participate in design. The results of design ethnographies and think-aloud protocols can help flesh out physics teachers' views of the concept of engineering design.

As engineers become more expert designers, they shift away from trial-and-error methods and rely more heavily on informed decision-making. For example, in one study, recently graduated engineers used a systematic trial-and-error approach in which they implemented and evaluated each design idea through many iterations. Their more experienced colleagues evaluated tentative design ideas before implementing them so that they could devote more of their time to the most potentially fruitful ideas (Ahmed, Wallace, and Blessing 2003). A case study of three exceptional engineering designers thinking out loud while designing a bicycle carrier, sewing machine, and racing car revealed three reflective stances that they all shared (Cross 2003). They all (1) deeply considered the problem space and framed the problem from the perspective of their own personal experiences, (2) articulated connections to physical principles throughout their design process, and (3) negotiated a productive tension between their own goals and the clients' requirements for an acceptable solution. Informed designers "design with an abundance of ideas" and use techniques such as brainstorming and divergent thinking to avoid favoring any single solution at first (Crismond and Adams 2012, Shah, Vargas-Hernandez, and Smith 2003). They are reflective about the benefits and trade-offs of potential design decisions, whereas beginning designers sometimes ignore these trade-offs. Informed designers are also explicit about the design strategies they are using, rather than following tacit procedures (Atman et al. 2007, Crismond and Adams 2012). Whether novice or expert or somewhere in between, all engineering designers use practices that involve creating representations of their work (Dym and Little 1999) to assist them in analyzing and testing the work they are producing (Bucciarelli 1994). These are habits of mind that we wish to instill in our students through the engineering infusions we choose for our science classes.

## Design and the Wind Tube Challenge

Envision again the vertical wind tube challenge that we mentioned at the beginning of the chapter. For this task, design involves planning and iterating multiple times on a hovercraft that will hover for 10 seconds inside the tube. When the students' first design—which might use a coffee filter—flies out of the wind tube in a few seconds, they will make modifications such as adding some paper clips around the filter's perimeter. If the new design sinks to the bottom, they once again will make modifications and often will begin to systematically vary the weight or surface area. They might also add objects to keep their design from tilting or collapsing. With each cycle of hovercraft design, physics students not only learn about the important role of failure and iteration in engineering, they also develop keener insights into the balance of forces that allow a hovering artifact to stay suspended in the air. As they iterate, teachers can ask students to try to generate rules of thumb that govern successful hovering devices. They can scaffold the students' search for rules of thumb by asking "What are you noticing about devices that work? What are you noticing about devices that don't work?"

When conducting the wind tube challenge, many students invariably come to admire one or two of the successful designs. This leads nicely into a discussion of other criteria for design that we value, such as simplicity and elegance, in spite of the difficulty in defining these qualities.

## Analysis

*Analysis* is the next core concept we used to frame our efforts to infuse engineering into physics learning. The Project Infuse definition of analysis is *the use of tools, knowledge, scientific and mathematical reasoning, and critical thinking to look for patterns in data and predict or explain the behavior of an object or system throughout its life.* Engineers' tools for analysis include physical, graphical, and mathematical models (to be defined in the next section) derived from both theoretical and empirical work, as well as experimental instrumentation (hardware) and computational power (software). Engineers conduct analysis to predict or explain the performance of existing designed systems and of proposed designs. Whether seeking to characterize an existing technology or working to propose a new technological solution, data are a crucial element of analysis. Empirical studies and the data they generate provide the evidence used by engineers to make and support claims about technologies, such as their pros and cons, their likelihood of meeting or exceeding criteria, or their probability of staying within or pushing the boundaries of constraints.

Analysis is the work of determining and supporting these kinds of claims. Sanjoy Mahajan, a physicist, engineering professor, and award-winning physics problem-solver, has developed innovative ways to teach engineers how to analyze scenarios and technologies, and he suggests that analysis is like the reverse of design (Mahajan 2014). If design gets you from thought to thing, as Henry Petroski (1996) said, then analysis gets you from thing to thought. According to Mahajan, strong capacities for analysis lead to better designs because if engineers design something that doesn't work, analysis will help them to figure out why and make an adjustment in a productive way. If we don't know how to analyze the failed design, we won't know what adjustment is most likely to lead to a better outcome next time.

Engineering analysis has its own specialized areas, such as finite-element analysis, cost–benefit analysis, and failure analysis. *Finite-element analysis* is a technique for understanding how a structure or device will respond to a number of different inputs, such as an applied force or a change in temperature. Using computer software, engineers model the structure or device as made up of thousands of tiny pieces, or *finite elements,* and use physical principles to determine the effect of the force or temperature change first on each element and then on the structure or device as a whole. Finite-element analysis can be used to understand why a structure is performing as it is, or as a strategy for predictive analysis—to predict whether a design will work as expected before investing resources into creating and testing a physical prototype.

Another type of analysis used to make decisions about designs under consideration is the *cost–benefit analysis,* which compares the resources required to bring a design to completion with the benefits it will bestow on all involved stakeholders. Cost–benefit analysis is an interesting specialty that requires estimating numerical values for things that are often hard to quantify, such as reduced noise pollution (in the case of a wind turbine design). A kind of engineering analysis that takes place after a design has been in use rather than for predictive purposes is *failure analysis*. Also called *forensic engineering* (Petroski 1996), failure analysis takes place after a structural failure, such as an airplane crash or a balcony collapse. It is the detailed study of the exact causes of the failure so that future technologies can be designed to perform safely. Engineers carefully examine all available evidence, ranging from design diagrams to pieces of wreckage, and determine whether the failure was triggered by a substandard material (e.g., a metal component with a crack in it), a design flaw (e.g., inadequate support for a walkway), a human error (e.g., neglecting to follow pressurization guidelines for a passenger cabin), or some sequence of events involving more than one of these possibilities. Sometimes failure analysis involves re-creating the failed structure and testing it under different conditions, such as flexing an airplane wing with hydraulic jacks to understand the effects of repeated transatlantic flights.

### Analysis and the Wind Tube Challenge

Returning to the example of the wind tube challenge, teachers can engage physics students in engineering analysis by asking them to generate an explanation that accounts for all of the successes and failures in their hovercraft design process. With the whole class, pick one student hovercraft that worked well and one that didn't work. Have all students draw free-body diagrams of these two hovercrafts. Focus student thinking on the variables that influence the upward force—the drag force from the air. What are the factors that determine how much drag force a given hovercraft will have? Perhaps have students explore several hovercraft designs where the weight is dominated by the same relatively heavy object (a binder clip, for example), but other variables are changed by very lightweight materials to see how those variables affect the drag force. Physics students know the equation for computing the weight of an object and can ascertain the variables that affect the drag force. Recognizing that some of the mathematical analysis may be beyond the scope of the high school course, it is still valuable to point out that the mathematical equations are known and are used in analysis.

## Models

*Models* is the third core engineering concept for Project Infuse. We define an engineering model as *a representation of an engineering design or analysis that reduces its complexity in some way.* Models can be pictorial, mathematical, graphical, three-dimensional (3-D), computer-based, or tangible. They are used to test and communicate ideas about designs or analyses, determine the effects of proposed changes to a design, visualize and support the analysis of complex systems, and enable more learning about what might happen in the next step of a design process or with the next version of a technology. Each kind of engineering model reduces complexity in a different way.

The goal of a mathematical model of a designed system is to abstractly represent relationships between two or more aspects of its behavior. Mathematical models consist of equations, graphs, or a collection of both, and they relate one variable of a system, such as wing length, to another variable that the engineer cares about, such as lift force. What is valuable about mathematical models is that they show the nature of the relationship for many possible values of each variable. An engineer can use this type of model to see how changing one design parameter will affect an important outcome. The equations and graphs that encapsulate relationships between design parameters and outcomes can be *computed* (derived from the use of physical principles and laws) or *empirical* (based on data gathered through experimentation). Engineering often uses computers both to generate equations and graphs from physical principles and to transform tables of experimental data into graphical representations and best-fit equations. A computer simulation is a type of mathematical model that takes a set of equations, allows one or more input variables to change, and represents the range of outcome variables to the engineer. Simulations can allow engineers to see how a designed system will perform over a much longer period of time or at a much larger or smaller scale than would be possible with a physical model or experiment. When used in an EDP, mathematical models allow designers to compare possible solutions and make informed choices by predicting performance before a major cost investment in physical materials. In engineering analysis, models help us understand the performance of a designed system parameter by parameter and identify the cause of failure in an existing designed system.

Whereas mathematical models show abstract quantitative relationships between aspects of a device or structure, graphical models are used in engineering to show abstract qualitative relationships or connections between the important factors of a process or product. These models use graphical elements such as shapes, arrows, and other symbols to describe behaviors of both engineering processes and products. For example, flow charts are graphical models that can represent the flow of information in an EDP or in a computer algorithm running on an engineering device. A block diagram of a feedback control loop shows how a designed system such as an air conditioner will collect information from the environment (e.g., using a thermostat) and use those data to change that system's behavior (e.g., power on the cooling cycle) to perform the function it has been designed to perform (e.g., lower the temperature of a room). The free-body diagrams, which engineers draw to represent the major forces acting on a physical body, is another important kind of graphical model used in engineering.

Two-dimensional (2-D) and 3-D models of the structures and functions of engineered design are a third very important class of models. Hand-drawn sketches and computer-aided design drawings (which are 2-D) can show the size, shape, and position of a structure or device. Physical prototypes (3-D) go a step further in representing the functionality of different components—they allow engineers to communicate and test the geometry, assembly, and functionality of their designs. Early in the design process, prototypes serve the purpose of proving a design concept and do not need to be made from the materials or with the manufacturing process that will be used for the final product. However, later-stage prototypes are used to test material choices and manufacturing techniques.

### Models and the Wind Tube Challenge

The wind tube challenge can support thinking about a few different kinds of engineering models. First, the hovering devices that students build can be considered physical, 3-D models of real-world technologies for parachuting, aircraft, or spacecraft descent. The wind tube can act as a model for air flowing around an object that is falling toward Earth. Engineers use physical models such as the wind tube to test products in a controlled setting and develop design principles. By reducing the complexity of a parachuting or vehicle descent situation, the wind tube model can help students generate design principles for parachutes and other descent equipment: What recommendations can the students make about how to slow the speed of a falling object? When studying kinematics, we talk about terminal velocity (downward motion when an object is no longer accelerating)—here is a way to make it happen and explore it. In the wind tube, the air blown up by the fan onto the coffee filter is like the air rushing past a skydiver, parachute, or descending vehicle.

Free-body diagrams of the hovercrafts are also engineering models. They are graphical models of entities and forces acting on those entities. By creating and analyzing free-body diagrams of the hovercrafts, teachers may be able to help students see that the working hovercraft has a balance of upward force (drag from the flowing air pushing on its downward-pointing surfaces) and downward force (weight due to gravity). By reducing the complexity of the wind tube–hovercraft system, the free-body diagram models can help students estimate the force of air resistance on this hovercraft (it should be just a bit less than the weight of the hovercraft). Students can explain how their wind tube is a model for parachutes as well as come up with pictorial models or graphical models to describe their wind tube design.

## Systems

The fourth core concept for engineering infusion into high school science is *systems*. *Systems engineering* is an approach to thinking about, designing, and analyzing complex technologies. We define an engineering system as *a group of interrelated and interacting technical artifacts designed collectively to achieve a desired function*. Engineers analyze and model complex technologies (and sometimes even not-so-complex technologies) as *systems* because doing so enables them to decompose complexity into more manageable pieces. For example, a complicated manufacturing machine can be decomposed into a system of simpler *subsystems* that perform a distinct function in the overall machine and consist of a manageable number of *components*. Each subsystem relates to all of the other subsystems in a complex technology through *interfaces*, which are transitions or connections between subsystems. Engineers strive to design interfaces in such a way that if one of the connected subsystems changes, the interface can be adjusted to accommodate that change without having to change the other connected subsystem.

The field of systems engineering is growing rapidly as technologies become more complex and more intricately linked with social norms and practices as well as with public policy and infrastructure. Systems engineers are trained to look at technologies from a broad perspective and identify how matter, energy, and information flow within them and between them and the natural world.

### Systems and the Wind Tube Challenge

The concept of systems can readily be applied to the wind tube challenge. First, students can decompose the wind tube itself into its major subsystems—the fan and the air channel. Then, within the fan subsystem, they can identify the main components: the motor, rotor, blades, plastic casing, adjustable stand, wiring, and switch. The air channel's components are its flexed wooden ribs and its acrylic sheeting. Systems thinking can lead students to consider the interface between the two main subsystems and help them reason about the effects of this interface on the behavior of their hovercraft. The fan directs air upward through the air channel, but a structural support (usually made of wooden columns and screws) serves as the interface between these two subsystems. The size, stability, position, and orientation of the interface influences how much of the air moved by the fan flows into the tube and how turbulent that flow is. Students can explore different designs or positions of the structural support and investigate how changing this interface affects the entire system's performance. In doing so, they would need to consider the hovercraft as another subsystem in the wind tube system. By analyzing the behavior of their hovercraft from a systems perspective, students may reason at a more sophisticated level about the interactions among the fan, the air channel, the structural support, the hovercraft design, and even the human user (e.g., how influential is one's technique for releasing the hovercraft in the wind tube?).

## THE *NGSS* AND DAMS IN ENGINEERING AND SCIENCE

We have discussed the DAMS framework in the context of the wind tube challenge to show how the concepts of design, analysis, models, and systems are fundamental to the world of engineering and how they surface in a classroom engineering activity. However, educators coming to engineering infusion from a science perspective may still be wondering about the overlaps and distinctions between these four terms as used in science and in engineering. We have found that the *Framework* and the *NGSS* provide helpful lenses for navigating the terrain of these four concepts across both disciplines.

When we compared the results of the Project Infuse Delphi study to the *Framework* and the *NGSS,* we noticed that all four of our Delphi concepts appear in the *NGSS*'s three dimensions of science education—design, analysis, and models in its science and engineering practices, and systems in its crosscutting concepts. The placement of design, analysis, and models in the *NGSS* list of eight science and engineering practices helps us remember that these refer to the things that engineers *do*, not just what engineers *know about*. In other words, designing, analyzing, and modeling are not different pieces of knowledge, but rather complex behaviors that engineers carry out by combining both knowledge and skills. However, as we develop engineering-infused physics lessons, we still call *design*, *analysis*, *models*, and *systems* our four core concepts of engineering because the word *concept* can also mean an idea that characterizes the essential features of something. Although we see them as part of engineering practice, the DAMS components are also concepts in the sense that they characterize the essence of engineering, which is important to infusing it in physics learning.

We also immediately saw that in the context of the science disciplines, the terms *design*, *analysis*, *models*, and *systems* do not always hold the same meaning they do in the engineering context. For example, a team of scientists might "design" (in the science sense) an experiment to explore a hypothesis they've posed, but to "design" (in the engineering sense) a piece of equipment needed to conduct that equipment, they usually need to team up with engineers as well. These two design activities (experimental design and technology design) are quite distinct. Similarly, science students will develop or critique a "model" that can describe a phenomenon such as how light travels, whereas engineers will build a 3-D, scale "model" of a technology such as an airplane wing to use in a wind tunnel to collect data to inform the design of a wing under consideration for a passenger plane. The science students would need to define the boundaries of the natural "system" they are modeling, but the engineers consider the wind tunnel a designed "system" and would be sure to take into account the interactions between the flowing air and the tunnel walls when they measure pressure at several points along the wing. Techniques for "analysis" are often similar across science and engineering endeavors, but the objects of analysis typically are different. Continuing with the same example, the science students might collect data about light intensity at various locations in the system they are modeling, and conduct an "analysis" of the data to check the accuracy of their model's predictions. The scientists' data analysis is aimed at improving an explanatory model. In contrast, the engineers in the airplane wing example will carry out an "analysis" of the pressure measurements in light of the overall lift force experienced by the wing. The engineers' data analysis is aimed at informing a designed artifact.

When teachers from the Project Infuse gathered, we often used Venn diagrams to represent the distinctions and overlaps among design, analysis, models, and systems in science and engineering. We learned to think specifically about one activity or experience, such as the wind tube challenge, and to consider the four concepts in both of the disciplines as they relate to that specific experience. Table 2.1 (p. 26) shows how another approach similar to Venn diagrams works for the wind tube challenge.

**TABLE 2.1. Comparison of the Four Core Concepts as Used in Science and in Engineering**

| Concept | Science for the Wind Tube Challenge (Physicists) | Engineering for the Wind Tube Challenge |
|---|---|---|
| **Design** | • We designed an experiment.<br>• We do not use household objects we are given as-is; rather, we very precisely vary the surface areas and masses of the nested coffee filters and determine relationships regarding size and speed of movement.<br>• We design the best experiment possible, disregarding the costs of the materials. | • We design an artifact that hovers in the wind tube for 10 seconds.<br>• We use the household objects that we were given, such as coffee filters.<br>• We are sensitive to the costs of the materials as we try to optimize our design. |
| **Analysis** | • We use much simpler models of hovering coffee filters to check whether their mathematical analysis is consistent with the experimental evidence.<br>• We use analysis that is based on principles such as Newton's laws of motion. | • We analyze our designs using physics principles and related equations to understand the performance of our designs.<br>• We analyze the forces acting on the hovercraft and use this analysis to inform design revisions.<br>• We have to adapt general principles for the complexity of our designs. |
| **Models** | • We model the forces on the object using free-body diagrams.<br>• We use pictorial models to show the air currents on the object. | • We use the wind tube challenge as a physical model for a parachuting person descending toward Earth.<br>• We use sketches to model the ideas we have for improved designs. |
| **Systems** | • We investigate the net forces on the object to determine whether the system as defined by the object and the fan are in equilibrium. | • We are concerned with the fan subsystem, the air channel subsystem (and its friction), and the electrical switch subsystem that can limit the fan.<br>• We consider the interfaces and interactions between these subsystems. |

## REFERENCES

Ahmed, S., K. M., Wallace, and L. T. Blessing. 2003. Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design* 14 (1): 1–11.

Atman, C. J., R. S. Adams, M. E., Cardella, J. Turns, S. Mosborg, and J. Saleem. 2007. Engineering design processes: A comparison of students and expert practitioners. *Journal of Engineering Education*, 96 (4): 359–379.

Bucciarelli, L. L. 1994. *Designing engineers.* Cambridge, MA: MIT Press.

Cardella, M. E., C. J. Atman, J. Turns, and R. S. Adams. 2008. Students with differing design processes as freshmen: Case studies on change. *International Journal of Engineering Education* 24 (2): 246–259.

Crismond, D. P., and R. S. Adams. 2012. The informed design teaching and learning matrix. *Journal of Engineering Education* 101 (4): 738–797.

Cross, N. 2003. The expertise of exceptional designers. In *Expertise in design*, ed. N. Cross and E. Edmonds, 23–35. Sydney: Creativity and Cognition Press.

Cross, N. 2011. *Design thinking: Understanding how designers think and work.* Oxford: Berg.

Custer, R. L., J. L. Daugherty, and J. P. Meyer. 2010. Formulating a concept base for secondary level engineering: A review and synthesis. *Journal of Technology Education* 22 (1): 4–21.

Dym, C. L., and P. Little. 1999. *Engineering design: A project-based introduction*. New York: Wiley.

Madhavan, G. 2015. *Applied minds: How engineers think*. New York: W. W. Norton.

Mahajan, S. 2014. *The art of insight in science and engineering: Mastering complexity.* Cambridge, MA: MIT Press.

National Research Council (NRC). 2012. *A framework for K–12 science education.* Washington, DC: National Academies Press.

NGSS Lead States. 2013. *Next Generation Science Standards: For states, by states.* Washington, DC: National Academies Press. *www.nextgenscience.org/next-generation-science-standards.*

PIE (Play Invent Explore) Institute, Exploratorium. 2017. Things to try: Wind tubes. *www.exploratorium.edu/pie/downloads/Wind_Tubes.pdf.*

Petroski, H. 1996. *Invention by design: How engineers get from thought to thing*. Cambridge: Harvard University Press.

Shah, J. J., N. Vargas-Hernandez, and S. M. Smith. 2003. Metrics for measuring ideation effectiveness. *Design Studies* 24 (2): 111–134.

Wilkerson, K., and M. Petrich. 2007. Wind tubes, Play Invent Explore (PIE) Institute. *www.exploratorium.edu/pie/downloads/Wind_Tubes.pdf.*

# 3

# Implementation

**Arthur Eisenkraft and Shu-Yee Chen Freake**

The consensus is that, as science teachers, we should be providing our students with exposure to engineering concepts. The rationale, justification and meaning of this have been described in the first chapters. As we have discovered from teachers' experiences, implementation requires more than good intentions. *A Framework for K–12 Science Education* (*Framework;* NRC 2012) and the *Next Generation Science Standards* (*NGSS;* NGSS Lead States 2013) help inform what should be done and what expectations should be met but leave the implementation strategies to others to develop.

Our claim is that infusing engineering into high school physics and physical science classes is an opportunity to familiarize all students with engineering concepts (specifically design, analysis, models, and systems) without the expectation that students must take a standalone engineering course. We further claim that infusing engineering into science can provide another dimension to the physics concepts in our traditional courses and may actually increase physics achievement.

In exploring engineering infusion over many years with many teachers, we focused on how to do it, when to do it, various issues of implementation, and how often to do it. These four aspects of infusion will form the headings for this chapter.

## HOW TO INFUSE ENGINEERING INTO HIGH SCHOOL PHYSICS AND PHYSICAL SCIENCE

Schools have made efforts to offer electives programs such as robotics, engineering design, and other after-school enrichment opportunities. However, many schools across the country simply do not have the resources or the time in students' schedules to participate in these programs. Therefore, the *Framework* (and the related *NGSS*) presents a unique challenge and opportunity for teachers and administrators to find a way to incorporate both scientific and engineering practices into mainstream science classrooms. Because science teachers across the country have different degrees of experience with engineering, it is important to consider implementation models, strategies, challenges, and societal implications when infusing engineering into a science classroom.

The challenge of teaching and exploring engineering concepts can be realistically met in a science classroom with a few modifications and implementation considerations and without adding a tremendous amount of time to the course. This is especially true in the physics classroom because many of the engineering concepts and practices tie in very well with the physics concepts in the new *NGSS* physics standards.

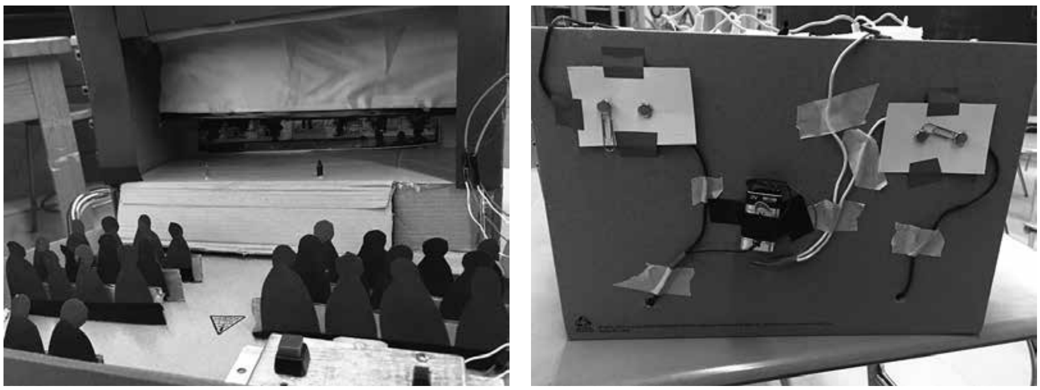
The problems surrounding engineering instruction are not limited to K–12 classrooms. Universities have been struggling with this as well—for their engineering majors! In some engineering programs, design may be a capstone course that aims to have students apply all of their content knowledge from their first three years of courses to a successful design project similar to what they might be faced with in their first job. In contrast, other engineering programs provide students with the opportunity to design in a freshman course and refer back to this experience until the senior year, when students once again participate in a design challenge.

Kris, an engineering student turned physics teacher, notes the following:

> *Most of my "engineering" classes at MIT were actually physics classes, with few engineering applications. How do you know if you're on the right path if you never see it all come together until your senior year of college? Luckily in my senior year at MIT, in the [Project Laboratory] class, we worked in small groups to* ***develop solutions*** *to particular problems. We had to* ***brainstorm solutions, model*** *them mathematically and experimentally, and* ***present our results*** *to the class. We completed this cycle three times in the month-long intensive class and it was the first time I could see everything that I'd learned coming together in a way that replicated how engineers actually worked.*

The bolded terms reflect similar language to the science and engineering practices emphasized in the *Framework* and *NGSS*. Using the engineering-infused model of implementation in our science classroom, we can introduce ways for students to bridge physics content knowledge with the exciting, real-world application of engineering concepts and practices. Student engagement with the material will certainly increase, and their ability to problem-solve and communicate ideas, which are essentials for scientific inquiry, will be enhanced with the right balance between science and engineering content in our classrooms. For example, instead of a worksheet with 10 problems using Ohm's law to explore complex circuit problems, students can be asked to design and construct the lighting in a miniature theater for a specific scene of their choice, thus truly understanding each component of a complex circuit and the mathematical model that helps them troubleshoot any problems (Figure 3.1).

**FIGURE 3.1. Examples of Students' Model Theater Lighting Circuits**



**(a) Students designed a theater in a box. The curtain and lights on the stage can be controlled by the operator.**

**(b) The circuit behind the stage design where students use paperclips as switches is shown. The project requires students to conduct a mathematical analysis of the circuits after they have finalized their design but before moving on to the construction period.**

## Concept-Focused or Process-Focused Infusion Model

Different strategies for infusing engineering into physics classes exist. All of these strategies require the teacher to find the right balance between engineering process and concept.

In classrooms, teachers strive to move students away from the rote memorization of facts for the sake of standardized tests to teach both science concepts and practices at the same time. The *NGSS* and Advanced Placement (AP) redesign both have a strong emphasis on these types of three-dimensional (3-D) lessons, which goes beyond the simple content objectives. (See *https://apstudent.collegeboard.org/apcourse* for more information on AP redesign.) In a similar way, engineering at the secondary level can also be concept-focused or process-focused. Either model can be useful in a science classroom, and it is important to give students opportunities to experience both or to blend them appropriately.

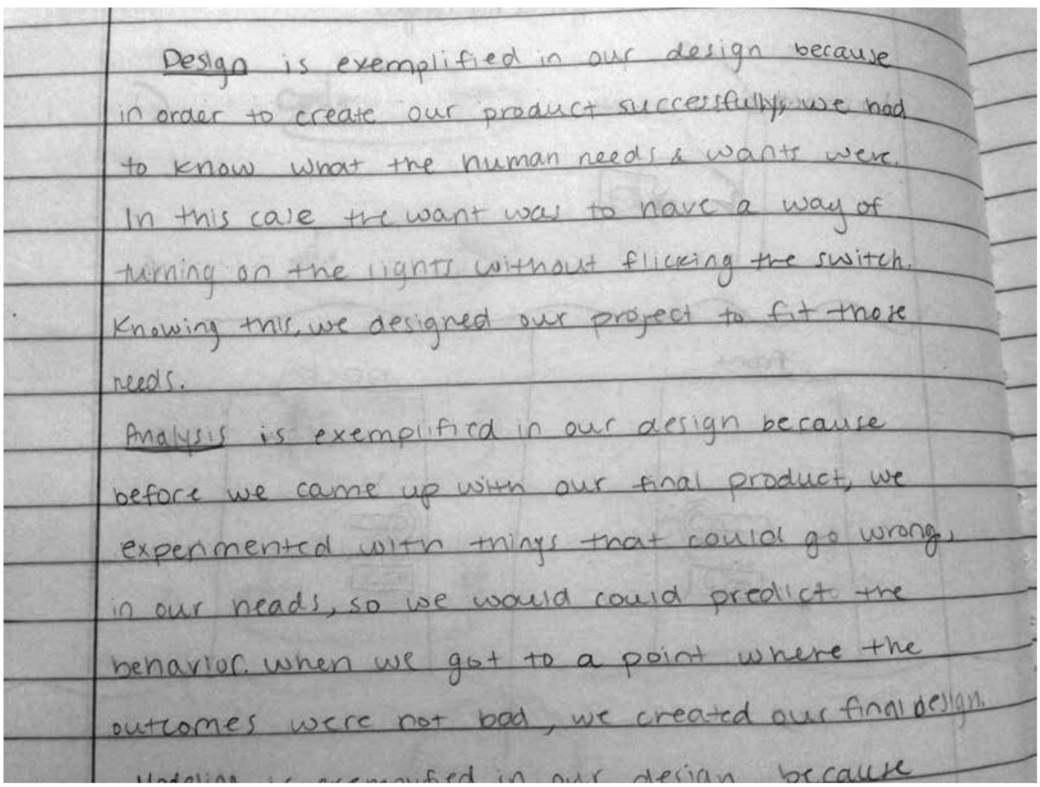
At one extreme, we have engineering infusion, which seeks to define, describe, and give examples of the four core concepts of design, analysis, models, and system. The goal of Project Infuse is to analyze and explicitly teach teachers about these concepts and definitions of engineering. At the other extreme, we have students building projects and completing challenges without any reference to those four concepts. The design projects are the most popular engineering curriculum for grades K–12, in which the focus is on building something or having students go through the engineering design process (EDP) through an activity or simulation.

In a *concept-focused* model, practitioners will have to spend some time examining where it makes sense for each concept to be introduced and taught explicitly so students can have a solid foundation of the four concepts in engineering terms. Using concept-based engineering can be as broad as asking students to perform material testing and failure analysis before launching their rockets or as narrow as identifying different components of systems (electrical system versus mechanical) within a working flashlight. The class can focus on the application of these concepts in the context of a design problem without actually having to physically make something (see Figure 3.2). However, if a teacher only focuses on teaching these concepts in isolated examples without engineering design opportunities, students will be shortchanged.

The process-focused (or design-focused) model is more common in the existing secondary engineering curriculum in circulation. This model involves the building projects, activities, and all of the "design" challenges that give students hands-on experience with engineering. This model is the one that traditionally takes up more time because to practice different skills of engineering, we have to build in these opportunities as well as repetition for more exposure to different levels of engineering skills. It can be argued that many of the one-off design challenges that are readily available are not truly process-focused because blind trial and error usually leads to random success in those projects. For process-focused engineering infusion to work, teachers need to build adequate time for teaching and practicing the skills. For example, simply asking students to narrow down and define the scope of the problems can be a difficult task. Making different prototypes, constructing scaled models, and evaluating which parts of the design should be kept or redesigned are all important yet time-consuming components of the EDP; thus process-focused infusion can take up a lot of instructional time. Although every design-centered project can be valuable, without careful consideration, students might come away thinking engineering is simply the fun challenges and projects without understanding the key concepts and habits of mind that drive the EDP. They might also mistakenly come to think that the holy grail of understanding engineering is to memorize the steps of the engineering process defined by their state standards.

The best practice is really a marriage between teaching concepts and process. It is unrealistic to assume that physics teachers will have twice the amount of time with the new *NGSS* standards, which would allow every topic to begin or end with a big engineering project. However, it is reasonable to find opportunities in the curriculum to include one concept or one skill that blends well with the physics lesson. For example, consider the *NGSS* performance expectation HP-PS2-2, which says "Use mathematical representations to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system." An engineering-infused activity can teach about the importance of analysis and skills of analysis using only mathematical analysis, without having students go through the entire design process to make a toilet-paper tube cannonball and spending three class periods during which students troubleshoot the mechanical parts of the contraption rather than focusing on the science and engineering objectives. Since the existing process-based curriculum repertoire is much richer, the lessons described in detail later in the book will emphasize where engineering concepts can be introduced in conjunction with engineering practices.

### FIGURE 3.2. Student Notebook Entry Relating Engineering Concepts and Their Application to the Student's Drawn Design


Design is exemplified in our design because
in order to create our product successfully, we had
to know what the human needs & wants were.
In this case the want was to have a way of
turning on the lights without flicking the switch.
Knowing this, we designed our project to fit those
needs.
Analysis is exemplified in our design because
before we came up with our final product, we
experimented with things that could go wrong,
in our heads, so we would could predict the
behavior. when we got to a point where the
outcomes were not bad, we created our final design.
Modeling is exemplified in our design because

**In the Enter a Room activity, students were asked to draw a paper design of how to complete a circuit when someone enters a room without a manual switch. After the class presentations, students were asked to write in their journals their reflections on the concepts of design, analysis, models, and systems that were involved in their design process.**

One important aspect of engineering infusion in the science classroom is to think about ways to integrate engineering using different mechanisms. A teacher can focus on the overlaps between science and engineering practices, thus designing curriculum to address the similarities. Alternatively, the teacher can focus on the differences between the engineering and science concepts (design, analysis, models, and systems) so students have experience and exposure that will enable them to articulate the differences between each component in the two fields. In each of the infused lessons, there is a chart summarizing how engineering and science core concepts can be different or similar for the lesson addressed.

## Anchor Activities: Engineering-Infusing Activities Requiring a Minimal Time Commitment

As noted in Chapter 2, Project Infuse has identified four concepts on which to focus: design, analysis, models, and systems. These are also mentioned in the *Framework* (NRC 2012) as scientific and engineering practices (i.e., developing and using models; designing solutions) and crosscutting concepts (i.e., systems and system models). These terms are used in science as well, but with different meaning than in engineering. As science teachers infusing engineering, it behooves us to have students learn the meanings of these terms as used in a science context and as used in an engineering context.

To assist students with design, analysis, models, and systems, we have created a set of anchor activities. Each anchor activity may have elements of each concept, but will have one of the concepts as its central focus. This provides students with a concrete example of the concept, which helps them to identify the concept in other situations. Teachers and students can refer back to these activities to explore each of the four concepts and to understand the difference between these concepts, especially in the context of engineering and how it's different from or similar to science. Some of the anchor activities widely used by teachers include the following:

- Design: Wind Tube Hovercraft
- Analysis: Pasta Cantilever
- Models: Soda Can Clock
- Systems: Rube Goldberg Device

These anchor activities and other examples are further articulated in Chapter 5. Although their context has been simplified to fit a classroom design challenge, teachers can easily find real-world applications that show why each activity could be part of an engineering problem a client might have. Here, we are concerned with how the anchor activities can be used as teaching strategies. Each anchor activity serves as the common experience from which we build our understanding of engineering concepts.

For example, a Rube Goldberg device allows students to complete a simple task in a very complicated way. Say a student team is asked to get a ball to press down on a switch to activate a lightbulb or buzzer, but must design the device so that the ball first goes down a slide, hits another ball, knocks over some cards, bounces three times, and then presses down on a switch. Creation of a Rube Goldberg device in a physics class may be used to have students explain energy transformations. As an engineering anchor activity, the Rube Goldberg device is the reference for systems. No student team gets to build the entire Rube Goldberg device. The teams must come up with a device that has four major parts. Each team then only knows what the height and position of the incoming ball will be and what the height and position of the outgoing ball should be. Each team builds its part of the Rube Goldberg device. The concept of engineering systems, components of systems, and inputs and outputs of systems is emphasized because each part of the Rube Goldberg device is designed and constructed independently and it is only when the four systems are linked that there is a working mechanism.

For the rest of the school year, the Rube Goldberg device is referred back to when engineering systems are discussed. For example, if students are asked to design a flashlight, they will realize that there is not only a mechanical system that includes a switch but also an electrical system that connects the switch and battery to the bulb, and the lighting system of multiple light-emitting diodes (LEDs). Each of these systems can be designed independently, but in the flashlight they must work together.

By providing some common experience and language for students to anchor their understanding, we can help students articulate the engineering skills and concepts they are using when solving different engineering problems throughout the year. We have used these anchor activities in our workshops, and many workshop participants find them to be the best way of describing and clarifying engineering concepts. These anchor activities also can serve as an alternative for engineering concept infusion that has a small time commitment, if that is the biggest hurdle for considering engineering infusion.

## Brief Engineering Exposures

As science teachers, we have always found ways to take advantage of "teachable moments." An item in the news, a movie release, a popular song, a new book, a scientist's birthday, or a discovery anniversary—teachers use all of these to help engage students and bring some history, human interest, and excitement to supplement our core curriculum. Now we can extend this practice to small infusions of engineering into our curriculum. Many of us have already done this with references to movies such as *The Martian* (Scott 2015). We can be more explicit by having the same discussion but using the terms design, analysis, models, and systems. This can be limited to a few minutes or part of a class period.

One idea involving little cost and time is to use case studies that tell a story about a product, an EDP, or an innovation. Incorporating such engineering engagement infusions is very similar to, for example, when a teacher starts the unit on energy conservation by showing visuals of a roller coaster ride. We just have to add an engineering lens to explore the engineering concepts for infusion to occur. As far as implementation is concerned, this might be the best place to start. Students can read a short case study about Frank Lloyd Wright's design process that outlines the challenges and solutions for his iconic Fallingwater house. After that, they can discuss the use of analysis tools and the steps taken by all of the engineers involved in the project and how the engineers solved the structural problem. We can even discuss the torque equation and then make this into a cantilever problem for our students to solve if that makes sense in our classroom. Some sample case studies are provided in Appendix D (p. 439).

Teachers also can introduce innovative products such as an inflatable bike helmet that is fashionable and functional. A physics teacher can jumpstart a unit on momentum by showing the video and discussing the g-force encountered in a crash, and to incorporate more engineering concepts, the video could be used to discuss what design choices had to be made and what constraints needed to be considered so people would want to wear the helmet. Watching videos can be an effective way of infusing engineering. In this example, the two young female inventors in the video also might inspire some young women in the class to pursue a STEM career.

Resources such as *Wired* magazine, Makezine.com, and Kickstarter (*www.kickstarter.com*) can all be inspirations for small opportunities for infusion. Teachers or students can read an article about how the changing magnetic field is affecting the ability of bees to pollinate, and bring this to the class's attention. Spanning from biology to physics to engineering, this complex problem, or one like it, can be used in an infusion classroom in so many different ways—to explore Earth's magnetic fields, adding opportunities to redesign using electromagnetics instead of permanent magnetics, or to collaborate and brainstorm on what iterations and prototypes might be necessary to test that complicated system.

These types of ideas that take little of the class time both allow small amounts of engineering to be easily infused into the classroom and provide a real-world context for how engineering process can help in solving a real problem. As Derek, a Project Infuse physics teacher and workshop leader, says, "I have found that if I see an article or video, it has such a broad appeal that many of my students would enjoy discussing this in the context of a physics class. Incorporating it into my class and highlighting the engineering aspect of the article or video I feel is an easy way to infuse engineering into a physics class."

## Design Challenges

There must be some magical power in the challenge of building a tower using limited spaghetti strands to support the weight of one marshmallow. Why else would the marshmallow challenge be so exciting for teachers, administrators, camp counselors, and even business leaders across the nation? In fact, when a science teacher is ready to do the marshmallow challenge, she might often hear students say, "I just did that in history class." After a brief moment of panic and frustration thinking that the history teacher had stolen her thunder, she can reply, "It's a team-building and engineering activity. You will learn to work with different people, so get to work!" In the science class, this can be followed up with a look at engineering concepts and how they were used or could have been used in the design.

Whether it's the thrill of the unexpected (building a bridge with different types of dried pasta), the competitive nature (Who can build the highest tower?), or the "no strings/grade attached" attitude that teachers have adopted, students are often quite engaged and interested when a small-build engineering challenge comes their way. They are fun, exciting, and engaging ways for students to explore the engineering concepts and participate in engineering practices. These projects almost always lead to discovery of physics principles and mathematical models that explain the science behind the observed phenomenon.

A design challenge can have multiple goals for different stakeholders. A high school engineering teacher, Cory, designed a "golf ball challenge" for his engineering students. Students are given the following goal: Build the longest bridge possible that will support the weight of a golf ball using two pieces of newspapers, one meter of tape, and one meter of string. The goals and objectives the teacher presents to students involve both physics and engineering:

- Practice working in groups and solving problems using the EDP. (Engineering)
- Use the final standing structures to begin talking about force vectors. (Physics)
- Build a scale model (prototype) of the bridge design. (Engineering)
- Determine center of mass. (Physics)
- Test different materials to understand their properties (in this case, string and newspaper). (Engineering)
- Discover and explore tension. (Physics)
- Engage in redesign and the iterative process. (Engineering)

It is important to structure the activity according to the main objective(s)—that is, structure it differently to emphasize certain components and make explicit connections to the science and/or engineering concepts—but also to take care not to lose the fun part of the design challenge. This might mean that the success criteria and lesson implementation will be different each time. Sometimes you might provide each group with three sets of materials to assess how students are able to use each failure and iteration toward a successful product. Other times you might only allow students one set of material after they have demonstrated their design thinking using physics laws of forces and a center of mass calculation on paper. If the solution is too obvious or if the challenge is overcirculated among the student group, the teacher needs to change the challenge so students don't all arrive at the same solution. As veteran teacher Norm notes, "After one pair of students used only duct tape to solve one of my complicated engineering design challenges, I knew this was the last year we would be doing this activity."

## Projects

Project-based engineering infusion is a comprehensive way of teaching engineering in a physics classroom. In the real world, isolated, simple problems like the ones written in typical examinations do not exist. We are constantly faced with complex issues that connect multiple disciplines, multiple stakeholders, and conflicting views. For this reason, one way to learn engineering is to look at a complex project and find ways to approach the best solution using all available resources.

Engineering design projects fit well with the recent attention to introducing project-based learning (PBL) into the classroom. *Active Physics* (Eisenkraft 2016) is arguably the best known curriculum and one of the earliest ones that support PBL. In *Active Physics*, the students learn physics through their investigation and completion of chapter challenges. For example, students may be asked to build an improved safety device for a car. Over a month of instruction and through laboratory investigations and readings, students learn the physics of Newton's laws, impulse, momentum, and energy. They then must use this physics knowledge in designing and creating their improved safety device. The device is then tested using an egg as a model for a human skull. Another example has students propose an appliance package that can be used in developing countries, where the electricity is limited to a single wind generator. In their physics labs and readings, students learn about circuits, power, and energy to ensure that their proposal subscribes to the given constraints. They also have to defend their choice of appliances by explaining the value of each to a family in that country.

*Active Physics* has clearly shown how physics and engineering can be merged. Each chapter of *Active Physics* requires that teachers move from the traditional physics content of teaching forces in the fall, waves in the winter, and solenoids in the spring to a content approach in which the physics needed for the chapter challenges is learned at the most appropriate time. Project-based engineering infusion also requires weeks rather than a day or two. This does not mean that weeks are spent on engineering at the expense of physics, but rather that to complete an engineering project requires physics knowledge that will take weeks to learn while the student simultaneously thinks about and reflects on the engineering project being solved.

Approaches to project-based infusion can begin from either the physics content or the engineering goal. Different teachers can have different starting points, but the ultimate goal is for students to explore both the science and engineering concepts. Teachers can begin by listing physics content topics that need to be addressed and then finding an engineering problem that uses those physics concepts. If the goal is for students to understand properties of waves, especially sound waves, teachers can have students construct a guitar out of recycled materials that can be used to play one song. In fact, the objectives for physics teachers are very clear here because they are the starting point for a project. A comfortable place for most teachers to start may be finding a project that matches the current content, and modifying it a little bit to incorporate engineering concepts or skills.

The reverse approach is to find some inspiration—such as finding an activity for building robots using a small motor, a battery, a toothbrush, tape, and some wires (e.g., bristlebots)—and then think about what concepts can be taught using that miniature design activity. Project Infuse teacher Derek explains how this can work:

> *My thinking about this project was to study an engineering model to understand a scientific model, something physics teachers will appreciate if they are to "cover the content." Using a simple engineering "tool" like the bristlebot opens up most of the scientific models that are part of the traditional physics curriculum. With little modification, a teacher can use this to study distance/displacement, vectors/scalars, speed/velocity.… I realized that the random chaotic nature of the bot resembles the electron's "random walk." With no modification of this initial, short build, it requires little imagination to see how this bot can be used as a scientific model for current (one bot=one Coulomb), heat (kinetic theory of temperature), and atomic structure (dip the bot in some paint and see the patterns it traces).*

## WHEN TO INFUSE ENGINEERING

One can spend countless hours discussing the roles and importance of engineers and scientists in our society. What is certain is that without one another, scientists and engineers would not be able to accomplish their main objectives. Scientists may start by asking the kind of questions they are interested in, and then acquire the help of engineers to construct instruments for further investigation. Engineers use science and mathematics principles to design a product that fits under a set of constraints. The interplay between science and engineering allows us to suggest three natural places where infusion makes sense: at the beginning of a unit (i.e., activator), during the unit, or at the end of a unit (i.e., capstone).

Building a Lego cantilever, testing different types of switches, or showing a video about insulation materials can all be engineering activators that build interest so students are invested in learning about forces, electrical components, or heat transfer. When engineering is used in the beginning of a unit, the need to learn more physics is driven by the need of the engineers in the classroom. This can be both exciting and disconcerting for many teachers. Many teachers already have a collection of these activators. The challenge for teachers is to carefully choose the activity that will generate the needs for specific physics concepts or to be comfortable enough to see what concepts and questions arise naturally. As mentioned in the previous section, a small activity or product can have many different physics connections; it is really the role of the teacher to provide the necessary bridge and focus so the science content surfaces after the engineering activity.

As an application, engineering can be used to contextualize physics concepts during the middle of the unit. Building a bungee cord after learning about Hooke's law, analyzing the coefficient of friction of flooring materials for a dance studio after learning about friction, or conducting failure analysis on what kind of fabric allows ultraviolet (UV) light to pass through are all examples of how teachers infuse engineering into their classrooms. The goal here is to build a foundation for the science to drive the engineering decisions and to emphasize how that science and the mathematical models provide the data for an informed design process.

As mentioned in the discussion of PBL, the culminating project for a unit can be a capstone in which multiple physics concepts are used in the satisfactory completion of an engineering project. One consequence of beginning the unit with the engineering challenge rather than introducing the challenge after the physics is learned is that in the latter case, students better understand the value of the physics content and how it can be applied in novel situations. Students who know that they will be transferring their physics knowledge to an engineering challenge rarely ask, "Why do I have to learn this?" In fact, this kind of PBL not only increases student engagement but also reflects how actual problems are solved when each component contributes to the function of a complex system. Project-based learning in which the engineering infusion is the capstone event is a worthy goal for physics teachers.

## IMPLEMENTATION ISSUES AND SUGGESTIONS

Cytogeneticist and Nobel Prize winner Barbara McClintock describes her passion for science: "I was just so interested in what I was doing I could hardly wait to get up in the morning and get at it. One of my friends, a geneticist, said I was a child, because only children can't wait to get up in the morning to get at what they want to do."

We want every one of our students to be passionate about his or her learning in our classrooms. By providing some contextualized physics content through the lens of engineering, we can help to attract a more diverse range of students who might be more interested in the application of science than in the beauty of the science itself. Earlier in the chapter, we discussed ways to make small to large changes to the curriculum and to vary the timing of infusion. One might wonder if engineering infusion is as simple as finding good sources for the activities mentioned above without considering changing teacher practices. Just like a classroom that focuses on inquiry, there are some teacher practices that can help teachers anticipate and respond to the common situations that can occur in a student-centered classroom. Some of the tricks of the trade are the same for a teacher comfortable running an inquiry-based classroom, but there are some subtle differences worth considering.

## The Difference Between an Engineering-Infused Classroom and a Guided-Inquiry Classroom

One of the biggest challenges in an engineering-infused classroom is how to structure student-group dynamic during an engineering design activity. Perhaps the difficulty and complexity in deciding how to structure and foster positive student interactions speaks to why it is important to have these experiences in a classroom.

An engineering-infused classroom is very similar but not synonymous to a guided-inquiry classroom. In both, the teacher is not the expert in the room. Students are encouraged to solve a problem while the teacher acts as the coach. Engineering design process allows another degree of freedom for students because there are aspects of engineering that inevitably lead to multiple solutions. For example, in a guided-inquiry classroom, students might be asked to investigate how different factors affect friction. Students have the freedom to consider different materials during their experiment, but the final conclusion will often be the one the teacher already knows the answers to (weight and surface type affect friction, and surface area does not). Because the teacher knows the "correct" answer, it is a little easier to anticipate where the questions and sticking points might be when designing the lesson. Students know there is one expected, correct solution.

This dynamic changes drastically when the teacher cannot possibly anticipate all of the different designs because design activities are inherently open-ended. Students can solve the same problem with many different designs. For example, when the question becomes "Can you build something to reduce the friction of this car on the ramp given these constraints?" the student–teacher dynamic changes significantly. Even though the same physics concepts will arise from the exploration, the path to the engineering solution is unknown to the teacher and each design is a unique solution to the same problem. The engineering designs produced by the students will then serve as a driving force for the physics content. When one group of students produces a solution that uses different surfaces but another group produces a solution that uses weight changes, the teacher has the important role of making the physics connection through the design choices. The design process engages students to be problem solvers, and the designed solutions propel the class to explore the underlying science principles. Teachers have to practice being comfortable reacting to and reflecting on the specific designs.

## Structuring a Design-Centered Classroom

*"Can you help us? My switch won't work and I have tested it three times."*

*"We don't know where to begin!"*

*"What should we write in the engineering notebook?"*

It can seem daunting and exhausting when a teacher walks around from group to group to help students troubleshoot their designs. As a teacher adopts the coaching role, careful planning can help alleviate some of these common questions that arise when students are asked to be in the driver seat in problem solving. Teachers should plan the activity while keeping in mind that providing proper materials, tools, and insightful prompts are all essential for a successful experience. Many effective strategies for a guided-inquiry classroom also hold true for a designed-centered classroom.

One of the major differences is that teachers need to structure the design activity and materials according to the objectives of physics and engineering. Using the example of frictional forces again, the objective of the physics content is to explore different factors related to friction. The engineering objective will dictate how teachers approach the lesson planning: If the engineering objective is to involve students in the process of design, teachers should consider providing many different types of material or providing different constraints to different groups so as to generate many different solutions. This experience will support the future discussion in the classroom regarding factors affecting friction. If the engineering objective is focused on using models so students will communicate and perform failure analysis, the teacher could regroup and do a short "stand up meeting" so the whole class can troubleshoot and help each other to move forward. If the engineering goal of the activity is to emphasize the use of documentation and communication skills, the teacher could provide written prompts for students to document each design and iteration change. The teacher might even consider a group member swap midway for students to practice the skill of communication and to emphasize the importance of documentation.

## Dealing With Competitiveness

*"They copied our design!"*

*"My bulbs are bad. They have better ones."*

Using scientific knowledge to find a solution to a problem is the essence of engineering. With that product-centered mindset, an engineering design-based activity in the classroom can easily motivate students to compete with one another for the best solution. The desire to succeed can be a great driving force for student motivation and engage a diverse range of students. However, that competitive spirit in the classroom is a double-edged sword and one of the biggest challenges in facilitating an engineering design activity. Because engineering is goal-oriented, students often want to play to win, which can bring frustrations about the project, group members, or other groups' performances in an activity.

Experienced teachers already have a large repertoire of strategies for addressing the competitiveness issue should it arise. Classroom management techniques such as creating a safe and supportive learning community, switching groups often through the year (or even halfway through a project, which mimics real-world company personnel shifts), and celebrating each student's success are all preemptive ways to lessen the negative impact of the competitive nature of these projects. However, other approaches that stem from the nature of engineering can allow for a smoother project and should be considered during the planning phase.

Engineering design is a process that requires iteration, creativity, and a great amount of collaboration between members within an engineering team. The teacher can emphasize these elements by setting up an engineering design activity that embodies these important characteristics. It is essential to set up a true team-based activity that requires each member to contribute. To simulate how an engineering firm might operate, the teacher can de-emphasize the need for each team to compete to be the first by framing it as a problem for all teams to solve collaboratively. The teacher can frame the design activity so that the whole class functions as an entity trying to come up with the best design and each team is assigned to explore different parameters. This can lead to richer class discussion, drive students to find more unique solutions, and alleviate the competitiveness that might arise in the classroom. The classroom can mimic industry if the entire class assumes itself to be a research and development firm with teams that come up with unique solutions to the problem. As a research and development firm, the class can then discuss which solution to invest its company's resources in and then promote to the client. Through highlighting the importance of team dynamics in each activity, students will learn to appreciate more of the process than just the outcome.

## What About Creativity and Innovation?

*"Wow, that was cool!"*

*"The final test for flashlight design is when we turn off the lights, try to escape the room using only our flashlight in one hand while fighting off zombies with another."*

In the wind tube challenge, students must create a structure that will hover above a fan for 10 seconds. The structure may not touch the fan or fly out of the plastic cylinder that extends vertically for one meter above the fan. A brown paper bag with some paperclips was the surprising and overwhelming favorite hovercraft among teachers in a wind tube challenge during our first Project Infuse summer workshop. We all agreed that it had an elegance and was aesthetically pleasing. An idea often has something beautiful, simple, and creative about it that is hard to define or predict. It is similar to an elegant proof or simple equation that describes the world around us. Engineering also has a creative side. As science teachers in the classroom, it is important for us to challenge students' ideas about scientists and engineers being uncreative. It is crucial to set up an engineering design activity that allows for creative solutions. The act of brainstorming is an incredibly creative process that students don't often have the opportunity to participate in or practice fully. To foster this, we can add structure by adding competing constraints to the challenge so the students have to really stretch their thinking. Alternatively, we can emphasize the aesthetics of the design or add a user's requirement so that even though the science solution might be obvious, to encourage students' creative ideas the final designed product depends on those surprising elements that we cannot evaluate easily.

Some ideas for design activities or challenges might seem totally insane, contrived, or ridiculous at first glance. In reality, we will never have to make a flashlight because of the zombie apocalypse, or build a playing card tower that will withstand wind from a hair dryer. However, if these situations will serve to engage students, promote meaningful discussion, and achieving the learning objectives, there is no harm in being a little creative in coming up with these fun design activities and then trying to make real-world connections to the application of skills or contents learned.

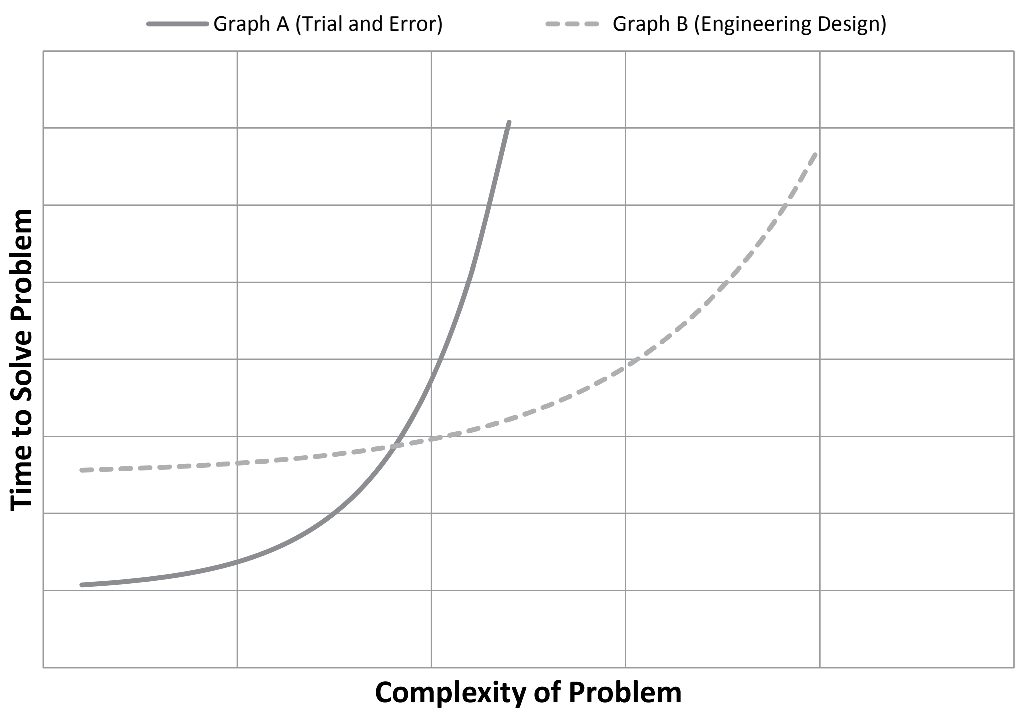
## Trial and Error: The Only Tool of "Classroom" Engineering

*"Shallow men believe in luck. Strong men believe in cause and effect."*
—Ralph Waldo Emerson

There is definitely room for the accidental discovery and the unpredicted outcome in science and engineering. However, if students always succeed through basic trial and error, they really haven't experienced true engineering process. If kindergartners can accomplish a design challenge as well as a group of high school students, then the challenge provides no overarching principles or concepts that increase students' understanding and mastery of engineering skills. *Progressive iteration* is the notion that engineers must carefully analyze previous failures and move toward the solution in incremental steps. Instead of the novice approach of throwing things together again and again, engineers will critically evaluate the pros and cons of the previous version before proceeding. Think back to those short, engaging challenges. If the skills required are easy and timing is short, participants will usually use the more rookie trial-and-error approach to solve the problem. If sophistication of the required skills and the time alloted increase, students will have more of a chance to practice true iteration and use other engineering and physics principles.

We can better understand the appeal of trial and error by referring to a theoretical graph. If we were to graph the time required to solve a problem against the complexity of the problem, our assumption is that the more complex the problem, the more time will be needed to solve it. Some problems are very complex and cannot be solved even if given a huge amount of time. Therefore, the graph on solving problems using trial and error would not be linear and may look like graph A in Figure 3.3 (p. 46). If the problem is relatively simple, it takes very little time to solve it. For example, ascertaining which paper towel is stronger can be easily done through trial and error by placing a weight on each paper towel and seeing which one rips. As the problem becomes more complex, the time required to solve it increases. If we want to know the minimum number of paper towels that can hold a given weight, we can try placing heavy weights on one layer of paper towels, then two layers, three layers, and so forth. We can continue this trial-and-error approach for different weights and solve the problem. If someone were to present us with the problem of optimum thickness of paper towels for given weights, we would have to consider thicknesses of between three or four layers of paper towel. This problem cannot be solved with trial and error because we cannot test for 3.75 layers of paper towels. This last task's complexity is beyond the asymptote of graph A, showing that the time required is infinite.

FIGURE 3.3. **Comparing the Trial-and-Error Approach With the Engineering Design Approach**




Graph B represents the same problems solved through engineering design, including analysis. For the problem of optimal thickness, graphs can be used to show the relationship between rupture weights and the number of paper towels. Interpolating from the graphed data, we can predict fractional thicknesses of paper towels. This approach of engineering uses math and science tools to help focus on design. It will also solve the earlier, simpler problems of ascertaining which paper towel is stronger and the minimum number of paper towels to hold a given weight. However, solving the easy problem with engineering approaches (graph B) will take more time than the trial-and-error approach of graph A. What we can see is that for simple problems, trial and error and engineering design both can solve the problem. In fact, trial and error may be more efficient in that it takes less time. As the problems we confront become a bit more complex, engineering design becomes the more efficient strategy. As the problems become even more complex, they no longer can be solved by trial and error at all.

Trial and error is one way to solve a problem. From an outsider's perspective, engineering design could seem like trial and error; however, the choice of what to do is really based on experience and informed choices. Engineering also uses principles of engineering, incorporates concepts of physics, and recognizes the constraints of science on all designs. If a proposed design solution requires that energy be magically created, an engineer will know to reject it out of hand since physical law requires that energy be conserved.

Trial and error is not as satisfying as mathematical analysis and use of physics principles. A successful and engaging traditional physics lab can be used to illustrate this. A lab exercise that many physics students complete is to have ball roll down a ramp and across a table. The students calculate the speed of the ball on the table and use this speed and the height of the table to figure out where the ball will land. A cup is placed at that position and the students are delighted when the ball goes into the cup. Why are there shouts of glee from the students? Why are they so pleased? It probably has to do with a sense that the equations work and that they can make predictions that were impossible for them before they studied physics. They see the value of their knowledge. Contrast this with a similar lab where the cup is placed in a random position on the floor and the students use trial and error in placing the ball on the ramp so that it will land in the cup. If the ball falls short of the cup on the first trial, they move the ball farther up the ramp for a second trial. Based on this result, they move to another ramp position and repeat. They continue, by trial and error, until the ball lands in the cup. The students will be pleased that it finally works, but they will not feel the same satisfaction as the group that used physical principles and equations to solve the problem. Teachers and curriculum designers should avoid these situations in which students can solve the problem using trial and error; they can do this by adding specific constraints to the amount of materials, increasing the complexity of the problem, or limiting the amount of "testing" students can perform without sound reasoning.

Somewhat related to trial and error as a way to bypass engineering principles is to overengineer a solution. If you aren't sure how much a few books weigh, then why not use heavy lumber for the bookcase? If you don't know the locations of gas stations for a cross-country trip, install a 100-gallon gas tank in your car. Overengineering may waste materials, but it can be faster than trying to do the proper analysis. Overengineering may be done intentionally to make something safer; however, too often it is done to compensate for a lack of analysis or is an outcome of poor design.

## Cost of Material and Physical Space

One of the biggest hurdles for many teachers who are excited about infusing engineering is to consider the cost of different design materials and what kind of physical space is necessary to create a collaborative environment for problem solving. Low-cost alternatives can be explored through infusion activities that are not project-based. Inexpensive household items such as aluminum foil, cups, paperclips, straws, construction paper, and so on can be kept in the classroom for multiple engineering infusion activities throughout the year. Label a couple drawers or bins in the classroom as "engineering supplies" and start a collection of random items (with student help). Most of these common items can be used in many of the activities described in detail later in this book.

In terms of funding and higher-budget items, being proactive is always helpful. Contacting a company to obtain a sample of their product to use for a demonstration may result in getting an entire class set. Small annual grants, local businesses, or fundraising events are all possible means of expanding your engineering materials. Also, a note with some descriptions or photos from your class would be a welcome thank-you.

In addition to setting up materials, it is essential to have students practice physically moving from one place of the room to another quickly, focusing on the task, and putting the desks together for group work. Having designated area for students to file their engineering notebook daily, training them to get the notebook stamped by the project manager (the teacher) daily before leaving the class, projecting a timer on the board so the students are aware of the time constraints—these are all helpful ways teachers can create an engineering-infused atmosphere and help the class run smoothly. One teacher suggested setting up a bulletin board that highlights an "Engineering Hall of Fame" or "Engineering Current Events" to both provide information and celebrate the success of the students as engineers.

## Grouping

One of our Project Infuse teachers, Nivedi, has contributed the following insights regarding group work:

> *Engineering is best done in groups. This is true in the workforce, where engineers are often placed on teams, and as a result the high school student should have this experience during engineering-infused lessons. There are certainly engineering lessons for which students could work alone, but the vast majority require groups. As it turns out, working effectively in groups is an experience that high school graduates should be familiar with, and they should have plenty of opportunity to hone the skills associated with group processes.*

### Assigning Groups

In most cases, the teacher should assign the groups. This prevents any student from feeling awkward or left out during the group selection process and lessens the social drama so often associated with teenagers. It also ensures that students work with different people each time. Exposure to different group dynamics is integral to students developing the skills necessary to function within a group. Groups can be assigned in the following ways:

- Have students count off. (Random)

- Have students organize themselves by birthday, alphabetical order, and so forth and then pair up. (Random)
- Determine clock buddies at the start of the year. (Student or teacher preselected)
- Before class, group students by ability. (Teacher preselected)

For most of the lessons in this book, a group size is suggested but that number can be modified. The size of the group can be determined by considering the following factors:

- The amount of available materials
- The physical size of the project itself (e.g., it might not make sense to have groups of five students hovering over a small circuit)
- The available space in the classroom
- The number of roles necessary to complete the activity
- The attendance record of students

### Roles Within a Group

Once teachers determine the size and makeup of groups, they should consider whether or not to assign (or have students self-assign) roles. For some projects, it will make sense to give students more structure as they undergo the *process* of design, perform analysis, construct models, or work on the components of the systems. There are many different group roles that can be assigned; some of them are as follows:

- Facilitator—makes sure that everyone contributes and keeps the group on task.
- Recorder—keeps notes on group processes and/or ensures that the engineering notebook is filled out thoroughly.
- Timekeeper—ensures that the project will be completed on time by giving updates of time remaining and suggestions for how time can be better spent.
- Checker—checks for accuracy, for clarity, and that constraints are being met. May also check written work and calculations.
- Spokesperson/press secretary—asks the teacher any questions that the group has. May also share out to the whole class during check-in time.
- Materials manager—ensures that the group has all of its materials at the start of the project and that it is not running out of any materials.

Group roles can be determined by the group itself or by the teacher. However, it is important to take note of who is in which role for each activity to ensure that roles are equitably filled by males and females and that the same student does not always facilitate or lead the group.

### Self-Assessing Group Contributions

At the completion of engineering projects and activities, have students complete a self-assessment. It does not have to be time-consuming. In fact, a ticket-to-leave can be effective. This is an opportunity for students to reflect on their contributions to the project, their frustrations with the project or group members, or even what they have learned from the project.

## HOW MUCH ENGINEERING IS ENOUGH?

When is it not a physics course anymore? This is a legitimate question, and it brings out broader philosophical questions: What is the fundamental difference between science and engineering? As educators, how can we guide students in our classroom when they are novices in both domains and expect them to appreciate the excitement and beauty of both fields? How do we do this when we are already struggling to cover all of the required science content in a school year?

There are two models that can guide teachers in understanding engineering infusion activities for physics classes. One model considers physics as water and engineering as alcohol. When the physics and engineering are combined, they become a mixture. Depending on other external characteristics (e.g., temperature and stirring), the mixture may be homogeneous or heterogeneous. Regardless, the total volume of liquid is the sum of the volumes of the two liquids before being mixed—for example, 300 ml of water combined with 100 ml of alcohol will require a 400 ml beaker. Correspondingly, combining three hours of physics instruction with one hour of engineering instruction will require a total of four hours of instructional time.

A second model considers physics as water and engineering as sand. In this case, we know that 300 ml of water and 100 ml of sand will not require a 400 ml beaker because the sand has space for some of the water. Correspondingly, combining three hours of physics instruction with one hour of engineering instruction might only require a total of three and a half hours of instructional time. This is where the synergy of physics and engineering provides benefits.

We don't know which model is the correct one and whether the adopted model is identical for all teachers and all students. It is one of the questions that more and more teachers infusing engineering will eventually be able to answer.

On the more practical level, how does a teacher get started and with how much infusion? Should a teacher start with one major unit project or sprinkle some smaller engineering anchor activities and case studies throughout the academic year? In all our years of involvement in Project Infuse trying to incorporate engineering into physics curriculum, one thing was true year after year: Each teacher had a favorite approach and most comfortable way to infuse engineering in the classroom. By simply committing to try one new infusion activity (either small or large scale) for the school year, teachers have discovered a way to implement infusion that works for them and that engages and enriches students without compromising the valuable time for physics content learning.

Physics and biology teacher Shu-Yee vividly remembers that in the fall of 2012, she decided to give engineering infusion a try. "I was beyond excited on the first day of school; I started all my science classes with some kind of fun engineering activity. Yes, I chose the marshmallow challenge. I thought this activity would spark an interesting journey of finding connections between engineering and science in my classroom. Well, it turned out my biology students absolutely loved building and constructing a spaghetti tower for one day, and then I went on and taught my biology course exactly the same way as I always have been, and only mentioned the word engineering when we discussed genetic modified organism in March."

She continues, "What that failure really taught me, though, is to reflect on the goals and objectives for each choice I make, and how important it is to find a good match between engineering concepts and skills and the science concepts and skills that I want students to master. I will not ask my students to build that marshmallow tower again in my class unless my goal is to engage students and build a cooperative classroom environment."

Shu-Yee concludes that infusing engineering is not successful if students have only an isolated exposure to a design challenge without careful planning and explicit, progressive learning goals. There is a need to return to engineering at regular intervals so that students to understand engineering concepts and practices. This can be done with any physics lab experiment. When the experiment has been completed, students can critique the lab from an engineering perspective. Should the equipment have been different? Is there an approach that would have been more efficient? What could they do if a supply was missing?

Engineers are constantly testing their product and improving the features. The iterative process is essential for students to experience and practice. We recognize that, as teachers, we are constantly racing against time to cover the curriculum, but it is important to leave room for students to reflect and redesign. Students should be able to test their product and then to physically or mentally redesign to improve on it. In an ideal world, there should be redesign done on every engineering design cycle, but if that's not possible, it should at least be mentioned as a step in the engineering design cycle. Some time-saving strategies can be implemented: Ask students to write down three ways for improvement in their engineering notebook, set up a presentation time during which groups can provide one piece of constructive feedback for another group's design, or ask students to spend only 10 minutes improving one part of their design without tweaking the rest. These processing times not only serve to help students understand engineering, but also are essential in personal learning and cognitive development.

## CONCLUSION

*"Success is to be measured not so much by the position that one has reached in life as by the obstacles which he has overcome while trying to succeed."*
—Booker T. Washington

One teacher infusing engineering made an observation that students in honors classes are very unsure of these engineering activities; they are afraid of making mistakes and of trying new things. A great way to foster a growth mind-set in the classroom is to embrace the idea of failure from engineering infused activities. With the increasing emphasis on viewing failure as a necessary part of the learning process, students need to be comfortable with making mistakes and be able to learn from mistakes. Failure analysis is part of the design criteria and can be used to help students learn to deal with disappointment and criticism within this context.

Since the goal of an engineered product is to fulfill a function within a society, considerations for choosing a design are never purely technical. Economic, social, and cultural contexts are all important components of decisions about and success of an engineered product. In our classroom, we should take a holistic approach and include these elements, look at the cultural concept of aesthetics and beauty, and explore boundaries that might need to be set because of the societal perception about the technology developed. This will make the problem more complicated but also more realistic, since no technology or science is developed without the context of the culture in mind. Students in a diverse classroom may have different opinions when rating the beauty or even the success of the design; therefore, it is important to fully consider the range of cultural perspectives that students bring.

Social and environmental factors have resulted in women as a minority in many STEM careers. As educators, we need to be cognizant of student perceptions about their own abilities, encourage female students to break these systematic issues, and be aware of our responses by providing a supportive environment for female students. We should support them by providing more engineering opportunities that explicitly help people, assigning them to be lead engineer, and providing them with examples of female inventors. The same is true for minority students and other underrepresented groups. Trying to present engineering problems that are meaningful for these underrepresented groups can also help them become more invested in the process of learning about engineering.

Social justice is another aspect of engineering design that can be important for students to explore. Much of the technology might be too expensive or unavailable in certain areas of the world. Engineering design activities that push students to think about the impact of their product beyond their own immediate need can help students appreciate issues of sustainability, accessibility, and equality. Teachers can explore engineering design activities that also address these social issues as an interdisciplinary connection to extend student learning beyond our science and engineering objectives.

Each method of implementation is closely related to the style, pace, and the comfort level of the classroom. Ultimately, it is really important for classroom teachers to decide on the scope, modification, and the complexity that will best fit the students in front of us.

## REFERENCES

Eisenkraft, A. 2016. *Active Physics.* Mount Kisco, NY: It's About Time.

National Research Council (NRC). 2012. *A framework for K–12 science education.* Washington, DC: National Academies Press.

NGSS Lead States. 2013. *Next Generation Science Standards: For states, by states.* Washington, DC: National Academies Press. *www.nextgenscience.org/next-generation-science-standards.*

Scott, R., dir. 2015. *The martian.* Los Angeles, CA: Twentieth Century Fox.

4

# Assessments

**Arthur Eisenkraft and Shu-Yee Chen Freake**

Three facets of assessment are crucial to successful infusion of engineering into high school physics. The materials chosen or developed for curricula should meet certain criteria. The instruction of those curricula must meet the expectations teachers have for good teaching in general and good engineering in particular. Finally, we need clear student assessments that communicate high expectations and promote learning and achievement.

All of these assessments should support the goals that we have for our students when we adopt engineering infusion. These goals range from a first glimpse of the needed skills to be a successful engineer for some students to an awareness (and enjoyment) of engineering for all students. What do we look for in successful engineers? What skills and dispositions do companies value when they hire an engineer? Keeping these questions in mind leads us to our underlying questions when we consider curriculum, teaching, and student assessment: What must students know and be able to do before moving to the next level of an engineering course? What explicit engineering skills and concepts do we need students to master in our classrooms?

We have described these goals in the previous chapters outlining the justification for infusing engineering, the four core concepts of engineering, and the implementation of engineering infusion. Now we can move to assessments that teachers can use as they begin engineering implementation.

As physics teachers, we can use either the *Next Generation Science Standards* (*NGSS;* NGSS Lead States 2013) or *Common Core State Standards* (*CCSS;* NGAC and CCSSO 2010) to articulate content objectives that are in clear, student-friendly language and then design assessments and instruction around the objectives. Do we have something like that for engineering? How can we assess core concepts of engineering in authentic, practical, and meaningful ways to inform our teaching and provide students with feedback? Going back to our original question about what makes a good engineer, how do we know whether our students are ready for the next level of engineering content and skills after going through an engineering-infused lesson? More importantly, how do we know where they are on the progression from novice to expert problem solvers? Let's consider the idea of assessment from three angles—of the engineering activities, of ourselves as practitioners of physics–engineering infusion, and of students who perform these engineering activities in our classroom.

## ASSESSING ENGINEERING ACTIVITIES

As teachers, we are always assessing the curricula that we choose to introduce in our classrooms. Whether the curriculum item is something we found in a textbook or on the internet or was given to us by a colleague, we pass it through a set of four general filters to determine whether it is right for us. The first filter is whether the lesson makes sense to us. The second filter is whether the lesson is appropriate for our students. This requires matching the complexity of the lesson with the ages and content backgrounds in science and math of our students. The third filter is whether the lesson can be completed in the allotted time. If we have only one class period but the lesson requires three weeks of instruction, it will not be used. The fourth filter is whether we have the materials or equipment necessary to conduct the lesson.

When adopting an engineering-infused physics lesson, teachers need additional guidance. The Project Infuse leadership team attempted to create and refine some guidelines—known as the innovation configuration (IC) map—to provide some underlying principles when looking at engineering-infused lessons. Because of the complex nature of engineering, we do not believe there is only one way to evaluate activities; however, we do believe that the IC map is worth considering when teachers are examining engineering activities and making curriculum decisions.

### Assessing Curriculum Materials

Section A of the IC map lists descriptors for evaluating curriculum materials. The IC map states that "The curriculum materials chosen by the teacher should include engineering **concepts,** an **open-ended design challenge,** and be designed to facilitate the **connection** between engineering concepts and science learning. Materials should be **standards-based** and include a **student assessment** component." The elements in bold in this statement are further delineated in the rubric in Table 4.1.

A1 specifically links the engineering to the NGSS or the parallel document being presented in many states. In this approach, all lessons should include disciplinary core ideas, crosscutting concepts, and science and engineering practices. These are the essence of the new national standards. Engineering infusion for a classroom should be based on the engineering concepts rather than just the engineering design "cycle." Without a strong articulation of concepts essential to engineering (design, analysis, models, systems [DAMS]), students may mistake the discipline of engineering for a cycling of trial and error until they get lucky. If the curriculum can clearly outline and target the engineering objectives and goals that are concept-based and measurable, then the activity should be more meaningful as an engineering activity, rather than just a fun day of building a random object for the sake of student engagement.

**TABLE 4.1.** IC Map Section A–Curriculum Materials

| a | b | c | d |
|---|---|---|---|
| A1. Curriculum targets engineering concepts articulated in science standards appropriate to the course. | Curriculum targets engineering concepts articulated in science standards, but the concepts targeted are not well-matched to the course or unit. | Curriculum targets engineering concepts, but the concepts targeted are not standards-based. | Curriculum does not target science and engineering standards. |
| **a** | **b** | **c** | **d** |
| A2. Materials chosen include at least one open-ended engineering design challenge that requires understanding of scientific concepts and an iterative process for optimal solutions. | Materials chosen include an engineering design challenge that requires understanding of scientific concepts for solutions, but the scientific concepts are not those targeted by the teacher (unit, standards). | Materials chosen include an engineering design challenge that can be solved simply by trial and error without understanding of science concepts. | Materials chosen do not include an open-ended engineering design challenge. |
| **a** | **b** | **c** | **d** |
| A3. Curriculum materials make explicit connections between engineering concepts and science learning. | Curriculum materials include engineering concepts, but connection to science learning is not explicit. | Curriculum materials include engineering concepts but present them in total isolation from science concepts. | Curriculum materials lack explicit engineering concepts. |
| **a** | **b** | **c** | **d** |
| A4. Materials include a standards-based student assessment that explicitly targets both science and engineering concept understanding in an authentic context. | Standards-based student assessment is included and targets engineering concepts, but coverage of engineering concepts is minimal or exclusively at the knowledge/comprehension level. | Student assessment includes engineering concepts but is not in line with appropriate standards. | There is no evidence of student learning assessment that includes engineering concepts. |

Finding curriculum elements that can make realistic, specific connections for science and engineering is another essential component to consider. Engineering-infused activities should address particular needs by explicitly making connections among science, engineering concepts and practices, and some realistic problem. For example, physics teachers might ask students to design a musical instrument, without having specific criteria or the constraints of a realistic budget or equipment; the musical instrument activity is more of a physics application of the maker movement (following step-by-step instruction to make or modify something to achieve a specific function) than a true experience connecting the science and engineering principles to a clients' need.

A2 stipulates that there be one open-ended engineering design project. Feedback from the Project Infuse teachers suggests that it is counterproductive to insist that all engineering infusion comprise open-ended design projects, so A2 specifically states that there should be one but does not preclude having many other inclusion opportunities. Other ways to infuse engineering include focusing on the failure analysis, using mathematical models, and considering the inputs and outputs of a system. All of these are essential engineering concepts that ultimately lead to better design process but can be taught explicitly through an engineering-infused activity without design of a product. In certain situations, a teacher might require the use of a motor in the engineering design challenge or ask students to build an electromagnet as part of the solution. Sometimes the whole class will split into different subsystems and then come together to make one finalized design for the project. Therefore, although we may aim to have some open-ended design challenges that lead to multiple solutions, sometimes we purposefully narrow the scope of the project to achieve our physics content and engineering objectives.

A3 reminds us that engineers use physics knowledge in their approach to engineering design. They recognize and use physics principles in their models and in their analysis. An engineer will not explore a solution which requires that Newton's laws, Kirchoff's laws, or energy conservation be circumvented. Just as economic requirements and time commitments provide constraints on an engineering project, so too do physics principles, although unlike the former, physics principles are non-negotiable constraints.

A4 of the IC Map alerts the teacher that the choice of curriculum includes a choice of student assessments. We will expand on what valuable student assessments may look like in a later section.

## Assessing Teaching of Engineering Concepts

The second and third components of the IC map deal with teaching. Instruction is the bridge between the curriculum and the students. The lesson plans that are the focus of Chapters 5–9 of this book provide many specific examples of the broad range of teaching that can fulfill the intent of these IC map recommendations. You will notice that each lesson in those chapters follows a 7E instructional model (Eisenkraft 2003) on a day-to-day basis and includes all sorts of ways to engage students, elicit their prior understanding, have them explore and explain the results of their investigation, and elaborate and extend their knowledge while the teacher evaluates by testing for student understanding throughout.

Section B of the IC map—Teacher Practices: Design-Centered—states that "the design challenge should be structured as an open-ended team-based activity in which each team is expected to generate a unique solution. When implementing the challenge, the teacher should take on the role of consultant and guide and support student teams in the use of a rational design process. To support science learning, the teacher should make explicit connections to science concepts when supporting design teams and routinely ask students to provide science-based rationale for design decisions." These are elaborated on further in the rubric in Table 4.2.

**TABLE 4.2. IC Map Section B–Teacher Practices: Design-Centered**

| a | b | c | d |
|---|---|---|---|
| B1. Teacher structures the design challenge as a team-based activity such that all team members contribute to the design solution. Checks and balances are in place to ensure that all students participate. | Teacher structures the design challenge as a team-based activity, but checks and balances are not always effective in ensuring that all students participate. | Teacher structures the design challenge as a team-based activity, but checks and balances are not in place to ensure that all students participate. | Design challenge is structured as an individual activity. |
| Examples of checks and balances include the teacher actively asking about participation while moving from group to group, assigning individual students to play specific roles during the design challenge, including a peer-rating system in students' report-out or grade, and requiring each student to report out on results. | | | |
| **a** | **b** | **c** | **d** |
| B2. Teacher encourages a unique solution from each team and actively supports students in creating a unique solution during the design process. | Teacher encourages a unique solution from each team in the activity's introduction but does not actively support students in creating a unique solution during the design process. | Teacher does not provide direction to students regarding uniqueness of design solution. | Teacher actively directs students toward a single solution. |
| Open-ended design challenges have multiple solutions. In engineering, it is desirable for a design to have attributes that differentiate it from competitors. The word *unique* as used above is meant to capture this element of engineering design. In the best-case scenario, there would be some element or attribute to each group's design that is a bit different from all the others, something that differentiates it and makes it unique. | | | |

Table 4.2. (*continued*)

| a | b | c | d |
|---|---|---|---|
| B3. Teacher actively checks on group progress and provides individual coaching to groups by making specific suggestions for additional considerations or next steps. | Teacher actively checks on group progress and provides general coaching to the class as a whole rather than on an individual group basis. | Teacher observes group work to check on progress but does not provide coaching at either the class or individual group level. | Teacher neither checks on group progress nor offers coaching to support group work. |
| **a** | **b** | **c** | **d** |
| B4. Teacher requires students to engage in an iterative design process with at least one opportunity for redesign, testing, and analysis. | Teacher requires one cycle of redesign on paper but does not include testing or analysis of the new design. | Teacher requires students to briefly document what they would do differently if allowed to redesign. | There is no evidence of redesign. |

Whereas Section B of the IC map speaks to the overall design process, Section C—Teacher Practices: Engagement with Engineering Concepts—focuses on the requirement that the teacher continue to have students use and apply the physics content to the problem at hand. Section C states that "Teachers should make explicit connections to engineering concepts throughout the lesson or unit and routinely use appropriate engineering terminology. Teachers should explicitly connect science concepts with real-world engineering applications and describe these applications as a rationale for the learning of science." The rubric in Table 4.3 spells out some of the details.

Both of these components of the IC map are centered around teacher practices on the process of engineering design and the engagement with the engineering concepts. In an attempt to evaluate this instrument and our practices at the same time, the Project Infuse teachers used each other's classroom engineering design videos as ways to discuss each element specified in the IC map during our training sessions. The IC map can be used as a guide in the selection of curriculum and the creation of lessons and guidance during teaching. The teachers' consensus was that IC maps should not be used as a checklist for planning but rather should serve as suggestions that contribute to the ultimate product—an engaging and meaningful engineering-infused activity. It is also important not to think of this as a rubric of teacher evaluation because some of the elements within the themes are not appropriate for the specific goals of all activities, especially when design is not the focus of the particular infusion activity. It is extremely difficult to use the IC map outside the context of an actual lesson because it is better suited as a self-assessment

**TABLE 4.3. IC Map Section C–Teacher Practices: Engagement With Engineering Concepts**

| a | b | c | d |
|---|---|---|---|
| C1. Teacher makes explicit connections to engineering concepts throughout the lesson/unit (i.e., in the lesson introduction, primary activity, and wrap-up). | Teacher makes explicit but sporadic connections to engineering concepts. | Teacher makes implicit connections to engineering concepts. | Teacher does not make connections to engineering concepts. |
| **a** | **b** | **c** | **d** |
| C2. Teacher uses engineering terminology correctly and provides explicit instruction on terminology to students. | Teacher uses engineering terminology correctly but does not provide explicit instruction to students. | Teacher uses engineering terminology but sometimes uses terms incorrectly. | Teacher does not use engineering terminology. |
| **a** | **b** | **c** | **d** |
| C3. Teacher provides rationale for science learning throughout the lesson by using real-world engineering application(s) OR focusing on the science needed to solve a real-world engineering challenge. | Teacher provides rationale for science learning using real-world applications but significant "missed opportunities" are evident. | Teacher sometimes mentions real-world applications but those examples are not related to the rationale for science learning. | Teacher does not mention real-world applications of science concepts. |
| **a** | **b** | **c** | **d** |
| C4. Teacher routinely asks students to provide scientific or engineering rationale for design decisions and supports students in developing detailed, correct responses. | Teacher sporadically asks students to provide scientific or engineering rationale and supports students in developing detailed, correct responses. | Teacher asks students to provide scientific or engineering rationale but accepts superficial or incorrect responses. | Teacher does not ask students to provide scientific or engineering rationale for design decisions. |

tool for specific teaching practices. Let's discuss the two teaching components articulated in parts B and C of the IC map in the context of a design-centered lesson: testing insulation materials to design a glove.

The goal of the project is to make a glove that can be waterproof and slow the rate of heat transfer for someone holding one hand in an ice-bucket for four minutes. Teachers need to look for evidence that all members of the teams are contributing and working on the components of the glove, rather than one person only being responsible for documentation. Ideally, there should be enough supplies consisting of different materials to allow each team to develop a different solution so there is not only one "best answer." During the designing phase of the class time, the instructor should be asking questions, meeting with team members, and making suggestions so teams can be using the design process and making progress during class. Finally, if time allows, students should have at least one chance to test their gloves in the ice water, analyze the data, and redesign (on paper or by tweaking the actual design). In addition, for the group that is the most successful in the design activity, its process and success of the product should not be the result of luck, but rather should correlate to the students' understanding and execution of the iterative design process and using their data of material testing to justify material and layering choices.

For the component of the IC map that is focused on engineering concepts within the same lesson, the teacher should explicitly teach the concepts of analysis (e.g., materials testing), failure analysis (e.g., when water seeps into the glove), and the iterative process of design. Students should be able to use some of the engineering terminology, perhaps in their reports or the informal discussion about performance issues of different materials. By connecting the glove lab to actual issues with sportswear in hiking or camping, the teacher can make real-world engineering come alive so students can see the parallel between the heat transfer and using engineering skills and concepts to solve insulation problems. The goal is to provide enough support so students can elaborate on their choices using sound scientific and engineering rationales.

The IC maps can be a helpful tool for professional growth and self-reflection. They can serve as ways for educators to discuss and reflect on engineering-infused lessons in a more concrete, specific, criteria-based manner.

## Assessing Students in Engineering

To teach effectively, teachers must know what is going on in the minds of their students. Since people cannot peer into the minds of others, we must rely on probing questions. After the probe, the teacher must then listen to the response and interpret that response to glean what's in the student's mind. The assessment triangle (Pellegrino, Chudowsky, and Glaser 2001) reminds us that three distinct elements in assessment must all be coherent. If the probe is poor or the interpretation of the response to the probe is flawed, then the thoughts of the student will remain hidden.

We have a variety of assessment tools available to us as science teachers. We give quizzes and tests. We check homework. We ask questions during class and lab. We require lab reports. The list can go on forever. Often we develop a rubric or system for evaluating pieces of content knowledge and the science and engineering practices. When students are working in groups, we have to also assess what role each plays in the group. We walk around and note their progress, listen to their conversation, and even keep track of how many times they are testing materials.

Assessing students during engineering-infused physics classes presents some new challenges. From our workshops, it seems that the same set of questions for assessing engineering-infused lessons always surfaces during discussions:

- How do you know whether students are using sound engineering skills?
- Should we use a lab practical to see whether students can actually accomplish the engineering tasks?
- How many points should be awarded for making a product that fits all of the criteria?
- What if the students worked really hard the whole time but never got anything to work?
- What if the students goofed off the entire time but managed to have something that fits all of the requirements?

We asked Project Infuse teachers to discuss the importance and general goals of assessing students in their science classroom. Before delving into methods of student assessment, we will note some of those teachers' comments and insights here.

- Kris says, "The purpose of assessment is to determine whether instructional goals have been met. Therefore, it is essential to develop clear goals for student learning. For physics-infused engineering projects it is recommended to have both physics and engineering objectives and to assess them separately. Physics objectives associated with an engineering challenge or project can be assessed in the same ways we normally assess physics learning (tests, quizzes, lab reports, homework, and so forth) but some products of an engineering project provide some other opportunities to assess physics objectives. As discussed further in the "The Power of an Engineering Notebook" section (p. 67), one thing students can be asked to keep track of is their understanding of physics concepts. They may also be asked to explain physics concepts orally if they are doing a presentation at the end of the project."

- Dave, a former engineer, explains the rationale for developing an engineering notebook in place of a design package (which is typically used in the engineering company): "In actual engineering companies, the design package may contain other considerations such as cost and cost changes; however, those are eliminated from this discussion for purposes of allowing us to focus purely on physics and engineering aspects of the design process. The engineering notebook will be the primary document that the teacher and student will use to document and assess the project. The student will document and justify his or her thought process, including sound understanding of the physics concepts behind the design. The teacher will review the notebook and assess the project based on the completeness of the analysis incorporated in the design and the ability to replicate the students' design."
- Emma talks about the parallels between lab reports and engineering design process: "As physics teachers, we understand that there are many ways to have students record and analyze lab data. These can be student-driven and open-ended, or thoroughly scaffolded, depending on the level of the students or needs of the experiment. Similarly, there are many ways to have students record design ideas and analyze prototypes." She offers possibilities ranging from a full-blown engineering notebook and using multimedia to record, to the less formal check-in type questions that allow for different levels of assessments.

There is a range of assessment methods that teachers have tried and found helpful, but the common theme is clear—assessment should be carefully planned according to the goals and objectives of the project and assessment of the engineering process is as important as content and is more important than the final product.

## TYPES OF ASSESSMENTS

Table 4.4 lists four types of assessment that can be used to evaluate both how well students are progressing toward goals while learning (formative) and what knowledge and skills they have gained after learning is complete (summative). All of these methods are valid and can be adapted to different infusion activities; teachers must carefully choose the method that best matches the goals of the assessments and the activity.

**TABLE 4.4. Types of Assessment**

| Informal Formative | Informal Summative |
|---|---|
| • Teacher observation of students or groups<br>• Teacher conferencing with students or groups<br>• Interviews with designer to evaluate criteria<br>• Scrum or stand-up meeting | • Student self-assessment<br>• Group self-assessment<br>• Design review (peer review) |
| **Formal Formative** | **Formal Summative** |
| • Preliminary individual design proposal<br>• Engineering notebook entries<br>• Iteration listing or change log<br>• Written reflections of group work<br>• Daily or weekly quizzes | • Engineering product<br>• Final presentation or write-up<br>• Unit test<br>• Guest panel of judges to evaluate product<br>• Instructional manual as the product<br>• Extension questions with new constraints or failure predictions |

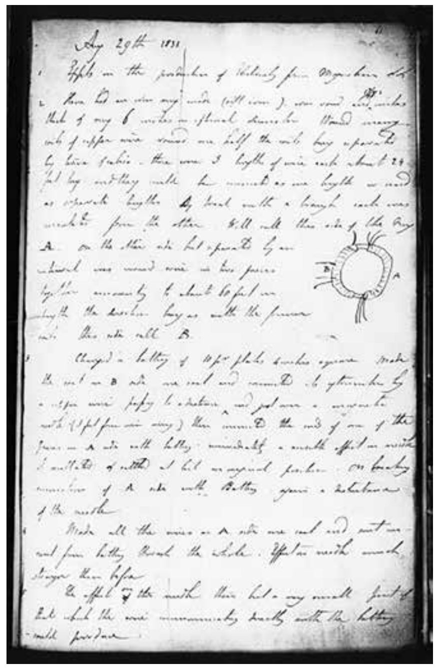
## Engineering Notebooks for Formative Assessment

Let's begin our examination of different types of assessment by looking at the most commonly talked about assessment method, the engineering notebook. To make the point more relevant, let's examine a famous engineering notebook by one of the best experimental scientists of the 19th century, Michael Faraday (Figure 4.1, p. 66). Faraday's notebook on induction carefully outlines the steps he took along the way.

Faraday documented design work, decisions, and test results with numbered steps and dated pages. He provided enough details in both writing and drawings for readers to reproduce the exact instruments. The notebook also serves as documentation that proves and validates his discoveries, which is one extremely important reason for keeping an engineering notebook. Patenting rights, communication of design, and personal work accountability are all good reasons for keeping a good engineering notebook.

Faraday's notebook can be used as evidence of his work as a scientist and an engineer because the instructions in it are clear and understandable. Teachers can encourage students to create their own notebooks that likewise can be used to assess the processes or concepts of engineering. Keeping a notebook can be a daunting task for students and for teachers. Because of that, we will now explore different examples of "notebooks" that range from the full-fledged engineering notebook (design package) to the less formal stand-up meetings, which can all be different forms of student assessment.

## FIGURE 4.1. Page of Michael Faraday's Engineering Notebook on Induction



**(a) Notebook page showing Faraday's handwritten notes on induction**

August 29th 1831

1. Experiments on production of Electricity from Magnetism, etc.
2. Have had an iron ring made (soft iron), iron round and 7/8 inches thick and ring 6 inches in external diameter. Wound many coils of copper wire round one half, the coils being separated by twine and calico—there were 3 lengths of wire each about 24 feet long and they could be connected as one length or used as separate lengths. By trail with a trough each was insulated from the other. Will call this side of the ring A. On the other side but separated by an interval was wound wire in two pieces together amounting to about 60 feet in length, the direction being as within in the former coils; this side call B.
3. Charged a battery of 10 pr. Plates 4 inches square. Made the coil on B side one coil and connected its extremities by a copper wire passing to a distance and just over a magnetic needle (3 feet from iron ring). Then connected the ends of one of the pieces on A side with battery; immediately a sensible effect on needle. It oscillated and settled at last in original position. On breaking connection of A side with battery again a disturbance of the needle.
4. Made all the wires on A side one coil and sent current from battery through the whole. Effect on needle much stronger than before.
5. The effect on needle then but a very small part of that which the wire communicating directly with the battery could produce.

**(b) Transcription of page shown in part a**

## The Power of an Engineering Notebook

Setting up a formal engineering notebook is similar to setting up the expectations and format of lab write-ups. We need to make clear to students what the goals of the notebook are and how they will be assessed. The engineering notebook has a more process-oriented purpose than the traditional lab report; it is more like the rough laboratory notebook idea. Engineers must go through an iterative process to arrive at a solution, and the writing in the notebook should be expected to reflect that kind of thought process. Some elements that should be included are as follows:

- Definition of the initial scope of the project
- Background research performed to understand the problem
- Considerations and thinking about requirements and constraints
- Initial design concept with the justification for the design (e.g., physical constraints, cost, marketing constraints, calculations, sketches, manpower and man-hour requirements, schedule)
- Ideas and sketches from the initial concepts and subsequent iterations
- Materials required for each step of the prototype
- The type and results of each testing
- A log of all the prototype changes and the rationale behind them
- Sketches of the final design
- Results of the final test performed on the product
- Analysis of whether the final design met the design criteria and constraints
- Reflections on what could have been changed to make the design better
- Explicit documentation of the physics concepts involved in the design

This list of elements for engineering notebooks can be overwhelming for teachers, let alone students, so we highly recommend scaffolding the process of writing by providing templates, exemplars, sentence starters, graphic organizers, and prompts to support students in this endeavor. Students need to be explicitly taught how to write in their engineering notebook. Helpful ways to encourage students to keep a written record include a separate handout prompting key elements to add to the notebook, constantly checking in on the progress of their notebook entries, and creating a need for communication by switching group members after a certain amount of time. Teachers may need to structure time within the lesson for writing and provide structures and constant feedback to reinforce student learning.

Engineering notebooks come from a tradition of engineering intellectual property, which gives them some value in the engineering-infused classroom. They are arguably among the most realistic assessment tools for the process of engineering.

### Alternatives to Traditional Engineering Notebook for Formative Assessment

As realistic as engineering notebooks are for assessment, the use of them for documentation of work done is not instinctive. In the Project Infuse workshop, we had an amusing and insightful occurrence along these lines. One day after we discussed the importance of using an engineering notebook, teachers were asked to participate in a design challenge. The 20 teachers were thoroughly engaged and successful in the challenge. However, we then realized that only two of them had recorded their processes in an engineering notebook of any kind. Was it because the notebook was not assigned as part of the workshop requirement? Was it because a notebook was not useful for the engineering process? Did people use something else instead of an engineering notebook? Those questions led us to a broader discussion and then experimentation with different formats for the engineering notebook and strategies to encourage its use. For example, one type of engineering "lite" notebook has teachers design worksheets that ask for (1) sketches of design ideas, (2) iteration logs, and (3) testing and results (Figure 4.2). This is an easier, more accessible version of the engineering notebook that can be used as a starting place or as differentiated graphic organizer for students who are still in the early continuum of the writing process.

Technology is another great tool for providing a convenient, faster, and easier form of communication and evidence for student assessment. Students can use cell phones or electronic tablets to take photographs at timed intervals, adding notes as captions on Google Docs, or to put together a design presentation video at the end of the project (see Figure 4.3, p .70). Prompts such as "take a picture and record changes every three minutes" or "after you voted from all your sticky notes and chart paper, take a pictures of the final votes" are great strategies for helping students incorporate multimedia into their learning and allowing for teachers to assess students' process. Photo-voiceover software packages such as Voicethread might be especially helpful to students who have dysgraphia or motor control issues.

## FIGURE 4.2. Engineering Notebook "Lite" Template Designed by One of the Project Infuse Teachers

Spend 10 minutes creating labeled drawings of four possible design ideas below.

| Design 1 | Design 2 |
| --- | --- |
| Design 3 | Design 4 |

| What You Tried | What Worked | What Didn't Work | Changes Needed |
| --- | --- | --- | --- |
| | | | |
| | | | |
| | | | |

Discuss with your engineering group before creating a *detailed and labeled* final design drawing below. Often it helps to include aspects of mutiple designs to create the best design possible.

| Final Design |
| --- |

## FIGURE 4.3. Example of Using Technology to Document the Design Process

***Engineering Design Process:***

***Problem***

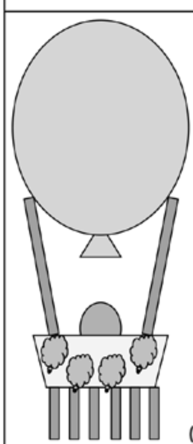
| What problem are you trying to address with your design? |
|---|
| An egg needs to be protected from breaking after being dropped from varying heights. In our design, we are trying both to slow down the velocity of the egg during flight and lengthen the time of the impact by having the device that holds the egg compress. |

***Brainstorm***

| Come up with a list of solutions to keep the egg safe. |
|---|
| **1.**“Hot air” balloon – Balloon slows the fall of the egg which is in a paper basket below.<br><br>**2.** Use the packing peanuts as cushioning for the egg<br><br>**3.** Use the straws almost as legs of the paper basket to absorb the force of the fall<br><br>**More…** |

***Choose a Design***

**Draw a picture. Be specific about measurements and supplies. Take a photo of the design you chose to build and explain why you chose it.**

| Picture of the design you built for your first design. | Why did you choose this design instead of the other designs for the first design? |
|---|---|
|  (Green packing peanuts located inside of basket) | We chose this design because it looks and, in some ways, acts like a real life object that safely carries humans through the air. The design also utilized nearly all of the materials that we had, making it a good choice for learning new things about the different materials.<br>Also, we thought that the balloon would be effective in keeping the device from descending too rapidly, but we concluded that it would work better to keep the egg safe if the balloon was filled with a mixture of helium/regular air.<br>We chose this design because it made the egg more secure and the balloons helped the design from the design dropping at a high speed.<br>We chose this design because it woked better then the other ones. And because when we droped it we figured the balloon would help it descend slower |
| **Picture of final design.** | **Use evidence (numbers from your data) to explain why you choose this design for your final? What changes did you make from the first design until now?** |

## Other Assessment Methods

Formative assessments are also especially important for any process-oriented objectives. For activities that require many tests and iterations (e.g., the wind tube challenge), teachers can stand at the testing station and ask students to discuss the design process, predict performances, and evaluate failures. Then students can be reminded that the discussion should be recorded in the engineering notebook. The teacher can work with individual groups throughout a multiday design project to have a miniature conference type of evaluation.

Another way to check in with students informally is to adapt the daily scrum or stand-up meeting that is widely used in engineering companies. Ask the entire class to stop working and listen to teams reporting out their status and their challenges. Some questions to consider are the following:

- What have you done so far?
- What do you need to do next?
- Is there anything you need help with?

The meetings are designed to be succinct and the goal is for them to act as formative assessments allowing the teacher and the students to work together to problem solve and move forward with the engineering design process. For very abbreviated projects, such as 15-minute activators, an even leaner version of this protocol can be used in which students simply hold up their design halfway through and state their confidence on a scale of 1 to 10, with 1 being "I couldn't finish this if I had all day" and 10 being "I've totally got this and I'm basically done." This is quick but it allows the teacher to gather information about the process and it focuses attention on groups or students with low confidence who may be stuck.

Creating formal, evaluative assessments of multiple-choice or open-response questions to demonstrate students' understanding of engineering concepts and skills requires time and effort. For research purposes, the Project Infuse leadership team developed a set of engineering-concept–based questions called the Engineering Concept Assessment as an instrument for evaluating a teacher's understanding of engineering concepts. Some of the questions even evaluate physics content and engineering practices simultaneously, so it is worth considering as an evaluation sample when designing student evaluation.

### Assessing Process or Product

So far, our focus has been on assessing the processes and concepts of engineering rather than the product of the engineering design. However, engineering is product-oriented, and the assessment of product is also important. Assessment of the product is based on how successful the student or group is in meeting the design criteria. If the infusion activity is meant as an application of the physics concept in an engineering design challenge, the product should also be assessed.

The distinction between process and product can be described with a simple example. The pasta cantilever challenge asks students to build a cantilever using a set amount of a certain type of pasta. The cantilever needs to support as many pennies as possible at least 25 inches out from the edge of a table. To make this challenge more interesting and allow analysis of materials, different groups of students can be given different types of pasta. Because different groups are given different materials (e.g., lasagna versus angel hair pasta), it is entirely possible that some groups will not be able to build a cantilever with the minimum distance. In fact, that happened when we did this challenge in our Project Infuse program with teachers.

When assessing, we must consider how to evaluate such a "failure." Do those groups deserve a failing grade? If we did this challenge in our classes, would we assess students solely on how well their design performed? If this challenge were assessed solely based on the performance of the design, would it be appropriate?

Because engineering design challenges involve both a process and a product, by their nature they are performance assessments. Wiggins and McTighe (2011) suggest a two-question validity test for a good performance assessment, which is helpful in thinking about assessment of process versus products. Using the logical premise that students who understand something well should perform well on a performance assessment, he suggested that if either of the two following statements are true, the assessment is not aligned with the goals:

- Students can do well on the assessment with limited or no understanding of the subject or content.
- Students can understand the subject or content very well, but do poorly on the assessment.

These are the questions we need to consider when we develop engineering challenges. In order to fully assess the physics and engineering objectives, we need to include some assessment of the engineering process so we get a full picture of what students have learned. For the pasta cantilever challenge, before students can pick up their materials, they are required to both answer questions about materials testing and physics concepts that might apply to the challenge and draw a diagram of a possible design. This represents the beginning of the process and is one document that could be collected and assessed. For that challenge, teachers might be interested in assessing how groups tested their materials, how many iterations the group went through, how effectively the group worked together, how much the design improved during the process, and to what extent groups based their design decisions on physics principles. For the pasta cantilever challenge specifically, having the process be the main focus of assessment is important because different groups use different materials, some of which are more challenging to use.

An important contrast must be made between the pasta cantilever challenge and the project on designing a musical instrument. The main goal of designing an instrument is to assess students' understanding of sound properties and waves. If groups in that challenge produce a group of instruments that vary in the notes they play from one note to an entire octave, then a portion of the assessment should reflect that degree of design success because the degree of success is very much tied to students' application of physics concepts. A way to think about product evaluation is that if a customer asked for a particular food with some dietary restrictions, the quality, quantity, and accuracy of the food presented should still match the customer's expectations, and consumers can rate the level of satisfaction based on the product offered.

## CONCLUSION

Just as important as the assessment itself is sharing with students how their engineering projects will be assessed. This can alleviate stress for students who are struggling to get their design to meet the design criteria, and it can emphasize the importance of documenting their process. A rubric given out or better yet developed with students' input improves transparency and student achievement. It is possible that no elements other than participation are assessed if the engineering activity is a five-minute video and follow-up discussion that is meant to jumpstart a new unit of study. The clearer teachers are about the methods and measures of assessment, the better the students' products and experience will be.

Requiring students to write in an engineering notebook is a great practice as well as an assessment tool. However, we understand that not all teachers have the time and resources to implement a successful engineering notebook. We encourage teachers to use any or all of the methods described here that are suitable for their own classroom. It remains important to not lose sight of the process within the engineering design project because assessing a project based only on the product is problematic. Design is complex, and the results often seem strange without any context about the process that created them.

By exploring assessment of the curriculum material, student understanding, and teacher practices, we are able to engage in academic discourse that helps us to understand engineering infusion from a more practical level. In terms of assessing engineering skills and concepts, we try to find some similarities between different teaching styles, subjects, and scopes of the projects. We also want to have some criteria for examining curriculum materials and teacher practices to help teachers grow professionally. From these discussions of assessment, we can see that realistic problems, achievable and transparent goals, and articulation of science and engineering concepts all are elements that contribute to higher rates of student success.

Many engineers say that the most important trait of a good engineer is not always having the best solution, but rather having a better approach to the problem. Ultimately, as with many other professions, the difference between novice and expert engineers is in their approach. Experts find patterns and use general principles to solve any problem. They can evaluate and question their own thinking. And they can discuss the complexity of a system and predict how elements will interact with each other in the future. We should keep in mind these differences when assessing curriculum, students, and ourselves as we implement and assess our understanding of engineering infusion.

## REFERENCES

Eisenkraft, A. 2003. Expanding the 5E model: A proposed 7E model emphasizes “transfer of learning” and the importance of eliciting prior understanding. *The Science Teacher* 70 (6): 56–59.

National Governors Association Center for Best Practices and Council of Chief State School Officers (NGAC and CCSSO). 2010. *Common Core State Standards.* Washington, DC: NGAC and CCSSO.

NGSS Lead States. 2013. *Next Generation Science Standards: For states, by states.* Washington, DC: National Academies Press. *www.nextgenscience.org/next-generation-science-standards.*

Pellegrino, J. W., N. Chudowsky, N., and R. Glaser, eds. 2001. *Knowing what students know: The science and design of educational assessment.* Washington, DC: National Academies Press.

Wiggins, G., and J. McTighe. 2011. *The understanding by design guide to creating high-quality units.* Alexandria, VA: ASCD.

5

# Engineering Infusion Using Anchor Activities

A major emphasis of engineering infusion in this book is to consider teaching engineering concepts along with the engineering practices. The anchor activities in this chapter are designed to focus on one or more engineering concepts in depth. Without a common language, schema, or experience that the whole class can relate to, engineering design activities can be misunderstood simply as building exercises.

Some teachers have expressed concern that they have to follow a strict curriculum and cannot fit project-based engineering activities into the school year. One possible approach in that situation is to pick four anchor activities, each addressing a different core concept in engineering.

Even though the physics content is not the main focus in this chapter, using the anchor activity to introduce engineering concepts can also be a springboard into some of the science practices or concepts that are important in our classrooms. For example, you could start the forces unit with the wind tube challenge and ask students to draw the force vectors acting on their hovercraft. Similarly, you might finish the school year with a Rube Goldberg design and be sure to ask students about how the inputs and outputs of systems have to work together. Table 5.1 (p. 76) provides basic curricular details for the six anchor activities.

**TABLE 5.1. Chapter 5 Anchor Activities**

| Activity Name | Core Concept(s) | Class Periods | Brief Description |
|---|---|---|---|
| **Pasta Cantilever** | • Design<br>• Analysis<br>• Systems | 1 | Construct a cantilever that supports the maximum amount of weight at the greatest distance from the edge of a desk. |
| **Cards to the Sky Gummy Bear Tower** | • Design<br>• Analysis | 1 | Use playing cards to build a tower that can withstand wind such that gummy bears can stand on top of it. |
| **Marshmallow Tower** | • Design | 1 | Use tape, string, and 20 strands of spaghetti to build the tallest tower that will support one large marshmallow on its top. |
| **Soda Can Clock** | • Models | 1 | Create a mathematical model to predict the time it will take for a soda can punctured with holes of different sizes to drain. |
| **Wind Tube Hovercraft** | • Design<br>• Analysis<br>• Models | 1 | Predict and analyze how different materials will behave in a wind tube, then design and test a hovercraft that can stay in the wind tube for 10 seconds. |
| **Rube Goldberg Device** | • Systems | 1 | Create a Rube Goldberg device that includes at least three energy transfers and eventually pops a balloon. |

# ANCHOR ACTIVITY 5A: PASTA CANTILEVER

**Contributors: Neil Kenny and Shu-Yee Chen Freake**

**Time frame:** 1 class period

**Engineering focus:** Design, analysis, systems

### Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Experimental design<br>o Weight versus deflection<br>o Placement of weight | • Design of the cantilever under given constraints |
| **Analysis** | • Net force = 0 N | • Testing of various properties of pastas |
| **Models** | • Free body diagram<br>• Torque ➔ drawing diagram | • Model of a real cantilever |
| **Systems** | • Sum of the net force = 0 N<br>• The cantilever itself<br>• Net torque = 0 N | • Attachment to table<br>• Interaction of materials |

## PROJECT OVERVIEW

In this activity, students are challenged to construct a cantilever that supports the greatest weight at the greatest distance from the edge of a desk using only the materials provided. Dried pasta works well as a construction material because it is both inexpensive and challenging to work with. This is an excellent activity for demonstrating the role of constraints in the engineering process (e.g., limited time, quantity of materials, and quality of materials). It also

Students using pennies to anchor the cantilever allows for creative solutions if each group is given a different type of dried pasta, requiring students to carefully consider the properties of the materials provided.

## ENGINEERING VERSUS PHYSICS CONCEPT

Although the activity requires students to design, it can be used to focus on analysis of the material and the types of analysis that are necessary to solve a design problem. Students can use mathematical analysis (providing or deriving the torque equation) when applicable. Alternatively, students can simply graph the deflection versus the weight at different distances to analyze the behavior of a cantilever. If each group is given a choice of different types of dried pasta, students can also perform analysis of the materials to determine the weakest point, based on the pasta's dimensions.

## Assessment: Determining Acceptable Evidence

### Formative

- Mini-conferences with groups
- Class discussion and chart discussion of constraints and final test requirements
- "Do Now" activity, class notes and discussions, spot check homework assignments

### Summative

- Individual: engineering notebook, homework assignments
- Group: demonstration of cantilever supporting weight

## Materials and Preparation

### Materials (Groups of 3–4)

- Dried pasta—50 pieces. The teacher may elect to give all groups the same type of pasta, or assign different types to each group. The amount of pasta may vary depending on type. For example, although each group may get the equivalent total mass of pasta, the group with lasagna pasta would receive fewer pieces than the group with angel hair pasta.
- Masking tape. At the teacher's discretion, groups may be given a limited quantity of masking tape (e.g., one meter) and students could be allowed to request additional tape.
- A weight to be supported by the cantilever (e.g., masses or a number of coins)
- Meter stick

- 1 meter of string

### Materials per Student

- Safety glasses or goggles
- Engineering notebook

## Safety

- Remind students about general lab safety procedures.
- Participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Remind students not to eat any food used in this activity.
- Students should wash hands with soap and water upon completing this activity.

### Pasta Cantilever Lesson Plan for Day 1 (55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Instructor Doing? | Engineering Opportunities |
|---|---|---|---|
| **5 mins.**<br><br>**Engage** | — | • Place a piece of pasta on the lab table so it hangs over the edge and so that students can watch you bend it slowly, see it oscillate, and watch you bend it until it breaks. Repeat this with a longer piece of pasta. | — |
| **5 mins.**<br><br>**Elicit**<br>**Evaluate** | • Work on Do Now questions individually then share with the class.<br>• View a picture of a cantilevered object (e.g., a hanging flower pot) and draw a free-body diagram showing the forces that act on that object.<br>• Suggest ways the cantilever could be redesigned to support more weight. | • Elicit students' prior knowledge and help them make connection from previous experience.<br>• At this point, evaluate where students are. | • Properties of materials<br>• Functionality<br>• Aesthetics |
| **5 mins.**<br><br>**Engage** | • Engage in whole-class discussion about design challenge and how project success will be determined. | • Engage students by generating questions about the design task.<br>• Clarify questions related to the task. | — |
| **25 mins.**<br><br>**Explain**<br>**Explore**<br>**Evaluate** | • Work in groups on the cantilever construction. | • Coach students during group work (i.e., have them Explain) on materials testing.<br>• Evaluate group dynamics, emphasizing exploring different design options.<br>• Check for understanding (evaluate, explain) by asking students about their design process. | • Encourage students to consider multiple solutions and to test for failure before committing to a final design. |
| **10 mins.**<br><br>**Explain**<br>**Evaluate** | • Demonstrate their cantilever to the class and discuss the rationale for their design. | • Each cantilever is scored according to agreed-on criteria. | — |

## Optional Modification and Extension (Extend)

- Provide each group with a "budget" to stay within as they "purchase" materials. Tape could be sold by the centimeter and different pastas could vary in price (i.e., lasagna noodles would cost more than angel hair pasta). Students could be given time to test different materials before they submit an itemized materials request.
- Have students develop a mathematical model by collecting data at different points to optimize the model for the best distance-weight combination.

## Supplemental Material

- Handout 5A: Pasta Cantilever

# HANDOUT 5A: PASTA CANTILEVER

A *cantilever* is a device that supports a weight but itself is supported only at one end. Cantilevers are often used in the construction of bridges and as supports for traffic lights, flower pots, signs, and other objects. In this engineering project, you will design and construct a cantilever.

Examples of cantilevers in (a) nature, (b) art, and (c) technology

## PROJECT OBJECTIVES

- Describe how the forces act on an object supported by a cantilever.
- Design and construct a cantilever using specified materials.
- Analyze your cantilever design for weaknesses and strengths.

## YOUR TASK

Your group will be provided with the following equipment and materials:

- Safety glasses or goggles for each student
- 50 pieces of dried spaghetti or a given mass of different types of dried pasta
- 1 meter of masking tape
- A 20-g weight (or pennies or nickels)
- 1 meter of string

Using only these materials, your task is to design and construct a cantilever that supports the weight at the greatest possible distance from the edge of your lab table.

## SAFETY PRECAUTIONS

- Follow all general lab safety procedures.
- Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.

- Do not to eat any food used in this activity.
- Wash your hands with soap and water upon completing this activity.

## PRE-LAB QUESTIONS

1. What is a cantilever?

2. Give two examples of a cantilever.

3. Using the picture of the lamppost on the first page, draw a free-body diagram showing the forces acting on the lamp.

4. Draw a sketch showing a proposed design for your cantilever.

## POST-LAB QUESTIONS

5. Draw a diagram of the final design of your cantilever.

6. What was the maximum distance from the lab table at which your cantilever supported the weight?

7. After looking at all the designs in class, sketch the design that was the most successful.

8. Describe the factors that you think led to the most successful design.

9. If you could redesign your cantilever, how would you change it to support the weight farther from the table edge? Explain your answer.

# ANCHOR ACTIVITY 5B: CARDS TO THE SKY GUMMY BEAR TOWER

**Developed by the Project Infuse Leadership Team**

**Time frame:** 1 class period

**Engineering focus:** Design and analysis

### Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Wind speed<br>• Distance of the wind versus time standing | • Build the tower, satisfying the criteria.<br>• Use an iterative process to fine-tune the design of the tower. |
| **Analysis** | • Net force = 0 N<br>• Torque = 0 N | • Shapes<br>• Failure point analysis of the tower<br>• Failure point analysis using the wind<br>• Constraint of materials and properties of materials |
| **Models** | • Force diagrams<br>• Net torque | • Model for a big tower |
| **Systems** | • Surface<br>• Tower<br>• Wind | • Interactions between cards<br>• Interaction between air and tower |

## PROJECT OVERVIEW

This quick challenge was designed to introduce students to the engineering concepts of design, testing, and analysis. The students are engineers of the Royal-Flush engineering design firm, and their challenge is to use playing cards, tape, and scissors to build a tower that can withstand wind (hair dryer) for the bears that live in Bear Valley.

The time frame is only one class period. Special emphasis can be placed on the requirement that the building components be modular pieces and on the testing and iteration aspects of this challenge. Students should be allowed to test their towers with the hair dryer while designing and building them so that they can change their design as needed.

Once time is up, each tower is tested for its ability to withstand the wind and whether it meets other constraints. When towers are presented and tested, students should be able to "sell" their tower idea to the rest of the class, explaining why their design is the best one for the bears of Bear Valley. A vote to determine the best design could be done by the class or by a small "Bear Valley committee" of outside students or teachers. It is a good idea to provide students with reflection questions to answer that help summarize the design, testing, and iteration aspects of this activity.

**Sample tower designs from two views, using scissors as the base and tape as anchor on the side**

Reflection questions could include the following:

- How did you deal with the competing constraints? Which design criteria did your group think were most important and why?
- How did you consider the modular-component issue? How did you decide to approach that problem?
- Of the towers that you saw presented in class, which one did you think was the best design solution? Why?

## ENGINEERING VERSUS PHYSICS CONCEPT

The gummy bear challenge itself has great potential for testing and iteration, gives very specific constraints, and requires teamwork, which are all important elements of engineering design. Unlike hypothesis-driven experimental design in science, this challenge does not focus on a question or observation about nature, but rather a problem to solve.

This anchor activity can also be used to highlight the similarities between the engineering and physics design process. In engineering, the process of iteration helps to create a solution to a problem.

## Assessment: Determine Acceptable Evidence

### Formative

- Checking with students during the design process

### Summative

- Groups sharing their design, design process, and reasoning behind their choices
- Engineering-notebook recordings of the design process and answers to reflection questions

## Materials and Preparation

### Materials (Groups of 4)

- Safety glasses or goggles for each student
- 1 deck of playing cards
- 1 roll of tape (masking or cellophane)
- 1 pair of scissors
- 6 gummy bears
- Calculator for determining mass

### Materials per Student

- Engineering notebook
- Safety glasses or goggles

### Class Equipment

- Hair dryer

**Tower design using the scissors and tape dispenser as part of the structural support**

## Safety

- Remind students about general lab safety procedures.
- Personal protective equipment (eye protection) is to be worn during the set-up, hands-on, and takedown segments of the activity.
- Remind students not to eat any food used in this activity.
- Remind students to use caution in working with sharps (scissors), which can cut or puncture skin.
- Students should wash hands with soap and water upon completing this activity.

**Cards to the Sky Gummy Bear Tower Lesson Plan for Day 1 (55-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Instructor Doing? | Engineering Opportunities |
|---|---|---|---|
| **5 mins.**<br><br>**Engage**<br>**Explain** | • Read the project description silently and sketch initial design ideas. | • Encourage students to think about the properties of the materials and some building structures they have seen. Also emphasize the modular constraint for this project. | — |
| **5 mins.**<br><br>**Elicit** | • Ask questions about the challenge, organize in groups, and meet group members.<br>• Prepare engineering notebooks. | • Emphasize the focus for this design activity and reiterate what should be written in the engineering notebook as the tower is being design, tested, and then redesigned. | • Analyze the problem and do some predictive analysis on the properties of materials. |
| **30 mins.**<br><br>**Explore** | • Work on constructing the tower and testing during the process. | • Encourage students to use an iterative process to evaluate their designs and fine-tune the structure. | • Use the design process.<br>• Perform tests and analyze strengths and weaknesses of the current prototype. |
| **15 mins.**<br><br>**Explain**<br>**Elaborate**<br>**Evaluate** | • Group presents designs to the class. Be prepared to discuss how the tower was designed, explain the modular components of the tower, and to “sell” the tower design to other students.<br>• After towers are presented, finish engineering notebooks by reflecting on the process. | • Measure the final structures, test them for their ability to withstand the wind, and lead a discussion on the design process. | • Consider the clients’ requirements and criteria again. Have the class discuss how different groups focus on different aspects of the criteria. Include a decision about how a tradeoff matrix is used in engineering for analyzing competing constraints. |

## Supplemental Material

- Handout 5B: Cards to the Sky Gummy Bear Tower

# HANDOUT 5B: CARDS TO THE SKY GUMMY BEAR TOWER

Royal-Flush, Inc., an architectural and structural engineering firm, has a contract with the Bear Valley Community to design and build the community's first skyscraper structure. You work for Royal-Flush, and have been assigned to complete the project.

## MATERIALS AND PREPARATION

- Safety glasses or goggles for each student
- 1 standard deck of playing cards, including the box
- 1 roll of tape
- 1 pair of scissors
- Chart paper
- Markers

## SAFETY

- Follow all general lab safety procedures.
- Safety glasses or goggles required for this activity! Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Do not to eat any food used in this activity.
- Use caution when working with sharps (scissors), which can cut or puncture skin.
- Wash your hands with soap and water upon completing this activity.

## RULES AND REQUIREMENTS

The design must incorporate the following elements:

- A tower that is 14 inches high. This might seem a bit short, but the average height of a bear is ¾ inch, so that's a pretty tall building in bear terms.
- A platform on the top of the structure that will hold six bears, for viewing lovely Bear Valley.
- Enough stability to withstand a hair-dryer wind source 14 inches from the west. Designs that exceed this requirement are also acceptable.
- The tower should be pleasant to look at.

- The structure should have as small a mass as possible because it will be constructed off-site and then trucked into the valley for final installation.
- For construction, use one standard deck of playing cards, one roll of tape, and a pair of scissors.
- The final structure must contain the roll of tape and the pair of scissors.

Other regulations are as follows:

- Construction must be completed in 30 minutes. This may seem like a short time, but the life span of a Bear Valley Community bear is only two days, so there is no time to waste!
- You must give a 2 minute client presentation during which you discuss the design features and rationale. (Chart paper and markers will be supplied.)

## Time

You might want to divide your 30-minute design-and-construction period as follows:

- 10 minutes—brainstorming and planning
- 15 minutes—construction and iteration
- 5 minutes—preparation for a 2-minute presentation for your bear clients
- 2 minutes—presentation that includes the following:
  - The basic design approaches your team considered
  - The design requirements on which your team focused
  - The estimated mass of your structure
  - Proof that the structure meets the wind requirement
  - How your team spent its time

## Masses

The following information should help in estimating the mass of your skyscraper:

| Item/Number of Cards | Mass (g) |
|---|---|
| Card box | 5.13 |
| 1 | 1.63 |
| 5 | 8.15 |
| 10 | 16.30 |
| 15 | 24.45 |
| 20 | 32.60 |
| 25 | 40.75 |
| 30 | 48.90 |
| 35 | 57.05 |
| 40 | 65.20 |
| 45 | 73.35 |
| 50 | 81.50 |

*Source:* Adapted from Sheppard, S. 2001. The compatibility (or incompatibility) of how we teach engineering design and analysis. *International Journal of Engineering Education* 17 (4-5): 440–445.

# ANCHOR ACTIVITY 5C: MARSHMALLOW TOWER

**Adapted from the Marshmallow Challenge by Tom Wujec**

**Time frame:** 1 class period

**Engineering focus:** Design

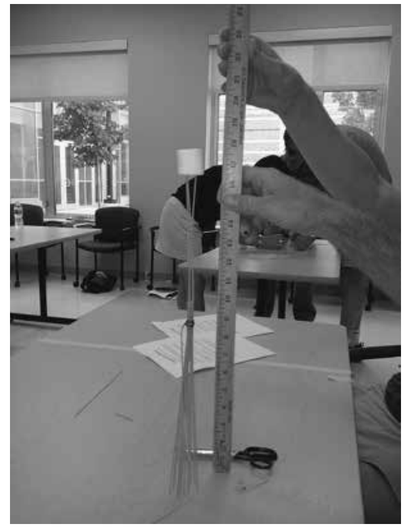
### Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Design an experiment to test the strength of the spaghetti strands in different configurations | • Build the tower that satsfies the criteria. |
| **Analysis** | • Net force = 0 N<br>• Torque = 0 N<br>• Center of mass | • Different shapes for structural support<br>• Failure point analysis of the tower<br>• Weight distribution<br>• Constraint of materials and properties of material |
| **Models** | • Force diagrams<br>• Net torque<br>• Center of mass mathematical model | • Physical model for a big tower |
| **Systems** | • Surface<br>• Tower | • Interactions between spaghetti strands<br>• Interaction between the tower and the weight of the marshmallow |

## PROJECT OVERVIEW

The challenge is simple: Within 18 minutes, use 20 strands of spaghetti, 1 meter of tape, and 1 meter of string to build the tallest tower that supports one large marshmallow on its top. Often, students forget to test the structure with the marshmallow, do not try to use the string for balancing, or wait until the time is almost elapsed to put the heavy marshmallow on top—and when they do, they watch the tower fall.

Most of the teachers in the engineering infusion workshop used the marshmallow challenge afterward. It has been by far the most popular group-building activity in the last few years, used in classrooms, faculty meetings, and even district-level trainings. Earlier in this book, we discussed why the marshmallow challenge is not a good "infusion" activity; however, the challenge itself presents opportunities for learning engineering concepts. Therefore, we decided to use it as an anchor activity to discuss the tools of engineering and the process of design. In our summer Project Infuse group, we had the opportunity to work with eight different groups of students (middle school and high school) to test out different ways of facilitating an engineering design activity. Here are some of the interesting variations we have tried with students to address the process of design:



**Sample marahmallow tower designed by a group of high school teachers during training**

- Asking students to fill out an engineering notebook template throughout the design process, noting each iteration after some failure analysis
- Allowing five minutes for students to interact with the materials before using them for building
- Requiring students to brainstorm and design on paper before choosing a design to build
- Encouraging students to analyze how the weight of the marshmallow can affect the stability of the spaghetti tower early in the build
- Giving students a list of reflection questions related to the design process after the challenge
- Having students compare and contrast the engineering design process and the scientific method

Because this is a design-centered activity, we structured it to steer students away from blind trial and error and toward using design techniques by highlighting components of the design process and the essential engineering concepts that lead to good designs.

## ENGINEERING VERSUS PHYSICS CONCEPT

The marshmallow challenge itself has potential for testing and iteration, gives a very specific constraint, and requires a great amount of teamwork, which are all important elements of engineering design. Unlike hypothesis-driven experimental design in science, this challenge does not focus on a question or observation about nature, but on a problem to solve.

This anchor activity can also be used to highlight the similarities between the engineering and physics design process. In engineering, the process of iteration helps to create the solution to a problem.

## Assessment: Determining Acceptable Evidence

### Formative

- Checking with students during the design process

### Summative

- Groups sharing their design and discussing design process
- Questions related to how design process can be streamlined

## Materials and Preparation

### Materials (Groups of 3)

- Safety glasses or goggles for each student
- 1 large marshmallow
- 20 strands of spaghetti
- 1 meter of tape
- 1 meter of string

### Class Equipment

- Scissors

## Safety

- Remind students about general lab safety procedures.
- Participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Remind students not to eat any food used in this activity.
- Students should wash hands with soap and water upon completing this activity.

**Marshmallow Tower Lesson Plan for Day 1 (50-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Instructor Doing? | Engineering Opportunities |
|---|---|---|---|
| **10 mins.**<br><br>**Engage**<br>**Elicit** | • Read the marshmallow challenge description silently and draw initial design ideas. | • Encourage students to think about the properties of the materials and some building structures they have seen. | — |
| **2 mins.**<br><br>**Explain**<br>**Elicit** | • Ask questions about the challenge, organize into groups, and meet group members. | • Emphasize the focus for this design activity. For example, if the activity focuses on material testing before the design process, ask students to test and make note of how different materials can be used and why some configurations are more suitable for the task than others. | • Consider different elements of tower design that might be a good place to start (e.g., that triangle or pyramid shapes might be more stable). |
| **18 mins.**<br><br>**Explore** | • Work on constructing the tower and testing during the process. | • Encourage students to use an iterative process to evaluate their designs and fine-tune the structure. | • Students analyze and test their designs throughout the process. Beware of tunnel vision where they only commit to one idea and it fails without testing along the way. |
| **20 mins.**<br><br>**Explain**<br>**Elaborate**<br>**Evaluate** | • Students present their designs and discussions of the design process. | • Measure the final structures after the 18 minutes have elapsed. | • Depending on the focus, Have students reflect on their design process, write down what tools of analysis they used, look at models of towers that worked and towers that did not, and look for a common theme. |

## Supplemental Material

- Handout 5C: Marshmallow Tower

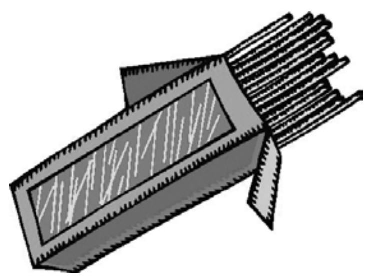
# HANDOUT 5C: MARSHMALLOW TOWER

## GOAL

The goal for design teams is to build the tallest freestanding structure as measured from the surface of the table to the top of the marshmallow. (*Note:* The final structure must be freestanding. Therefore, it cannot be suspended from a higher structure such as a chair, the ceiling, or a chandelier.)

## MATERIALS

- 20 strands of spaghetti
- 1 meter of masking tape
- 1 meter of string
- 1 marshmallow



## RULES

- The entire marshmallow must be on top! Cutting or eating part of the marshmallow will disqualify the team.
- Use as much or as little of the materials provided. Feel free to break up the spaghetti and cut the tape and string to create new structures.
- The time limit is 18 minutes! No one may hold onto the structure when the time runs out. Teams touching or supporting the structure at the end of the exercise will be **disqualified**.

*Source:* Activity adapted from Tom Wujetc, "Marshmallow Challenge," *www.tomwujec.com/design-projects/marshmallow-challenge.*

# ANCHOR ACTIVITY 5D: SODA CAN CLOCK

**Contributors: Project Infuse Teacher Team**

**Time frame:** 1 class period
**Engineering focus:** Models

### Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Volume versus time<br>• Hole size versus time | • Design a drip timing system that matches a song's beat. |
| **Analysis** | • Graph the data and be able to interpolate and extrapolate. | • Material of water holder<br>• Failure point ( Is the time when there still is water inside but the system has stopped dripping consistent?) |
| **Models** | • Pressure versus height<br>• Bernoulli principle<br>• Develop a model of constant flow. | • Mathematical model for analysis<br>• Model for how fast to drain a reservoir or a body of fluid in a container |
| **Systems** | • Force<br>• Conservation of energy | — |

## PROJECT OVERVIEW

In this activity, students are challenged to create a mathematical model of a simple soda can water clock to accurately predict a known time interval. By creating a graph of volume of water dripped versus known time intervals, students can then use the graph to measure unknown times. Different types of bottles and or cans will work for this activity and are readily available. This is an excellent activity for demonstrating the ways in which mathematical models such as graphs or equations can be used to predict physical values.

## Assessment: Determining Acceptable Evidence

### Formative

- Observe groups develop procedures; ask probing questions
- Spot check graphs during data collection

### Summative

- Individual: Graph of collected data
- Group: Accuracy of group prediction of unknown time interval

## Materials and Preparation

### Materials (Groups of 4)

- Safety glasses or goggles for each student
- Soda can or bottle with a small hole in the bottom. (The teacher may choose to give cans or bottles with different-size holes to different groups of students.)
- Graduated cylinder (at least 200 ml)
- Stopwatch (or timer apps on students' smartphones)

## Safety

- Remind students about general lab safety procedures.
- Students should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Remind students not to eat any food used in this activity.
- Remind students to use caution in working with sharps (soda can opening), which can cut skin.
- Students should wash their hands with soap and water upon completing this activity.

**Soda Can Clock Lesson Plan for Day 1 (55-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Instructor Doing? | Engineering Opportunities |
|---|---|---|---|
| **10 mins.**<br><br>**Elicit**<br>**Engage** | • Share how they might be able to measure time without using a stopwatch or clock.<br>• View a video or a picture of a water clock (e.g., the video "Galileo and Motion"; see the Supplemental Materials" section, p. 101).<br>• As a class, discuss ways in which to calibrate a water clock made from soda cans or bottles. | • Elicit student ideas about measuring time.<br>• Engage students in discussing data collection for the purposes of calibrating a water clock. | • Designing data collection<br>• Types of mathematical models |
| **5 mins.**<br><br>**Engage**<br>**Explain** | • As a class, discuss the soda can challenge and how the success of the mathematical model will be determined. | • Engage students by generating questions about the modeling task.<br>• Clarify questions related to the task.<br>• Encourage students to be specific in their data collection plans. | — |
| **30 mins.**<br><br>**Explore**<br>**Explain**<br>**Evaluate** | • In groups, collect data.<br>• Create graphs of water volume dripped versus time.<br>• Evaluate data to determine whether they show a clear pattern. | • Coach students during group work on data collection.<br>• Encourage students to do a full or partial practice run of data collection to determine whether their method is effective. | • Encourage students to graph their data as they collect them so they can easily determine if they have collected enough data to determine a pattern. |

Soda Can Clock Lesson Plan for Day 1 (*continued*)

| Time Allotted and 7e Model Stage | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Instructor Doing? | Engineering Opportunities |
|---|---|---|---|
| **10 mins.**<br><br>**Explain Evaluate** | • Use their soda can clocks to determine the length of an unknown time interval. Each group measure how the same time and submits its prediction on a piece of paper.<br>• Groups discuss what might have affected the accuracy of their predictions. | • Play a tone at known time intervals.<br>• Encourage discussion of the quality of the models. | • Discuss the accuracy of the mathematical models.<br>• Discuss how the data collection may have affected the quality of the mathematical models. |
| **Extend** | • Have students write about why their mathematical model was accurate or not accurate and how they could change their data collection to improve the accuracy of their model. | — | — |

## Optional Modification and Extension (Extend)

- Give the groups a different starting volumes of water or cans with different-size holes. After all groups have created their graphs, have the class compare the graphs to determine whether the starting water volume or hole size affects the shapes of the graphs.

## Supplemental Material

- YouTube video: "Galileo and Motion," *www.youtube.com/watch?v=MAvPlHAfGbQ*

# ANCHOR ACTIVITY 5E: WIND TUBE HOVERCRAFT

**Contributor: Kristen Wendell**

**Time frame:** 1 class period

**Engineering focus:** Design, analysis, and models

## Opportunities for Science Versus Engineering Concepts

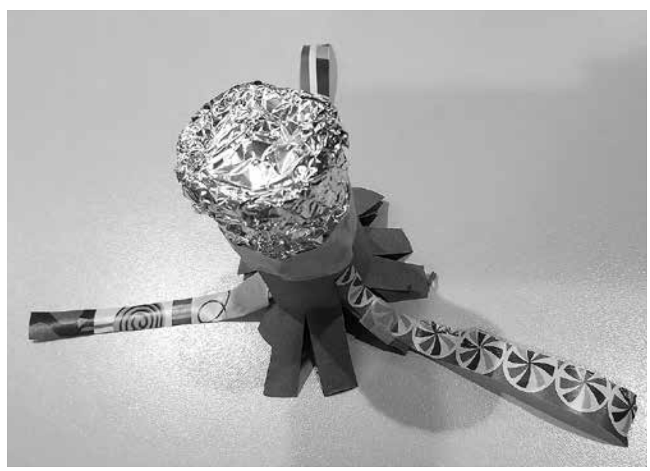
| Concept | Science | Engineering |
|---|---|---|
| **Design** | • In designing an experiment, physicists would not use household objects as-is but would vary the surface areas and masses of the nested coffee filters very precisely and determine relationships regarding size and speed of movement. Physicists design the best experiment regardless of the cost of the materials. | • Engineers design an artifact that hovers in the wind tube for 10 seconds. They use the household objects such as the coffee filters as-is. Engineers are sensitive to the costs of the materials as they try to optimize the design. |
| **Analysis** | • Physicists will use much simpler models of hovering coffee filters to check whether their mathematical analysis is consistent with the experimental evidence. Their analysis is based on first principles such as Newton's laws of motion. | • Engineers will use physics principles and related equations to analyze and understand the performance of their designs. Analysis of the forces acting on the hovercraft can inform design revisions. Engineers must adapt general principles for the complexity of their designs. |
| **Models** | • Physicists will model the forces on the object using free body diagrams. They will use pictorial models to show the air currents on the object. | • Engineers will use the wind tube challenge as a physical model for a parachuting person descending toward Earth. They will also use sketches to model the ideas they have for improving designs. |
| **Systems** | • Physicists will investigate the net forces on the object to determine whether the system as defined by the object and the fan are in equilibrium. | • Engineers are concerned with the fan system, the air channel system (and its friction), and the electrical switch system that can limit the fan. |

## PROJECT OVERVIEW

Students must construct a hovercraft device that remains in a vertical wind tube for at least five seconds without flying out of the top or touching the surface of the fan at the bottom. They are only allowed to use some common materials around the classroom. A key feature of engineering is developing small-scale models to predict and test the performance of a product. In this lesson, students will explore design principles for parachutes and other skydiving equipment, and will think about what recommendations they can make for how to slow the speed of a falling object.

Setting up a few testing stations around the classroom encourages students to test many materials and combination of designs. They can quickly analyze the performance of each iteration and adjust their design accordingly. This allows for rapid prototyping and refinement in a short period of time.

One of the main goals is to explore some common rules that allow for balancing forces against the parachute design. To best explore these rules, it is important to ask students to document their process along the way or regroup at the end of the project to examine different designs together.



**Example hovercraft design by Project Infuse Teacher during summer workshop**

## ENGINEERING VERSUS PHYSICS CONCEPT

Analyzing different materials to use in engineering design and making predictions are important aspects of engineering. Engineers use knowledge from their testing to analyze future designs and evaluate products. Although students are testing and iterating their hovercraft, each analysis will serve as a way to check whether they have satisfied design criteria and constraints.

## Assessment: Determining Acceptable Evidence

### Formative

- Checking with students during the design process

### Summative

- Groups sharing their design and discussing design process
- Questions related to how design process can be streamlined

## Materials and Preparation

### Materials for the Class

- Safety glasses or goggles for each student
- Recycled and classroom materials, such as paper bags, cups, coffee filters, paper towel and toilet paper tubes, paperclips, tape, drinking straws, wooden sticks, strings, nonlatex rubber bands, paper, cardboard
- Scissors
- Masking tape
- Wind tube: Clear acrylic tube with diameter of 18 inches and height of 6 feet partitioned into two sections so that any items that get stuck can be easily removed
- Fans that can be rotated and placed under the tube to push air upward through the tube

**Hovercraft design by students during a introduction to forces unit activator activity**

## Safety

- Remind students about general lab safety procedures.
- Participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Remind students not to eat any food used in this activity.
- Remind students to use caution in working with sharps (scissors, clips, sticks, and so on), which can cut or puncture skin.
- Students should wash hands with soap and water upon completing this activity.

**Wind Tube Hovercraft Lesson Plan for Day I (50-minute block)**

| Time Allotted and 7e Model Stage | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Instructor Doing? | Engineering Opportunities |
|---|---|---|---|
| **5 mins.**<br><br>**Engage** | • Observe the wind tube. Share ideas and reasoning about a situation in the real world that might be represented by the vertical wind tube in the classroom. | • Show students the vertical wind tube. Ask, "If I drop a coffee filter in this tube, do you think that situation would be more like a jet flying through the sky or a skydiver jumping out of a plane?"<br>• Help students understand that the air being blown upward by the fan onto the coffee filter is like the air rushing past a skydiver's body as he or she falls. | • The wind tube is a model for air flowing around an object falling toward Earth. Engineers use physical models such as the wind tube to test products in a controlled setting and develop design principles. |
| **5 mins.**<br><br>**Elicit** | • Predict the behavior of a coffee filter, a paper bag, and a paper plate in the wind tube. Write and sketch about their predictions individually. Compare predictions and reasoning with a neighboring student.<br>• As a class, test the three objects. Students share what they notice about the behavior of each object. | • Show a coffee filter, paper bag, and paper plate and ask, "Will each item fly out of the tube, hover, or drop to the bottom?"<br>• Have students share some predictions and reasoning with the whole class. | — |

Wind Tube Hovercraft Lesson Plan for Day 1 (*continued*)

| Time Allotted and 7e Model Stage | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Instructor Doing? | Engineering Opportunities |
|---|---|---|---|
| **20 mins.**<br><br>**Explore** | • Work in teams to plan, build, and test devices.<br>• Work through the specific design challenge of using only the available materials to create a device that hovers in the wind tube without touching the fan surface or flying out of the top for five seconds. | • As they iterate, remind students to think about the rules of thumb they are noticing for how to make a hovering device. | • Prototypes can be constructed and tested quickly, so students can iterate many times and should keep in mind that the overall engineering goal is to develop design principles for parachutes and skydiving gear. In their engineering notebooks, students document the iterations of their hovercraft (the design changes and the rationale behind each change) AND the design rules of thumb they are pulling from their iterations. |
| **10 mins.**<br><br>**Explain** | • Student teams show at least one prototype they tested and describe its behavior in the wind tube, then share at least two possible rules of thumb—one thing that they noticed about what worked well and one thing they noticed about what didn't work. | • If needed, scaffold the rules of thumb activity by asking, "What are you noticing about devices that work? What are you noticing about devices that don't work?" | — |

Wind Tube Hovercraft Lesson Plan for Day 1 (*continued*)

| Time Allotted and 7e Model Stage | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Instructor Doing? | Engineering Opportunities |
|---|---|---|---|
| **10 mins.**<br>**Elaborate** | • Individually, draw free-body diagrams of one student hovercraft that worked well and one that didn't work.<br>• To focus their thinking on the variables that influence the upward force—the drag force from the air—students consider what factors determine how much drag force a given hovercraft will have. Students explore several hovercraft designs where the weight is dominated by the same relatively heavy object (e.g., an AA battery), but other variables are changed by very lightweight materials, to see how those variables affect the drag force. | — | — |
| **Extend** | • **Homework:** Refine the rules of thumb identified in this activity into a design principles memo to be sent to a parachute design company. | — | — |

## Supplemental Material

- Handout 5E: Wind Tube Hovercraft

*Source:* Adapted from "Things to Try: Wind Tubes" by the PIE Institute of the Exploratorium, San Francisco, CA, *www.exploratorium.edu/pie/downloads/Wind_Tubes.pdf.*

# HANDOUT 5E: WIND TUBE HOVERCRAFT

## GOAL

- Construct a device that remains in a vertical wind tube for at least 10 seconds without flying out of the top or touching the surface of the fan at the bottom.
- You may use only the materials available in the room.

## SAFETY PRECAUTIONS

- Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Do not to eat any food used in this activity.
- Use caution in working with sharps (scissors, clips, sticks, and so on), which can cut or puncture skin.
- Wash your hands with soap and water upon completing this activity.
- Do not place your hands near the fan blades.

## WIND TUBE DETAILS

- Clear acrylic tube 18 inches in diameter and 6 feet high
- Placed on top of a vertically oriented fan that pushes air upward through the tube
- Partitioned into two sections so that items stuck in the tube can be removed easily

## MATERIALS AND TOOLS

- Safety glasses or goggles for each student
- Paper bags
- Paper cups
- Plastic cups
- Coffee filters
- Paper towel cardboard tubes
- Toilet paper cardboard tubes
- Paperclips

- Tape
- Drinking straws
- Wooden sticks
- String
- Rubber bands
- Paper
- Cardboard
- Scissors

*Source:* This challenge is based on "Things to Try: Wind Tubes," PIE Institute, Exploratorium, San Francisco, CA, *www.exploratorium.edu/pie/downloads/Wind_Tubes.pdf.*

# ANCHOR ACTIVITY 5F: RUBE GOLDBERG DEVICE

**Contributor: Kristin Newton**

**Time frame:** 1 class period

**Engineering focus:** Systems

### Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Experiment with different forms of energy and how energy can be transformed. | • Design a Rube Goldberg device that accomplishes the specific goal. |
| **Analysis** | • Analyze mechanical energy (kinetic energy and gravitational potential energy)<br>• Analyze efficiency of transformation of energy. | • Predict efficiency using mathematical and physics analysis. |
| **Models** | • Transformation of energy<br>• Conservation of energy | • Drawings and blueprint for communication |
| **Systems** | • Each transformation can be isolated into one system. | • Examine the inputs and output of each system.<br>• Approach this design challenge and analyze failure in operation by checking how each part can affect the other parts of the system. |

## PROJECT OVERVIEW

In this activity, students will create a Rube Goldberg device that includes at least three transfers of energy and pops a balloon at the end. When introducing the project, you can share one or more of the many possible videos of modern Rube Goldberg machines and/or the original cartoons designed by Rube Goldberg.

As an anchor activity, the main purpose of this challenge is to teach students how to design systems that work together to complete a task. Encourage students to separate their device into multiple systems and think about the inputs and outputs of each system.

It is possible for students to draw out this activity for a long time. Set a time limit and resist the temptation to extend it. When it is time to present devices, have each group present what they have, even if they haven't met all the criteria for the challenge. Afterward, it can be instructive to discuss the challenges of getting multiple systems to work together. Some groups might have come up with a very complicated plan and have had trouble completing it; other groups might have one problematic transition between systems.

## ENGINEERING VERSUS PHYSICS CONCEPT

This activity focuses on systems and systems thinking. Students often can create elaborate and functional designs, but they have few experiences in the classroom with complex projects that need to be separated into different systems. This activity forces students to break down the task and creates authentic need for communication and links across different systems.

Compare the systems design challenge to an assembly line. A product must pass down the line from one station to another during the manufacturing process. This engineering systems anchor activity is meant to highlight the importance of connections and links among the systems.

## Assessment: Determining Acceptable Evidence

### Formative

- In discussions with students or groups, ask students to provide evidence and reasoning for their design decisions.
- Prompt students to share how they are going to link separate systems.

### Summative

- Final performance of the Rube Goldberg device
- Students describe their three energy transformations and what the systems were in their design.

## Materials and Preparation

This list includes many possible ideas for materials that could be useful. Include enough to provide students with choices.

### Materials for the Class

- Safety glasses or goggles for each student
- Scissors
- Tape (masking, duct)
- Paper, posterboard, foam board
- Balls (table-tennis balls, golf balls, tennis balls, marbles, ball bearings)
- Paper or plastic cups, plates, bowls
- Straws, popsicle sticks, skewers, wooden dowels, toothpicks, pipe cleaners
- Nonlatex balloons
- String
- Packing peanuts
- Pipe insulation, plastic tubing
- Toy racing tracks and cars
- Pulleys
- Meter sticks, rulers
- Zip ties
- Wooden shims, wooden blocks
- Dominoes
- Motors, batteries, switches, wires
- Ring stands, rings
- C-clamps
- Weights
- Springs, clothes pins, nonlatex rubber bands

**Example Rube Goldberg Device built by high school students**

## Safety

Testing one of the stations in the design challenge

- Remind students to be aware of their surroundings while they are operating their devices.
- Personal protective equipment (eye protection) is to be worn during the set-up, hands-on, and takedown segments of the activity.
- Remind students to use caution in working with sharps (scissors, pipe cleaners, sticks, and so on), which can cut or puncture skin.
- Immediately pick up any balls, marbles, and so on that fall on the floor. These create a slip-and-fall hazard.
- Make sure there are no fragile materials in work zone while operating devices.
- Students should wash hands with soap and water upon completing this activity.

### Rube Goldberg Device Lesson Plan for Day I (55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Instructor Doing?) | Engineering Opportunities |
|---|---|---|---|
| **5 mins.**<br>**Engage** | — | Introduce the design challenge using a video or Rube Goldberg cartoons. | — |
| **5 mins.**<br>**Elicit** | Share energy transformations that they see in the device. | Facilitate conversation about the types of energy transfers or systems in the devices. | Discuss types of systems in devices. |
| **30 mins.**<br>**Explore** | Work in groups to build the Rube Goldberg devices. | Ask students to share reasoning for design decisions. Encourage students to break up the project into systems and have different students working on different systems. | Determine the best way to link multiple systems. |
| **10 mins.**<br>**Explain**<br>**Evaluate** | Demonstrate the devices to the class and describe the energy transfers and systems. | Facilitate demonstrations of devices. | Describe the different systems in devices. |
| **Extend** | **Homework:** Have students create a step-by-step sketch and/or flow chart of their device and write a reflection on which parts of it were successful and which could be improved. | — | — |

## Supplemental Material

- Handout 5F: Rube Goldberg Device

*Note:* This activity was inspired by the Design Assembly Loop Challenge that the Project Infuse Leadership Team developed.

# HANDOUT 5F: RUBE GOLDBERG DEVICE

## MATERIALS

You will be provided with ample choices of materials for working within the challenge. The teacher will provide you with a list of available materials.

## SAFETY PRECAUTIONS

- Be aware of your surroundings while you are operating your device.
- Wear personal protective equipment (eye protection) during the set-up, hands-on, and takedown segments of the activity.
- Use caution in working with sharps (scissors, pipe cleaners, sticks, and so on), which can cut or puncture skin.
- Immediately pick up any balls, marbles, and so on that fall on the floor. These create a slip-and-fall hazard.
- Make sure there are no fragile materials in the work zone while operating devices.
- Wash hands with soap and water upon completing this activity.

## CONTEXTUALIZING PROBLEM

A product often needs to pass through an assembly line to be constructed. This challenge simulates an assembly line in which energy transformation would allow for a sequence of events to lead to a final process.

## DESIGN GOAL

Create a Rube Goldberg device that includes at least three transfers of energy and pops a balloon at the end. Human interface should only occur at the beginning of the first station. The device must carry on without interference.

## SPECIFICATIONS

- There should be at least three energy transfers.
- The final goal is to pop a balloon.

## CONSTRAINTS

- Students must complete this challenge by the end of the 40-minute time cap.
- Humans may only "start" the first station. There can be no interference after that beginning.
- You must use only the materials in the classroom.

6

# Engineering Infusion With Mechanics

A natural place to start infusing engineering in the physics classroom is with some existing projects in the mechanics unit. Mechanics is the most straightforward place to try engineering infusion activities and certainly offers many possibilities from which to choose. Some of the activities in this chapter are designed to introduce and explore specific content such as Newton's laws or kinematics. Others are meant to be culminating activities or performance assessments to demonstrate what students have learned.

Look at the balloon cart and mousetrap cars activities if you want a theme that ties together an entire mechanics unit. Alternatively, you might decide to start with a no-cost engineering infusion to understand transfer of momentum, and design amusement park bumper cars using only a computer and a PhET simulation. Have you always done an egg drop project but want to add some engineering rationale to it? Introduce it with some clips from the movie *The Martian*, ask students to identify and explain how Mark Watney analyzed his engineering problem, and then connect Watney's analysis to students' own analyses for their egg drop designs.

If teachers have the luxury to select and use many different activities, choose ones that complement one another by focusing on different aspects of engineering. Begin the forces unit by asking students to analyze different materials for a trampoline, then end with a project where students are asked to consider all the net forces acting on an aluminum foil boat. Table 6.1 (p. 118) provides basic curricular details for the seven activities in this chapter.

**TABLE 6.1. Chapter 6 Activities**

| Activity Name | Physics Concept(s) | Core Concept(s) | Class Period(s) | Brief Description |
|---|---|---|---|---|
| **Balloon Cart Project** | • Distance<br>• Time<br>• Velocity<br>• Newton's laws<br>• Energy | • Design<br>• Analysis<br>• Models | 2–3 | Use limited materials to design a balloon-powered cart that travels three meters in less than five seconds. |
| **Newton's Third Law Paper Trampoline** | • Newton's third law<br>• Forces | • Analysis | 1 | Learn about Newton's third law by testing fabrics and other materials for a trampoline designed to provide the highest possible bounce of a steel ball. |
| **Bristlebots** | • Distance<br>• Time<br>• Velocity<br>• Vectors | • Design<br>• Analysis<br>• Models<br>• Systems | 1 | Use a toothbrush, a small motor, and some wires to make a bristlebot, then optimize it for maximum displacement. |
| **Mousetrap Car Challenge** | • Motion (kinematics?)<br>• Force | • Design<br>• Models<br>• Systems | 4 | Design a mousetrap-powered car that goes the  fastest down a narrow racetrack. |
| **Amusement Park Engineer–Bumper Cars** | • Momentum | • Design<br>• Analysis<br>• Models | 3 | Using PhET simulation, create a proposal for design of a set of bumper cars that are safe, fair, and fun for children, teenagers, and adults. |
| **Egg Lander–Motion Design CEPA** | • Impulse | • Design<br>• Analysis<br>• Models | 4 | Design a vehicle that successfully lands an egg dropped from a height of two meters. Use force plates, motion detectors, and other tools for analysis along the way. |
| **Golf Ball Boat** | • Net force<br>• Buoyancy | • Design<br>• Models | 3 | Use a 30 cm × 30 cm piece of aluminum foil to construct a boat that supports the weight of the largest number of golf balls. |

# ACTIVITY 6A: BALLOON CART PROJECT

**Contributor: David Scott and Peter Schoonmaker**

**Time frame:** 2–3 class periods
**Physics focus:** Newton's laws, momentum, and energy
**Engineering focus:** Design, analysis, and models

## Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Air-to-distance ratio<br>• Different types of wheels and grips on the car (friction)<br>• Various masses | • Design a balloon cart using engineering skills to satisfy certain criteria.<br>• The design must use the limited materials allowed and meet the constraints given by the challenge. |
| **Analysis** | • Free-body diagram<br>• Momentum<br>• Energy<br>• Newton's second law of motion<br>• Kinematics<br>• Newton's third law pair | • Mechanical analysis: structure and rigidity<br>• Adjustments that are useful for the design goal<br>• Analysis of materials, including materials' failure points<br>• Ways to reduce friction<br>• Directional stability |
| **Models** | • Gas model (molecular model of the gas)<br>• Full-body diagram<br>• Friction and air resistance<br>• Depiction of Newton's third law forces<br>• Average force is constant<br>• Mass or massless gas | • Simulation of a small-scale vehicle |
| **Systems** | • Car versus external force (air) (i.e., the system is different when the car is in the air versus when it is on the floor) | • Balloon system<br>• Wheel system<br>• Connection (structural support) |

## PROJECT OVERVIEW

Instead of teaching students about Newton's laws, momentum, and energy through several individual units, you can use this balloon cart project during each unit. It also works well as a capstone activity that ties all of those units together for the students. The balloon cart project covers many of the topics that typically are on mid-year examinations, and students will see it as a fun and competitive activity to perform just before those examinations. In addition, it will enable students to apply what they have learned while they accomplish a challenge in which they can see how making small adjustments to their design will affects the balloon cart's performance.

## THE CHALLENGE

Students work in pairs and must design and build a balloon-powered cart capable of traveling a specified distance (typically three meters) in a specified time frame (typically five seconds) using only the materials provided. If they accomplish this, they have successfully completed the challenge. Bonus points are awarded to the team whose balloon cart travels the farthest and to the team whose balloon cart travels the specified distance in the shortest time.

On the first day of the challenge, students are told the rules and shown the materials that they will be given. They should not be given the supplies right away, because they will immediately start trying to build something without thinking it through. The only hint provided is that the balloon is fairly small and thus only provides a small puff of air. To be successful, students must think about all aspects of their design. Typically, it takes 20–30 minutes to develop a design, and another 20 minutes to develop three drawings (front, top, and side views). The teacher must approve the design and drawings before students receive their supplies. There are always flaws in the design, but they can be left to be discovered by the students. However, occasionally a design is so flawed that the teacher should provide some guidance for improvement. When the students' design is complete, they may be given the materials and may construct their balloon cart.

The second day begins with students building the carts. The first prototype is usually very rough—students will have given little thought to how to make the cart go the farthest or travel the fastest. The first brave team finally approaches the teacher usually about 20 minutes into the class, ready to test its cart. The trial area will have been marked on the floor with two pieces of masking tape three meters apart, one labeled "Start" and the other "Finish." A first design may look like this: the entire index card is used, the skewer has been cut in half and used as an axle, the wheels are on crooked, and the balloon is taped to the index card at the balloon's widest part—this cart has *no* chance. The entire class is watching this pioneer team with anticipation as students blow up the balloon, put the cart down, and release the balloon. The cart moves about six inches before the balloon shrinks enough to become unattached and fly off. Everyone laughs, but everyone has also learned that the balloon cannot be taped directly to the cart, at least not at the balloon's widest part. The remainder of the second day is spent with each team testing its design and everyone else standing around watching and learning what works and what doesn't.

Eventually, a common design begins to emerge. The skewer is cut into two pieces and the straw into three pieces. Two pieces of the straw are taped to the bottom of the index card and the skewers are slipped inside the straws. The wheels are attached to the skewers and both rotate with very little friction between the skewer and the inside of the straw. The third piece of straw (preferably the piece containing the flexible portion) is used to secure the balloon to the index card. The balloon is placed over the flexible portion and taped to the straw. The straw can then be taped to the rear of the index card to provide the force to move the cart. If the straw hangs over the edge, the balloon can be inflated through the straw.

Even though the design appears as though it should work, there are still a number of potential problems, mostly related to sloppy construction. These include the following:

- Wheels are not centered properly, causing them to wobble, which creates a slight force in the wrong direction.
- The straws are taped on crookedly, so the cart doesn't travel in a straight line.
- Wheels rub against the index card, causing friction.
- There is too much mass for the balloon to overcome.

Eventually, teams complete the challenge successfully, but then want to modify their cart try to gain the bonus points. Someone will finally recognize that Newton's second law is in play and realize that to win the bonus points for fastest time, they must reduce their cart's mass. They begin trimming the index card in half widthwise, cutting off as much of the skewers as possible, and eliminating anything else to decrease the mass. This cart retests and, sure enough, it has the fastest time. Another team decides that if reducing the mass a little is good, then reducing it by even more must be even better. They cut their index card in half not only widthwise but also lengthwise. When they retest their cart, it flies around in a circle or flips over. They went too far and the cart lost all stability.

The third day is spent finishing testing for one or two groups and then developing lab reports. The lab reports describe students' design process, how they arrived at their initial design, how it was modified over the course of the activity, and why. Students need to include their design drawings and an analysis report that includes the following information:

- The cart's
    - Time to cover three meters
    - Total distance traveled
    - Total time of travel
    - Average speed over three meters
    - Mass and weight
    - Average momentum over three meters
    - Average kinetic energy over three meters
    - Potential energy at the beginning (hint: conservation of energy)
    - Average acceleration over three meters
- The average force acting to stop the cart (hint: impulse)
- The total work done (hint: work–energy theorem)
- A paragraph explaining Newton's third law and how it applies to the cart's motion (or, explaining how impulse and momentum relate to the motion)
- A paragraph explaining Newton's second law and how it applies to the cart's design and motion

## BIG IDEAS

- **Physics:** Energy is a quantitative property of a system, which can affect the motion of an object. Increases in energy can cause an object to accelerate or to perform some form of work. When a system performs work, the total energy of the system decreases.
- **Engineering:** Engineers use models to confirm mathematical or hypothetical designs. Models typically require a number of design modifications to make corrections to the original design or incorporate improvements on the basis of empirical data.

The raw materials for the first balloon car prototype

## Connections to the *Next Generation Science Standards*

### Performance Expectation

- HS-PS3-3: Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy,

### Science and Engineering Practices

- Developing and using models
- Using mathematics and computational thinking
- Constructing explanations and designing solutions
- Obtaining, evaluating, and communicating information

### Disciplinary Core Ideas

- PS3.A: Definitions of Energy
- ETS1.A: Defining and Delimiting Engineering Problems

### Crosscutting Concepts

- Cause and effect
- Systems and system models
- Energy and matter

## Assessment: Determining Acceptable Evidence

### Formative

- Drawing review
- Question and answer opportunities during test phase

### Summative

- Lab report
  - Typically 50% of the grade is related to the drawing and design process, proper application of force vectors, and the success of the balloon cart in traveling three meters in five seconds.
  - The remaining 50% is related to the lab report write-up. Each calculation is assigned a value (typically 1–3 points, depending on the difficulty) and the open-response questions are assigned 5–15 points. Teachers may adjust these as appropriate.

## Materials and Preparation

### Materials (Groups of 2)

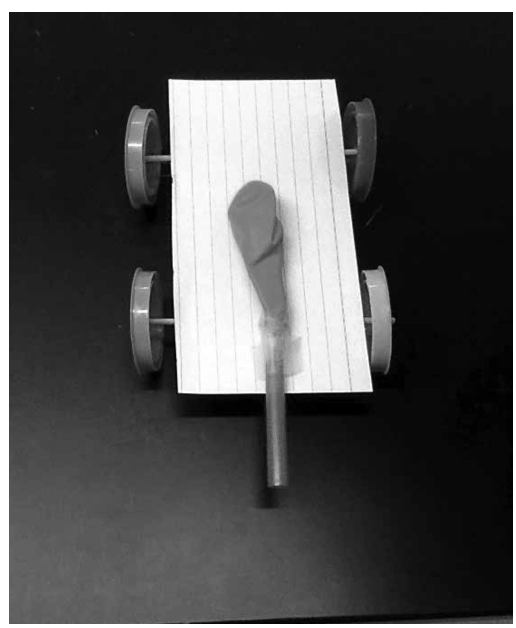
- Safety glasses or goggles for each student
- 1 3 in. × 5 in. index card
- 1 bamboo skewer
- 1 drinking straw with a flexible end
- 4 thin plastic bottle caps (each student provides 2).
- 1 small nonlatex balloon

### Class Equipment

- Clear cellophane tape (may be used only to connect pieces together, not as a structural support)
- Scissors

## Safety

- Remind students about general lab safety procedures.
- Participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Remind students to use caution in working with sharps (scissors, skewers, and so on), which can cut or puncture skin.
- Remind students to use caution when poking holes in the bottle caps. They should always push the skewer down into the tabletop or some other hard surface to avoid injuries to the face, eyes, and skin.
- Students should wash their hands with soap and water upon completing this activity.



The assembled first iteration of the balloon cart

## Balloon Cart Project Lesson Plan for Day 1–Sketch Designs and Begin Construction (58-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| 1 min.<br>Engage | — | • Introduce the challenge: "Rocket cars can attain speeds of over 750 mph. Can you imagine that speed on the highway? You would be able to travel 750 miles in one hour. Your challenge here is to construct a balloon cart that can travel approximately 1 mph propelled by the air from a balloon." | — | — |
| 3 mins.<br>Elicit | • Contribute to the discussion any past experience they have had with Estes rockets, bottle rockets, and balloon carts. | • Ask the students, "Has anyone ever built a balloon car or a water rocket?" | — | — |
| 10 mins.<br>Elicit<br>Evaluate | • Brainstorm possible designs using think, pair, share.<br>• Ask, What causes motion?<br>• Ask, What possible combinations of materials could accomplish the task?<br>• Ask, How do I put those components together to accomplish the task? | • All students have prior knowledge about velocity, acceleration, potential energy, kinetic energy, work, energy, and momentum. Guide students to make connections between the individual topics. | • Kinematics<br>• Energy<br>• Momentum | — |

Balloon Cart Project Lesson Plan for Day 1 (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **34 mins.**<br><br>**Explore** | • Work to refine their design and assemble required drawings.<br>• Inspect the materials and discuss possible designs to assemble. | • Guide students to think beyond the most obvious issues. They will get the easy design considerations correct but will miss some of the more subtle design flaws. In particular, they will not recognize areas of the design with high friction possibilities. They also will not realize how small the puff of air from the balloon will be. | • Friction<br>• Opposing forces | • Friction minimization<br>• Importance of alignment |
| **10 mins.**<br><br>**Explain** | • Describe their cart design to instructor. | • Ask students to explain the design basis of their cart. If the design is sound but not complete (i.e., has fatal flaws), allow the students to proceed with the materials so they can identify the flaws during the testing process. | — | • Identify design changes based on empirical data that are collected or observed during testing phase. |

**Balloon Cart Project Lesson Plan for Day 2–Complete Construction and Begin Testing (58-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **1 min.**<br><br>**Engage** | — | • Remind students about the rocket cars and make a prediction that some teams will be successful today in getting their cars to work. | — | — |
| **57 mins.**<br><br>**Explore**<br>**Explain**<br>**Evaluate** | • Continue to test their designs and observe other groups' design performances.<br>• Identify aspects of other designs that work better than their own current design and incorporate those changes to improve the performance of their cart. | • Provide guidance on specific design questions. Frequently, students will have all of the correct design aspects but will have assembled the parts quickly and without recognizing subtle issues that will cause their cart's failure. Provide guidance on areas to evaluate without giving any specific instructions about what to change. | • Identify a physics concept that is preventing successful completion of the task. | • Change the design to eliminate problems that are causing failure of the task. |
| **Evaluate** | • Evaluate their design and modify as necessary. | • Continue to aid students in identifying possible points of failure. | — | — |

Balloon Cart Project Lesson Plan for Day 2 ((*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
| --- | --- | --- | --- | --- |
| **Elaborate** | • Students who have successfully completed the initial task make additional changes to their design to try to win the bonus points. This involves considering what aspects of the design affect the speed or the ability to travel farther, as well as how they can incorporate these concepts into their design. | • Answer student inquiries with some of the suggested questions above. Allow the students to make new connections between those various topics with information that they already possess. | • F = ma for a constant force; the acceleration is greater for a smaller mass.<br>• A greater acceleration will allow travel of a greater distance. | • Reduced mass means higher efficiency but reducing mass too much can lead to instability of design (trade-offs in design). |

### Balloon Cart Project Lesson Plan for Day 3–Complete Testing as Required and Develop Test Report (58-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **4 mins.**<br><br>**Engage** | — | • Summarize some of the successes and failures of the previous class. Mention the fun (and frustration) that was involved in learning. This is what engineers do for a living. | — | — |
| **11 mins.**<br><br>**Elicit** | • Groups meet to discuss ways to determine all of the items required by the lab report. Specifically, how can the unknown variables be determined based on the information that is measured during the test activity (distance, time, and mass)? Also, how do Newton's three laws apply to the design and motion of the car? | • Ask questions that guide students to the correct answers. | • Relate motion, energy, friction, and momentum. | • Explain how various physics concepts are used to determine and improve car design. |
| **35 mins.**<br><br>**Explain**<br>**Evaluate** | • Individually, develop a lab report containing all of the required information. Concisely explain use of Newton's laws, momentum, and energy in the design of their cart. | • Assist students in making connections between the topics. Ensure that students tie together not only the words associated with the different topics, but also the associated equations. | • Relate motion, energy, friction, and momentum. | — |
| **8 mins.**<br><br>**Extend** | • Use physics and engineering experiences from this lesson and raise questions about new factors such as the role of air resistance when the speed is greater. | • Ask students, "What strategies would you use to build a rocket car to break the world record of more than 750 mph?" | — | — |

## Optional Modification and Extension (Extend)

- Describe what aspects of the design contributed to the cart stopping and how they could have been minimized or reduced even further.
- Describe the physics behind the design changes that students made during the construction process.

## Differentiated Instruction

### Special Needs

- Ensure that students with fine-motor coordination issues still contribute to the designs and building of the carts by providing scaffolds or encouraging them to take on different roles with their partner's help.

### English Language Learners

- Provide students with appropriate pictorial instructions as needed. Pre-teach key vocabulary.

## Supplemental Material

- Handout 6A: Balloon Cart Project

# HANDOUT 6A: BALLOON CART PROJECT

## TASK

- Each team will construct a cart using an index card, a bamboo skewer, a drinking straw, four bottle caps, and a balloon.
- Each cart must be capable of traveling at least three meters within five seconds under its own power.
- Success will depend on good design and proper application of Newton's laws.

## SAFETY PRECAUTIONS

- Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Use caution in working with sharps (scissors, skewers, and so on), which can cut or puncture skin.
- Use caution when poking holes in the bottle caps. They should always push the skewer down into the tabletop or some other hard surface to avoid injuries to the face, eyes, and skin.
- Wash your hands with soap and water upon completing this activity.

## MATERIAL

- The instructor will provide the following materials to each team:
  - Safety glasses or goggles for each student
  - 1 index card
  - 1 balloon
  - 1 bamboo skewer
  - 1 drinking straw
- Each team must provide four bottle tops to be used as wheels.
- Scissors and tape will be available in the classroom. Tape may be used to fasten objects together but not as a structural support material. Use of any other materials will result in disqualification.

## DELIVERABLES

- A rough sketch showing three views (front, top, and side) of your cart design. Neatness will be considered in your grade. (One sketch per team.)
- A free-body diagram showing the **forces** acting on the cart while it is in motion. Vector lengths should indicate the relative magnitude of the forces.
- A completed balloon cart ready for testing.
- An analysis report containing all of the information identified as part of the analysis report in the "Grading" section. Each team member must supply his or her own analysis report.

## RULES AND SPECIFICATIONS

- Rough sketches must be completed and approved before materials will be allocated.
- The start and finish lines will be clearly marked on the floor.
- Testing of carts will be done in the order that teams complete their construction. All teams that have not had an initial attempt to complete the course will be allowed an initial attempt before any team may have an additional attempt.
- No one may touch the cart once it has been released.
- The instructor will time the cart's travel over the three meters. He or she will give you (1) the time your cart took to complete the three-meter course and (2) the overall time that your cart continued after the three meters for determining which team receives the bonus points. **Someone on the team must record both of these times.**
- The total distance traveled by your cart will also be measures for bonus points. **Someone on the team must record this distance.**
- In the event of a tie on any of the bonus points, the car with the highest speed-to-weight ratio will be declared the winner. However, no team may receive both sets of bonus points. If one team wins both sets, the runner up in the "longest distance" category will receive the second set of bonus points.
- The instructor will be the final judge on any disputes. All decisions are final.

## Grading

| Graded Element | Points |
|---|---|
| **Design report (one copy per group)** | 10 |
| **Cart moves under its own power** | 20 |
| **Cart covers three meters in five seconds** | 20 |
| **Analysis report: Students will self-grade according to the values below and include an explanation of how they arrived at each point value.**<br>• Date of report—2 points<br>• Total distance cart traveled—2 points<br>• Time to cover three meters—2 points<br>• Total time of travel—2 points<br>• Cart's average speed over three meters—2 points<br>• Cart's mass and weight—2 points<br>• Cart's average momentum over three meters—2 points<br>• Cart's average kinetic energy over three meters—3 points<br>• Cart's average speed over the entire distance—2 points<br>• Cart's average kinetic energy over the entire distance—2 points<br>• Average force acting to stop cart (hint: impulse) —2 points<br>• Cart's potential energy at beginning—2 points<br>• Total work done—2 points<br>• Cart's average acceleration over three meters—3 points<br>• Paragraph explaining how Newton's third law applies to the cart's motion—10 points<br>• Paragraph explaining how Newton's second law applies to the cart's design and motion—10 points | 50 |
| **Fastest car over three meters (bonus points)** | 5 |
| **Longest distance traveled (bonus points)** | 5 |

# ACTIVITY 6B: NEWTON'S THIRD LAW PAPER TRAMPOLINE

**Contributor: Emma Dalton**

**Time frame:** 1 class period
**Physics focus:** Newton's third law
**Engineering focus:** Analysis

### Opportunities for Science Versus Engineering Concepts

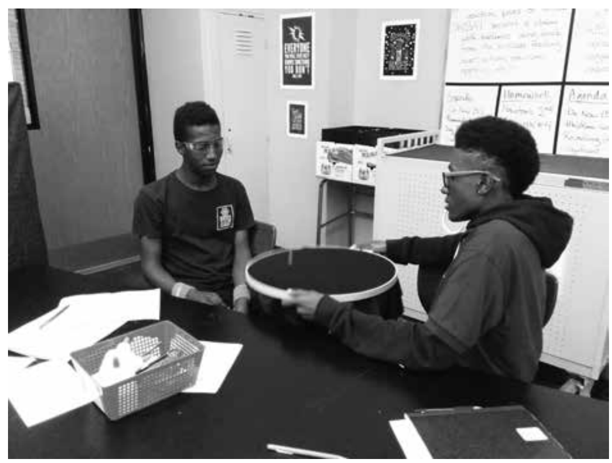
| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Vary the mass<br>• Vary the tension of the fabric | • Using informed data to choose the materials that will get the correct rebound<br>• Determining how to be consistent in dropping—dropping in the same way and from the same height |
| **Analysis** | • Conversation of energy and loss of energy<br>• Kinematics<br>• Hooke's law | • Analyzing the fabric<br>• Analyzing how the material is attached to the support |
| **Models** | • Action–reaction pair<br>• Problems involving elastic collision versus inelastic collision | • Developing a model of a trampoline<br>• Developing a model of a floor |
| **Systems** | • The trampoline and the ball are one system. | • The structural support system that holds the fabric and the apparatus<br>• The mechanism for dropping the ball identically each time |

## PROJECT OVERVIEW

Students often have difficulty understanding the concepts of Newton's third law and identifying the action–reaction pairs in force interactions. This 30-minute activator is a good place to start exploring Newton's third law of motion because it gives all students a common experience to expand on. It also serves as a good method for introducing common terminology (action force, reaction force, force pairs, and so on). Furthermore, it shows some of the ways that evidence and data are used by engineers to help develop solutions to problems.

For this activity, students must construct a "trampoline" for a steel ball bearing that meets the design criteria. Different design criteria can be used to alter the level of difficulty of the challenge. A somewhat simpler design criterion would be to create a trampoline that bounces the ball bearing the highest. A more difficult design criterion would be to create a trampoline that causes a ball bearing to bounce the closest to 50% of its initial height.

Before beginning the challenge, it might be useful to have a class discussion around what method could be used to determine the bounce height. This is a great way to remind students of the importance of keeping the methodology the same among different test groups so that results will be comparable. To save time, the method for determining height could be decided ahead of time and presented to the students as part of the instructions.



**Students conducting initial tests to compare the bounce height of a marble on fabric**

After students have been provided time to explore, test, and evaluate, they should present their findings to the class. These presentations are meant to lead into a discussion of Newton's third law and its importance to real-world applications. The trampoline challenge allows a discussion about the difference between a moving massive object and a force. The force pair between the trampoline base and the ball bearing is the interaction of the trampoline and ball. There is the force of the trampoline on the ball and the force of the ball on the trampoline.

## BIG IDEAS

- **Physics:** Different factors that can affect how much force is needed to change an object's motion (mass of object, time needed to change the motion, the type of surface, and what kind of force it can supply).
- **Engineering:** Engineers conduct tests and analysis to optimize their design.

## Connections to the *Next Generation Science Standards*

### Performance Expectations

- MS-PS2-1: Apply Newton's third law to design a solution to a problem involving the motion of two colliding objects.
- HS-PS2-3: Design, evaluate, and refine a device that minimizes the force on a macroscopic object during a collision.

### Science and Engineering Practices

- Analyzing and interpreting data
- Engaging in argument from evidence
- Obtaining, evaluating, and communicating information

### Disciplinary Core Ideas

- PS2.A: Forces and Motion
- ETS1.A: Defining and Delimiting Engineering Problems
- ETS1.C: Optimizing the Design Solution

### Crosscutting Concept

- Systems and system models

## Assessment: Determining Acceptable Evidence

### Formative

- Ask students to describe the forces acting on the steel ball during the collision and also to identify the Newton's third law pair of forces in the collision between the ball and the trampoline.
- Engage in class discussion on how different materials affect the size of the forces.

### Summative

- Students can identify Newton's third law pairs in other collisions and interactions.

## Materials and Preparation

### Materials (Groups of 2–3)

- 10-inch embroidery hoop
- 1 15" × 15" piece of stretchy fabric (e.g., spandex)

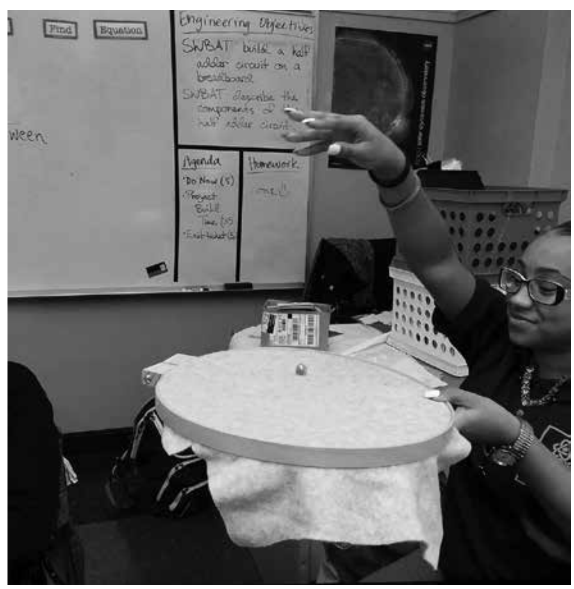
- Plastic wrap, bubble wrap, or other random recycled materials
- Sheets of transparency film
- Assorted paper: tissue paper, copier paper, or lined paper
- 1 steel ball bearing
- 1 meter stick
- 1 Lab stand or other means of suspending a hoop horizontally above table

### Materials per Student

- Safety glasses or goggles

## Safety

- Remind students about general lab safety procedures.
- Participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Immediately pick up any ball bearings and other materials that fall on the floor. These create a slip-and-fall hazard.
- Remind students to make sure there are no fragile materials in work zone while they are operating devices.
- Students should wash their hands with soap and water upon completing this activity.



**A student using marble and woven cotton layer for her material-testing stage of the design process**

### Newton's Third Law Paper Trampoline Lesson Plan for Day 1 (40 minutes)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins. Engage** | — | • Jump into the air.<br>• Show the class a video of a person jumping on a trampoline.<br>• Tell the class, "Today, you will be building a trampoline." | — | — |
| **5 mins.**<br><br>**Elicit** | • Brainstorm forces that are acting on the person in the video.<br>• Attempt to draw the forces that happen when a person jumps on a trampoline. | • Jump in the air again. Ask, "What instructions could you give to someone who has never jumped?"<br>• Ask, "Why can you jump higher on a trampoline?" | • List forces acting in the scenario. | — |
| **15 mins.**<br><br>**Explore** | • Use various materials to create a trampoline that meets the given design criteria. Possible design criteria include the following:<br>• Design a device that provides the highest rebound.<br>• Design a device that provides a rebound height that's closest to 50% of initial drop height. | • Facilitate the exploration of materials. Possibly demo one material before students complete testing and evaluation of remaining materials.<br>• Prompt students to develop a best method for collecting data for bounce height. | • Forces<br>• Reducing forces by increasing time<br>• Force pairs of person on trampoline and trampoline back on person<br>• The force that a person places on a trampoline depends on his or her mass and initial speed when hitting the trampoline. | • Testing various materials<br>• Gathering evidence and evaluating results<br>• Communicating results of testing |

Newton's Third Law Paper Trampoline Lesson Plan for Day 1 (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **10 mins.**<br><br>**Explain Evaluate** | • Share results with the class, justifying which material makes the optimal solution for the given design criterion. | • Ask students to share reasoning and evidence for their results.<br>• Prompt groups to determine the best way to collect data for the bounce height. | — | — |
| **5 mins.**<br><br>**Elaborate** | • As a class, discuss the Newton's third law pair of forces and how the material type affects the forces in the collision. | • Facilitate a discussion. | • Newton's third law<br>• Action–reaction force pairs | • Analysis of evidence |

## Optional Modification and Extension (Extend)

1. For students who finish early or if extra time is available, have the students design a trampoline—using only the tissue paper—that does not break.
2. To save time, have each group only test one or two materials and then report their findings. Class discussion can follow as to which material best meets the design criteria.
3. Have students draw one free-body diagram of the ball and another one of the material at the instant the ball and the material are in contact.

## Differentiated Instruction

### Special Needs

- Demonstrate one trial before beginning.
- Provide a blank data table for recording results.
- Provide the method for collecting the height data for each trial.

### English Language Learners

- Pre-teach key vocabulary.
- Provide both written and oral directions.

# ACTIVITY 6C: BRISTLEBOTS

**Contributor: Derek van Beever**

**Time frame:** 1 class period

**Physics focus:** Kinematics and vector versus scalar

**Engineering focus:** Design, analysis, models, and systems

### Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Type of surface versus displacement | • Design a course to maximize the displacement.<br>• Design a bot to stand up and not fall over. |
| **Analysis** | • Calculate velocity and speed<br>• Determine displacement, distance | • Adjust or trim bristles to affect path.<br>• Change different parts of the path. |
| **Models** | • Kinematics equations for average velocity and average speed<br>• Types of motion (constant *v*, constant *a*,circular, and so on) | • Model of a robot<br>• Model of insect motion |
| **Systems** | • Whole bristlebot is a system | • Electrical system<br>• Mechanical and structural system<br>• Environment or navigation system (obstacle course) |

## PROJECT OVERVIEW

The challenge in this activity is to design and build a course that maximizes displacement of the bristlebot for the 10-second interval. The goal of this project is to study an engineering model to understand a scientific model; something physics teachers will appreciate if they are to "cover the content." Using a simple engineering tool such as the bristlebot opens up most of the scientific models that are part of the traditional physics curriculum (more on that later). Because this little bot is very simple to build, it requires limited time, which is good for teachers. Because it is very fun to watch, the bot is a natural hook for engaging students with both physics and engineering.

A lesson plan for an introductory unit on motion follows. With little modification, a teacher can use this to study distance and displacement, vectors and scalars, and speed and velocity. In this design challenge, the students try to get the bots to have the greatest displacement in an arbitrary time period (10 seconds). Yet there is much more to this challenge. The random chaotic nature of the bot resembles the electron's "random walk" in an electrical circuit. With no modification of this initial, short build, it requires little imagination to see how this bot can be used as a scientific model for current (one bot = one Coulomb), heat (kinetic theory of temperature), and Brownian motion (dip the bot in some paint and see the patterns it traces). In this chapter, we only provide a lesson for displacement as a way to demonstrate how this little toy can help students understand physics and engineering.

We recommend that the instructor build a bristlebot first to gauge the time frame for the initial build. For example, it might take longer than expected to build because the tape will not stick to the motor. This little lesson in materials science reminds us that sometimes just the type of tape used can have a giant effect on the project and that choosing the right materials for testing can allow for greater student engagement and success of the projects. For those teachers fortunate enough to have a budget, there are kits that can be purchased.

## BIG IDEAS

- **Physics:** Be able to describe the motion of an object. Distinguish between vector and scalar quantities such as distance versus displacement and speed versus velocity.
- **Engineering:** Students design and create their own obstacle course. The observe and analyze the movement of the bots to optimize displacement and use the engineering model of the bots to understand the scientific model of kinematics.

## Connections to the *Next Generation Science Standards*

### Performance Expectation

- Not applicable

### Science and Engineering Practices

- Developing and using models
- Using mathematics and computational thinking
- Constructing explanations and designing solutions

### Disciplinary Core Ideas

- PS2.A: Forces and Motion
- PS3.A: Definitions of Energy

### Crosscutting Concept

- Patterns

## Assessment: Determining Acceptable Evidence

### Formative

- Check in with students during the building time.
- Look at the type of data students are collecting or discussing while observing their own bots.

### Summative

- Final obstacle course design and trial results
- Assessment questions relating to constant speed, average speed, and average velocity

## Materials and Preparation

### Materials (Groups of 3)

- Safety glasses or goggles for each student
- Stopwatch
- Toothbrush
- Pager motor
- 1.5–3V watch battery
- Double-sided tape (make sure it sticks to motor and toothbrush)

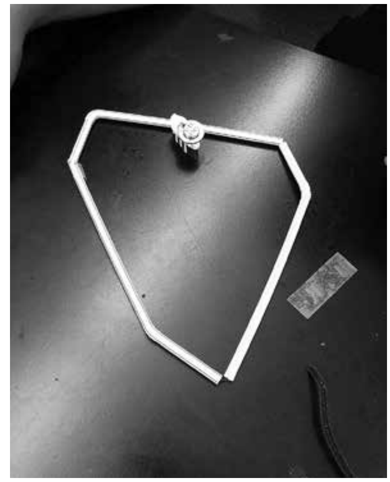
### Class Equipment

- Meter sticks
- Random objects for obstacles

**Test run by students using a straight line course for recording the speed of the bristlebot**

## Safety

- Remind students about general lab safety procedures.
- Participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Remind students to make sure there are no fragile materials in work zone while they are operating devices.
- Students should wash their hands with soap and water upon completing this activity.



**A student-designed course that allows the bristlebot to turn and changes direction of travel**

### Bristlebots Lesson Plan for Day 1 (55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| 3 mins.<br><br>Engage | — | • Start by telling the class, "Bees communicate with each other by doing what's known as a *waggle dance.* The dance communicates the direction of the pollen source, the distance to the source, and the type of pollen to be found there."<br>• Show the class a video "The Waggle Dance" (see the "Supplemental Materials" section, p. 146). | — | — |

Bristlebots Lesson Plan for Day 1 (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins.**<br>**Elicit**<br>**Evaluate** | • Read project description and examine all materials provided.<br>• Answer the question, "How can you measure displacement and distance?" | • Read through project description with students and answer questions and clarify instructions. | • Distance<br>• Displacement<br>• Speed<br>• Velocity | — |
| **10 mins.**<br>**Explore**<br>**Engage** | • Build and play with the toothbrush, battery, and motor to explore the motion of the bristlebot.<br>• Start to explore what types of structures and obstacles might affect the motion of the bot and how they can use that cause-and-effect relationship to their advantage when designing an obstacle course to maximize displacement. | • Provide guidance to students needing help.<br>• Move around the classroom, encouraging students to improve their obstacle course design. | — | • Design<br>• Test<br>• Evaluate |
| **10 mins.**<br>**Explain** | • Students return to their seats and share with the class their observations about bristlebot motion. | • Facilitate group discussion about bristlebot motion. | — | • Evaluating<br>• Results |
| **10 mins.**<br>**Elaborate** | • Groups design and build a course that maximizes displacement of the bristlebot for the 10-second interval. | • Discuss the differences between distance and displacement, average speed, and average velocity within the context of this challenge. | • Distance<br>• Displacement<br>• Speed<br>• Velocity<br>• Vectors | • Design<br>• Testing<br>• Analysis<br>• Iteration<br>• Optimization |

Bristlebots Lesson Plan for Day 1 (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **15 mins.**<br><br>**Evaluate**<br>**Elaborate**<br>**Explain** | • Share their design with the class, including their theory of action—how did they design their course?<br>• Have their courses evaluated to determine which group wins the challenge.<br>• Answer questions in their engineering notebooks. | • Facilitate presentation of obstacle courses. | — | • Communicating results |
| **Extend** | **Homework:** Students answer the question, "What experiences in your life are like the motion of the bot?" Students complete the summarizing questions in their engineering notebooks. | | | |

## Optional Modification and Extension (Extend)

- After students have completed this activity, provide thems with three different courses and ask them to decide which course will maximize displacement.
- For added difficulty, rewrite the challenge so the bots will be placed on an incline. This can allow richer discussion about velocity, angle of incline, two-dimensional motion, and so on.
- Link this project to the electricity and magnetism unit of the course by changing the criteria so students investigate motors and circuit diagrams rather than the motion of the robot.

## Differentiated Instruction

### Special Needs

- Supply students with outlines, graphic organizers, or engineering notebook templates for the project.
- Choose groups so that students' strengths are highlighted in the group dynamic and check in with students at key points in the activity.

### English Language Learners

- Provide students with opportunities to become familiar with the concept of a robot if it is less obvious to them culturally.
- Provide students with writing and speaking prompts when appropriate.

## Supplemental Materials

- Handout 6C: Bristlebots
- Article: “Sleep-Deprived Bees Do Weirder Waggle Dances,” *www.wired.com/2014/11/berrett-klein-honeybees*
- YouTube video: “The Waggle Dance,” *www.youtube.com/watch?v=-7ijI-g4jHg*
- Article: “Bristlebot: A Tiny Directional Vibrobot,” *www.evilmadscientist.com/2007/bristlebot-a-tiny-directional-vibrobot*

# HANDOUT 6C: BRISTLEBOTS

## CHALLENGE

- Build your bristlebots so that they have the largest displacement in a 10-second time period

## SAFETY PRECAUTIONS

- Follow all general lab safety procedures.
- Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Make sure there are no fragile materials in work zone while operating devices.
- Wash your hands with soap and water upon completing this activity.

## MATERIALS PER GROUP

- Stopwatch
- Toothbrush
- Pager motor
- 1.5–3V watch battery
- Double-sided tape (make sure it sticks to motor and toothbrush)
- Meter sticks
- Random objects for obstacles

## PHYSICS LEARNING OBJECTIVES

- Distance and displacement
- Vector and scalar
- Speed and velocity

## ENGINEERING OBJECTIVES

- Design—students create their own obstacle course.
- Analysis—students have to observe how the bots move so that they can optimize displacement.
- Models—An engineering model is used to understand a scientific model.

## BUILD AND OBSERVE

- 10–15 minutes

## DATA

- After playing and observing the bots for several minutes, come up with a way to have your bot have the greatest displacement in a 10-second time period. You may not touch the bot once it is in motion, unless it is going to fall off the table.
- For each new timed trial, record the displacement and observations in your engineering journal.

## WRAP-UP

- Use this activity as a starting point to talk about distance versus displacement, vectors versus scalars, and average speed versus average velocity.

## ASSESSMENT QUESTIONS

1. Did your bristlebot have a constant speed? Explain and use examples from your observations and contest.

2. Imagine that the bristlebot has been dipped in paint and is allowed to "paint" on a piece of paper. How would you calculate the bristlebot's average speed from painting on the paper for 10 seconds?

3. Using the same scenario as described above, how could you calculate the average velocity of the bristlebot after 10 seconds?

# ACTIVITY 6D: MOUSETRAP CAR CHALLENGE

Contributors: Julie Mills and Jon Kelley

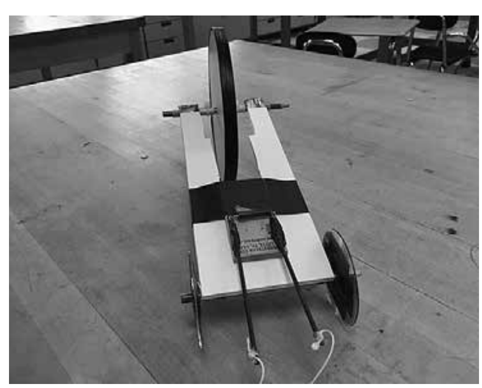
**Time frame**: 4 class periods, plus additional time outside of class
**Physics focus:** Motion (speed, average speed, distance, time) and energy (elastic, kinetic)
**Engineering focus:** Design, models, and systems

### Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Experimental design—what data to collect | • Design specifications for mousetrap cars |
| **Analysis** | • Velocity<br>• Energy lost to friction<br>• Kinematics motion<br>• Energy | • Analysis of materials<br>• Computational model as a tool to perform analysis |
| **Models** | • Vector diagrams<br>• Efficiency of the energy transfer | • Mathematical model<br>• Use of the mousetrap car as a model of the different types of toys that can be propelled with elastic energy |
| **Systems** | • The entire car is one system | • Propulsion system<br>• Vehicle and friction |

## PROJECT OVERVIEW

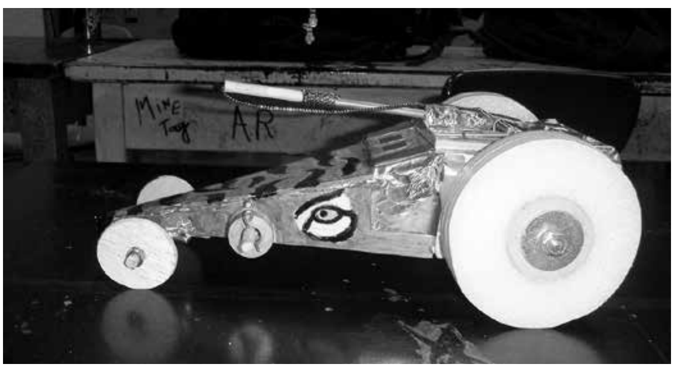
The mousetrap car is a classic engineering–physics project that can be taught as part of a motion unit (as described here) or as part of an energy unit, as it covers both topics well. This project closely mimics more familiar mousetrap car competition guidelines. Within the unit on motion, this project is introduced toward the beginning. After introducing the project, several days are spent in



Typical mousetrap car

class creating a design and beginning the build process. Students complete the remaining build process outside of the classroom while the motion unit is being completed. Competition day is set for the end of the motion unit.

The goal of the mousetrap car project is to build a device that runs on the elastic energy stored in a single mousetrap. In addition to this goal, there are constraints set on the car's dimensions and performance. The mousetrap car will be judged not only on its speed but also its ability to run through an entire 6-meter-long course. The cars are built partially in class (one day of introduction and design and two days building and testing) and partially outside of class (completing the build and testing). For this project, students work in small groups (1–3 students) of their choosing. The completed mousetrap car is due on the day of competition. The project write-up typically is due several days after the competition day.



**Another example of a mousetrap car**

The teacher provides the mousetrap for each group and some supplies for building a chassis, including balsa wood, cardboard, and foam board, but should encourage students to provide their own materials as well (to be teacher-approved first). Students are encouraged to provide their own materials for wheels and axles, and most groups will find that old compact discs, pencils, and wheels and axles from an old toy car work quite well. In addition to these basic materials, the teacher should provide basic tools (scissors, tape, glue, and box cutters) that students will need while in the classroom. Students are not required to return the mousetrap at the end of the project, but teachers might want to salvage the ones with materials that could be reused in future years.

To introduce the project, the teacher can start by showing a variety of videos (search for some on YouTube) that demonstrate a mousetrap car in motion. Students analyze the parts of the car from the videos to determine what they will need to get the car to work. A class discussion helps focus students around some of the more important aspects of designing a mousetrap car, such as determining the number of wheels to be used, and figuring out how to attach the wheels to the chassis. The class discussion also includes brainstorming how to get the motion of the mousetrap (spring-loaded arm) to translate into turning a wheel/axle system.

After introducing the project and discussing the constraints, the teacher gives students some time in class to research design solutions, brainstorm as a group, and sketch their initial design. A guiding worksheet is used to help students through the process and to require them to provide reasoning for their design choices. Once groups have their initial design approved, they can begin the build process. Two days are provided in the class for students to build and test their design. It is very rare for a group to have completed their build within those two days, so most groups must continue and complete the build project outside of class time. Throughout the brainstorming, design, and build process, students are asked to make entries in their engineering notebook, and these are checked daily during the in-class portion of the project. The notebooks are checked one additional time at the end of the project.

Before the competition day, the track should be marked out in an appropriate location in the classroom, such as by using painter's tape to mark the floor. The track layout is found in the student handout (p. 160) along with the guidelines for determining the competition winners. On the day of competition, each car is allowed to complete two or three trials, with students' score being the best run from their trial results. Adjustments to the cars are allowed between trials as long it the car still meets the constraints. After the competition day, students are allowed several more days before their group engineering report must be submitted. One report is submitted per group.

## BIG IDEAS

- **Physics:** Average speed, calculated from distance and time; energy and energy transfers.
- **Engineering:** Design is an iterative process that can be used to produce a product. Systems thinking allows for ways to break down design complexity and troubleshoot certain components separately. Communication is essential for the design process.

## Connections to the *Next Generation Science Standards*

### Performance Expectation

- HS-PS3-3: Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.

### Science and Engineering Practices

- Developing and using models
- Planning and carrying out investigations
- Constructing explanations (science) and designing solutions (engineering)
- Obtaining, evaluating, and communicating information

### Disciplinary Core Ideas

- PS3.A: Definitions of Energy
- PS3.D: Energy in Chemical Processes and Everyday Life
- ETS1.A: Defining and Delimiting Engineering Problems

### Crosscutting Concepts

- Systems and systems models
- Energy and matter
- Structure and function

## Assessment: Determining Acceptable Evidence

### Formative

- Mini-conferences with groups
- Class discussion and chart discussion of essential aspects of a mousetrap car, constraints, and final test requirements
- "Do Now" activity, class notes and discussions, engineering notebook entries at end of each day

### Summative

- Individual: engineering notebook
- Group: successful mousetrap car, project report

## Materials and Preparation

### Materials (Groups of 2–3)

- 1 mousetrap
- Cardboard (optional for building chassis)
- Balsa wood (optional for building chassis)
- Foam board (optional for building chassis)

### Materials per Student

- Safety glasses or goggles
- Engineering notebooks or worksheets

### Class Equipment

- Scissors
- Box cutters
- Tape
- Glue
- Hot-glue guns and glue sticks

## Safety

- Remind students about general lab safety procedures.
- Participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Remind students to use caution in working with sharps (scissors, box cutter, and so on), which can cut or puncture skin.
- Remind students to use caution in working with hot objects (glue gun, hot glue). These can burn skin!
- Provide a short lesson on box cutter safety and hot glue gun safety before beginning the building process. Students should not use a box cutter or glue gun until they are safety trained. Remind students to follow all safety procedures.
- Remind students to use caution when working with a mousetrap. Their spring-loaded release can injure fingers.
- Students should wash their hands with soap and water upon completing this activity.

## Mousetrap Car Challenge Lesson Plan for Day 1 (55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins.**<br>**Engage** | • Watch videos showing various mousetrap cars in action. During the videos, student should make a mental list of the parts of a mousetrap car. | • Set up three mousetraps in the front of the room and snap the first one. Then, ask students how much time they think the snap requires and go on to snap the second. Finally, inform the students that they will be using a mousetrap to power a car, and after that, snap the third mousetrap. | — | — |
| **5 mins.**<br>**Elicit**<br>**Explore** | • In small groups, observe a mousetrap and create a chart listing the mousetrap's parts and what they believe the purpose is of each and whether they think it is essential to the car's functioning. | • Write guiding introductory questions on the board, such as "What are the parts of a mousetrap car?" and "How do the parts of a mousetrap car function together to get the car to move?"<br>• Elicit prior knowledge through questioning and small group discussion. | — | • Parts of a system and what role the function of each part plays in the function of the whole system |
| **10 mins.**<br>**Explain**<br>**Evaluate** | • In groups, present their findings to the class and create a master list on the board. The discussion should be around the parts and functions of a mousetrap car and how changes to those parts might affect a car's performance. Examples might include use of different wheels, use of an extension arm, and placement of mousetrap. | • Informally evaluate each student's contribution to class discussion through the answers they give to the guiding questions, ensuring that all students are included in the discussion.<br>• Create the class chart from the individual group answers. | • Motion topics: speed, distance, time, friction<br>• Energy topics: elastic energy, kinetic energy | • Identification of the function and relationship between different subsystems (e.g., propulsion versus transport) |

Mousetrap Car Challenge Lesson Plan for Day 1 (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **10 mins.**<br>**Explain** | • Read through the Mousetrap Car Challenge handout while the teacher explains the challenge goals and constraints. | • Explain the goals, constraints, and competition criteria for the Mousetrap Car Challenge, making sure students understand the time line and requirements for each stage of the project. | • Motion topics: speed, distance, time, friction<br>• Energy topics: elastic energy, kinetic energy | • Goals, identification of design constraints |
| **25 mins.**<br>**Explore** | • In groups, brainstorm materials needed and ideas for designing their mousetrap car. Each group completes the Brainstorming and Initial Design Worksheet (p. 162) as part of the brainstorming process.<br>• Make entries in their engineering notebooks for goals, constraints, and initial design ideas. | • Circulate among groups to troubleshoot and answer questions. When groups have completed their design worksheet, approve the design.<br>• Assess students' engineering notebooks (using a rubric) before the start of the next meeting day. | — | • Research<br>• Design<br>• Provide feedback<br>• Communicate<br>• Explain ideas |
| **Extend** | **Homework:** Gather materials from home to bring in for building the mousetrap car. | | | |

### Mousetrap Car Challenge Lesson Plan for Days 2 and 3 (55-minute blocks)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins.**<br>**Engage** | — | • Set a mousetrap and release it.<br>• Review some of the successes of the previous class with students. | — | — |
| **40 mins.**<br>**Explore** | • Engage in the building process. They begin by evaluating the materials they brought in from home and altering their design if needed. They then start the build process. Tools and some materials are provided for groups to use.<br>• Throughout the build process, students record their steps in the engineering notebook. | • Circulate through the classroom to assist with answering questions, providing guidance, and troubleshooting as needed.<br>• Toward end of class, assess engineering notebook entries using the rubric.<br>• Have engineering notebooks ready for students to use the following day in class or to complete their build process at home. | • Motion topics<br>• Friction<br>• Force and torque<br>• Rotational motion | • Design<br>• Build.<br>• Receive and process feedback (through testing and analysis or teacher critique).<br>• Alter design as a result of feedback. |
| **10 mins.**<br>**Evaluate** | • At the end of the second build day, groups should evaluate where they are in the build process and plan out what they still need to complete. They should leave with a general plan of the next steps of the project. | • Circulate through the groups and evaluate each group's progress, making sure students are aware of the steps needed to complete their mousetrap car. | — | — |
| **Elaborate** | **Homework:** Complete the remaining build of the mousetrap car to ready it for competition day. Complete the remaining entries in the engineering notebook. | | | |

**Mousetrap Car Challenge Lesson Plan for Day 4–Competition Day (55-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **10 mins.**<br><br>**Engage** | • Prepare their cars for competition (making last-minute adjustments) and create data tables in their engineering notebooks. | • Track should be ready to go when students enter the room.<br>• Write a blank data table on board that includes columns for group, trial, distance traveled, time, average speed, mass, tier and multiplier, and final score. | • Average speed<br>• Distance<br>• Time | • Testing<br>• Analysis<br>• Provide feedback<br>• Communicate |
| **5 mins.**<br><br>**Explain** | • Before competition trials begin, present their car, explaining their design and reasoning to classmates. | • Provide prompting questions during presentations, as needed. | — | • Communicate<br>• Share ideas<br>• Explain |
| **30 mins.**<br><br>**Explore Evaluate** | • Run their car through two trials. Make adjustments between trials.<br>• When not competing, make calculations to determine final scores. | • Run timing trials, inputting distance and time data on data table. | — | • Test<br>• Evaluate |
| **10 mins.**<br><br>**Evaluate** | • After the competition is finished and the winner has been determined, write a summary statement in their engineering notebooks about how their group's car performed. | • Present summary statement prompt: "How did my car perform? What worked well and what didn't work well and why? What changes to improve the car would I make if given the opportunity and how and why would I make those changes?" | — | • Provide feedback<br>• Communicate |
| **Elaborate** | **Homework:** Students write up the project report and complete the final engineering notebook entry (with data from the results of the competition). | | | |

## Optional Modification and Extension (Extend)

- Have students alter their mousetrap car to run on a different form of energy (such as solar or electric), given various constraints.
- Modify competition criteria to have separate competitions for length of run and speed of run, allowing for adjustments and changes between the two competitions.
- Have students calculate the kinetic energy achieved by the car and explain where that energy came from.
- Have students compare the mousetrap car with a typical automobile.

## Differentiated Instruction

### Special Needs

- Provide students with a checklist of daily goals.
- Use preprinted engineering notebook templates for students who need the structure for documentation.
- For students who might struggle with a handwritten engineering notebook, allow for different types of documentation, such as using a computer to type and phones or tablets to take photographs and then add captions.

### English Language Learners

- Have visuals around the classroom for the engineering design process and terms such as speed, average speed, distance, time, elastic energy, and kinetic energy.
- Provide sentence frames and use technologies for students to record in their engineering notebook.

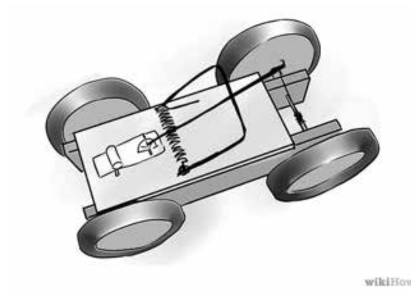
## Supplemental Materials

- Handout 6D-1: Mousetrap Car Challenge
- Handout 6D-2: Mousetrap Car Challenge—Brainstorming and Initial Design Worksheet
- Handout 6D-3: Mousetrap Car Challenge—Final Report Format
- Handout 6D-4: Mousetrap Car Challenge Rubric

# HANDOUT 6D-1: MOUSETRAP CAR CHALLENGE

## DESIGN CHALLENGE

Design and build a car powered by a mousetrap that will travel the farthest and fastest down a narrow racetrack.




## SAFETY PRECAUTIONS

- Follow all general lab safety procedures.
- Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Use caution in working with sharps (scissors, box cutter, and so on), which can cut or puncture skin.
- Use caution when working with hot objects (glue gun, hot glue). These can burn skin!
- Do not use a box cutter or glue gun until you are safety trained by the teacher. Follow all safety procedures.
- Use caution when working with mousetrap. Their spring-loaded release can injure fingers.
- Wash your hands with soap and water upon completing this activity.

## MATERIALS PROVIDED

- Mousetrap, balsa wood sheets, foam boards, cardboard, nonlatex rubber bands, plastic wheels, CDs, metal axles (variety), glue, duct tape, string, plastic straws, safety glasses or goggles
- Use of other materials is acceptable but they must be approved by the teacher.

## DESIGN CONSTRAINTS FOR THE MOUSETRAP CAR

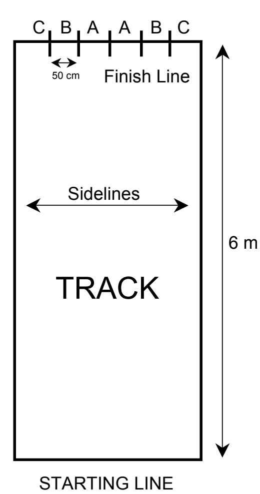
- It must run only on the power of a single mousetrap.
- It must be able to start on its own, without a push.
- It must stay within the following dimensions: 45 cm maximum length and 25 cm maximum height from floor to highest point.
- It must have at least three wheels.

## COMPETITION GUIDELINES AND SCORING

- The car should reach the finish line as quickly and as close to the target as possible.
- The car's trial ends when the first of the following events occurs:
  - An entire car crosses the finish line
  - Any wheel crosses the sideline
  - 60 seconds elapse
- There are two tiers for scoring:
  - Tier 1—Cars that cross the finish line before the trial ends
  - Tier 2—Cars that don't cross the finish line before the trial ends
- Note: Any car in tier 1 automatically beats a car in tier 2, regardless of which car was faster or more accurate.

### Tier 1 Scoring

- If a car passes the finish line in zone C, the score = average speed × 1.0
- If a car passes the finish line in zone B, the score = average speed × 1.1
- If a car passes the finish line in zone A, the score = average speed × 1.2
- A car is scored as finishing in the highest value zone if one wheel crosses the finish line in that zone.




### Tier 2 Scoring

- The score = forward distance traveled at point of leaving track.
- The dimensions of the track, including the A, B, and C zones are shown in the diagram to the right. The track will be taped off on level, smooth ground. Cars will begin behind the "start" line.

### Hints and Pointers

- Four wheels make a vehicle sturdy but add more mass to the vehicle, making it need more force to move it. A lot of mass is *not* good.
- Placing the mousetrap farther from the power axle will make it travel farther.
- The pull cord is a key component. As it unwinds, it pulls the car forward by turning the axle. You need a pull cord slightly shorter than your vehicle's length.

- Without an axle hook, the pull cord will slip off the axle and the car will not move.
- Cars will not move straight if the wheels are not aligned properly.
- A good loop knot at the end of the pull cord will not "shrink" as it pulls on the axle hook. A knot that shrinks will cause the rope to get stuck on the axle hook—which will act as a brake for the car.

## PROCESS

1. Research the problem using the internet (for homework and as needed).
2. Brainstorm (one-half of a period) and then have a notebook check.
3. Complete initial design sketches on the worksheet and get sketches approved by the teacher) (one-half of a period).
4. Construct the car, testing as needed (two days in class and remaining time outside of classroom). Have a notebook check at the end of each day (returned the next day).
5. Competition day (one day). Have a notebook check at the end of the day.
6. Type up and turn in report on Google Classroom.

## ENGINEERING NOTEBOOK ENTRIES

- Notebook check 1—End of brainstorming: Goals, constraints, partner's name, brainstorming with sketches and ideas
- Notebook check 2—End of day 1 construction: Goal for the day, accomplishments for the day, sketches, problems and solutions, plans for the next day
- Notebook check 3—End of day 2 construction: Goal for the day, accomplishments for the day, sketches, problems and solutions, plans for the next build time
- Notebook check 4—Competition day: Entries for any other build time, data and result from competition

## POSSIBLE TOPICS TO RESEARCH

- How to build a mousetrap car
- How to maximize distance with a mousetrap car
- How to maximize speed with a mousetrap car

Name: ____________________________________________________________

# HANDOUT 6D-2: MOUSETRAP CAR CHALLENGE— BRAINSTORMING AND INITIAL DESIGN WORKSHEET

## INTRODUCTORY QUESTIONS

1. In your own words, state what you have been asked to do:

I have been asked to __________________________________________________ that will ____________ ____________________________________________________.

2. What do you think will be the most challenging part and how might you overcome the difficulties?

## DESIGN DESCRIPTIONS

After brainstorming possible design solutions in your engineering notebook, describe which prototype you've chosen to build and explain why you chose that one. *If you can't tell me why that prototype is insanely great, you shouldn't be building it.*

## DESIGN SKETCHES

Create clear, specific, and labeled diagrams of your design from three different views (front, top, and side).

| Front View | Materials Needed (Available in Class)<br><br>Materials Needed (Bring From Home) |
| --- | --- |
| Side View | Top View |

Get your designs approved by your teacher.

**Teacher's Signature:**________________________________

Names of Group Members:__________________________ Date: ______________

# HANDOUT 6D-3: MOUSETRAP CAR CHALLENGE–FINAL REPORT FORMAT

The final report for this project must follow the format outlined below and must be typed.

### Title of Project

### Project Goals

### Project Constraints

### Research Summary

Three to four sentences summarizing what you discovered when you researched mousetrap cars

### Design Sketch

Detailed, labeled sketch of the final design as seen from the side

### Materials and Tools

### Build Process and Reasoning

Steps that your group followed during the build process (the order in which you built your car) and the reasoning behind why you made the choices/decisions that you did.

### Changes Made During the Build

Describe at least three changes you made from your initial design to your final design and tell why you made those changes

### Data

Data table for tier 1 and tier 2 cars

### Observations and Conclusions

- Include a summary statement of how your car performed on competition day. Include any issues your car had and changes you made in between trials to try to fix those issues.
- Reflect on the entire process and include a discussion of issues and challenges that arose during the building and testing of the car. Describe how you were able to overcome those challenges.
- Reflect on what changes you would make to your car if you were to repeat this project, and explain why you would want to make those changes.

Name: ____________________________________________

# HANDOUT 6D-4: MOUSETRAP CAR CHALLENGE RUBRIC

## Engineering Notebook Checks

**Check 1: End of Brainstorming (15 points)**

| | |
|---|---|
| Notebook in correct format (date, group members, signature) | |
| Goals and constraints listed | |
| Multiple brainstorming ideas with sketches and explanations | |

**Check 2: End of Day 1 Construction (30 points)**

| | |
|---|---|
| Notebook in correct format (date, group members, signature) | |
| Goal for the day written at beginning | |
| Accomplishments for the day listed and described | |
| Sketches of car in current condition | |
| Problems encountered and how they were overcome | |
| Plans for next time | |

**Check 3: End of Day 2 Construction (30 points)**

| | |
|---|---|
| Notebook in Correct Format (date, group members, signature) | |
| Goal for the day written at beginning | |
| Accomplishments for the day listed and described | |
| Sketches of car in current condition | |
| Problems encountered and how they were overcome | |
| Plans for next time | |

**Check 4: Competition Day (20 points)**

| | |
|---|---|
| Remaining entries follow the format from previous two days | |
| Remaining entries show how car was completed | |
| Data from competition day is given in table format—both Tier 1 and Tier 2 cars | |
| Statement about how your car performed—what worked well, what didn't work well | |

**Completed mousetrap car that meets the constraints** _______ / 20

- Correct use of mousetrap
- Car starts on its own
- Mousetrap car fits within size constraints

### Written Project Report

| Part | Points Earned | Possible Points |
|---|---|---|
| Heading | | 5 |
| Project goals | | 5 |
| Project constraints | | 5 |
| Research summary | | 5 |
| Design sketch detailed and labeled | | 7 |
| Materials and Tools | | 5 |
| Build process with reasoning | | 10 |
| Changes to original design | | 8 |
| Data (in table format) | | 10 |
| Observations and conclusions | | 15 |

**TOTAL ______ / 75**

# ACTIVITY 6E: AMUSEMENT PARK ENGINEER—BUMPER CARS

**Contributors: Danielle Raad, Nivedi Chandrasekaran, and Marna Eckels**

**Time frame:** 3 class periods (preferably one long block)
**Physics focus:** Mass, velocity, momentum, conservation of momentum, and acceleration
**Engineering focus:** Design

### Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Experimental design: what data to collect | • Design specifications of the bumper car |
| **Analysis** | • Energy lost to the system<br>• Velocity and momentum | • Analysis of materials<br>• Computational model as a tool to perform analysis |
| **Models** | • Vector diagrams<br>• Efficiency of the energy transfer<br>• Momentum conservation | • Simulation (computational model) |
| **Systems** | • Change of the momentum ($p$) of each car individually<br>• Total $p = p'$ | • Restraint system<br>• Collision cushioning system<br>• Wheels<br>• Electrical systems of the cars |

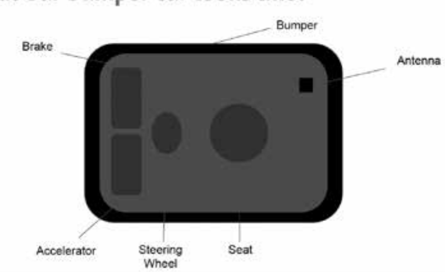
## PROJECT OVERVIEW

Students act as an amusement park engineer and create a proposal for a new bumper car ride that is safe, fair, and fun for all. The proposal will be presented to the "Eight Flags" amusement park committee. The contributing teachers used this activity at the end of a motion unit that had covered kinematics, forces, and momentum. Ending the unit with momentum, the bumper car challenge works well as a culminating project and could be used as a unit review before a test.

The lesson starts with students brainstorming and sharing what it means for a bumper car ride to be safe, fair, and fun for people of all ages and what potential engineering design constraints would be. Possible constraints include budgetary and space constraints. After determining constraints and clarifying what is meant by "safe, fair, and fun," groups work to put together a proposal, starting with modeling the bumper car ride with the PhET collisions simulation.

The guidelines are intentionally left flexible for this problem and support a project-based learning environment. Students are given the freedom to determine which of the criteria and requirements are more important and which ones will take a back seat. While the groups are designing their bumper car ride, the teacher rotates among them, helping them resolve road blocks without telling them how to design their ride, and serving as a sounding board for their new ideas.

**What our bumper car looks like:**




**Number of Collisions and Final Car Velocity Based on Initial Car Velocity**

| Initial Car Velocity (m/s) | # of Collisions | Final Car Velocity (m/s) |
|---|---|---|
| 1 | 18 | .528 |
| 1 | 14 | 1.311 |
| 1 | 19 | 1.284 |
| 1.5 | 23 | .441 |
| 1.5 | 20 | .325 |
| 1.5 | 22 | .307 |
| 2 | 36 | .388 |
| 2 | 30 | 1.515 |
| 2 | 30 | 1.041 |

| Data Collected: | Car 1 | Car 2 | Car 3 | Car 4 |
|---|---|---|---|---|
| Mass | 0.5 | 1.0 | 1.5 | 2.0 |
| | 1.0 | 1.0 | 1.0 | 1.0 |
| | 0.5 | 1.0 | 1.5 | 2.0 |
| Velocity | 1.00 | 1.00 | 1.00 | 1.00 |
| | 0.50 | 1.00 | 1.50 | 2.00 |
| | 0.50 | 1.00 | 1.50 | 2.00 |
| Momentum | 0.50 | 1.00 | 1.50 | 2.00 |
| | 0.50 | 1.00 | 1.50 | 2.00 |
| | 0.25 | 1.00 | 2.25 | 4.00 |
| Description of Path | Speeds up by a lot and then averages out | Stays at a fairly average speed, sometimes a bit faster | Stays at a fairly average speed, sometimes a bit slower | Slows down and stays slow |
| | All stay at an average speed, and take turns becoming the fastest and slowest. If there is a long period of time when one is not bum stays either very slow or very fast which is not a safe change in acceleration. | | | |
| | All cars stay around the same fast velocity which make the car's fair and fun. | | | |

**Constraints**

- One constraints we have for our bumper cars is our materials
  - Strong, safe, and comfortable materials are important for an enjoyable ride
  - We aren't capable of having all of the finest materials due to cost and availability
- Another constraint we have is our budget
  - some of the best materials are also the most expensive
  - bumper carts is also cheap to create
  - They won't be able to be mass produced
    - It will be a time consuming production
  - The fun rides you go on usually have high speeds, the more speed usually means more fun but if you push it to the limits it might not be safe

**What makes a ride safe?**

A ride is safe if no one is in danger of being hurt and the ride is well built. A safe ride should have simple rules to keep riders safe.

**SAFETY- our #1 concern**

We are committed to having a ride where our customers are not exposed to injury and harm. We will strive for a safe and friendly environment dedicated to fun.

Team candyland will achieve this through:

1.) Limiting speed of cars
2.) Limiting mass of cars
3.) Seat Belts and other restraints

**Sample slides from student presentations**

On presentation day, groups are given 5–10 minutes to present their bumper car ride to the Eight Flags committee to try to justify why their ride is the best solution. At the end of the presentations, either the committee can vote, or all students can vote to determine the winning group.

## BIG IDEAS

- **Physics:** Momentum, momentum conservation, motion, speed, acceleration, and forces
- **Engineering:** Engineers design solutions to problems by drawing on physics concepts. Engineers must meet given goals while working within a set of constraints. Engineering allows for creativity.

## Connections to the *Next Generation Science Standards*

### Performance Expectations

- HS-PS2-2: Use mathematical representations to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system.
- HS-PS2-3: Apply scientific and engineering ideas to design, evaluate, and refine a device that minimizes the force on a macroscopic object during a collision.

### Science and Engineering Practices

- Asking questions and defining problems
- Using mathematics and computational thinking
- Constructing explanations and designing solutions
- Engaging in argument from evidence
- Obtaining, evaluating, and communicating information

### Disciplinary Core Ideas

- PS2.A: Forces and Motion
- ETS1.A: Defining and Delimiting Engineering Problems
- ETS1.C: Optimizing the Design Solution

### Crosscutting Concept

- Systems and System Models

## Assessment: Determining Acceptable Evidence

### Formative

- Individual and group assessments through discussions as students work together to create their bumper car design

### Summative

- Rubric-based grading of student presentations of their bumper car proposals

## Materials and Preparation

### Materials (Groups of 2–4)

- Projector
- PhET Collisions Lab online access
- Computers that can run PhET simulations (at least one per group)

**Amusement Park Engineer–Bumper Cars Lesson Plan for Day 1 (50-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins.**<br>**Engage** | • Watch a video of people on a bumper car ride. | • Tell the class, "Car accidents are *not* fun. Bumper cars are amusement rides."<br>• Show a video from YouTube of people on riding bumper cars. Talk with students casually about their experiences on amusement park rides. | — | • Researching existing experience and background knowledge |
| **5 mins.**<br>**Engage** | • Learn about the objectives of the assignment and are given the task or assigned the mission.<br>• Read through the project handout. | • Project or write out on the board the objectives of the activity, and pass out the handout. | — | — |
| **5 mins.**<br>**Elicit** | • Brainstorm and jot down ideas for what it means for a bumper car ride to be safe, fair, and fun. Then, after thinking for three minutes, share ideas. Consider possible constraints on an engineer designing such a proposal. | • Give students some dedicated quiet time to write on their sheet while a colorful slide is projected on the screen. Elicit prior knowledge, and help students make connections to their own experiences on amusement park rides. | • Momentum, force<br>• Considering the physics behind a ride that is safe, fair, and fun | • Considering the engineering behind designing a ride that is safe, fair, and fun |
| **10 mins.**<br>**Elicit** | • In groups, determine the group name and brainstorm the criteria for success for this project.<br>• In groups, share their criteria for success. As a class, decide on the project criteria as a whole. | • Describe the requirements of the project in much more detail, along with the time line.<br>• Facilitate a discussion on criteria for success and explain to students how the grading will work (rubric). | — | — |

Amusement Park Engineer—Bumper Cars Lesson Plan for Day 1 (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **20 mins.**<br><br>**Explore** | • Use the PhET Collisions Lab simulator, which will be used to model the bumper car ride. As a group, determine 10–15 pieces of data to collect. | • Provide students with the common experience of using the collisions lab simulator. Provide support in guiding students how to use the simulator, leaving the decision of what data to collect up to the individual groups. | • Mass<br>• Velocity<br>• Momentum<br>• Data collection<br>• Force<br>Time | — |

### Amusement Park Engineer–Bumper Cars Lesson Plan for Day 2 (80-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins.**<br><br>**Engage** | • Share a few conclusions from the previous lesson. | • Open by telling students, “Bumper cars are fun. Yesterday you learned from the simulation some physics requirements of bumper cars. Today you will design and share your bumper cars.” | — | — |
| **50–75 mins.**<br><br>**Elaborate**<br>**Explain** | • Immediately begin working with their groups on computers. They have the entire period to create their proposal. | • The classroom reflects a true project-based learning environment. The second day is less structured. Check in with each group often and encourage and challenge groups to upgrade their work. | • Students now must take what they learned from the collisions simulator and elaborate on their ideas, transferring what they learned yesterday and their preexisting physics knowledge and applying it to designing their bumper car proposal. | • Students realize that they need to focus on only one or two of the categories that they will be graded on (safe, fair, fun, modeling, or constraints). Everything needs to be included, but only two may be emphasized in the allotted time. |
| **At home**<br><br>**Elaborate**<br>**Evaluate** | • Depending on how far they get during class time, possibly finish up parts of their presentation at home before the presentation day. | • Check-in with groups and see where they are with their proposal and presentation. Remind students that they may need to divide the remaining work among themselves to be completed at home. | — | — |

**Amusement Park Engineer–Bumper Cars Lesson Plan for Day 3 (55-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **50 mins.**<br><br>**Explain Evaluate** | • Each student group has 5 minutes to present its proposal. Students are competing for the contract, and must convince their audience that their ride is safe, fair, fun, and within the constraints. | • Make sure students have shared all the presentation and are queued up and ready to go. Facilitate questions after each presentation. Ask the class to vote for the best ride at the end. | • Apply physics knowledge to explain their design. | • Communicate ideas to the audience.<br>• Pay special attention to constraints of budget, time, and space. |
| **Evaluate** | • Students will be graded on their proposal as presented today. | • Evaluate each presentation using the rubric in the handout (p. 180). | — | — |

## Optional Modification and Extension (Extend)

- Set up an air track with different masses and allow students to do physical modeling in addition to the simulation.
- Have students complete mathematical calculations to verify a portion of their data trials.
- Extend collisions beyond just one dimension.
- Allow presentations to be done using a digital format or paper or poster format, as best fits the classroom.
- Ask students to answer, "How does what you learned about bumper cars relate to designing passenger cars on the road?"

## Differentiation

### Special Needs

- Provide a data table format for data collection.
- Provide a more detailed explanation of what data should be collected.
- Provide a written guide or outline for presentation requirements.

### English Language Learners

- Post definitions and descriptions of important vocabulary words (*momentum, impulse,* and *force*) and concepts (*fair, safe,* and *fun*).
- Provide a skeleton structure for presentations.

## Supplemental Material

- Handout 6E-1: Amusement Park Engineer—Bumper Cars
- Handout 6E-2: Criteria for Success
- Handout 6E-3: Reference Sheet

# HANDOUT 6E-1: AMUSEMENT PARK ENGINEER—BUMPER CARS

## OBJECTIVE

Eight Flags wants to build a new bumper car ride that can accommodate the whole family, and has asked your team to compete for the contract. Your job as an engineering team is to come up with a proposal for designing a set of bumper cars for the ride that is safe, fair, and fun for children, teenagers, and adults. Your team will present its bid to the Eight Flags committee.

## TIMELINE

| Day 1 | Day 2 | Tuesday, 12/22 | Day 3: Wed, 12/23 |
|---|---|---|---|
| Get oriented and model the bumper cars. | Create the proposal presentation. | Conduct motion test. | Present proposals. |

## PART I. GET ORIENTED WITH THE ENGINEERING PROBLEM

1. Come up with a team name!
2. What does it mean for the ride to be **SAFE**?
3. What does it mean for the ride to be **FAIR**?
4. What does it mean for the ride to be **FUN**?
5. What would be some **CONSTRAINTS** on the project?

## PART II. MODEL BUMPER CARS WITH A SIMULATION

During our next class, you will design a proposal for a new bumper car system. A strong proposal is backed by experimental data. So today you will use a PhET computer simulation to investigate what happens in different collisions. The PhET Collision Lab at *https://phet.colorado.edu/sims/collision-lab/collision-lab_en.html*.

It is up to your group what data you will collect using the simulation. Decide what type of information might be most useful to back up your bumper car proposal. These data can be qualitative or quantitative. Be sure to record at least 10 pieces of data in the space below.

**Collision Simulation Data**

What trends or relationships do you see in your data?

How will this information help you in the design of your new bumper cars?

## PART III. DESIGN A BUMPER CAR PROPOSAL

How can you use the results from your bumper car modeling, the collisions activity done in class, and what you know about momentum to inform your proposal?

Is there any more information that you need to look up to help you?

## PART IV. PRESENT YOUR PROPOSAL TO THE COMMITTEE

Make a Google Slide presentation that outlines your group's proposal for a set of bumper cars that are safe, fair, and fun for children, teenagers, and adults. You will present this to the "committee" at a later date and will have **five minutes** for your presentation. Your group will receive a grade according to the "Criteria for Success" chart (see next page).

# HANDOUT 6E-2: CRITERIA FOR SUCCESS

| Criteria | Below Expectations (0 pts.) | Approaches Expectations (1 pt.) | Meets Expectations (1.5 pts.) | Exceeds Expectations (2 pts.) |
|---|---|---|---|---|
| **Safe** | There is no consideration in the proposal for keeping the ride safe. | The proposal makes an attempt at designing a safe ride. | The proposal considers what it means for the ride to be safe and reflects it in the design. | The proposal defines what it means for the ride to be safe for all ages and clearly outlines the ways in which unsafe conditions would be avoided. |
| **Fair** | There is no consideration in the proposal for making sure the ride is fair. | The proposal makes an attempt at designing a fair ride. | The proposal considers what it means for the ride to be fair and reflects it in the design. | The proposal defines what it means to be fair and outlines a plan for making the ride fair for all ages. |
| **Fun** | There is no consideration in the proposal for making sure the ride is fun. | The proposal makes an attempt at designing a fun ride. | The proposal considers what it means for the ride to be fun and reflects it in the design. | The proposal defines what it means for the ride to be fun and ensures that the whole family will enjoy it. |
| **Constraints** | The proposal does not consider engineering constraints. | The proposal attempts to operate within engineering constraints. | The proposal considers several engineering constraints, which are reflected in the design. | The proposal outlines several engineering constraints and makes an effort to operate within these constraints. |
| **Modeling** | There is no mention of the collisions simulation or physics concepts. | The simulation and physics concepts are mentioned but do not seriously inform the proposal. | Results from the simulation were used to make the proposal, and important physics concepts are discussed. | The proposal is data-driven and clearly informed by the simulation and physics concepts from class. |
| **Collaboration** | Group members rarely spoke to one another or they argued with one another or used inappropriate language. | The group dynamic was rocky, although members put in effort to work together. Most group members were involved. | The group worked well together and everyone had a role to play. Discussions were respectful and collegial. | Group members worked efficiently together, engaged in collegial discussions, respected one another's opinions, and involved everyone. |
| **TOTAL ______ / 12** | | | | |

# HANDOUT 6E-3:
# REFERENCE SHEET

| Person/Item | Mass Range (kg) |
|---|---|
| Child | 20–40 |
| Teenager | 35–75 |
| Adult | 60–100 |
| Bumper car | 75–125 |

*Safe acceleration:* 0.5 g

*Average collision time:* 0.5 seconds

*Safe change in velocity:* $\Delta v$ = 2.5 m/s

# ACTIVITY 6F: EGG LANDER–MOTION DESIGN CEPA

Jointly developed by Cambridge Rindge and Latin School teachers Liza Hansel, Dionne Harden, Helen Harlan, Jack Haverty, Andrew Miller, Kristin Newton, Ramazan Nigdelioglu, and Tal Shavit

**Time frame:** Approximately 4 class periods

**Physics focus:** Impulse, momentum, force, acceleration, and velocity

**Engineering focus:** Design, analysis, and models

### Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Maximum speed versus height | • Designing the egg drop device that satisfies the criteria<br>• Iterative cycle—build, test, andrebuild |
| **Analysis** | • Measure impact force, impact time, maximum velocity, acceleration, and mass | • Materials testing<br>• Cost analysis |
| **Models** | • Full-body diagram<br>• F = ma | • Depends on "story"—imperfect model for safety equipment<br>• Mars rover: delicate landing of equipment<br>• Food delivery |
| **Systems** | • Look at effects of outside force on the overall system | • Compressive subsystem (crushable part)<br>• Air-catching subsystem (parachute)<br>• Compartment –door subsystem (to check egg status) |

## PROJECT OVERVIEW

This lesson is an engineering extension of classroom activities around force, impulse, and momentum. The purpose is for students to design a device that successfully lands an egg dropped from a height of two meters or higher, up to 3–4 stories (12–16 meters).

The egg lander is a model for delicate instrumentation being dropped onto another planet. Students will do their tests and at the end of the project will reflect on how their design would need to be adjusted if materials were being dropped onto another planet or the moon. The project days do not have to be consecutive; it can be effective to alternate project work days with content lessons that support the project.

On the first day, students brainstorm designs, build a first prototype, and document their process on a shared Google document. Students are given a limited amount of time for building and a specific set of building materials. Designs are tested quickly from a height of two meters in the classroom. As a follow-up outside of class, students are each required to reflect in the shared Google doc about the strengths and weaknesses of their designs.

The second project day involves data collection and testing to help students determine the best design and materials to use in their final design. For the final design, materials are given monetary values and students are limited to a budget of $10. This ends up being slightly less than the monetary value of the materials they were given for the first prototype, so they need to prioritize the most important materials. The materials provided and their costs can be varied from year to year so as to encourage creativity and limit copying of designs from a previous student.

During the testing day, students are given data collection equipment, such as motion detectors, force plates, stopwatches, and video analysis software. The project can also be done with only low-technology equipment. All students must make certain measurements (force, acceleration *or* velocity, mass) but they can also make any additional measurements they choose.

Once students have done their testing, they have one class period to build their final design. Groups are again limited to $10 for their materials. If materials are damaged, they are not given replacements. Devices can either be tested the same day or the following day. They are dropped first from two meters in the classroom, then from one story, two stories, and three stories, and higher if drop locations are available. Eggs have to survive from two stories for full credit on the success criteria portion of the rubric.

Following the drop testing, the class will discuss how the designs would need to be adapted to work on a different planet (e.g., Mars or Jupiter) or on the Moon. What are the differences between those locations and the Earth? How do different atmospheres and different gravitational pulls affect the design?

The last part of the project involves student reflections about their own contributions to their group work as well as the contributions of their partners. This can be completed in class or as homework.

## Online Collaborative Journals

The contributing teachers share their insights about using collaborative online journals instead of a handwritten engineering notebook:

> *Now that our physics team has used online journals in multiple projects over multiple semesters, we have learned a lot about how to make them most effective.*
>
> *As much as possible, we try to have all of the online journal work done in one Google document that is shared via Google Classroom. We have a set of five iPads for each classroom as well as five desktop computers in each class. During the egg lander project, we gave each group an iPad that they could use to take pictures and then upload those pictures to their Google doc. Some students were able to do this with their phones as well. Between the desktop and iPad, every group had two devices, so while some kids were building, others could be recording data or reflecting on the design process.*
>
> *At the top of each shared Google doc, there is a chart in which students indicate the color in which they are going to do their work within the document. This makes it very easy to scan through a document to see how equitably the work is shared. We can also check the edit history to confirm that everyone has participated. As much as possible, we ask students to agree on who is responsible for specific parts of a shared document and indicate that. We tell students not to do others' work for them, and promise in return that they won't be penalized if they do their work but someone else does not do theirs.*
>
> *Grading projects can be challenging. For example, in the analysis section of our journal, there are four physics questions, and each student is explicitly told to answer one. If students do not complete their question, they get a zero for the whole analysis section. The other students who did complete their question are excused from questions missing because partners did not complete their work. It is not a perfect system, but it does hold students accountable for their part of the work.*
>
> *We were disappointed when grading to see that some of our students had not contributed to the online document at all. It was hard to know how much they had contributed to the design and building of the device, and we realized that our rubric doesn't have a good way of capturing that. These students ended up not getting much credit for the design journal, but we gave them a chance to resubmit it. In the future, we will work in some kind of journal check after the first egg prototype. Hopefully, this will prompt everyone earlier in the process and encourage them to participate in the online journal.*

## Grading the Project

In our egg lander project, 15% of the grade was assigned to how well the device worked, with surviving two floors being the criterion for full credit (2 meters got 5 points, 1 story got 10 points, 2 stories got the full credit of 15 points, and more than that got extra credit). When we gave the students the rubric, a few of them were really put off by the idea that they would get points deducted if their device didn't work. It led to an interesting conversation about the purpose of designing a device and how to balance success with effort.

| Date | Time falling (s) | Maximum Velocity (m/s) | Mass (kg) | Change in velocity (m/s) | Time to stop (s) | Acceleration ($m/s^2$) | Force (N) | $p_{max}$ | □p | Impulse = Ft |
|---|---|---|---|---|---|---|---|---|---|---|
| 10/4 balloon | 0.5543 | 4.09 | 0.009 | 4.09 | 0.075 | 54.53 | 0.5 | 0.04 kgm /s | 0.04kg m/s | 0.04 N-s |
| 10/4 parach ute | 0.5624 | 3.25 | 0.013 | N/A | N/A | N/A | N/A | 0.04 kgm /s | 0.04kg m/s | N/A |
| 10/4 legs | 0.5494 | 4.75 | 0.015 | 4.75 | 0.08 | 59.375 | 0.9 | 0.07 kgm /s | 0.07kg m/s | 0.07 N-s |
| Final Design | 1.5 | 2.42 | 0.015 | 2.42 | 0.114 | 21.228 | 0.3 | 0.03 6 | 0.036 | 0.03 N-s |

**Sample data table to help teachers see what students can do and what they should demand**

Based on the criteria, one group got extra credit, but three groups got zero points for egg-lander success. We felt badly that some of the kids who worked really hard couldn't get more than an 85 on the project, but we could also see the flaws in their design process (and they could too, upon reflecting). We've wondered if we should adjust the points to make the outcome of the device woth a smaller percentage. We're not sure what the right balance is; however, it is the right message to send that yes, the quality of your design matters. We were a little surprised that we didn't have more students complaining once their projects were graded. It definitely helped to share the rubric when the project was introduced so that students went into the project understanding that a successful device was an important criterion.

## BIG IDEAS

- **Physics:** Total momentum of the system changes when the system interacts with outside forces.
- **Engineering:** Engineers apply scientific ideas and evaluate the criteria and constraints to solve an engineering problem.

## Connections to the *Next Generation Science Standards*

### Performance Expectation

- HS-PS2-3: Design, evaluate, and refine a device that minimizes the force on a macroscopic object during a collision.

### Disciplinary Core Ideas

- PS2.A: Forces and Motion
- ETS1.A: Defining and Delimiting Engineering Problems
- ETS1.C: Optimizing the Design Solution

### Science and Engineering Practices

- Analyzing and interpreting data
- Constructing explanations and designing solutions
- Engaging in arguments from evidence

### Crosscutting Concepts

- Systems and system models
- Structure and function

## Assessment: Determining Acceptable Evidence

### Formative

- Ask students to provide evidence and reasoning for their design decisions.
- Ask students to clarify what data they are collecting and how that will help them improve their design to reduce the force of the collision.

### Summative

- Final performance of egg lander
- Completion and quality of answers in design journal

## Materials and Preparation

### Materials (Groups of 4)

A variety of materials can be used for the landers. The following materials are suggestions:

- Safety glasses or goggles for each student
- Masking tape
- Paper

- Straws
- Nonlatex balloons
- String
- Packing peanuts
- Scissors

### Class Equipment

Required measurements can be adjusted according to the equipment available in the classroom.

- Balance for measuring mass
- Force plate
- Stopwatch
- Motion detector equipment
- Computer, tablet, or student smartphones for accessing shared Google documents or for accessing video analysis software.

## Safety

- Remind students about general lab safety procedures.
- Remind students not to eat any food used in this activity.
- Participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Make sure there are no fragile materials in work zone while they are operating devices.
- Students should use caution in working with sharps (scissors and so on), which can cut or puncture skin.
- Use caution when leaning over railing at elevated heights as this is a potential fall hazard.
- The teacher should clear landing area before eggs are dropped.
- Students should wash their hands with soap and water upon completing this activity and particularly after cleaning up any broken eggs.

### Egg Lander–Motion Design CEPA Lesson Plan for Day 1 (55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **3 mins.**<br><br>**Engage** | | • Start by telling students, "The cost of a Mars Rover mission is more than two billion dollars."<br>• Present a real-world lander problem and the egg as the model for the lander. | | |
| **7 mins.**<br><br>**Elicit** | • Brainstorm factors that will affect their designs. | • Introduce the design challenge. | • Keep track of physics words that come up in discussion. Focus students on reducing the force and impulse of the collision. | • Reinforce the engineering design process: define the problem, brainstorm and research, design the , prototype, test, and evaluate. |
| **30 mins.**<br><br>**Explore**<br>**Explain** | • Design the first egg-lander prototype in small groups of three or four. Document their process in a shared Google doc. | • Ask students to share their reasoning for design decisions. | • Ask students to explain how their design reduces force and impulse. | • Clarify the reasoning behind design decisions.<br>• Relate the design changes to the physical attribute being adjusted. |
| **10 mins.**<br><br>**Evaluate** | • Drop eggs from a two-meter height. | • Facilitate testing of the egg-lander devices. | • Reflect on factors that affected the force and impulse on the egg. | • Testing of first prototype |
| **Elaborate** | **Homework:** Students reflect on the results of testing their first prototype. | | | |

### Egg Lander–Motion Design CEPA Lesson Plan for Day 2 (~55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **15 mins.**<br><br>**Engage**<br>**Elicit**<br>**Explain** | • Students share reflections on their egg lander testing (or *The Martian* if extension was done).<br>• Students brainstorm ideas for analysis they could do and data they could collect. | • Facilitate discussion. | • Review momentum, impulse, and Newton's Second Law and how quantities like force, mass, velocity, and acceleration are related. | • Brainstorming Analysis and data collection |
| **35 mins.**<br><br>**Explore**<br>**Explain**<br>**Evaluate** | • Students have open-ended time for the following:<br>• Data collection<br>• Materials testing<br>• Recording results<br>• Discussing how results will affect final design | • Prompt students about why they are collecting certain data and what their tests are telling them. | • Determine how changes in particular variables will affect impact force/impulse. | • Analysis and data collection<br>• Modifying design based on results of tests |
| **Elaborate** | **Homework:** Students reflect on the results of data collection and analysis. | | | |

### Egg Lander–Motion Design CEPA Lesson Plan for Day 3 (~55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **10 mins.**<br><br>**Engage**<br>**Elicit** | • Share in large group what they learned from their testing, their surprises, and their confirmations. | • Facilitate discussion. | • Discussion of force, mass, velocity, acceleration, momentum, and impulse data | • Reviewing analysis and data collection |
| **40 mins.**<br><br>**Engage**<br>**Explore**<br>**Evaluate** | • Have open-ended time for the following building their final design and documenting their design process. | • Prompt students about the reasons for their design decisions. | • Discussion about how to reduce force and impulse | • Construct final design based on analysis and testing |
| **Elaborate** | **Homework:** Students reflect on the building of the final design and complete physics content portion of design journal. | | | |

### Egg Lander–Motion Design CEPA Lesson Plan for Day 4 (~55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **20–30 mins.**<br><br>**Evaluate** | • Drop egg-lander devices from increasing heights until all eggs are broken or maximum height is reached. | • Facilitate egg lander testing and keep the landing space clear. | • Students observe speed and impact of egg landers. | • Testing of final design |
| **20–30 mins.**<br><br>**Extend**<br>**Evaluate** | • Hold a brief small-group or whole-class discussion about the success of some designs compared to others.<br>• Compare atmosphere and gravitational attraction of Earth to other planetary bodies to determine how designs would need to be modified if used on another planet or the Moon. | • Facilitate discussion. | • Students discuss how varying atmosphere or gravitational attraction affects physics quantities such as force, velocity, etc.<br>• Review how acceleration due to gravity is determined on other planets before traveling there. | • Revision of design |
| **Elaborate** | **Homework:** Students complete design journal and project reflection. | | | |

## Optional Modification and Extension (Extend)

- This is an extension that is appropriate after students have built their first prototype, but before they do analysis and collect data to inform their final design. Show students all or a part of *The Martian* or have them read a chapter of the book. Ask students to identify an engineering problem Mark Watney is trying to solve and identify the analysis and testing that Mark is doing to help solve the problem. Then ask students to identify analysis and testing they could do to figure out how to improve their egg drop devices. Contributing teacher reflections about the Martian extension are as follows:

  *Last year, I had the idea of showing the movie* The Martian *to my students as an example of the engineering design process. Students watched parts of the movie on days I was absent for professional development. After they'd watched about 45 minutes, I gave them a chapter to read (Chapter 7) from the book on which the movie was based along with some questions about the engineering design and analysis that Mark Watney did. At the same time, we were about to start doing analysis for the egg-lander project, and I asked students to make connections to that project.*

  *I've been really pleased with students' response to the movie as well as their ability to discuss the engineering. They were able to identify and explain the engineering analysis done in the movie and come up with good ideas for analyzing their own egg drop projects. Later in the semester, I assigned another chapter (chapter 18) that coincided with our electricity unit and focused on the design challenge of generating electrical power.*

  *I gave the following note to students before they read the first chapter of* The Martian:

  *A note about language: This book and this chapter have some swear words in it. I thought about whiting them out, but after talking to an English teacher, I decided to leave them in. They are the author's words and the author chose to use them to help tell the story. The fact that there are swear words in the story that we are reading in class does not mean that it is okay to use that language in class or that your teachers condone that kind of language when you are speaking to each other in school.*

*Note:* A classroom edition of the Martian that "cleans up" this objectionable language is now available.

## Differentiated Instruction

### Special Needs

- Use the provided graphic organizer.
- Provide sentence starters for design journal entries.

### English Language Learner

- Pre-teach key vocabulary.
- Provide sentences frames for design journal as necessary.
- Use the provided graphic organizer.
- Provide a model of a design journal.

## Supplemental Materials

- Handout 6F-1: Egg Lander—Motion Design CEPA
- Handout 6F-2: Rubric for Egg Lander—Motion Design CEPA
- *The Martian* movie or *The Martian* book by Andy Weir (Broadway Books, 2014)
- Possible videos to use for project introduction
  - Jafflechutes (food delivery by parachute), *http://jafflechutes.com*
  - Food relief program: "Australia, Japan, U.S. Drop Food, Toys on Pacific Islands," *www.apnews.com/f4f32175842c4655a5331c08eeef5001*

# HANDOUT 6F-1: EGG LANDER–MOTION DESIGN CEPA

## OBJECTIVE


Work with a group to design a device to keep your egg safe when dropped from predetermined heights by reducing forces.

## SAFETY PRECAUTIONS

- Follow all general lab safety procedures.
- Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Make sure there are no fragile materials in work zone while you are operating devices.
- Do not to eat any food used in this activity.
- Use caution in working with hot objects (scissors). These can burn skin!
- Wash your hands with soap and water upon completing this activity.

## DELIVERABLES

Your final project must have the following three parts:

### Part I. The Device

Build a device to protect an egg when it is dropped from various heights. You must be able to remove your egg without taking apart or ripping your device. In other words, it must be easy to put the egg in and take it out.

- First design: physical prototype built from a particular set of materials provided by your teacher.
- Redesigns: You will have $10 in "physics bucks" to spend on a particular set of available materials.

## Part II. Online Design Journal

- Your online design journal should include three components: the engineering design process, your daily data collection, and your scientific analysis. See the rubric in this handout for the specific requirements for each component.

## Part III. Professionalism

- Your journal should be neat and organized with proper spelling and grammar.
- You will receive a grade for your active and honest participation in completing all group tasks.

## HONORS OPTIONS

Pick one of the following options to complete *individually* for honors credit. If more than one group member is doing honors, you may pick the same option but must complete it on your own.

### Option A: Extend the Physics

- Explain impulse. How does it relate to momentum? How does it relate to force?
- Analyze your design using momentum. What part of the momentum equation did your design change? How did that affect the forces on the egg?
- Using the data you collected in your final trial, calculate the following values:
  - The momentum before and after the collision (hint: be careful with signs!)
  - The impulse of the collision
  - The approximate time of the collision (hint: you will need force)

### Option B: Research

Research and write an explanation of a real-world device that reduces the force of a collision or fall. This should be a thorough discussion that demonstrates research. You should extend yourself beyond the knowledge you had when entering this course. Include a works cited section.

Pick at least two of the following topics to discuss:

- How and why did the device change over time?
- How does the device work?
- How does the device reduce force?
- How does the device change terminal velocity? (This topic will not apply to all applications.)

Name: ______________________________

# HANDOUT 6F-2: RUBRIC FOR EGG LANDER–MOTION DESIGN CEPA

| Requirements for Design (20 pts) | Your Points | Possible Points |
|---|---|---|
| The final design demonstrates revisions to improve the prototype. | | 5 |
| Final design survived a two-story drop.<br>(2 m = 5 points; 1 story = 10 points; 2 stories = 15 points; 4 stories = extra credit) | | 15 |
| **Requirements for Journal (65 pts)** | | |
| **Engineering design process** | | |
| • Identified the problem and included a list of solutions that your group brainstormed | | 3 |
| • Identified the criteria used to select your final solution | | 3 |
| • Photographic documentation of the sketch and project redesigns | | 4 |
| • Daily engineering record, including your comments on successes and improvements (*individual grade*) | | 15 |
| • Analysis of the design process, including how you decided to use your money and why | | 5 |
| **Daily data collection**<br>• Summary of all qualitative and quantitative tests<br>• Observed results<br>• Numerical data | | 15 |
| **Scientific Analysis**<br>Each person is to answer one question, but this is a group grade. If you do not contribute, you will get a zero on this section. | | |
| • Explain what you did you decrease the force on your egg. | | 5 |
| • Using Newton's second law and your data, explain the physics related to reducing the force on your egg. | | 5 |
| • Create a free-body diagram of your apparatus in free fall. | | 5 |
| • Create a free-body diagram of your apparatus hitting the ground and explain Newton's third law. | | 5 |
| **Requirements for Professionalism (15 pts)** | | |
| Your group proofread the text for correct spelling and grammar. | | 5 |
| You were an active participant in your group and completed all tasks assigned to you (*individual grade*). | | 5 |
| You thoughtfully and honestly answered all questions in the self-reflection (*individual grade*). | | 5 |
| **Overall Score**<br>**Honors Option: 15 points** | | **100** |

# ACTIVITY 6G: GOLF BALL BOAT

**Contributor: Gita Hakerem Foster**

**Time frame:** 3–4 class periods

**Physics focus:** Net force and buoyancy

**Engineering focus:** Design, modeling, communication, and iteration

### Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Weight versus displacement in water | • Iterative cycle—build, test, and rebuild |
| **Analysis** | • Free-body diagram<br>• The net force acting on the boat<br>• Newton's laws | • Materials testing<br>• Small-scale prototype for analysis |
| **Models** | • full-body diagram<br>• F = ma<br>• Buoyancy (Archimedes' principle) | • Model for larger boats, vessels in fluids<br>• Visual design blueprint |
| **Systems** | • The entire boat as a whole system | • Weight distribution<br>• Boat stability<br>• Boat rigidity |

## PROJECT OVERVIEW

The goal of this project is to build a boat with a 30 cm × 30 cm piece of aluminum foil that can hold as many golf balls as possible. The project works well after completing the discussion about forces and Newton's laws. The teacher can introduce a new force called buoyancy and discuss how—for a boat to float—the upward force of buoyancy and the downward gravitational force must balance.

The project begins with students completing research that will guide them toward designing and building a successful boat. The research is completed in the library and by using the internet. Answers to the guiding research questions (the pre-activity questions on the student handout) should be recorded in students' engineering notebooks.

After the initial research stage, students are asked to sketch a variety of design options for their boat. This brainstorming session should lead to several different boat ideas. There is a separate sheet that students use when they build and test a boat that asks the students to explain that design in more detail and to describe the results of the test. Students are allowed to create and test two prototypes leading up to their final boat—each time receiving a fresh piece of aluminum foil. While creating and testing their different iterations of the final boat, students should be recording the process and their reasoning in their engineering notebooks.

**A boat being tested**

This project can be presented as a competition between groups. Students often find activities much more engaging if they are competing against their peers. Once the final boat designs have been tested and a winner has been declared, each group must complete entries in their engineering notebook and write a summary project report.

## BIG IDEAS

- **Physics:** Forces, equilibrium, balanced forces, Newton's second law, buoyant force, buoyancy, Archimedes' principle, volume, density, mass
- **Engineering:** Design is an iterative process. The next iteration should build on what was learned in previous attempts.

## Connections to the *Next Generation Science Standards*

### Performance Expectation

- HS-PS2-1: Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.

### Science and Engineering Practices

- Developing and using models
- Planning and carrying out investigations

- Using mathematics and computational thinking
- Constructing explanations (science) and designing solutions (engineering)
- Obtaining, evaluating, and communicating information

### Disciplinary Core Idea

- PS2.A: Forces and Motion

### Crosscutting Concepts

- Cause and effect
- Systems and system models
- Stability and change

## Assessment: Determining Acceptable Evidence

### Formative

- Check in with students as they work on their prototypes.
- Discuss with each group what students learned from their prototype and what kinds of changes are needed.
- Ask students to provide claims and evidence regarding failures of the prototypes.

### Summative

- Success of the boat remaining afloat for 20 seconds
- Engineering notebook
- Group report

## Materials and Preparation

### Materials (Groups of 2)

- Safety glasses or goggles for each student
- 3 30 cm × 30 cm sheets of aluminum foil
- 1–2 dozen golf balls
- Large bin filled with water (can be shared between two groups)
- Paper towels

## Safety

- Remind students about general lab safety procedures.
- Participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Immediately pick up golf balls that fall on the floor and wipe up water that spills on the floor. These create a slip-and-fall hazard.
- Keep water away from electrical receptacles—electrical hazard.
- Students should wash their hands with soap and water upon completing this activity.

### Golf Ball Boat Lesson Plan for Day 1 (50-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **1 min.**<br><br>**Engage** | — | • Open class by posing this scenario: "The cruise ship *Oasis of the Seas* has a mass of over 200,000 tons." | — | — |
| **10 mins.**<br><br>**Elicit** | • Write what they think the answer is.<br>• Some students present their ideas and lead a class discussion on what needs to happen to make something float. | • Ask, "How do you float in a pool?<br>• Ask, "How does the Oasis of the Seas stay afloat?" | • Buoyant force<br>• Buoyancy<br>• Archimedes' principle<br>• Balanced forces | — |
| **5 mins.**<br><br>**Explain** | — | • Explain the purpose, time line, and logistics of this project to students, using the student handout as a guide. | — | — |
| **20 mins.**<br><br>**Explore** | • Begin research to answer the pre-activity questions and write their answers in their engineering notebooks. | • Facilitate the finding of sources for the research portion of the activity. | — | • Research ideas to help guide design choices. |
| **14 mins.**<br><br>**Explore** | • Draw and design their first prototype, including measurements. Then, build and test their first prototype. | • Encourage students to improve their drawings and to include all measurements.<br>• Facilitate the testing of the prototype. | — | — |
| **Extend** | **Homework:** In their engineering notebooks, students describe three lessons learned from yesterday's design, prototype building, and testing of the prototype. | | | |

### Golf Ball Boat Lesson Plan for Day 2 (50-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Are the Students Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **2 mins.**<br>**Engage** | — | • Remind students about the mass of the cruise ship. | — | — |
| **8 mins.**<br>**Explain** | • In groups, discuss their homework.<br>• Each group shares one lesson learned from yesterday's design and prototype test. | — | — | — |
| **20 mins.**<br>**Explore** | • Plan their prototype 2. This process is repeated through prototype 2 and then the final design. | • Facilitate the design, build, and testing of the different boats. | — | • Iterative design changes to maximize area of the base of the boat with minimum depth<br>• Optimizing relationship between area, depth, and weight |
| **10 mins.**<br>**Elaborate** | • After testing their final design, make final entries in their engineering notebooks, including physics principles and how their design takes into account Newton's laws, equilibrium, and buoyancy. They should include vector force diagrams. | • Remind students that they should include equations and diagrams in their notebooks. They should also approximate values and be as quantitative as possible. | • Weight and forces<br>• Buoyant force<br>• Equilibrium | — |
| **10 mins.**<br>**Extend** | • Describe how the knowledge from this lesson provides insights into how the cruise ship stays afloat. Draw a sketch of the cruise ship in the water. | • The student sketches should show the volume of the boat below and above the water.<br>• Remind students that the volumes in the sketch should be proportional to the size needed to keep the boat afloat. | — | — |

## Optional Modification and Extension (Extend)

- Have students predict how many golf balls their boat will hold by using the volume of water their boat can displace and the mass of a single golf ball.
- Have students calculate the number of golf balls their boat should have displaced given the actual volume of the boat and the mass of a single golf ball. Then students can include an error analysis for what the boat should have held and what it actually held.

## Differentiated Instruction

### Special Needs

- Provide students with a checklist of daily goals.
- Use preprinted engineering notebook templates for students who need the structure for documentation.
- Allow for different types of documentation for students who might struggle with a handwritten engineering notebook,  such as using computer to type or phones or tablets to take photographs and then add captions.

### English Language Learners

- Have visuals around the classroom for the engineering design process and terms such as buoyancy, balanced forces, and Archimedes' principle.
- Provide sentence frames and use technologies for students to record in their engineering notebook.

## Supplemental Material

- Handout 6G: Golf Ball Boat

*Note:* Boris Korsunsky and Leah Gordon helped design this project.

# HANDOUT 6G: GOLF BALL BOAT

**A Sink-or-Swim Physics-Engineering Project**

## GOAL

The goal of this project is to use a piece of aluminum foil and scissors (and no other equipment) to build a "boat" that can hold as many golf balls as possible without sinking. General guidelines are as follows:

- You'll be allowed to build and test two prototypes before you build and test the third and final design.
- Each piece of foil will be 0.3 m long. You will have access to the tank to measure it also. You will have access to a bucket of golf balls.
- The boat loaded with the golf balls must be able to float in a large plastic tub filled with water approximately 0.3 m deep.
- The boat must be loaded while it is afloat.
- After the last ball has been loaded, the boat must remain afloat for at least 20 seconds without taking in water.
- Each group must submit one report. The same grade will be given to all members of the group. All work except diagrams and calculations must be typed up neatly. Do the pre-activity questions in this handout first!
- The engineering notebook must contain:
- Answers to the pre-activity questions
- Detailed description of your designs, with the diagrams and the detailed descriptions of the test results (the prototypes and the final design), as well as improvements you made between designs and why
- Analysis diagrams, calculations, and sentences to explain the forces on the boat, including gravity and buoyancy forces
- Conclusions, including suggestions on further improving your final design
- Appropriately formatted bibliography with at least three sources cited

## SAFETY PRECAUTIONS

- Follow all general lab safety procedures

- Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Immediately pick up golf balls that fall on the floor and wipe up water that spills on the floor. These create a slip-and-fall hazard.
- Keep water away from electrical receptacles—this constitutes an electrical hazard.
- Wash your hands with soap and water upon completing this activity.

## PRE-ACTIVITY QUESTIONS

1. What is buoyancy? What determines how large the buoyant force is? A one-sentence answer is not sufficient. Please include a lot of detail. Remember to cite your sources.
2. What are some advantages of using foil to support golf balls? What are some disadvantages?
3. What factors influence whether boats float or sink in the real world? Of these, which are risks to your boat, which might be risks, and which are definitely not risks you will face? Be as complete as possible. Again, cite your sources.
4. Sketch at least three possible ways you could use foil to support golf balls.

# 7

# Engineering Infusion With Energy

One valuable way to think about engineering in the physics classroom is to consider types of energy that different products might use. Engineers often have to evaluate all the components that can affect the energy inputs and outputs of a system. Therefore, it is useful to take an existing product or design and ask students to manipulate and problem solve to optimize for efficiency of energy transfer (or in the case of the glove construction in this chapter, for delaying the process of heat transfer).

Mathematical models are heavily used in engineering design and sometimes in the communication of product performance. The bungee jumping activity asks students to focus on predictive nature of a mathematical model, and glove construction and Coffee Joulies use data collection and graph to compare different systems.

If you are hungry for more ideas, try expanding the Rube Goldberg device anchor activity (in Chapter 5, p. 110) for use in an energy unit. Consider asking the entire class to function together as an engineering team working on different parts of a system, communicating about and analyzing the inputs and outputs of the system as a whole. Table 7.1 (p. 206) provides basic curricular details for the activities in this chapter.

**TABLE 7.1. Chapter 7 Activities**

| Activity Name | Physics Concept(s) | Core Concept(s) | Class Period(s) | Brief Description |
|---|---|---|---|---|
| **Bungee Jumping Cord Design** | • Energy transformation | • Design<br>• Analysis<br>• Models | 1 or 5 | Use mathematical models to create solutions for a successful bungee cord for different conditions. |
| **Construct a Glove** | • Heat transfer<br>• Thermal equilibrium | • Design<br>• Analysis<br>• Models | 6 | Design a wearable and usable insulating glove that can slow the temperature drop that occurs when it is placed in ice water for a three minutes. |
| **Coffee Joulies** | • Heat transfer thermal equilibrium | • Analysis<br>• Models<br>• Systems | 4 | Analyze and predict behaviors of a designed system using Coffee Joulies. Use graphic models to explain and communicate the effectiveness of the product and conditions tested. |

# ACTIVITY 7A: BUNGEE JUMPING CORD DESIGN

Contributors: Blair Cochran and David Carbonneau

**Time frame:** 1 or 5 class periods
**Physics focus:** $F = kx$ and energy
**Engineering focus:** Design, analysis, and models

## Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Multiple bungees<br>• Predicted linearity of the bungees | • Use the materials provided to design the correct lengths of bungee cords. |
| **Analysis** | • Free-body diagram<br>• Hooke's law<br>• Potential energy = *mgh*<br>• Kinetic energy = 1/2 $mv^2$ | • Forces and stress on the system<br>• Energy of the system<br>• Failure analysis of the cords |
| **Models** | • Free-body diagram<br>• Vector diagram<br>• Timing | • Forces<br>• Elasticity of bungee<br>• Deceleration and acceleration |
| **Systems** | • Bear (weight) per bungee | • Cord per bungee<br>• Support structure<br>• Multiple bungees |

## PROJECT OVERVIEW

Being strapped to a bungee cord and jumping over the Royal Gorge Bridge in Colorado for 321 meters is something that many students will want to experience, either as spectators or actual participants. As a way to bridge the excitement of the sport and the physics behind springs and energy, this lesson gives students the opportunity to analyze how a bungee cord behaves mathematically and to use that analysis to design a safe bungee jump for a object such as a raw egg. The activity is designed to focus on the analysis aspect of engineering specifically, using mathematical analysis as a tool.

Students are asked to manipulate three variables—spring constant, fixed cord length, and elastic length—on a mathematical model provided by the teacher to find the best design for a specified bungee jump. The teacher can provide five situations with different ranges and limits for students to explore. Students are asked to print out their final solutions for each of the situations and to write a paragraph analyzing the characteristics and performance of the cord.

This quick activity can be easily expanded to a project where students design the actual bungee cord to drop a small stuffed bear and other objects. Students can begin by doing a spring lab in which they use a nonlatex rubber band and rulers to find the relationship between force and stretch, and then use the mathematical modeling spreadsheet to better predict the elasticity of the rubber band (because it is not linear). (Be sure students are wearing safety glasses or goggles while using rubber bands.) Giving students time and material to design, build, and test the bungee cord makes it a fun final project for an energy unit.

**Students getting ready to drop their designed bungee cord**

## BIG IDEAS

- **Physics:** On a microscopic scale, energy can be stored in the relative position of the object and converted to different forms.
- **Engineering:** Mathematical models can be used to predict the outcome and behavior of a product.

## Connection to the *Next Generation Science Standards*

### Performance Expectations

- HS-PS3-1: Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known.
- HS-PS3-3: Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.

### Science and Engineering Practices

- Developing and using models
- Analyzing and interpreting data

- Using mathematics and computational thinking
- Constructing explanations and designing solutions
- Engaging in argument from evidence

### Disciplinary Core Ideas

- PS3.A: Definitions of Energy
- PS3.B: Conservation of Energy and Energy Transfer
- PS3.D: Energy in Chemical Processes and Everyday Life
- ETS1.A: Defining and Delimiting Engineering Problems

### Crosscutting Concepts

- Patterns
- Cause and effect

## Assessment: Determining Acceptable Evidence

### Formative

- Class discussion about parameters for bungee cords
- Check-ins with students during the mathematical modeling time

### Summative

- For each situation, students design solutions for best bungee cord within the parameters and conduct analysis for the performance.

**Students taking measurements to adjust fixed cord length**

## Materials and Preparation

### Materials (Groups of 3)

- Safety glasses or goggles for each student
- Computer for analysis
- Spreadsheet predesigned by teacher (or ask students to plot graphs)

### Class Equipment

- Nonlatex rubber bands, static cord, bungee cord and other strings
- Camera for recording the drop

## Safety

- Remind students about general lab safety procedures.
- Participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Students must use caution when leaning over railing at elevated heights as this constitutes a potential fall hazard.
- Students should wash their hands with soap and water upon completing this activity.

## Bungee Jumping Cord Design Lesson Plan for Day 1 (50-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins.**<br><br>**Engage** | • Watch video clips of different bungee jumps. | • Tell students: The highest bungee jump was over 200 m (equivalent to 50 floors of a building).<br>• Use a variety of videos or pictures to engage students in their discussion of bungee cords. | • Types of energy<br>• Energy transfer | — |
| **10 mins.**<br><br>**Elicit**<br>**Explore**<br>**Evaluate** | • Explore the materials on their table and discuss features to consider while bungee jumping. | • Lay out some materials such as bungee cords, strings, springs, elastic bands, and different "passengers."<br>• Elicit and evaluate students' prior knowledge about the materials, concepts of energy, and spring force.<br>• Ask students to discuss the types of energy transfer they see in the videos. | • Properties of springs<br>• Force<br>• Energy | • Analysis of materials |
| **5 mins.**<br><br>**Explain** | • Read the "bungee mathematical modeling exploration" handout. | • Work with students who have questions. | — | • The importance of mathematical models as an analysis tool in engineering before the process of design |

Bungee Jumping Cord Design Lesson Plan for Day 1 (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **25 mins.**<br><br>**Explore**<br>**Elaborate** | • Working in pairs, use a computer and the provided spreadsheet to perform mathematical modeling and use the prediction to analyze and design the best parameters for the specified situations. | • Encourage students to test different settings and find the optimal range for each situation.<br>• Support students in discussing and analyzing the performance of the bungee cords. | • Properties of spring<br>• Spring constant<br>• Explanation of energy transfer | • Mathematical modeling<br>• Analysis of results |
| **5 mins.**<br><br>**Evaluate**<br>**Extend** | • Turn in their final analysis and results of the simulation. | • Possible extension at this point is to actually have students sketch (but not build) a design with varying length of the drop height or varying mass of the hanging passenger. | • Energy transfer<br>• Force<br>• Spring constant | • Predictive analysis |

## Optional Modification and Extension (Extend)

- Make this into a project for the entire energy unit as described in the introduction section. Each group could have different criteria or test different types of elastic materials. Students can also learn to calculate the energy stored in the system and analyze the energy at different points of the bungee jump.
- Change the project by adding the systems component—ask students to manipulate the inputs and outputs of each of the components: bungee cord requirements or passengers weight requirements.

## Differentiated Instruction

### Special Needs

- Supply students with flow charts on how to manipulate the spreadsheet. Give student hands-on opportunities by having some cords with varying lengths or springs with varying spring constants so they can make a physical model to understand the mathematical model.

### English Language Learners

- Provide students with images of bungee jumping as a sport. Finding relevant locations that students might be familiar with is especially helpful.

## Supplemental Materials

- Handout 7A-1: Bungee Jumping Cord Design—Mathematical Modeling Exploration
- Handout 7A-2: Bungee Jumping Cord Design—Designing Your Bungee Day(s)
- Handout 7A-3: Bungee Jumping Cord Design—Building Your Bungee Day(s)
- YouTube video: "How to go from Mathematical Design to Physical Design on 05," *https://youtu.be/jtjQT_eqqOs*
- Excel file: Bungee Bear Mathematical Model.xlsm, available online at *www.nsta.org/eggdrop*

Team: ______________________________________________

# HANDOUT 7A-1: BUNGEE JUMPING CORD DESIGN—MATHEMATICAL MODELING EXPLORATION

## OBJECTIVE

The objective is to use mathematical modeling to create solutions for designing a successful bungee cord.

## BACKGROUND

Using the provided spreadsheet set up by your teacher, your group will create theoretical bungee cords. The formatting and background equations are complicated so be careful not to change any values except the ones you are instructed to change.

Download and then open the Excel spreadsheet named "Bungee Bear Mathematical Model" (see the "Supplemental Materials" section, p. 213).

***Important:*** The Excel spreadsheet uses small programs called *macros* that must be allowed to run. When you open Excel, you should get a security message that asks you whether it is okay to run these macros—choose "Enable Content" to allow them to run. You might also need to enable the solver. To enable the solver go to "File" on the ribbon along the top, then click "Options" near the bottom left. In the box that pops up, click "Add-Ins," then highlight "Solver Add-In" in the list and click "Go." Now make sure that "Solver Add-In" is checked, then click "OK." You will need to do this if you use the spreadsheet at home.

In using the spreadsheet, you can change the values for spring constant, fixed cord length, and elastic length. As these values change, the characteristics of the bungee cord will change. These are the three design parameters you will control in the design of your bungee cord. You want to check your block's success criteria to make sure your solutions are optimal. You will use these solutions to later create your bungee.

**Important: ONLY CHANGE VALUES IN YELLOW ON SPREADSHEET.**

## EXPLORATIONS

For each of these explorations, ranges or limits are given for the different characteristics of the bungee cord. **Using these limits creates a solution that best meets the success criteria for your block.** You might not be able to meet all of your success criteria in every trial. You will have to choose your highest priorities on each exploration. (*Strong hint:* Don't let the bear hit the ground.) Watch the graphs on the page for additional information about your bungee cord.

For each exploration, use the ranges and limits in the table on the next page and record your solution by capturing a screenshot of it. Paste that screenshot of the spreadsheet into the table for each exploration. Your solutions will be evaluated according to how well you met the success criteria for your block along with the ranges and limits of the exploration.

| Exploration | Ranges and Limits | Solution |
|---|---|---|
| 1 | • Spring constant: below 10.0 N/m<br>• Fixed cord length: any length<br>• Elastic cord length: 1.00 m to 2.00 m<br>• % stretch: less than 200 | Put in a picture like this one that shows your solution.<br>**Numerical Modeling Data Sheet**<br>**General Parameters**<br>Bungee Bear Height (m) 0.30<br>Starting Height (m) 5.31<br>Gravitational Field Strength (N/kg) 9.80<br>Mass (kg) 0.61<br>**Bungee Parameters**<br>Spring Constant(k) (N/m) 23.00<br>Fixed Cord Length (m) 2.20<br>Elastic Cord Length (m) 2.00<br>Total Length (m) 4.20<br>KE at Low Point (J) 0.00<br>Stretch (m) 1.76<br>%Stretch [Maximum = 200%] 88.01<br>**Jump Statistics**<br>**Low Point (bottom bear head) (m) -0.95**<br>Max Velocity (m/s) 9.21<br>Max Acceleration (g's) [Max. = 3.0] 3.52 |
| 2 | • Spring constant: any value<br>• Fixed cord length: 3.00 m<br>• Elastic cord length: less than 1.00 m<br>• % stretch: less than 150 | |
| 3 | • Spring constant: below 20.0 N/m<br>• Fixed cord length: any length<br>• Elastic cord length: any length<br>• % stretch: less than 100 | |
| 4 | • Spring constant: between 5.00 N/m and 9.00 N/m<br>• Fixed cord length: 2.50 m<br>• Elastic cord length: any length<br>• % stretch: below 200 | |
| 5 | • Spring constant: below 20 N/m<br>• Fixed cord length: any length<br>• Elastic cord length: less than 0.75 m<br>• % stretch: any value | |

**Check with the teacher before continuing to the next assignment.**

Team: ______________________________________________

# HANDOUT 7A-2: BUNGEE JUMPING CORD DESIGN—DESIGNING YOUR BUNGEE DAY(S)

## OBJECTIVE

To design a bungee cord, static and elastic cords together, that will meet the success criteria for your block.

## BACKGROUND

Your bungee must meet the criteria set by your block for success and also some design constraints imposed on you by the teacher to make this a more realistic design.

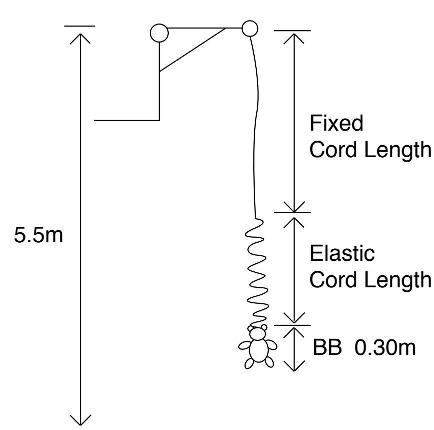
| Design Constraint | Value |
|---|---|
| Percent stretch | Less than 200% |
| Maximum acceleration | 3 g (29.4 m/s/s) |

Your group will use the same spreadsheet you used earlier to mathematically design your bungee, and use the information you gained from testing the elastics to physically design your bungee and create a parts list.

## PROCEDURE

Your group is going to design three different bungees according to set criteria that are different for each design. A fourth design will be your group choice. All of the designs should still meet your block's criteria for success.

- Design solution 1: Maximize the fixed cord length.
- Design solution 2: Maximize the elastic cord length.
- Design solution 3: Minimize the k value of your elastic cord.
- Design solution 4: Team choice. (Be ready to explain.)




Here is a video showing how to work through this sheet: *https://youtu.be/jtjQT_eqqOs.*

| Design Solution | 1 | Criteria: |
|---|---|---|

**Mathematical Design**

Replace with a screenshot of your spreadsheet solution.

| | |
|---|---|
| Physical design of elastic cord | |
| *k* of a single elastic | |
| Length of elastic series strand | |
| Number of elastics in strand | |
| Final length of strand | |
| *k* of each series strand | |

**Numerical Modeling Data Sheet**

| | |
|---|---|
| **General Parameters** | |
| Bungee Bear Height (m) | 0.3 |
| Starting Height (m) | 5.31 |
| Gravitational Field Strength (N/m) | 9.80 |
| Mass (kg) | 0.50 |
| **Bungee Parameters** | |
| Spring Constant(k) (N/m) | |
| Fixed Cord Length (m) | |
| Elastic Cord Length (m) | |
| Total Length (m) | |
| KE at Low Point (J) | |
| Stretch (m) | |
| %Stretch [Maximum = 200%] | |
| **Jump Statistics** | |
| **Low Point (bottom bear head) (m)** | |
| Max Velocity (m/s) | |
| Max Acceleration (g's) [Max. = 3.0] | |

| | |
|---|---|
| Number of parallel elastic strands | |
| Final *k* of elastic cord | |

Parts List

| Elastics | Fixed cord length (m) |
|---|---|
| | |

Describe your bungee cord, mentioning all parts and arrangements.

| | | |
|---|---|---|
| **Design Solution** | **2** | **Criteria:** |

**Mathematical Design**

Replace with a screenshot of your spreadsheet solution.

| Numerical Modeling Data Sheet | |
|---|---|
| **General Parameters** | |
| Bungee Bear Height (m) | 0.3 |
| Starting Height (m) | 5.31 |
| Gravitational Field Strength (N/m) | 9.80 |
| Mass (kg) | 0.50 |
| **Bungee Parameters** | |
| Spring Constant(k) (N/m) | |
| Fixed Cord Length (m) | |
| Elastic Cord Length (m) | |
| Total Length (m) | |
| KE at Low Point (J) | |
| Stretch (m) | |
| %Stretch [Maximum = 200%] | |
| **Jump Statistics** | |
| **Low Point (bottom bear head) (m)** | |
| Max Velocity (m/s) | |
| Max Acceleration (g's) [Max. = 3.0] | |

| | |
|---|---|
| Physical design of elastic cord | |
| *k* of a single elastic | |
| Length of elastic series strand | |
| Number of elastics in strand | |
| Final length of strand | |
| *k* of each series strand | |
| Number of parallel elastic strands | Parts List |
| Final *k* of elastic cord | Elastics \| Fixed cord length (m) |

Describe your bungee cord, mentioning all parts and arrangements.

| Design Solution | 3 | Criteria: |
|---|---|---|
| **Mathematical Design** | | Replace with a screenshot of your spreadsheet solution. |
| Physical design of elastic cord | | |
| *k* of a single elastic | | |
| Length of elastic series strand | | |
| Number of elastics in strand | | |
| Final length of strand | | |
| *k* of each series strand | | |
| Number of parallel elastic strands | | Parts List |
| Final *k* of elastic cord | Elastics | Fixed cord length (m) |
| | | |
| Describe your bungee cord, mentioning all parts and arrangements. | | |

| Numerical Modeling Data Sheet | |
|---|---|
| **General Parameters** | |
| Bungee Bear Height (m) | 0.3 |
| Starting Height (m) | 5.31 |
| Gravitational Field Strength (N/m) | 9.80 |
| Mass (kg) | 0.50 |
| **Bungee Parameters** | |
| Spring Constant(k) (N/m) | |
| Fixed Cord Length (m) | |
| Elastic Cord Length (m) | |
| Total Length (m) | |
| KE at Low Point (J) | |
| Stretch (m) | |
| %Stretch [Maximum = 200%] | |
| **Jump Statistics** | |
| **Low Point (bottom bear head) (m)** | |
| Max Velocity (m/s) | |
| Max Acceleration (g's) [Max. = 3.0] | |

| Design Solution | 4 | Criteria: |
|---|---|---|

**Mathematical Design**

Replace with a screenshot of your spreadsheet solution.

| Numerical Modeling Data Sheet | |
|---|---|
| **General Parameters** | |
| Bungee Bear Height (m) | 0.3 |
| Starting Height (m) | 5.31 |
| Gravitational Field Strength (N/m) | 9.80 |
| Mass (kg) | 0.50 |
| **Bungee Parameters** | |
| Spring Constant(k) (N/m) | |
| Fixed Cord Length (m) | |
| Elastic Cord Length (m) | |
| Total Length (m) | |
| KE at Low Point (J) | |
| Stretch (m) | |
| %Stretch [Maximum = 200%] | |
| **Jump Statistics** | |
| **Low Point (bottom bear head) (m)** | |
| Max Velocity (m/s) | |
| Max Acceleration (g's) [Max. = 3.0] | |

Physical design of elastic cord

*k* of a single elastic

Length of elastic series strand

Number of elastics in strand

Final length of strand

*k* of each series strand

| Number of parallel elastic strands | Parts List | |
|---|---|---|
| Final *k* of elastic cord | Elastics | Fixed cord length (m) |
| | | |

Describe your bungee cord, mentioning all parts and arrangements.

**Check with your instructor before continuing to the next assignment.**

Name: ____________________________________________

# HANDOUT 7A-3: BUNGEE JUMPING CORD DESIGN—BUILDING YOUR BUNGEE DAY(S)

Successful: (Fill in your block information.)

## DESIGN TRIALS FOR _______ BLOCK

BUNGEE

## DESIGN SPECIFICATIONS

| Bungee Jumping Cord Parameters | Value |
|---|---|
| Spring constant ($k$) (N/m) | |
| Fixed cord length (m) | |
| Elastic cord length (m) | |
| Number of elastics in strand | |
| Number of strands | |
| Explain what method your group used to come to these design specifications. (Include screen shots if appropriate.) | |

## SAFETY PRECAUTIONS

- Remind students about general lab safety procedures.
- Participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Students should wash their hands with soap and water upon completing this activity.

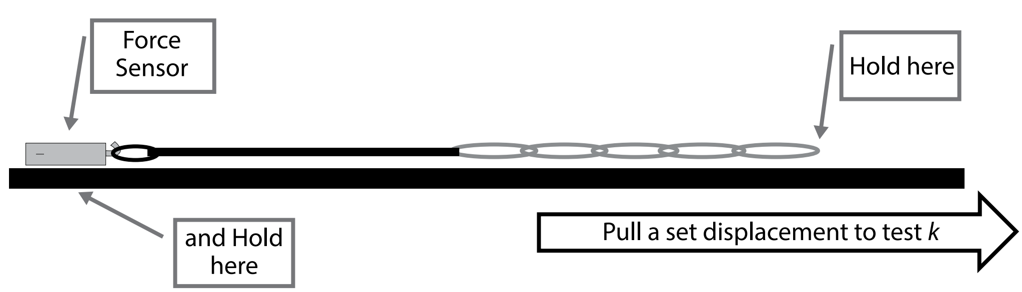
## BUILD YOUR BUNGEE CORD

Build what you have designed. Include a loop at the top of your cord to attach it to the platform.

## MEASURED SPECIFICATIONS

Use the available equipment to measure the bungee cord parameters for your bungee cord. Record all data obtained and show all calculations needed to find the bungee cord measurements below. Your teacher is available to check your method as needed.

Suggested Testing Set Up



## DATA AND CALCULATIONS: INITIAL MEASURED SPECIFICATION

| Bungee Jumping Cord Measurements | Measured | Percent Difference From Design |
|---|---|---|
| Spring constant ($k$) (N/m) | | |
| Fixed cord length (m) | | |
| Elastic cord length (m) | | |

How do you explain any discrepancies between your design specifications and the measurements you made of your bungee cord?

Make any modifications you need to your bungee jumping cord so it meets your design specifications. Explain how you modified it here.

Use the available equipment to measure the new parameters for your bungee jumping cord. Record all data obtained and show all calculations needed to find the bungee jumping cord measurements below.

## DATA AND CALCULATIONS: FINAL MEASURED SPECIFICATIONS

| Bungee Jumping Cord Measurements | Measured | Percent Difference From Design |
|---|---|---|
| Spring constant (*k*) (N/m) | | |
| Fixed cord length (m) | | |
| Elastic cord length (m) | | |

**Check with your instructor before continuing to the next assignment.**

# ACTIVITY 7B: CONSTRUCT A GLOVE

**Contributors: Shu-Yee Chen Freake, Kim Mayer, and Amy Winston**

**Time frame:** 6 class periods

**Physics focus:** Methods of heat transfer, temperature and thermal energy, and thermal equilibrium

**Engineering focus:** Design, analysis, and models

### Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Insulation materials versus temperature change | • Design the glove satisfying both thermal regulation and dexterity criteria. |
| **Analysis** | • Graphs for temperature change | • Use graphs for temperature change to select material.<br>• Test for dexterity. |
| **Models** | • Methods of heat transfer | • Modeling different ways to use the glove<br>• Gloves as models for other protective gears for winter |
| **Systems** | • The entire glove with the hand as one system compared to the outside environment | • Heat protection system<br>• Comfort system<br>• Dexterity system |

## PROJECT OVERVIEW

Living in New England can be extremely exciting yet also dangerous during the months when snow blankets the ground. Students cannot wait to discuss skiing, snowboarding, and all the wonderful outdoor activities that they take part in. We want to provide students with a rationale for learning using some of the heat and temperature concepts they have learned in previous lessons, so when we begin our classroom investigation of thermal energy in mid-January, we take the opportunity to connect the concepts to students' love of winter outdoor activities. We came upon the National Science Teachers

Association's *Science by Design* series and decided to modify the lesson to fit with our demographics and goals.

The main goal of this activity is to apply conservation of energy and quantifying insulating properties through the context of an engineering design challenge. Since a high percentage of students in our class had special education accommodations and needed more structure to fully explore different elements related to this project, we decided to use prompting questions and a worksheet format instead of a more traditional engineering notebook to help students focus on the exploration rather than organization of their ideas.

One of the major modifications we added to the lesson was using the context of hiking in New England as a way to discuss some of the connections between science, engineering, and realistic problems that students can relate to. We used an article published by the Boston Chapter of the Appalachian Mountain Club, which has a brief overview of the issue, the relationship between the types of heat transfer and how it contributes to heat loss, and some suggestions for materials that are great for students to gather ideas from.

The most exciting part of the project actually was watching students manipulate the fabric and look for solutions that not only insulate, but also are useful in a glove design. If the challenge was to just build something to insulate the temperature probe, materials would be the only design element to consider. By adding the constraint that it must be a useable glove, offering dexterity to the wearer, students were engaged in thinking about other aspects of design and the competing issues of adding too many insulation layers at the risk of losing usability. This complexity of engineering design—competing design needs—is something that students learned to appreciate when they were building the gloves.

## BIG IDEAS

- **Physics:** Energy is a quantitative property of a system that depends on the motion and interactions of matter and radiation within that system. Energy cannot be created or destroyed, but it can be transferred into or out of a system. The direction of heat transfer is from hot to cold.
- **Engineering:** Engineers create visual, mathematical, or three-dimensional models to test and communicate ideas. Engineers use mathematical and scientific models as design tools. Engineers use analysis to predict the behavior of a designed system and verify the quality of a design solution.

## Connection to *Next Generation Science Standards*

### Performance Expectation

- HS-PS3-4: Plan and conduct an investigation to provide evidence that the transfer of thermal energy when two components of different temperature are combined in a closed system results in a more uniform energy distribution among the components in the system (second law of thermodynamics).

### Science and Engineering Practices

- Developing and using models
- Planning and carrying out investigations
- Using mathematics and computational thinking
- Constructing explanations and designing solutions
- Obtaining, evaluating, and communicating information

### Disciplinary Core Ideas

- PS3.B: Conservation of Energy and Energy Transfer
- PS3.D: Energy in Chemical Processes and Everyday Life

**Testing the insulated glove in the ice-water bath**

### Crosscutting Concepts

- Energy and matter
- Systems and system models

## Assessment: Determining Acceptable Evidence

### Formative

- Reading guide questions for the AMC article
- Mini-conferences with groups during the planning, testing, and designing process
- Informal check-ins with students about material choices, data of the tests, and their choices
- Homework assignment, Do Now, class discussion, and chart discussion

### Summative

- Individual: engineering notebook and lab worksheets, self-assessment
- Group: glove performance, presentation

## Materials and Preparation

### Materials (Groups of 4)

- Safety glasses or goggles for each student
- 1 surface temperature probe
- 1 laptop or LabQuest running probe software (or graph paper)
- 1 nonlatex rubber glove
- Large plastic bin for ice water

One layer of the material added to the glove design by students, testing for fit and comfort before adding another layer of material

### Class Equipment

- 10 lb. bag of ice
- 3 boxes of vinyl gloves (1 each of sizes S, M, and L)
- Sewing thread, scissors, fabric, tapes of all kinds
- Random recycled materials for students to use. (Mylar sheets are especially helpful.)

## Safety

- Remind students about general lab safety procedures.
- Check with the school nurse or parents to make sure no student has a medical condition such as Raynaud's disease or poor circulation before allowing students to participate as test subjects for submerging hand in ice water.
- Carefully monitor the initial testing periods (especially during day 2). If the temperature of a participant's finger drops too quickly or is irregular, stop the experiment immediately.
- Participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Immediately wipe up any water spilled on the floor as this is a slip/fall hazard.
- Keep water away from electrical receptacles to avoid an electrical hazard.

- Students should wash their hands with soap and water upon completing this activity.


**Example of data collected during material testing stage of the project**

## Construct a Glove Lesson Plan for Day 1 (55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **3 mins.**<br><br>**Engage** | — | • Show some video clips of winter sports to engage students in the importance of designing good gloves. | — | — |
| **7 mins.**<br><br>**Elicit** | • Talk to each other about the Do Now questions to gain a sense of the context of the lesson.<br>• What is your favorite outdoor activity in the winter? How do you dress for that activity?<br>• Describe a time when you had too much fun playing in the snow and your fingers or toes became dangerously cold. | • Elicit students' prior experience with cold weather and frostbite. | — | • Analysis of problems that can occur in the winter while being outside. |

Construct a Glove Lesson Plan for Day 1 (continued)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **10 mins.**<br><br>**Explore**<br>**Elicit** | • Receive the design challenge and ask general questions about it. | • Give students some time to think and raise questions before moving onto the written, directed questions.<br>• Some students might want to start building right away, but emphasize the importance of understanding the problem. | • Thermal energy<br>• Heat transfer | • Engineering design usually requires some research into background information or a survey to understand the problem. |
| **25 mins.**<br><br>**Explore**<br>**Evaluate** | • Work on questions designed to explore parts and function of the hand, and make connections to using science vocabulary and concepts. | • Encourage students to spend some time exploring individually. The rest of the week will be group-focused; this will give some students a chance to make sure their ideas and explanations are written down so they might be more likely to voice them later.<br>• Evaluate student responses by checking in. | • Heat<br>• Temperature<br>• Insulation<br>• Heat transfer<br>• Conservation of energy | • Engineering design<br>• Research and refine the question.<br>• Explore the “client” (hand) requirements and specifications. |
| **10 mins.**<br><br>**Explain**<br>**Evaluate** | • Share their ideas and initial exploration with the whole class. | • Use chart paper to summarize what the class has learned so far. Evaluate whether it is necessary to explain more about tonight’s homework on the basis of student’s responses and understanding. | • Heat<br>• Temperature<br>• Insulation<br>• Heat transfer<br>• Conservation of energy | • Communication of ideas is important throughout the design process for the team. |
| **Extend** | **Homework:** Guided reading and answer questions for “Heat Management and Layering System” article (see the “Supplemental Materials” section, p. 238). | | | |

## Construct a Glove Lesson Plan for Day 2 (55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **3 mins.**<br><br>**Engage**<br>**Elicit** | — | • On the television show "The Big Bang Theory," the character Sheldon has a special place where he likes to sit. Do you think that different places in the same room can have different temperatures? | — | — |
| **7 mins.**<br><br>**Explore**<br>**Evaluate** | • Do Now activity: Use a thermometer (or surface probe, if available and they know how to use it) to measure the temperature in different parts of the room and of different parts of the body. | • Use this time to collect homework or spot check homework for understanding. Students should participate in data collection and be encouraged to find areas of different temperature. | • Heat<br>• Thermal energy<br>• Temperature<br>• Thermal equilibrium | • Explore the instrument and analyze temperature differences on hands for data collection and analysis. |
| **5 mins.**<br><br>**Elaborate**<br>**Explain** | • Gather background information about temperature range in different parts of the body. The article draws an analogy between the human body system and a home heating system. | • Explain why temperature differences occur within the body system.<br>• Elaborate on the analogy between the system that controls body temperature and the system that controls the temperature of a room. | • Introduce systems thinking in the science context.<br>• Explain the term *feedback loop.* | • Discuss similarities and differences of scientific versus engineering systems. Both are used to break down complex ideas or limit the scope. Engineering system focuses on how components work together to achieve a goal. |

Construct a Glove Lesson Plan for Day 2 (continued)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **35 mins.**<br><br>**Explore**<br>**Evaluate** | • Sketch a team member's hand, measure its surface temperature, and perform initial thermal equilibrium testing by wrapping the surface temperature probe around one finger, putting a vinyl glove on the hand over the probe, and placing the hand in ice water for 3 minutes. Then put a rubber glove over that vinyl glove and perform the test again. Record a temperature measurement every 30 seconds for three minutes. | • Ask students to be as detailed in their sketch and glove material as possible.<br>• Encourage all group members to help each other to participate in experimentation and documentation of the process.<br>• Evaluate student understanding of energy conservation by asking students questions related to energy loss during the activity.<br>• Extend to include biological processes if applicable. | • Thermal equilibrium<br>• Heat transfer<br>• Thermal energy<br>• Energy conservation | • Emphasize using the data from this experiment as a way to understand the problem. These data can be used as baseline data for comparison with other materials. |
| **5 mins.**<br><br>**Evaluate** | • Clean up their stations and show the teacher today's work. | • Evaluate student progress and understanding by asking questions during check-in. | — | — |
| **Elaborate**<br>**Evaluate** | **Homework:** Students complete homework questions related to materials and insulation. Ask students to bring in different materials for class. | | | |

### Construct a Glove Lesson Plan for Day 3 (55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **10 mins.**<br><br>**Elicit**<br>**Evaluate** | • Do Now activity: Go over questions from homework assignment. | • Check in with students about their understanding of the physics concepts taught and see what they know about different insulating materials. | • Heat transfer<br>• Thermal equilibrium<br>• Insulation. | — |
| **40 mins.**<br><br>**Explore** | • Test at least four different materials and analyze their performance for the purpose of insulation. | • Encourage students to use a variety of materials during testing.<br>• Check in with individual groups about their tests and ask them to explain what the graph is showing compared to the baseline graph from yesterday. | • Property of insulators<br>• Temperature versus time graph | • Students analyze data and create visual models for communication.<br>• Remind students about different factors to consider (e.g., one material that is good for insulation might be too stiff to be part of the finger portion of the glove). |
| **5 mins.**<br><br>**Explain**<br>**Evaluate** | • Clean up their stations and show their data to the teacher. | • Check for student progress, encouraging teams to discuss the project with each other and to bring in materials for construction. | — | — |
| **Extend**<br>**Elaborate** | **Homework:** Look at the materials and data collected to determine a design for gloves tomorrow. | | | |

### Construct a Glove Lesson Plan for Day 4 (75-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **10 mins.**<br><br>**Elicit**<br>**Evaluate** | • Teams read through and discuss the design criteria and double check the rubric. | • Make sure all members of the group are contributing and working together.<br>• Check in with groups. | — | • Focus on design criteria—ask students to draw an initial design blueprint and explain the reasoning behind each layer of material. |
| **65 mins.**<br><br>**Explore**<br>**Evaluate** | • In groups, work on glove construction and redesign, documenting changes in engineering notebooks. | • Encourage all students to be active participants in this process, evaluating and asking extension questions.<br>• Ask students to collect data on the designs and use them to inform their redesign. | • Review the physics vocabulary and concepts. | • Iteration of design<br>• Testing<br>• Prototyping<br>• Documentation of the design process |
| **Explore** | **Homework:** Groups work together to finish the construction or approach completion for testing. | | | |

## Construct a Glove Lesson Plan for Day 5 (55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **15 mins.**<br><br>**Elaborate**<br>**Evaluate** | • Groups meet to get ready for the official test. | • Make sure all members of the group are contributing and working together.<br>• Check in with groups. | — | • Make final changes to redesign or fine-tune the design to meet criteria and constraints. |
| **40 mins.**<br><br>**Explain**<br>**Evaluate** | • The engineers test the gloves for performance.<br>• The engineer wears the glove to pick up a pencil (or marker) to sign his or her name.<br>• The engineer wears the glove and collects temperature data for three minutes.<br>• The grading rubric for the final temperature and temperature change is in the lab handout.<br>• Groups waiting for the performance test or finished with it work on the presentation. | • For equipment protection, continue to ask students to use the inner vinyl glove, even if it's not in their design, to prevent the probe from being exposed to too much water.<br>• Evaluate glove performances and record the results of the performance test. | • Review the physics vocabulary and concepts of heat, heat transfer, and thermal equilibrium. | • Students are making visual models to communicate and explain the performance of their product.<br>• Students collect data for the final performance test and analyze the results. |
| **Extend** | **Homework:** Students work together to finish all the components of the presentation. | | | |

**Construct a Glove Lesson Plan for Day 6 (55-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **10 mins.**<br><br>**Elicit**<br>**Evaluate** | • Groups meet to get ready for presentations. | • Make sure all members of the group are contributing and working together.<br>• Check in with groups. | — | • Communication and presentation of ideas |
| **45 mins.**<br><br>**Evaluate**<br>**Elaborate** | • Groups give presentations of glove design. | • Encourage all students to be active participants in this process, evaluating and asking extension questions so students can elaborate on their ideas. | • Review the physics vocabulary and concepts. | • Communication of ideas—ask students to use the gloves as models and discuss performances.<br>• Ask students to consider the client aspect again and think about what sports might use these gloves. |
| **Evaluate** | **Homework:** Collect engineering notebooks (or class worksheets). Students write a conclusion to the Construct a Glove lab (similar to a design report). | | | |

## Optional Modification and Extension (Extend)

- The entire project can be modified to take place throughout the thermal equilibrium unit instead of at the end. One simple way is to ask students to consider each of the factors each day after introducing one type of concept. For example, after learning about convection, ask students to look at the winter gear that aims to prevent wind chill and write down what about it can be useful in the glove design.
- The format of the summative assessments can be really flexible depending on what makes sense for the classroom. Instead of having students make a poster presentation, they can make a sales pitch to panel of judges to explain their product. Students can write a user's manual or a TV advertisement script to explain the development and the pros and cons of the glove.

- The student handout has very specific step-by-step instructions because of the scaffolds created for the initial population of students. Prompts can be removed and adjusted to match student level. A teacher might consider asking students what kind of data they should collect, where the surface temperature probes should be located, and even open up the investigation so each group is working on a glove for a different sport so they have different criteria and constraints to consider in addition to heat transfer.

## Differentiated Instruction

### Special Needs

- Use the handout format or pre-printed engineering notebook templates for students who need the structure for documentation. Final presentation and self-assessment can be adapted to different format such as Google Presentations or pictures or images of the design process with labeled words.

### English Language Learners

- Have visuals around the classroom for the following terms: *insulation, thermometers, temperature scale, outdoor winter sports,* and *activities*. Provide students with visual and physical examples of conduction, convection, and radiation. Try to find culturally relevant activities or show images of the different activities. Provide sentence frames and use technologies for students to record in their engineering notebook.

## Supplemental Materials

- Handout 7B-1: Construct a Glove Inquiry Lab
- Handouts 7B-2, 7B-4–10: Construct a Glove
- Handout 7B-3: Construct a Glove: Modified
- Article: “Heat Management and Layering System” from the Appalachian Mountain Club, Boston Chapter, *www.hbbostonamc.org/docs/winterclothes.html*

*Source:* Adapted from NSTA Science by Design-Construct A Glove, Lead Author: Lee Pulis, Developed by TERC.

Name: ________________________________________ Block _______ Date: ___ / ___ / ___

# HANDOUT 7B-1: CONSTRUCT A GLOVE INQUIRY LAB

## SAFETY PRECAUTIONS

- Remind students about general lab safety procedures.
- Check with the school nurse or parents to make sure no student has a medical condition such as Raynaud's disease or poor circulation before allowing students to participate as a test subject for submerging hand in ice water.
- Carefully monitor the initial testing periods (especially during day 2). If the temperature of a participant's finger drops too quickly or is irregular, stop the experiment immediately.
- Participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Immediately wipe up any water spilled on the floor as this constitutes a slip/fall hazard.
- Keep water away from electrical receptacles as this is an electrical hazard.
- Students should wash their hands with soap and water upon completing this activity.

## DAY 1

### Background Information

- In this activity you will research, design, build, and performance-test a model of an insulated glove.
- You will investigate the physics of heat transfer and temperature regulation and the effectiveness of insulation materials and configurations.

### Design Challenge

1. You are a member of a product research and development team. You must design an insulated glove that keeps your hand as warm as possible in uncomfortably cold surroundings while still maintaining dexterity.

2. Present your group's final design to the class, including sketches, data, specifications, and limitations.

## Beginning Questions

1. What are the parts of the hand?

2. What are the functions of the hand?

3. In the space below, draw two sketches of a hand (top side and palm side) and label the important parts and functions.

**Top side:**

**Palm side:**

4. List as many special-purpose types of gloves as you can think of. When you are finished, place a "T" next to the gloves that are specifically designed to provide thermal protection.

5. What are temperature and heat, and how are they related?

6. To maintain your relatively constant body temperature of 37°C, what does your body do **automatically**?

7. What are some things you do **purposefully** to make yourself warmer or cooler?

*Source:* Modified from NSTA Science by Design-Construct A Glove, Lead Author: Lee Pulis, Developed by TERC

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# HANDOUT 7B-2: CONSTRUCT A GLOVE

## DAY 1: HOMEWORK

Read the article "Heat Management and Layering Systems" from the Appalachian Mountain Club (*www.hbbostonamc.org/docs/winterclothes.html*) and answer the following questions:

### Heat Management

1. What are two problems of exercising in winter?

2. In the winter, can it be dangerous to get too warm when playing outdoor sports? Explain the process in terms of heat and phase change.

### Proper Clothing Minimizes Heat Loss Under Many Different Conditions

3. Define the terms *conduction*, *convection*, *windchill*, *evaporation*, and *radiation.*

    a. Conduction

Give an example of a good conductor.

b. Convection

c. Windchill

Why should you stay dry when there is a strong wind on a cold day? (*Hint:* this has to do with windchill.)

d. Evaporation

How do you minimize evaporation on the skin on a cold day?

e. Radiation

## A Flexible Layering System Will Keep You Warm and Comfortable

4. What are some materials that are good to use as the inside wicking layer? What type of heat transfer is being affected?

5. What materials are good to use for the middle insulating layer?

6. What is the purpose of the outer shell layer?

## Cotton Is the Work of the Devil

7. What is one problem with using cotton?

## What Can You Use Instead?

8. Read through the list of materials and descriptions. Write down two materials you would like to use for the gloves and explain why you think they would be successful.

Name: ___________________________________ Block _______ Date: ___ / ___ / ___

# HANDOUT 7B-3: CONSTRUCT A GLOVE: MODIFIED

## DAY 1: HOMEWORK

Read the article "Heat Management and Layering Systems" from the Appalachian Mountain Club and answer the following questions:

### Heat Management

1. What are two problems with exercising in winter?

In the winter, you can get too ________________, or you can get too ___________ and sweat.

2. In the winter, why can it be dangerous to get too warm when playing outdoor sports? (Explain the process in terms of heat and phase change.)

When you're too _____________ , you ________________ to get rid of this heat, and in the cold, this sweat rapidly forms into liquid on your skin. When the sweat evaporates, it makes you colder.

### Proper Clothing Minimizes Heat Loss Under Many Different Conditions

3. Define the following terms and answer the questions about them:

   a. Conduction

Heat flows from any ________________________ object to any cold bodies (liquid, gas, or solid) ______________________ it unless something blocks it.

Give an example of a good conductor.

Water and ___________________ are very good conductors.

b. Convection

Quite a lot of cold air can pass over your body in very little time, and it will take plenty of your body ______________________ with it. This is heat loss by convection.

c. Windchill

If you are not shielded from the wind, you will lose ___________________________ from your body. This is because of windchill.

Why do you want to stay dry when there is a strong wind on a cold day? (HINT: this has to do with windchill)

Water helps wind conduct ____________________________ from your skin, so it's important not to get too sweaty or wet.

d. Evaporation

The raw process of having sweat ______________________ off your skin, so it's important not to get too sweaty or wet.

How do you minimize evaporation on the skin on a cold day?

To minimize both evaporative ________________________ and wind chill, you need a ___________________ layer closest to your skin.

e. Radiation

Radiation is similar to conduction, except that it refers to the transfer of heat as ________________________ light.

## A Flexible Layering System Will Keep You Warm and Comfortable

4. What are some materials that are good to use as the inside wicking layer? What type of heat transfer is being affected?

Usually ____________________ long underwear that wicks sweat away from the skin, and provides some insulation. Evaporation is being affected.

5. What materials are good to use for the middle insulating layer?

Breathable clothes that insulate by holding a warm _________________________ layer near the body, such as a ___________________ sweater or fluffy synthetic jacket.

6. What is the purpose of the outer shell layer?

The outer shell layer should provide _______________________ protection and help trap air within your insulation, while still allowing some ventilation and breath ability.

## Cotton Is the Work of the Devil

7. What is one problem with using cotton?

Cotton absorbs ______________ (and water vapor) like a sponge and holds it near your body for a long time.

## What Can You Use Instead?

8. Read through the list of materials and descriptions. Write down two materials you would like to use for the gloves, and explain why you think they would be successful.

Two materials I would like to use are ________________ and ________________. I would like to use these because:

Name: ___________________________________ Block _______ Date: ___ / ___ / ___

# HANDOUT 7B-4: CONSTRUCT A GLOVE

## DAY 2: INITIAL TESTING

### Background Information

Your **body,** like a home in cold climates, has a complex heating system that is programmed to maintain an internal temperature well above that of its surroundings. The digestion of food can be compared to the combustion of fuel in a furnace. Your circulatory system pipes heat to all parts of your body, just as air ducts or pipe loops do in the home.

Just as some parts of your home feel warmer or cooler than others, temperatures at different locations in and on your body can vary within a range of comfort or concern. Your body's many sensors can reduce or redirect heat or even activate a cooling system (sweating). Thermostats control home heating and cooling via on/off switches or speed-control fans and dampers, pumps, and valves. Rooms, or hands, that are too cool can be warmed by either adding heat or reducing heat with loss of insulation.

### Lab Procedures

Your team will work together to complete the following experiments concerning thermal energy, heating, cooling, and insulation. Each person is responsible for gathering and recording all data and answers.

1. Decide which person's hand will be used for this experiment (gloved and tested in cold water). Write that person's name below.

2. Why did you choose to use that person's hand? What factors did you consider? Is his or her hand large or small? Is it warm to touch? Does he or she have long fingernails, wear rings, and so on?

3. Trace his or her hand in the space below.

4. Add fingernails, lines, and markings to the drawing and label the fingertips, the knuckles, and the palm.

5. **Predict** which of those three areas of your teammate's hand will have the coolest and warmest **surface**.

Coolest:

Warmest:

6. **Measure** and **record** the surface temperature of each of those three parts of your teammate's hand. (Wrap or tape the wire of the surface temperature sensor around or against each part of the hand.) In the table provided, record your readings in degrees Celsius and describe briefly any difficulties you had reading the measurements.

| Area of Hand | Temperature (°C) | Difficulties |
|---|---|---|
| Fingertips | | |
| Knuckles | | |
| Palm | | |

7. Lightly wrap or tape the surface temperature sensor to the fingertip of the test hand. Put one of the smaller (tightest fitting) disposable gloves onto the test hand.

8. Place the gloved hand in the ice water, being careful not to allow water inside the glove. Monitor the temperature changes that occur over at least a three-minute period. Record those data in the table for data for test 1.

### Data for Test 1

| Time (min:sec) | Temperature (°C) |
|---|---|
| 0:30 | |
| 1:00 | |
| 1:30 | |
| 2:00 | |
| 2:30 | |
| 3:00 | |

9. Remove the gloved hand from the water and dry the outside of the glove with a towel. Do not remove the glove from the hand. In the space below, summarize your findings from the four-minute test.

10. Carefully put the store-bought glove on the test hand *over* the sensor and nonlatex glove already present. In the space below, describe the store-bought glove, including the material from which it is made.

11. Put the double-gloved hand in ice water, again being careful not to allow water inside either glove. Take temperature readings over at least a four-minute period. Record those data in the table for data for test 2.

**Data for Test 2**

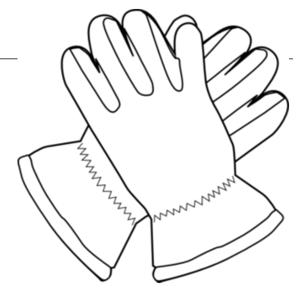
| Time (min:sec) | Temperature (°C) |
|---|---|
| 0:30 | |
| 1:00 | |
| 1:30 | |
| 2:00 | |
| 2:30 | |
| 3:00 | |

12. Carefully remove the gloves and sensors, keeping everything as dry as possible. Summarize your new data and compare them with the data from test 1.

Name: ___________________________________ Block _______ Date: ___ / ___ / ___

# HANDOUT 7B-5: CONSTRUCT A GLOVE

**Physics**



## DAY 2: HOMEWORK

1. What materials was the store-bought glove made from?

2. Do you think these materials worked well? Why or why not?

3. In the next class, you will test at least four different materials or material combinations. What materials will you bring to class to test? Why do you think those materials will be successful?

**Remember to bring materials to the next class to test!**

Name: ___________________________ Block _______ Date: ___ / ___ / ___

# HANDOUT 7B-6: CONSTRUCT A GLOVE

## DAY 3: MATERIALS TESTING

Today you will test several materials or material combinations to help you determine which materials you should use when you build your official glove.

### Lab Procedure

1. Lightly wrap or tape the surface temperature sensor to the fingertip of the test hand.
2. Insert the test hand into one of the smaller (tightest fitting) disposable gloves.
3. Apply a layer of insulation or spacer materials (your choice) to the outside of the gloved hand. Then carefully put a larger waterproof glove on the test hand over the insulation or spacer materials.
4. Put the gloved hand in ice water, being careful to not allow water inside either glove. Take temperature readings over a three-minute period, **recording the data in the data tables for materials testing on the pages that follow.**
5. Dry the outer glove and carefully remove it and the insulating material beneath it, leaving the surface temperature sensor and nonlatex inner glove in place.
6. Repeat steps 3–5 until at least four materials or material combinations have been tested.
7. When at least four tests have been completed, carefully remove all materials and return all equipment to the teacher.

| Trial Description | |
|---|---|
| Time (min:sec) | Temperature (°C) |
| 0:30 | |
| 1:00 | |
| 1:30 | |
| 2:00 | |
| 2:30 | |
| 3:00 | |

| Trial Description | |
|---|---|
| Time (min:sec) | Temperature (°C) |
| 0:30 | |
| 1:00 | |
| 1:30 | |
| 2:00 | |
| 2:30 | |
| 3:00 | |

| Trial Description | |
|---|---|
| Time (min:sec) | Temperature (°C) |
| 0:30 | |
| 1:00 | |
| 1:30 | |
| 2:00 | |
| 2:30 | |
| 3:00 | |

| Trial Description | |
|---|---|
| Time (min:sec) | Temperature (°C) |
| 0:30 | |
| 1:00 | |
| 1:30 | |
| 2:00 | |
| 2:30 | |
| 3:00 | |

| Trial Description | |
|---|---|
| Time (min:sec) | Temperature (°C) |
| 0:30 | |
| 1:00 | |
| 1:30 | |
| 2:00 | |
| 2:30 | |
| 3:00 | |

| Trial Description | |
|---|---|
| Time (min:sec) | Temperature (°C) |
| 0:30 | |
| 1:00 | |
| 1:30 | |
| 2:00 | |
| 2:30 | |
| 3:00 | |

| Trial Description | |
|---|---|
| **Time (min:sec)** | **Temperature (°C)** |
| 0:30 | |
| 1:00 | |
| 1:30 | |
| 2:00 | |
| 2:30 | |
| 3:00 | |

| Trial Description | |
|---|---|
| **Time (min:sec)** | **Temperature (°C)** |
| 0:30 | |
| 1:00 | |
| 1:30 | |
| 2:00 | |
| 2:30 | |
| 3:00 | |

Name: ______________________________ Block _______ Date: ___ / ___ / ___

# HANDOUT 7B-7: CONSTRUCT A GLOVE

## DAY 3: HOMEWORK

1. List the material(s) you tested.

2. Which materials provided the best insulation? Why were they good insulators? Please answer using complete sentences.

3. Which materials provided the worst insulation? Why were they poor insulators? Please answer using complete sentences.

4. What materials will you bring to class to use when you build your "official" glove next class? Why do you think you should use these materials?

**Remember to bring materials to the next class to build!**

Name: ___________________________________ Block _______ Date: ___ / ___ / ___

# HANDOUT 7B-8: CONSTRUCT A GLOVE

## DAY 4: BUILD YOUR GLOVE

Today your team will build your "official" glove. Use initial measurements and the results of your materials testing in your design process.

### Remember the Original "Design Challenge"

1. You are a member of a product research and development team. You must **design an insulated glove** that keeps your hand as warm as possible in uncomfortably cold surroundings while still maintaining **dexterity**.
2. Present your group's final design to the class, including sketches, data, specifications, and limitations

### Design Factors to Consider

- Comfort
- Durability
- Dexterity
- Flexibility
- Softness
- Bulk
- Stiffness
- Warmth
- Fit form and size
- Cushioning
- Drying time
- Weight
- Conduction/convection/radiation
- Temperature

Use your time in class to build and test your "official" glove. Please remember to use materials conservatively so that everyone has enough. It is also important that you clean up after yourself and return any unused materials. Good luck and happy constructing!

## Glove Testing Data

As you build your glove, feel free to use the following tables to record data about your glove.

| Trial Description | |
|---|---|
| Time (min:sec) | Temperature (°C) |
| 0:30 | |
| 1:00 | |
| 1:30 | |
| 2:00 | |
| 2:30 | |
| 3:00 | |

| Trial Description | |
|---|---|
| Time (min:sec) | Temperature (°C) |
| 0:30 | |
| 1:00 | |
| 1:30 | |
| 2:00 | |
| 2:30 | |
| 3:00 | |

| Trial Description | |
|---|---|
| Time (min:sec) | Temperature (°C) |
| 0:30 | |
| 1:00 | |
| 1:30 | |
| 2:00 | |
| 2:30 | |
| 3:00 | |

| Trial Description | |
|---|---|
| Time (min:sec) | Temperature (°C) |
| 0:30 | |
| 1:00 | |
| 1:30 | |
| 2:00 | |
| 2:30 | |
| 3:00 | |

Name: ______________________________ Block _______ Date: ___ / ___ / ___

# HANDOUT 7B-9: CONSTRUCT A GLOVE

## DAYS 5 AND 6: TEST AND SHARE YOUR GLOVE

- Day 5: Your team will test your "official" glove and begin preparing your presentation.
- Day 5 homework: Your team will prepare a presentation to teach the rest of the class about your design.
- Day 6: Your team will present your glove and your design process to the class.

### The Tests

- Temperature: Place a gloved hand in ice water and measure the temperature periodically for three minutes. The goal is to keep your hand as warm as possible.
- Dexterity: You will be asked to complete a few tasks, such as picking up a pencil with the gloved hand.

### The Presentation

You will present your glove to the class. Your presentation must include the following elements:

1. A labeled sketch of your glove.
2. Data from Day 3: Materials Testing.
3. An explanation for your choice of materials.
4. An explanation of the limitations of your glove.
5. An explanation of at least one problem your team encountered and how you went about solving it.
6. An explanation of the physics concepts you considered in the design of the glove. Consider temperature, heat, heat transfer, conduction, convection, and radiation.

### Rubric for the Glove Test on Day 5

| Criterion | Exemplary (4 pts.) | Accomplished (3 pts.) | Developing (2 pts.) | Beginning (1 pt.) |
|---|---|---|---|---|
| **Final temperature** | Final temperature is above initial temperature. | Final temperature is the same as initial temperature. | Final temperature is below the initial temperature. | Final temperature is extremely low. |
| **Consistency of temperature** | Temperature is constant for the last two minutes. | Temperature is constant for the last minute. | Temperature is continuously decreasing but leveling out. | Temperature is continuously decreasing. |
| **Dexterity** | Able to complete two dexterity tasks completely. | Able to complete one dexterity task completely and one task partially. | Able to complete two dexterity tasks partially. | Unable to complete the dexterity tasks. |

**TOTAL _______ / 12**

## Rubric for the Glove Presentation on Day 6

| Criterion | Exemplary (4 pts.) | Accomplished (3 pts.) | Developing (2 pts.) | Beginning (1 pt.) |
|---|---|---|---|---|
| **Labeled sketch** | Extremely neatly drawn sketch of both sides of the glove. All parts and materials are thoroughly labeled. | Somewhat neatly drawn sketch of both sides of the glove. Most parts and materials are labeled. | Neatly drawn sketch of one side of the glove. Many parts and materials are labeled. | Sketch of glove is drawn and labeled. |
| **Data from day 3** | 3 minutes of data are presented for at least 3 designs. | 3 minutes of data are presented for two designs. | Data are presented for two designs. | Data are presented for one design. |
| **Explanation of the choice of materials** | A thorough and detailed explanation is provided for the choice of each material. Choices are grounded in physics. | A thorough and detailed explanation is provided for the choice of most materials. Choices are grounded in physics. | An explanation is provided for the choice of most materials. Most choices are grounded in physics. | Some explanations are provided. |
| **Limitations of the glove** | At least two limitations of the glove are clearly presented and explained. | At least one limitation of the glove is clearly presented and explained. | At least one limitation of the glove is presented and explained. | At least one limitation of the glove is presented. |
| **One problem and how you solved it** | Problem and solution are clearly and thoroughly presented. | Problem and solution are presented. | Problem is presented. | No problems are presented. |
| **Physics concepts: heat and temperature** | Both heat and temperature are used completely correctly. | Both heat and temperature are used mostly correctly. | Either heat or temperature is used mostly correctly. | Both heat and temperature are used. |
| **Physics concepts: heat transfer methods** | Method(s) of heat transfer are accurately identified and explained. | Method(s) of heat transfer are accurately identified and attempted to be explained. | Method(s) of heat transfer are inaccurately identified but explained somewhat correctly. | Method(s) of heat transfer are inaccurately identified and inaccurately explained. |

**TOTAL ______ / 28**

Team Names: ____________________________________________

Name: ____________________________ Date: __________

# HANDOUT 7B-10: CONSTRUCT A GLOVE

## CONCLUSION

Describe in a paragraph or two the approach your team took in the designing and building of your glove. Your response should include answers to the following questions and might include the following terms or design factors.

1. What one feature of your insulated glove design are you most proud of?
2. Did you make good choices regarding which materials to use in your design? Why did you choose those materials?
3. If you had a chance to design another glove, which materials might you use instead?
4. Discuss at least one problem your team encountered and how you went about solving it.
5. Who were your partners, and how did your group work as a team?
6. What might your new glove design be used for? Sport? Occupation?

## Design Factors to Consider

Discuss the following design considerations while writing your conclusion:

- Comfort
- Durability
- Dexterity
- Flexibility
- Softness
- Bulk
- Stiffness

- Warmth
- Fit form and size
- Cushioning
- Drying time
- Weight
- Conduction, convection, and radiation
- Temperature

# ACTIVITY 7C: COFFEE JOULIES

**Contributor: Shu-Yee Chen Freake**

**Time frame:** 4 class periods

**Physics focus:** Heat versus temperature, heat transfer, thermal equilibrium, and phase change

**Engineering focus:** Analysis, models, systems, and communication

### Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Design an experiment to test different numbers of and treatment procedures using Coffee Joulies. | • Design a manual about how to use the product to maximize the coffee-drinking experience under different conditions. |
| **Analysis** | • Analysis of a thermal equilibrium graph<br>• Phase change material and phase change graph | • Analysis of different ways of preparing hot coffee<br>• Taste<br>• Analysis of the container size and properties of the container |
| **Models** | • Mechanism of heat transfer | • Use a mathematical model to predict performances. |
| **Systems** | • Coffee and container versus surroundings | • Container<br>• Cream and sugar additions to the coffee<br>• Coffee Joulies |

## PROJECT OVERVIEW

This project started with a discussion during a Project Infuse meeting in which someone mentioned a Kickstarter product called Coffee Joulies. Since Coffee Joulies are made of an engineered phase-change material that the developers claimed would keep coffee at a comfortable and safe drinking temperature (140°F), it seemed like a good material to analyze and use for exploring the concept of heat transfer and phase change for a physics class.

Coffee Joulies are made of phase-change materials with a stainless steel shell and can quickly transfer heat energy from boiling hot coffee and lower its temperature as the phase-changing materials inside them melt. The coffee can stay at that optimal drinking temperature for a while during this process.

But how can a teacher get enough sets of Coffee Joulies for students to run tests? Well, it turns out that a nice email to the company explaining the science and engineering connection in the classroom might be enough to acquire a class set to test! Of course, if that doesn't work out, any other product that can address thermal equilibrium and heat transfer can be used such as a thermos, cooler, foam cup, or other insulating materials.

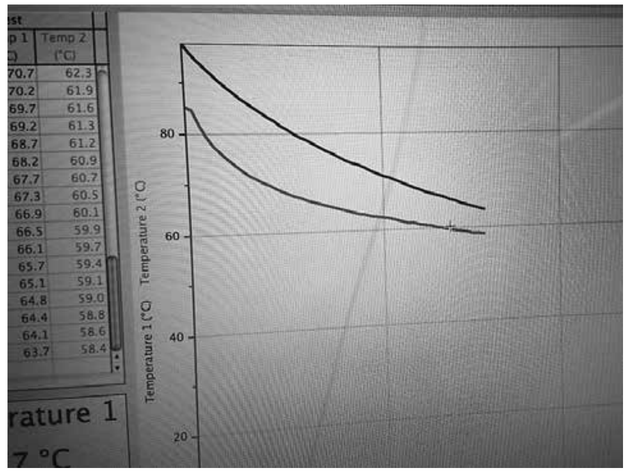
**Students' data-collection setups using temperature probes, insulator cups, and a laptop for monitoring thermal equilibrium**

Since this engineering-infused lesson starts with a manufactured product, it is not design-centered. It is an opportunity to explore and practice using analysis and models as part of the engineering practices. Therefore, the idea of this activity is using the scientific process of designing an experiment as a context. Then, students experience the connection of using the science data as tools of analysis and create visual models to communicate about the product.

It is also a way to do a wet lab that combines all those abstract concepts of temperature, thermal equilibrium, phase change, and heat transfer. Students also have suggested this can be a great final project after learning the physics of heat energy, because it can demonstrate their understanding of concepts. This activity can probably be done with any other interesting product such as an insulated food or beverage container, a lunch box, or even some camping equipment. Students will use those data to compare their experimental group and control group.

**One group's setup of four cups to compare hot water four ways (with milk, without milk, with Coffee Joulies, and without Coffee Joulies)**

## BIG IDEAS




**Screen of computer running software students use to collect data**

- **Physics:** Energy is a quantitative property of a system that depends on the motion and interactions of matter and radiation within that system. Energy cannot be created or destroyed but it can be transferred into or out of a system.
- **Engineering:** Engineers create visual, mathematical, or three-dimensional models to test and communicate ideas. Engineers use mathematical and scientific models as design tools. Engineers use analysis to predict the behavior of a designed system and verify the quality of a design solution.

## Connection to the *Next Generation Science Standards*

### Performance Expectation

- HS-PS3-4: Plan and conduct an investigation to provide evidence that the transfer of thermal energy when two components of different temperature are combined in a closed system results in a more uniform energy distribution among the components in the system (second law of thermodynamics).

### Science and Engineering Practices

- Developing and using models
- Planning and carrying out investigations
- Using mathematics and computational thinking
- Constructing explanations and designing solutions
- Engaging in argument from evidence
- Obtaining, evaluating, and communicating information

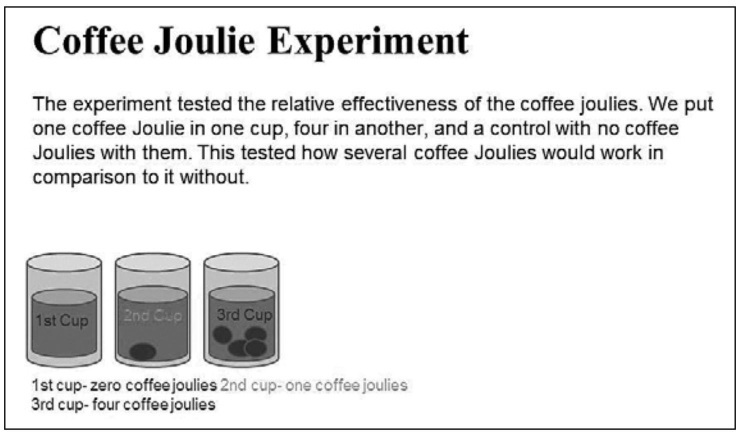
### Disciplinary Core Ideas

- PS3.B: Conservation of Energy and Energy Transfer

- PS3.D: Energy in Chemical Processes and Everyday Life

### Crosscutting Concepts

- Systems and system models
- Energy and matter




**Students' presentation slide showing how they set up their experiment**

## Assessment: Determining Acceptable Evidence

### Formative

- Mini-conferences with groups during the planning process
- Interview about goals and setups during the data collection time
- Class discussion and chart discussion about experimental design and setup
- Do Now questions, class notes and discussions, and homework questions

### Summative

- Individual: engineering notebook, homework assignments, letter to engineers
- Group: presentation slides, oral presentation

## Materials and Preparation

### Materials (Groups of 4)

- 1–4 temperature probes (or thermometers)
- 1 laptop or LabQuest running probe software (or graph paper)
- 1 set of Coffee Joulies (or another product such as an insulated food or beverage container, or an insulated lunch box)
- Foam cups and lids
- Safety chemical splash goggles, nonlatex aprons, and thermal gloves
- Large trays or plastic bins to hold the cups during experiment to prevent spills of hot water on people or electronic equipment.

### Class Equipment

- Electric kettle for boiling water
- Ice

## Safety

- Remind students about general lab safety procedures.
- Everyone should wear safety goggles during the experiment.
- The teacher should make sure the water containers are secured in a bin or tray to prevent spills.
- Immediately wipe up water that spills on the floor. This creates a slip-and-fall hazard.
- Keep water away from electrical receptacles as this creates an electrical hazard.
- Use caution when working with hot water—it can burn skin!
- Remind students about safety of electronic equipment around water and minimize movement whenever possible.
- The teacher should be the one handling hot and boiling water for distribution.
- Participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Students should wash their hands with soap and water upon completing this activity.

### Coffee Joulies Lesson Plan for Day 1 (55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **2 mins.**<br><br>**Engage** | — | • Relate to the class that McDonald's was sued for serving coffee that caused third-degree burns. Whereas most people prefer to drink coffee that is 140°F–160°F, the coffee McDonald's served was between 180°F–190°F, McDonald's lost the case and was told to pay $600,000, which was then negotiated to a smaller amount. | — | — |
| **10 mins.**<br><br>**Elicit**<br>**Evaluate** | • Using the think-pair-share technique, work on the Do Now questions.<br>• What is heat transfer?<br>• Give an example from your daily life for each type of heat transfer (conduction, convection, and radiation).<br>• How does a thermometer measure the temperature of a cup of water? | • All students have some prior knowledge about temperature differences and heat transfer, sometimes from their middle school curriculum. It is important to elicit their prior knowledge and experiences and evaluate what kind of vocabulary they used or misused from those experiences. | • Heat transfer methods<br>• Temperature versus heat | — |

Coffee Joulies Lesson Plan for Day 1 (continued)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **10 mins.**<br><br>**Explore** | • Work on the temperature sensing activity.<br>• Set up three cups of water of different temperatures.<br>• Put their hands in each cup and describe their sensation.<br>• Place fingers in hot and cold water simultaneously. Wait 30 seconds and then transfer fingers to the room temperature cup. Describe sensation. | • Some students might resist doing this activity because they believe they already "know" the expected result. It is important to engage students and encourage them to participate so they can have common experiences and use some common descriptive language to build their exploration together. | • Thermal equilibrium<br>• Heat transfer | — |
| **15 mins.**<br><br>**Explain** | • While the data are accumulating, read the temperature notes section and highlight or write notes and questions. | • Discuss what they felt during the water mini-activity.<br>• Watch the thermal equilibrium temperature demonstration.<br>• Ask students to do most of the explanation to create a scientific model of temperature. Before the demonstration, make sure students have written down their prediction so they can be engaged in discovering inconsistencies and improving their models of thermal equilibrium. | • Explain thermal equilibrium, temperature, heat, and atomic structure. | • Discuss similarities and differences between scientific models and engineering models. |

Coffee Joulies Lesson Plan for Day 1 (continued)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **20 mins.**<br><br>**Elaborate**<br>**Evaluate** | • Take class notes on definition of temperature, thermal energy, and thermal equilibrium.<br>• Work on discussion questions. | • Use drawings, movements, images, and videos to explain and elaborate on students' models.<br>• Evaluate student understanding by asking students to explain to each other. | • Temperature scales<br>• Definitions of thermal energy and temperature | — |
| **Extend** | **Homework:** Review questions related to temperature, thermal energy, and thermal equilibrium. (Old state examination questions can be used as review items.) | | | |

### Coffee Joulies Lesson Plan for Day 2 (75-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **2 mins.**<br>**Engage** | — | • Tell students, "Starbucks sells 4 million cups of coffee in the United States every day." | — | — |
| **10 mins.**<br>**Elicit**<br>**Evaluate** | • Peer-edit the homework from last night. Discuss each other's answers first, then switch papers to grade the open-response question. | • Provide students with the answer key to score open-response questions.<br>• Ask for questions and explanations to determine where students are with the basic definitions of key terms. | • Review heat, thermal energy, temperature, and thermal equilibrium. | — |
| **15 mins.**<br>**Elaborate**<br>**Explain** | • Watch promotional videos of Coffee Joulies on the Coffee Joulies website (*www.joulies.com*).<br>• Write down discussion points and questions. Form groups based on the questions generated. | • Briefly explain what a phase-change material is. Ask students to spend time thinking more about it while their experiment is running.<br>• Elaborate on the claim made by Coffee Joulies—that they keep temperature constant by using the energy to melt the phase-change material rather than lowering the temperature of the coffee. | • Focus on heat transfer and energy transformation in this case, not on phase-change yet. | • Discuss similarities and differences between scientific and engineering systems.<br>• Evaluate design materials for applicability. |

Coffee Joulies Lesson Plan for Day 2 (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **40 mins. Explore Evaluate** | • Set up, conduct, and test Coffee Joulies according to their experiment's conditions. They collect data using the temperature probes. They can run the experiment two to three times if time allows. | • The teacher should evaluate students' experimental designs by asking questions about their data collection. For example, some groups might decide to leave their "system" open because they believe people usually drink coffee without a lid on the cup (closed). That can be a great opportunity to discuss systems and experimental design! | • Experimental design (focusing on setting up good controls and variables to test)<br>• Data collection. | • Emphasize using the data from this experiment as a way to analyze the performance of the product. |
| **10 mins. Evaluate** | • Clean up stations. | • Evaluate student progress and understanding by asking questions during check-in. | — | — |
| **Extend** | • **Homework:** Review questions related to temperature, thermal energy, and thermal equilibrium. (Old state examination questions can be used as review items.)<br>• **Online assignment:** Search videos online that demonstrates "phases of matter and phase change graph." Be ready to share what you learned, as well as questions you might have about different phases of matter and phase change graphs. | | | |

### Coffee Joulies Lesson Plan for Day 3 (55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **10 mins.**<br><br>**Evaluate** | • Go over Do Now questions from homework assignment. | • Check in with students about their understanding of physics concepts taught and determine what they know about phase change from last night's homework. | • Review heat transfer and thermal equilibrium.<br>• Introduce phase change. | — |
| **15 mins.**<br><br>**Explain**<br>**Extend** | • As a class, discuss and take notes on phases of matter and phase-change graph interpretation. | • Use what students have learned and start with their questions to build an understanding for phases of matter and phase change.<br>• Extend the topic: Make connections by brainstorming about important phase-change materials used daily. | — | • Make connections to phase-change materials used to solve problems (e.g., ice packs for food or medicine and energy-efficient freezers). |
| **30 mins.**<br><br>**Explain**<br>**Elaborate** | • Work on data analysis and putting together a presentation that includes their experiment and the application of a different kind of phase-change material. | • Encourage students to use graphs and create visual models to explain their experiment and findings. | • Review the graph of temperature versus time.<br>• Review concepts from the entire unit. | • Analyze data for product evaluation.<br>• Create models to communicate ideas. |
| **Extend** | **Homework:** Review questions related to phases of matter and phase changes. Old state examination questions can be used for review. Students should coordinate with each other to finish the presentation. | | | |

**Coffee Joulies Lesson Plan for Day 4 (55-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **10 mins.**<br><br>**Evaluate** | • Groups meet to prep and get ready for presentations. | • Make sure all members of the group are contributing and working together. Check in with groups. | — | • Communication |
| **45 mins.**<br><br>**Elaborate**<br>**Evaluate** | • In groups, present experiment setup, data collected, analysis, and conclusions about the effectiveness of Coffee Joulies. | • Encourage all students to be active participants in this process, evaluating and asking extension questions so students can elaborate on their ideas. | • Review the physics vocabulary and concepts. | • Communication of ideas<br>• Using analysis and models to predict product performance |
| **Extend** | • Collect engineering notebooks and homework questions from the previous night.<br>• **Optional assignment:** Write a thank-you letter to the Coffee Joulies founders. | | | |

## Optional Modification and Extension (Extend)

- Because the science and engineering models are used to evaluate a product, the teacher can expand this kind of investigation by having different groups test different objects with similar functions—travels mugs (which students can bring in or ask to borrow from other people), heating blankets, stones that are meant to cool drinks, and so on.
- One suggestion students have made is to do this investigation at the end of the heat energy unit and incorporate the rate of heat transfer, finding out the amount of heat necessary for phase change to happen completely, the specific heat capacity of the material, and so on. Students can do more mathematical analysis if this activity is done at the end of the physics unit.
- The final project doesn't have to be a presentation of the experiment; it can be a sales ad that students put together to promote their way of using this product.

## Differentiated Instruction

### Special Needs

- Provide students with a chart or checklist for daily goals. Use preprinted engineering notebook templates for students who need the structure for documentation. For students who might struggle with a handwritten engineering notebook, allow different types of documentation such as using a computer to type or phones or tablets to take pictures and then add captions.

### English Language Learners

- Have visuals around the classroom for the terms and concepts of *thermos, insulation, different temperature scales,* and *atomic models*. Provide students with visual and physical examples of conduction, convection, and radiation. Try to find culturally relevant extension questions, such as images of a traditional stove for a different culture or the type of clothing people might wear for protection from heat or cold. Provide sentence frames and use technologies for students to record in their engineering notebook.

## Supplemental Materials

- Handout 7C-1: How Do You Like Your Coffee?, which is to be used by students daily during activities for main goals and objectives, Do Now questions, and key activities and homework assignments.
- Handout 7C-2: Kinetic Model of Temperature
- Samples of Google Presentations put together by students, online at *www.nsta.org/eggdrop.*
- Samples of students' letters to the Coffee Joulies founders, at *www.nsta.org/eggdrop.*

# HANDOUT 7C-1: HOW DO YOU LIKE YOUR COFFEE?

**Heat Transfer, Thermal Equilibrium, and Phase Change**


***Note:*** You should be using your **engineering notebook** for this laboratory investigation throughout. Set up your notebook for the "How Do You Like Your Coffee?" challenge, then answer all of your questions in your engineering notebook

## DO NOW QUESTIONS

1. What is heat transfer?
2. Give an example from your daily life for each type of heat transfer.
    a. Conduction
    b. Convection
    c. Radiation
3. How does a thermometer measure the temperature of a cup of water?

## GOALS

- Use engineering and science skills and concepts to analyze and predict the behavior of a designed system using Coffee Joulies.
- Provide mathematical models to communicate how effective the Coffee Joulies are in your system.
- Explain how heat transfer happens within your system.
- Explain how the phase-change material inside the Coffee Joulie works.
- Construct a model to use phase change of a certain material in a new design to perform specific functions.

## CONSTRAINTS

You have only the materials provided (see the "Day 2 Activity: Coffee Joulies Materials Testing" section in this handout) and one class period to put together your presentation. You will be presenting on the fourth day of this activity.

## SAFETY PRECAUTIONS

- Follow all general lab safety procedures.
- Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity
- Immediately wipe up water that spills on the floor. Spilled water creates a slip-and-fall hazard.
- Keep water away from electrical receptacles—electrical hazard
- Use caution when working with hot water. It can burn skin.
- The teacher should be the one handling hot and boiling water for distribution.
- Wash your hands with soap and water upon completing this activity.

## DAY 1 ACTIVITY: WHAT IS TEMPERATURE?

### Materials per Group

- Safety chemical splash goggles, nonlatex aprons, and thermal gloves for each student
- 4 foam cups

## Content Objectives

- Distinguish between temperature (average kinetic energy of particle) and thermal energy.
- Identify and use appropriate units for temperature and thermal energy. Describe the common temperature scales and memorize certain values.

### Sensing Temperature With Water

There are three contaniers filled with water, labeled *A, B,* and *C.* You will be exploring and describing the temperature of these containers by sensing them with your finger.

1. Fill cup A with water from container A. Insert a finger into the water. Describe your sensation.
2. Fill cup B with water from container B. Insert a finger into the water. Describe your sensation.
3. Fill cup C with water from container C. Insert a finger into the water. Describe your sensation.
4. Place your fingers from your left hand into the very warm water. Place your fingers from your right hand into the cold water. Wait about 30 seconds. Now place the fingers from both hands in the room temperature water. Describe what you feel.

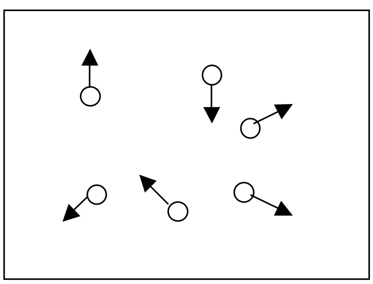
**Temperature Notes: Take notes while following along the class discussion on temperature and heat.**

## Discussion Questions

1. Complete the table below. When you write the names of the temperature scales, remember that spelling counts!

| Scale Name | Absolute Zero | Freezing Point of Water | Room Temperature | Body Temperature | Boiling Point of Water |
|---|---|---|---|---|---|
| Celsius | | | | 37°C | |
| | | 273 K | | | 373 K |
| | −459.7°F | | ~70°F | | |

2. Temperature Versus Thermal Energy

| | |
|---|---|
|  | |
| This box shows a gas with a certain **temperature** and a certain **internal thermal energy**. | Draw a gas with the **same** temperature but a **different** internal thermal energy. Did you show *more* internal energy or *less*? |
| | |
| Draw a gas with a **different** temperature but the **same** internal thermal energy as the first box. Did you show *higher* temperature or *lower*? | Suppose you have a gas with *heavier* particles than the first box. Can you draw a gas with the **same** temperature and the **same** internal thermal energy? |

3. When using a glass thermometer to check a person's temperature, why do you need to wait before reading the thermometer?

## DAY 2 ACTIVITY: COFFEE JOULIES MATERIALS TESTING

### Content Objectives

- Explain that heat moves from regions of high temperature to regions of cold temperature and how this results in thermal equilibirum.
- Relate a temperature–time graph for a substance to the phase (solid, liquid, or gas) of the substance and its boiling and melting points.

## SAFETY PRECAUTIONS

- Follow all general lab safety procedures.
- Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Immediately wipe up water that spills on the floor. Spilled water creates a slip-and-fall hazard.
- Keep water away from electrical receptacles—electrical hazard.
- Use caution when working with hot water. It can burn skin.
- The teacher should be the one handling hot and boiling water for distribution.
- Wash your hands with soap and water upon completing this activity.

### Goals

You will use Coffee Joulies and temperature probes to collect data for temperature versus time to determine how well Coffee Joulies work. You will test different conditions of drinking coffee based on a question you generated as a group (e.g., should you warm up the Coffee Joulies before putting them into the coffee with milk versus drinking black coffee, how do you provide instructions to people who brew/drink coffee at different temperature, testing how the amount of coffee is most optimal for the Coffee Joulies given, and so on), design an experiment, collect data, and present your data.

### Materials

- Safety chemical splash goggles, nonlatex aprons, and thermal gloves for each student
- Coffee Joulies (up to five per group)
- Temperature probes (two to four per group) with LabQuest or computer
- Electric kettle

- Foam cups and lids for thermal equilibrium experiments

## Product

By the end of the class today, your group should finish collecting data to answer the question you posed about Coffee Joulies.

## Class Discussion

1. What are Coffee Joulies? Watch the Coffee Joulies Kickstarter campaign video at *www.joulies.com.*
    a. What is the real "claim to fame" for Coffee Joulies?
    b. What questions do you have after watching this video? How would you test your question using the materials and the Coffee Joulies provided?
    c. How would you design a way to answer your questions? Discuss and write down an outlined procedure and sketch how you will set up your experiment to answer your question.
2. Thermal equilibrium in a simple system of coffee and the room temperature in a mug
    a. What does the thermal equilibrium graph look like?
    b. What is the direction of heat transfer?
    c. What happens to the temperature of the objects involved in this system?
    d. What are the parts of this system?

***Notes for data collection:* Don't forget to print out your data before you shut down the computers!**

## DAY 3 ACTIVITY: DATA ANALYSIS AND PREPARATION FOR PRESENTATION

### Content Objectives

- Explain that heat moves from regions of high temperature to regions of cold temperature and how this results in thermal equilibirum.
- Relate a temperature–time graph for a substance to the phase (solid, liquid, gas) of the substances and its boiling and melting points.
- Predict the phase of a material based on its temperature and its melting and boiling points.
- Relate energy to changes of phase, using appropriate vocabulary for phase change (melting, freezing, condensing, and subliming).

### Goals

By the end of the class today, your group should put together a presentation to present the following:

1. Explain how you analyzed the effectiveness of Coffee Joulies. How well does the system you designed with Coffee Joulies change the thermal equilibrium graph? Why was using a phase change material important in the design of Coffee Joulies?
2. Research and propose another phase-change material that can be used in your life. Explain the type of phase change that occurs, how the material is used, and what the limitations of that material are.

### Materials

- Your data from previous experiment
- Computers for research and presentation
- Papers and art supplies

### Class Discussion

1. What is phase change material?
2. What is the difference between *phase change* and *temperature change*?
3. What are the names of different types of phase changes?

Name: ______________________________ Date: ______________

# HANDOUT 7C-2: KINETIC MODEL OF TEMPERATURE

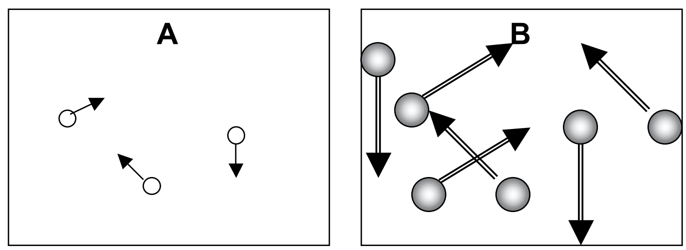
**Claims, Evidence, and Reasoning**

## PURPOSE

The purpose is to practice answering an open-response question using the "claims, evidence, and reasoning" method and to show you understand the kinetic model of temperature.

## QUESTION

Figures A and B represent boxes full of gas. Which box represents a gas at higher temperature? You will answer this question in three or four parts, as shown later.




**Claim:** In the space below, write a sentence that states the answer to the question.

**Evidence:** In the space below, write a sentence that describes what you see in the figure that supports your claim.

**Reasoning:** In the space below, write a sentence that explains what is meant by higher temperature that relates to the evidence you described.

**Rebuttal (optional):** In the space below, explain any assumptions you are making in your answers or discuss information you can see in Figures A and B that does *not* provide evidence for your claim.

*Source:* Developed by the Newton North High School Physics Team in 2012.

8

# Engineering Infusion With Waves

The *Next Generation Science Standards* (*NGSS*) have a strong emphasis on the important, yet mostly invisible, topic of electromagnetic radiation. It is difficult for students to understand the concepts of waves and wave energy without some tangible and meaningful experience exploring properties of waves. We wanted to ensure students have a strong foundation in the properties of waves, and since it is difficult to manipulate all the frequencies of electromagnetic waves easily in the classroom, concrete design activities that require a strong understanding of wave properties and wave model are a great option to help students gain understanding.

Before beginning a waves unit, take out a guitar and ask students, "What are some considerations engineers have to think about when designing a musical instrument?" The design of the instrument goes way beyond just making some vibrations, allowing users to easily tune the guitar in order to make beautiful sounds of different pitch and clarity. Ask students to extend their understanding of the wave model by looking at light as a wave. Why not ask them to evaluate criteria for a fun game or toy when they design a game using lenses and mirrors? The client-centered aspect of engineering can be the real motivator for many students, encouraging higher engagement than a traditional physics lab of working with tuning forks and drawing reflective rays on paper.

The pendulum activity is an interesting attempt at infusion, where the first portion is like a physics pendulum lab for understanding period and length. Then, the engineering challenge is added by asking students to match the pendulum to a beat and make a pendulum that can produce a sound at the top of the swing. Table 8.1 (p. 290) provides basic curricular details for the activities in this chapter.

**TABLE 8.1. Chapter 8 Activities**

| Activity Name | Physics Concepts | Core Concepts | Class Periods | Brief Description |
|---|---|---|---|---|
| **Pendulums–And the Beat Goes On** | • Period<br>• Frequency<br>• Simple harmonic motion | • Design<br>• Analysis | 3 | Students build a pendulum that acts as a metronome to keep pace with the beat of a song. |
| **Guitar Design Project–Exploring How Music Is Made** | • Sound<br>• Wave properties | • Design<br>• Analysis<br>• Models | 2 | Students use household items to make a functional guitar that can play at least one octave and a song. |
| **Game On!** | • Refraction<br>• Reflection | • Design<br>• Analysis<br>• Models<br>• Systems | 3 | Students design a board game that uses mirrors and lenses and demonstrates students' understanding of optics concepts. |

# ACTIVITY 8A: PENDULUMS—AND THE BEAT GOES ON

**Contributors: Julie Mills, Marna Eckels, and Neil Kenny**

**Time frame:** 3 class periods
**Physics focus:** Pendulum motion, period, and frequency
**Engineering focus:** Design, models, iteration, test, and evaluate

### Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Period versus length | • Design a functional pendulum that makes a clicking sound. |
| **Analysis** | • Angle of the pendulum<br>• Graphic analysis<br>• Period<br>• Frequency | • Materials analysis for strength, loss of energy from the sound<br>• Physics analysis to make prediction and inform design |
| **Models** | • Simple harmonic oscillation<br>• Wave model<br>• Energy transfer | • Model for clock, metronomes |
| **Systems** | • Pendulum itself as a system<br>• Energy | • Swing system<br>• Weight system<br>• Click system |

## PROJECT OVERVIEW

For an introductory physics course, pendulum motion can be a great segue topic between motion and waves. This engineering design challenge has components of the more traditional physics lab—in which students must determine how various factors affect a pendulum's period—but also includes an engaging engineering challenge.

The traditional physics pendulum lab asks students to test variables of length, mass, and angle to determine how these factors affect the period of a pendulum. For this engineering design challenge, students must build a pendulum that will act as a metronome, keeping time to a song of their choice. Because they probably do not have much prior knowledge of what factors affect the period of a pendulum, they must spend the first part of the activity determining how to adjust a pendulum to change its period. The first part of this activity more closely matches an inquiry-based physics lab. Students must gather data in a data table and present their findings in graph form for the class. When all groups have presented their findings, a consensus is found as to which factor or factors affect the period of a pendulum (length) and which do not (mass and angle). Students are asked to apply this new knowledge in an engaging way.

The engineering challenge portion of this activity asks students to find a song (school-appropriate is typically the only criterion) and to create a pendulum that keeps the beat to the song for at least 10 swings. Songs can be played using any electronic device available in the classroom. Finding the beat of a song can be tricky for some students, so we suggest beginning this project by asking students to rank themselves, on a scale of 1 to 10 , on their ability to find and clap to the beat. This helps create groups of mixed ability, ensuring that there won't be a group that is unsuccessful because its members can't determine the beat of a song. After students pick a song, they must determine the beat of the song and then create a pendulum that swings to the beat. Because they know that length is the only factor that affects the period, this engineering portion usually takes less than one class period. At a designated time, groups will present their pendulum–song combination to the class.

**Students' initial prototype of the pendulum**

The complexity (and the engineering aspect) can be enhanced by requiring students to create a pendulum metronome that makes an audible click for each swing (much like an actual metronome).

Throughout the project, students are collecting data and making calculations in their engineering notebooks. The graphs are created and inserted in the notebook. Summary questions that need to be answered by the students are provided. The rubric for this project is on the student handout (p. 302) and assesses students in the areas of data collection and calculation, graphs, written answers to the questions, and metronome performance.

## BIG IDEAS

- **Physics:** Energy cannot be created or destroyed but can be converted to different forms—potential to kinetic to sound.

- **Engineering:** Design is an iterative process that can be used to produce a product. Testing and evaluating prototypes can provide essential feedback that leads to changes and refinements in the design.

## Connection to the *Next Generation Science Standards*

### Performance Expectations

- HS-PS3-2: Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motions of particles (objects) and energy associated with the relative position of particles (objects).
- HS-PS3-3: Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.

### Science and Engineering Practices

- Asking questions and defining problems
- Planning and carrying out investigations
- Analyzing and interpreting data
- Using mathemats and computational thinking
- Constructing explanations and designing solutions
- Obtaining, evaluating, and communicating information

### Disciplinary Core Ideas

- PS3.A: Definitions of Energy
- PS3.D: Energy in Chemical Processes and Everyday Life
- ETS1.A: Defining and Delimiting Engineering Problems

### Crosscutting Concepts

- Patterns
- Cause and effect

## Assessment: Determining Acceptable Evidence

### Formative

- Group presentations of data and graphs
- Class discussion

**Summative**

- Individual: engineering notebook grading using rubric

## Materials and Preparation

### Materials (Groups of 2)

- Safety glasses or goggles for each student
- Meter stick
- Various masses
- String
- Protractor
- Ring stand
- Ring
- Electronic device to play music
- Scissors
- Stopwatch

**Students ready to collect data again after modifying the length of the pendulum from previous trials**

## Safety

- Remind students about general lab safety procedures.
- Participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Use caution in working with sharps (scissors), which can cut or puncture skin.
- Keep feet free of swinging masses in an oscillation pattern—this could injure feet.
- Make sure objects are removed from the path of the oscillation pattern.
- Participants should wash their hands with soap and water upon completing this activity.

**Pendulums–And the Beat Goes On Lesson Plan for Day 1 (55-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **2 mins.**<br>**Engage** | — | • Play a popular song and have the students clap to the beat. | — | — |
| **8 mins.**<br>**Elicit** | • Answer the Do Now questions.<br>• Consider, What is a metronome and what is it used for?<br>• List as many things they can think of that keep a steady beat or make a steady motion.<br>• Write answers to Do Now questions individually and then share during class discussion.<br>• Rank themselves on a scale of 1–10 on their ability to find and clap to the beat of a song. | • Elicit prior knowledge by writing the Do Now questions on the board for students to answer as they enter the room.<br>• Have a metronome in the classroom or an online metronome available for demonstration in class.<br>• Engage students through class discussion of the Do Now questions.<br>• Introduce the concept of a metronome while introducing the goal of the project.<br>• Use students' self-rankings of beat-finding ability to create heterogeneous groups. | • Period<br>• Frequency<br>• Harmonic motion | • Give students opportunities to do some initial brainstorming of ideas.<br>• Encourage students to draw their initial designs on paper no matter how out-of-the-box they sound. |
| **10 mins.**<br>**Explain** | • Read through the handout that explains the project and goals. In groups, gather materials. | • Explain to students the purpose of the activity and its two parts.<br>• Facilitate the grouping of students and the gathering of materials. | — | — |
| **35 mins.**<br>**Explore** | • Complete some of part 1 of the activity and enter data into their engineering notebooks. If time permits, graph data in class (or for homework). | • Facilitate the lab process for students as needed. | • Data collection<br>• Period<br>• Frequency<br>• Harmonic motion<br>• Graphing<br>• Calculations | • Encourage students to break down the problem and perform analysis using mathematical models. |
| **Elaborate**<br>**Evaluate** | **Homework:** Complete graphs of collected data. | | | |

**Pendulums–And the Beat Goes On Lesson Plan for Day 2 (55-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **40 mins.**<br><br>**Explore**<br>**Explain** | • Continue to complete part 1 of the activity and graph results on chart paper or individual white boards.<br>• In groups, present their findings for the effects of length, mass, and angle on the period of a pendulum. | • Facilitate the activity, visiting each group to make sure they are pacing themselves appropriately. | • Data collection<br>• Period<br>• Frequency<br>• Harmonic motion<br>• Graphing<br>• Calculations | • Students use the mathematical model created to fine-tune their understanding of this engineering design problem. |
| **15 mins.**<br><br>**Explain**<br>**Elaborate** | • In groups, present their findings to the class, explain their results, and elaborate on how they determined their results.<br>• One student should summarize findings on board.<br>• After analyzing all of the data together, answer a posed question in their engineering notebooks. | • Facilitate the sharing of information and the class discussion. | • Communicating results | — |

**Pendulums–And the Beat Goes On Lesson Plan for Day 3 (55-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **10 mins.**<br><br>**Elaborate**<br>**Evaluate** | • In groups, gather materials and determine which song they will use for the challenge.<br>• For their chosen song, measure the beats per minute (frequency) of the song and calculate the period of the metronome pendulum. | • Facilitate the choosing of the songs and the frequency and period measurement.<br>• If desired, give a brief review of frequency and period relationship.<br>• *Note:* Frequency units are typically given as Hertz (beats per second); however, song frequencies are described at beats per minute. If appropriate, include a brief explanation of the difference and the relationship. | — | • Students have an opportunity to use any tools to measure and analyze the beats of the song. |
| **30 mins.**<br><br>**Explore**<br>**Evaluate** | • In groups, use the information gathered from part 1 of the activity to construct a pendulum that can keep the beat for 10 swings. | • Facilitate the design and build process. | • Efficiency of energy transfer | • Engage students in the engineering design process, emphasize the importance of iteration, and ask students to consider how to solve the two competing criteria (making a sound versus having a constant swing). Working with competing criteria is often part of the engineering design process. |

Pendulums—And the Beat Goes On Lesson Plan for Day 3 (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| 15 mins.<br><br>Evaluate<br>Explain | • Student groups present their pendulums and songs to the class for evaluation. | • Use the rubric to score the metronome performance for each group.<br>• The other parts of the rubric can be scored when engineering notebooks are evaluated. | — | • Students communicate their results to the class. |
| Extend | **Homework:** Students should complete the summary questions in their engineering notebook. | | | |

## Optional Modification and Extension (Extend)

- Modify part 1 by having each group test only one variable. For example, have one group test the effect of varying the length, another group test the effect of varying the mass, and so on, and then have the groups present their findings. This will reduce the time needed for part 1.
- Modify part 1 by assigning each group to test one specific length, one specific mass, and one specific angle (holding other variables constant) and then present their period results to the class. Then have the class collate the data and determine which variables affect the period of a pendulum.
- Modify part 2: From part 1 data, have groups create a graph of beats/minute (frequency of pendulum) versus length of pendulum. Then give students songs with known beats per minute. Students will use their graph to predict how long their pendulum must be to match the beat of the song. Then they can build the predicted pendulum and see how close they are to the actual pendulum metronome.
- Create a pendulum metronome that makes an audible click for each swing (much like an actual metronome).

## Differentiated Instruction

### Special Needs

- Provide students with a checklist of daily goals.

- Use preprinted engineering notebook templates for students who need the structure for documentation.
- Have preprinted blank data tables and graphs with the axes labeled for student use.
- Allow for different types of documentation such as using a computer to type or for students who might struggle with a handwritten engineering notebook, using phones or tablets to take pictures and then add captions.

### English Language Learners

- Have visuals around the classroom for terms such as *engineering design process, period*, and *frequency*.
- Provide sentence frames and use technologies for students to record in their engineering notebook.

## Supplemental Material

- Handout 8A: Pendulums—And the Beat Goes On

# HANDOUT 8A: PENDULUMS—AND THE BEAT GOES ON

## DIRECTIONS

You are part of a team of engineers who are building a metronome (a device that helps musicians keep time). One type of metronome is a pendulum, which is a simple device that consists of a length of string or wire, a bob or some other type of weight, and a fixed point where at which it is attached to a solid object. The pendulum may swing in various directions.

## OBJECTIVES

Your goal is to build a pendulum that works as a metronome to keep pace with the beat of a song. You will investigate the properties of pendulums and use this information to inform your design.

## MATERIALS

- Strings
- Various masses
- Protractor for measuring angle
- Meter stick
- Rings and ring stands
- Scissors
- Safety glasses or goggles

## SAFETY PRECAUTIONS

- Follow all general lab safety procedures.
- Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Use caution in working with sharps (scissors), which can cut or puncture skin.
- Keep your feet free of swinging masses in an oscillation pattern to avoid injury.

- Make sure objects are removed from the path of the oscillation pattern.
- Wash your hands with soap and water upon completing this activity.

## PART 1: INVESTIGATING PROPERTIES OF PENDULUMS (1–2 DAYS)

Complete experiments to determine how length, mass, and angle of a pendulum affect the period of the pendulum. For each variable, gather enough data to be able to provide sufficient evidence (in graph form) for how that variable affects the pendulum's swing time. For each trial, record the time it takes to complete 10 swings and then calculate the period and frequency for each trial. Put all data into well organized and labeled data tables in your engineering notebook and graph the data to show the variable's effect on the swing time. Graphs should be inserted into the engineering notebook at an appropriate location.

After presenting your data results to the class and viewing all of the class's data, answer the following questions in your engineering notebook:

- From the class data, which factor(s) are consistently seen to affect the period of a pendulum?
- Which ones either don't affect or don't consistently affect the period of the pendulum? Use evidence to support your answers.

## PART 2: BUILDING AND PRESENTING A METRONOME (1 DAY)

Locate a song and construct a pendulum that keeps the beat with the that song. You will present the pendulum and song to the class, along with a calculation of the tempo of the song (beats per minute). The pendulum should keep pace with the song for at least 10 swings.

## POST-ACTIVITY QUESTIONS

Summarize your findings about what which variables greatly significantly affect the period of a pendulum.

1. How did your results from part 1 help guide your thinking in part 2 of this project?
2. How successful was your pendulum at keeping the beat to a song? Explain the success (or lack of success).

### Assessment Rubric

| Element | Excellent (5 points) | Good (4 points) | Fair (3 points) | Poor (1 point) |
|---|---|---|---|---|
| **Data collection and calculations** | All calculations and units are correct. | Most calculations and units are correct. | Some calculations and units are correct. | Few or no calculations or units are correct. |
| **Graphs** | Graphs are accurately plotted, have their axes labeled, and show correct units. | Graphs contain most elements listed in Excellent column. | Graphs contain some elements listed in Excellent column. | Graphs contain few or no elements listed in Excellent column. |
| **Question Responses to questions** | All questions are answered with exceptional clarity and detail. | All questions are answered clearly and in detail. | Answers are somewhat clear or detailed. | Answers lacking in clarity or detail. |
| **Metronome performance** | • Metronome keeps perfect time for 30 seconds.<br>• Metronome is very close to correct tempo after 30 seconds.<br>• Metronome is somewhat close to correct tempo after 30 seconds.<br>• Metronome is not close to correct tempo. | | | |

**TOTAL _______ / 20**

# ACTIVITY 8B: GUITAR DESIGNS—EXPLORING HOW MUSIC IS MADE

**Contributors: Julie Mills and Jon Kelley**

**Time frame:** 2 class periods plus additional time outside of class

**Physics focus:** Sound, waves, harmonics, vibrations, resonance, standing waves, and frequency

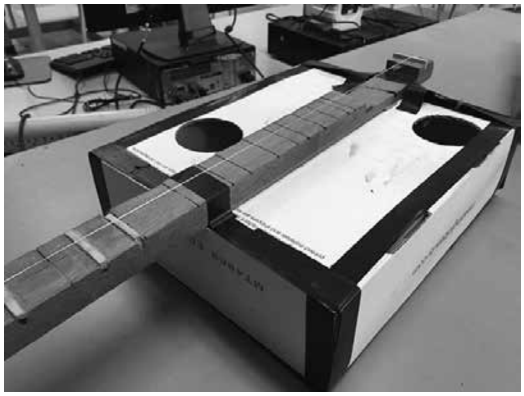
**Engineering focus:** Design, analysis, models, and communication

### Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • No experimental design<br>• Location of the frets | • Designing a functional guitar<br>• Reverse engineering |
| **Analysis** | • One octave higher is a doubling of the frequency. The notes within the octave have a mathematical relationship as well. | • Analysis of materials for strength, resonance, (materials testing)<br>• Analysis resonator for sound quality. |
| **Models** | • Wave model<br>• Standing wave | • Physical model (building the guitar) |
| **Systems** | • String, tension, and the strength of the post each can be isolated to understand the physics of each component. | • Resonator system, vibration system, post system |

## PROJECT OVERVIEW

Many students have a general understanding of how sound is created, but even those who play instruments don't really understand the how and why of different pitches and how it all fits together to make a pleasing sound. The goal of this activity was to create a design project that required students to explore the relationship between vibrations, pitch, and resonance at a deeper level than what is addressed in class. This design engineering project is completed toward the end of a unit on waves. Within the unit on waves, the ideas of sound and vibrations, frequency, standing waves, and resonance are discussed and demonstrated.



**Sample cavity designed by students using a small box, with neck of the guitar over the resonating cavity and offset holes**

To get students interested in this project, begin the activity by showing a video of children who make instruments from trash and then play those instruments in an orchestra setting (*www.youtube.com/watch?v=sJxxdQox7n0*). This video engages students and provides an anchor to introduce the project of creating guitars from recycled materials. Within the same class period, students work in small groups exploring the parts and design of a real guitar, the purpose of each part, and how the parts fit together. The groups report their results to the class and the class makes a comprehensive list for all to see. Afterward, students are given the constraints and requirements for this particular design project, with extra emphasis on the resonating cavity and string analysis requirement.

Because this activity is completed outside the classroom, it is important to spend time reiterating the process that should be followed and the purpose and requirements of the engineering notebook. Also, working on the project outside of class time gives students the option of working alone or with one or two other partners, with the understanding that all partners need to be present during the design and build process. Furthermore, it is ideal to make the classroom available during the day and after school for college preparatory and honors physics students who face obstacles getting together outside of the school day.

Students complete this project mostly on their own, so the teacher does not typically provide building materials for the students,[1] but he or she may make a variety of string types available (e.g., yarn, thread, kite string, twine, fishing line) for students to analyze in the classroom; then students can take home pieces of the strings they want to use for their guitars. The students analyze a string's performance by stretching a piece of it over an open box and plucking it to observe the sound made.

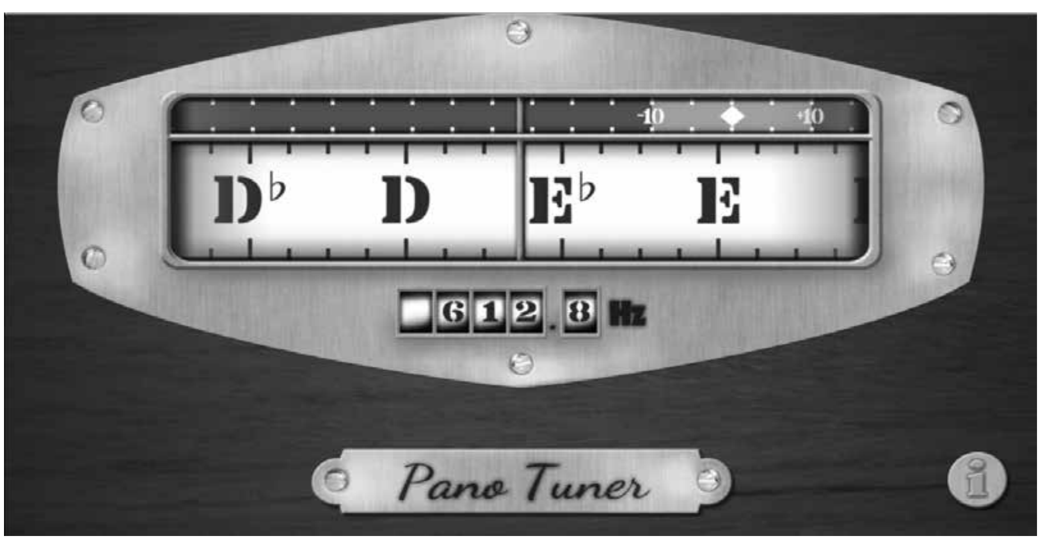
In addition to strings, the teacher may provide a variety of containers (different sizes and made of different materials) for students to analyze the resonating ability so that they can make informed design decisions. Analysis of resonating cavities can be performed by holding the base of a ringing tuning fork or their vibrating smartphone (the

1 The contributing teachers also do this project in a conceptual physics course, but in that context, the bulk of the designing and building is completed in class (about four additional class days). Students complete the string analysis and resonating cavity analysis in the classroom and then are provided with a variety of materials to complete the build in class.

app Real Razor works well for this) on the container and observing how much the sound is amplified. The analysis of string types and resonating cavity performance can also be performed at home. All observations must be recorded in students' engineering notebooks. When you're closer to the due date, spend about one half of a class period showing students how to mark the frets on their guitars so they get a perfect octave of notes. It is best to demonstrate this process on a sample homemade guitar that you can save and use year to year. Because students need to know the frequency of the notes played when the string is plucked, it is imperative that they have access to a tuning device that can detect and display the pitch (frequency in Hertz) and name (e.g., A, D, G,).

Fortunately, a variety of free smartphone apps for this are available (e.g., the Pano Tuner app). A handout showing the different notes of an octave is used as a guide. Individual help is provided to students after school if they are still struggling with marking their fret markings. Frets can be marked with a pencil or marker, or can be made more pronounced by gluing a small piece of wood at the fret location. One minor difference between how a real guitar is played and these homemade guitars is that, on a real guitar, the finger positions will be between frets, whereas on their guitar, the finger positions will be on the actual fret locations. This change is made to make it easier for students to play the guitar, as many of them do not play actual guitar.

Guitars are presented in class during one class period. Each student group presents its guitar, giving a short explanation of reasoning for its design choices. Then one of the students in the group will play a short song on the guitar. Song choices are discussed




**Pano Tuner app showing both the frequency of the sound and the name of the note. As students adjust their finger position along the neck of the guitar, this app tells them when they reach the desired frequency and note.**

ahead of time (a list of possible songs are provided, but groups can choose other songs with teacher approval). The song must use a wide variety of notes (finger placements). In addition to the class presentations by the groups, each student must turn in his or her engineering notebook for assessment and each group must turn in a guitar design report for assessment.

## BIG IDEAS

- **Physics:** Sounds are made from vibrations. Resonators amplify the sound. Some materials are better resonators than others. Standing waves created on strings can be altered by both the tension and the length of the string, affecting the pitch or frequency of the sound produced. All musical instruments create an amplified sound through standing waves and resonating cavities.
- **Engineering:** Collecting and analyzing the right data is integral to making informed design decisions. Each part of a system plays a role in the functioning of that system and affects the system's performance as a whole.

## Connections to the *Next Generation Science Standards*

### Performance Expectation

- HS-PS3-3: Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.

### Science and Engineering Practices

- Asking questions and defining problems
- Developing and using models
- Analyzing and interpreting data
- Constructing explanations and designing solutions
- Obtaining, evaluating, and communicating information

### Disciplinary Core Ideas

- PS3.A: Definitions of Energy
- PS3.D: Energy in Chemical Processes and Everyday Life
- ETS1.A: Defining and Delimiting Engineering Problems

### Crosscutting Concepts

- Cause and effect

- Systems and system models
- Structure and function

## Assessment: Determining Acceptable Evidence

### Formative

- Small group and class discussion of the parts of a guitar and their functions
- Quick check of collected data for string and resonating-cavity performance

### Summative

- Individual: engineering notebook
- Group: presentation of guitar and performance with it, group report

## Materials and Preparation

- Safety glasses or goggles for each student
- Several real guitars for groups to observe form and function
- Variety of string types (twine, kite string, fishing line, thread, yarn, and so on)
- Open boxes (any size will work)
- Smartphone with tuning app
- Engineering notebooks for each student
- Handouts for each student
- Method for showing a YouTube video to students as a class
- Optional: containers made of a variety of materials (e.g., plastic, glass, cardboard)
- Optional: tuning forks

## Safety

- Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.

### Guitar Design Project Lesson Plan for Day 1 (50-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **12 mins.**<br><br>**Engage** | • Introduce the project by showing the YouTube video "Landfill Harmonic Amazing and Inspirational." | • The YouTube video engages students by presenting a real-world example of how instruments can be made from recycled materials. | — | — |
| **15 mins.**<br><br>**Elicit**<br>**Explore** | • Work in small groups to explore the parts and function of an actual guitar. On one sheet of paper per group, sketch the guitar and label its important parts and their functions (or just list the parts and functions). | • While groups are revealing their prior knowledge about instruments and exploring actual guitars to determine the important parts and their functions, go through the room to answer questions and encourage groups to go beyond the most obvious parts and functions. Important parts include the resonating cavity (with holes), bridge (to raise the strings so that the full string vibrates), strings, frets, neck, and tuning keys (mechanism to change string tension). | • Exploring examples of resonance, vibration, frequency, and pitch | • Systems thinking and how system parts fit together to make the whole<br>• Explaining the function of various parts of an object<br>• Identifying design constraints based on type of instrument |
| **5 mins.**<br><br>**Explain**<br>**Evaluate** | • Each group presents part of its findings.<br>• Create a comprehensive list of findings and diagram on the board. | • Cycles through groups, having each group present a portion of its findings.<br>• Creates a comprehensive list of features and diagram on the board. | — | — |

Guitar Design Project Lesson Plan for Day 1 (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure What Are the Students Doing? | Instructional Notes What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **20 mins.**<br><br>**Explain** | • Read through the project expectations and rubric handout as the teacher explains the project.<br>• Write the introductory page of their engineering notebooks. | • Read through (orally) the comprehensive list and clarify parts and misconceptions.<br>• Demonstrate analysis methods for testing resonators and strings. | — | • Goals<br>• Constraints |

## Guitar Design Project Lesson Plan for Day 2–How to Mark the Frets to Play an Octave (30-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins.**<br><br>**Elicit** | • After listening to the teacher play eight random notes from low to high and then an octave of notes from low to high students describe their thoughts about the two sets of notes. Is one more pleasant sounding then another?<br>• Describe the spacing of the frets on a real guitar or homemade guitar, noting how the spacing varies as you move up the neck of the guitar. | • Post prompting questions<br>• Ask, "What makes a pleasant sounding set of notes, versus an unpleasant one?<br>• Ask, "How are the frets on a guitar spaced? What determines where the frets are marked on a guitar?"<br>• On a real or homemade guitar, play eight random notes from low to high and then eight notes in an octave from low to high so that students can hear the difference.<br>• Students should have access to a few guitars to play and look at fret spacing. | • Pitch and frequency<br>• String vibration<br>• Standing waves on string | • Materials, analysis selection versus design<br>• Application and constraints |

Guitar Design Project Lesson Plan for Day 2—How to Mark the Frets to Play an Octave (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins.**<br><br>**Elaborate Explain** | • As a class, discuss the difference between the random eight notes and the octave notes in terms of pleasantness of sound. | • Briefly explain frequency's role in creating the notes of an octave so students learn to recognize the difference between eight random notes and the eight notes of an octave (i.e., where the lowest note is twice the frequency of the highest note). | • Frequency<br>• Standing wave | • Students consider the client aspect of the design and think about sound quality.<br>• Students begin to consider materials for the design project. |
| **20 mins.**<br><br>**Explore** | • Watch the teacher demonstration of the Pano Tuner app (or similar app).<br>• Refer to the student handout "Setting Up Your Guitar to Play a Full Octave," which lists all of the notes of an octave given the first note of the octave. | • Demonstrate how the Pano Tuner app works.<br>• Demonstrate the fret-marking process.<br>• Explain to students that it typically is easiest to start with one string by plucking the open string (no fingers holding the string down). Once the open string note has been identified by the app, they can use the handout as a reference for determining the remaining seven notes of that octave. Adjusting the tension in the string can vary the frequency of the open string.<br>• By moving the finger that presses on the string down the neck of a guitar, students can locate the place where the string should be held to create the next note in the octave. Mark this fret location on the neck (pencil, pen, or marker works well). | • Frequency<br>• Resonance<br>• Frequency versus wavelength relationship | • Students analyze an existing product and use that as a model for their own design. |

Guitar Design Project Lesson Plan for Day 2—How to Mark the Frets to Play an Octave (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **20 mins.**<br><br>**Explore (*continued*)** | | • Repeat the process until the all eight notes of the octave have been marked and identified. At this point there will be seven frets marked.<br>• Optional extension: Have students calculate the length for notes using mathematical analysis.<br>• This fret location will be the same for all of the strings on the guitar, but students should understand that each string would play a different octave depending on the tension in the string and the type of string. For this reason, it is easier to stick with making a one-string guitar. | | |

### Guitar Design Project Lesson Plan for Day 3–Presentation Day (20-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **20 min**<br><br>**Explain Evaluate** | • Student groups present their guitars to the class whole-class presentation). Presentation includes a brief overview of students' design choices and reasoning, playing of the octave, and playing of a song.<br>• When not presenting, students can be rating other groups' guitars on their sound quality and guitar structure.<br>• After the presentations, if time remains, put the guitars on display for others to see up close and try out. | • Use the rubrics to score presentations and ask guiding and extending questions. | — | • Students can develop a class rating system to evaluate products. This is a chance for everyone to examine different constraints and design criteria. |

## Optional Modification and Extension (Extend)

- It is possible to complete this entire project in the classroom (about five additional days are needed). Students would complete the resonator analysis and string analysis in the classroom and then design and build their guitar, demonstrating how the results of their analyses guided their design choices. When done in class, ask students to bring in their own materials for resonators and guitar necks (although we suggest having some set aside for students who need them); the teacher typically provides the string.
- Have students calculate the speed of sound in their guitar string(s) using the frequency of the note of the open string (first harmonic) and the length of the string being played. (The first harmonic length is one half of the wavelength.) By repeating this calculation for several fret positions, an average speed of sound can be determined.
- It is helpful to have checkpoints along the way to the final due date with any out-of-class engineering project. Checkpoints usually involve having students show

what they have done so far (either by bringing in their guitar or showing pictures of it) and show entries in their engineering notebook of resonator and string analysis data.

## Differentiated Instruction

### Special Needs

- Provide students with a checklist of daily goals.
- Use preprinted engineering notebook templates for students who need the structure for documentation.
- For students who might struggle with a handwritten engineering notebook, allow different types of documentation such as using a computer to type or phones or tablets to take pictures and then add captions.

### English Language Learners

- Have visuals around the classroom for terms such as *engineering design process, frequency, resonator,* and *vibrations.*
- Provide sentence frames and use technologies for students to record in their engineering notebook.

## Supplemental Materials

- Handout 8B-1: Guitar Design Project Expectations and Rubrics
- Handout 8B-2: Setting Up Your Guitar to Play a Full Octave
- YouTube video: "Landfill Harmonic Amazing and Inspirational," *www.youtube.com/watch?v=sJxxdQox7n0*

# HANDOUT 8B-1: GUITAR DESIGN PROJECT EXPECTATIONS AND RUBRICS

## PROBLEM

- To build a guitar using recycled, reused materials that meets the listed constraints
- To present the guitar to the class and play an octave and a song using the guitar

## DUE DATES

- Presentation of guitar in class: ______________________________
- Final report: ______________________________________________

## CONSTRAINTS

- No parts or pieces can be from a real guitar.
- The guitar must be constructed out of recycled and re-purposed materials.
- The guitar must be clearly audible across the classroom.
- The guitar must be tunable (i.e., have a string or strings that can be tightened and loosened).
- The guitar must have frets marked so that a full octave can be played.
- The guitar must contain a resonating cavity.
- The guitar must be robust enough to be played multiple times.

## SAFETY PRECAUTION

Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.

## PROCESS

This project will be completed outside of class time. At the beginning of the project, it is expected that time will be spent brainstorming and trying out different ideas before finalizing and implementing a plan. *Enter all aspects of the design process in your engineering notebook, using the format at the back of the notebook.*

Make special note of the following aspects of your guitar design:

1. The design process you followed to get from the initial problem to the final solution (i.e., your brainstorming and sketches of initial ideas → your analysis of materials to choose the best ones → your building, testing, and redesign → the marking of the frets for playing an octave → the final result)

2. The analysis of the guitar's parts, pieces, and aspects to optimize the guitar to meet the constraints

3. How the various parts and pieces of the guitar were put together as a system to make the final product

If you need help on any aspect of this project, don't hesitate to ask the teacher. If you are lacking materials, see the teacher. If you need help with the tuning portion or marking the frets to play an octave, bring the guitar in to school before the day it is due so that the teacher can help you.

## PRESENTATION

To present your guitar to the class, you will be asked to play through the entire octave correctly and then to play a simple song. Some examples of simple songs are "Twinkle, Twinkle, Little Star," "Happy Birthday," and "Joy to the World"; however, you can choose another song, as long it uses most of the octave's notes and you get the teacher's approval ahead of time.

## GRADING

The grading for this project uses multiple rubrics. You will be graded on the final guitar, on your group's presentation, on your engineering design notebook (individual grade), and on your final report.

## FINAL REPORT

A final report (one per group) should be typed and submitted and should include the following items:

- **Heading:** Title, date, group members' names
- **Materials:** A list of materials that you used to build your guitar
- **Final Design Sketch:** A sketch of the final design of the guitar. It can be hand-drawn on the typed report, created by computer, or drawn and then scanned and inserted.
- **Build Process:** An explanation of the build process your group followed to build the guitar

- **Pictures:** Pictures of the guitar during the build process (can be jpegs inserted into the final report), with annotations for each picture. The pictures can be included within the "Build Process" section of the report separate after that section.
- **Analysis:** A summary of analysis that was done on parts and pieces of the guitar to gather data to make more informed design choices
- **Reflection:** A reflection about the project, including a discussion of how and why your final completed guitar differed from your original, brainstormed design. Also, within your reflection, include a discussion of difficulties your group encountered in the design and build process and how the group was able to overcome those difficulties.
- **Changes:** A discussion of changes your group would make if you had to build another guitar or to redo this project and why your group would want to make those specific changes.

Group members: ______________________________________________

## Rubric for Completed Guitar and Presentation

| Constraint Details | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|
| **Completed guitar met all constraints ____ / 12 (add at bottom)** | | | | | |
| **Use of recycled materials but not real guitar parts**<br>• No part of the guitar is from an actual guitar.<br>• You successfully and creatively used recycled and repurposed materials in creating the guitar. | | | | | |
| **Strings and frets**<br>• Frets are marked on the neck in the correct locations for playing an octave.<br>• String choice gives the guitar a nice sound. | | | | | |
| **Resonating cavity**<br>• Resonating cavity is designed to give nice resonance, making guitar easily heard. | | | | | |
| **Playability of guitar**<br>• Guitar is easily played.<br>• Playability was clearly taken into account when designing the guitar.<br>• Strings have an easy way to tune them. | | | | | |
| **Sound of guitar**<br>• Guitar is easily heard across the classroom, even when noisy.<br>• Guitar has a pleasant sound | | | | | |
| **Song played**<br>• Choice is creative.<br>• Song is recognizable.<br>• Song uses most of the notes of the octave. | | | | | |
| **Octave played**<br>• Octave is correct and easily played. | | | | | |

**Points for constraint details:** ______________________________

**Points from above for meeting constraints:** __________________

**TOTAL SCORE ______ / 40**

Group members: ____________________________________________

**Rubric for Guitar Project Final Report**

| Element Graded | Base Points | | | | Point Calculation | Total Points |
|---|---|---|---|---|---|---|
| | 4 | 3 | 2 | 1 | | |
| **Materials**<br>• Materials list includes all materials used AND all tools used. | | | | | × 1 = | |
| **Final design sketch**<br>• Detailed sketches (several if needed) including labels of parts/ materials used on the sketch<br>• Dimensions are included on the sketch | | | | | × 2 = | |
| **Build process**<br>• Complete and thorough description of entire build process from beginning to end (can be step-by-step or paragraph form) | | | | | × 2 = | |
| **Pictures**<br>• A variety of pictures (easy to see) are included from the entire build process and pictures are annotated | | | | | × 2 = | |
| **Analysis**<br>• More than one analysis process is described, including what was done during the analysis, what was being tested, the results of the analysis, and how the results helped inform design decisions | | | | | × 2 = | |

Rubric for Guitar Project Final Report (*continued*)

| Element Graded | Base Points 4 | 3 | 2 | 1 | Point Calculation | Total Points |
|---|---|---|---|---|---|---|
| **Reflection**<br>• Detailed discussion of how and why your final completed guitar differed from your original brainstormed design.<br>• Difficulties your group encountered in the design and build process and how the group was able to overcome those difficulties. | | | | | ×2 = | |
| **Changes**<br>• Detailed discussion of several changes your group would make if you had to build another guitar or to redo this project<br>• Reasoning provided for why your group would want to make those specific changes. | | | | | ×2 = | |

**REPORT TOTAL ______ / 52**

Name: ____________________________________________

## Rubric for Engineering Design Notebook (Individual Grade)

| Graded Element | Details | Points |
|---|---|---|
| **Daily Log Format** | • Dates, group members in attendance, signature at end, neat layout | ________ /10 |
| **Level of Detail** | • Detailed entries including notes/thoughts and reflections (can be seen on multiple occasions) | ________ /15 |
| **Data and Analysis** | • Data collected in neat format so that it is easily understood, can be seen on multiple occasions<br>• Each time data is collected, claims are made (What can you tell from the data collected and what evidence do you have to show this?)<br>• Analysis of data included, summarized, and explained each time data is collected | ________ /15 |
| **Sketches** | • Sketches are included throughout the process (multiple occasions) and are annotated/labeled<br>• Sketches include initial brainstorming ideas, along-the-way sketches, and final designs | ________ /10 |
| **Notes** | • Meaningful notes are taken throughout the process<br>• Notes include personal reflections and thoughts about the process.<br>• Notes include what you completed and what you are planning on completing at the next group meeting. | ________ /15 |

**TOTAL ______ / 65**

# HANDOUT 8B-2: SETTING UP YOUR GUITAR TO PLAY A FULL OCTAVE

An *octave* is a series of eight notes whose frequencies vary in such a way that the lowest note of the octave has a frequency that one half as much as the highest note of the octave. Here is a chart of all of the notes on a piano and their frequencies:

| Note | Hz | Note | Hz | Note | Hz | Note | Hz | Note | Hz | Note |
|---|---|---|---|---|---|---|---|---|---|---|
| C1 | 32.7 | C2 | 65.4 | C3 | 130.8 | C4 | 261.6 | C5 | 523.3 | C6 |
| C#1 | 34.6 | C#2 | 69.3 | C#3 | 138.6 | C#4 | 277.2 | C#5 | 554.4 | C#6 |
| D1 | 36.7 | D2 | 73.4 | D3 | 146.8 | D4 | 293.7 | D5 | 587.3 | D6 |
| D#1 | 38.9 | D#2 | 77.8 | D#3 | 155.6 | D#4 | 311.1 | D#5 | 622.3 | D#6 |
| E1 | 41.2 | E2 | 82.4 | E3 | 164.8 | E4 | 329.6 | E5 | 659.3 | E6 |
| F1 | 43.7 | F2 | 87.3 | F3 | 174.6 | F4 | 349.2 | F5 | 698.5 | F6 |
| F#1 | 46.2 | F#2 | 92.5 | F#3 | 185.0 | F#4 | 370.0 | F#5 | 740.0 | F#6 |
| G1 | 49.0 | G2 | 98.0 | G3 | 196.0 | G4 | 392.0 | G5 | 784.0 | G6 |
| G#1 | 51.9 | G#2 | 103.8 | G#3 | 207.7 | G#4 | 415.3 | G#5 | 830.6 | G#6 |
| A1 | 55.0 | A2 | 110.0 | A3 | 220.0 | A4 | 440.0 | A5 | 880.0 | A6 |
| A#1 | 58.3 | A#2 | 116.5 | A#3 | 233.1 | A#4 | 466.2 | A#5 | 932.3 | A#6 |
| B1 | 61.7 | B2 | 123.5 | B3 | 246.9 | B4 | 493.9 | B5 | 987.8 | B6 |

**Notes and Frequencies Chart**

The Major Scale

| Key | C | C# | D | D# | E | F | F# | G | G# | A | A# | B | C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C | 1 | | 2 | | 3 | 4 | | 5 | | 6 | | 7 | 1 |
| D | | 7 | 1 | | 2 | | 3 | 4 | | 5 | | 6 | |
| E | | 6 | | 7 | 1 | | 2 | | 3 | 4 | | 5 | |
| F | 5 | | 6 | | 7 | 1 | | 2 | | 3 | 4 | | 5 |
| G | 4 | | 5 | | 6 | | 7 | 1 | | 2 | | 3 | 4 |
| A | | 3 | 4 | | 5 | | 6 | | 7 | 1 | | 2 | |
| B | | 2 | | 3 | 4 | | 5 | | 6 | | 7 | 1 | |

On a guitar, the frets mark where to place your fingers so that as you move them down the neck, you can play a full octave of notes on one string. On a real guitar, the finger is placed between two frets, but for the purposes of this project guitar, you can just mark the frets where you actually need to place your finger.

To set up your guitar to be able to play an octave, do the following:

1. Get a tuner app (such as the Pano Tuner app) to know what note you're playing and its frequency.

2. Pluck the open string on your guitar. Determine what note it is played and tune the string so that it will play the starting note of any major scale keys shown in the major scale chart. This will tell you what major scale octave your string will play after you mark the frets.

3. Once you know your starting note (denoted by a 1 on the major scale chart), determine what frequencies you will need to locate for notes 2–8 (the rest of the octave).

4. Move your finger along the string, pressing on the string and plucking the string until you can locate the frequency for note 2 on your octave. When you find it, mark it on your guitar.

5. Repeat step 4 for each remaining note until you have seven frets marked (for notes 2–8). The open string is note 1.

# ACTIVITY 8C: GAME ON!

**Contributor: Marna Eckels**

**Time frame:** 3 class periods

**Physics focus:** Light, reflection, refraction, and Snell's law

**Engineering focus:** Design, analysis, models, systems, iteration, and communication

### Opportunities for Science Versus Engineering Concepts

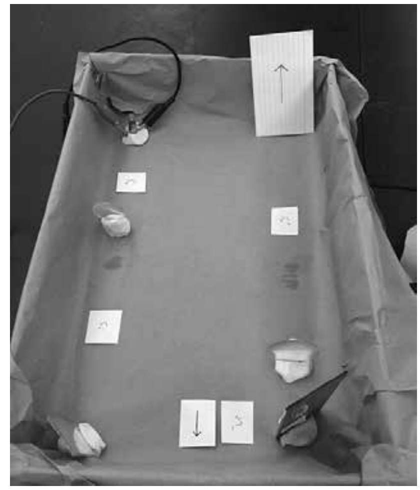
| Concept | Science | Engineering |
|---|---|---|
| Design | • Test paths through which light travels based on different mediums and boundaries. | • Design a fun game to satisfy these criteria. |
| Analysis | • Predict angle and path the light travels using the physics models. | • Analyze the light quality.<br>• Analyze the light paths and intensity. |
| Models | • Reflection<br>• Refraction<br>• Light as a wave model<br>• Optics | • Model for how light can be set up for a theater production or a museum. |
| Systems | • Each method of light travel can be separated into a subsystem. | • Each "station" can be its own system with inputs and outputs specified.<br>• Game-playing methods |

## PROJECT OVERVIEW

The many misconceptions about mirrors and lenses are often hard to break without some interactions with the materials. Instead of a traditional physics lab, this activity is an open-ended design project in which students design a game using basic principles of reflection and refraction. The goal of each game design can be different, but all game designs must use two different methods of allowing to light travel through the game board.

While students are spending time in class analyzing and testing, they also need to learn about the laws of reflection and refraction using a flipped classroom model. Students can read, watch online lessons, or try a few problems, and then the teacher can support students in solving the actual engineering problem using physics principles during class time.

The different criteria for the uniqueness and value of the game is something to discuss during the initial period. Students develop rubrics for assessment knowing the criteria for success. Some examples include the following:



Sample prototype that projects an image of a light source on screen a distance away using two lenses and two mirrors

- The game fits in any recycled cardboard box lid. (Try collecting box lids from copier paper boxes.)
- The game design demonstrates two examples of optics concepts.
- The game is unique and aesthetically pleasing.
- The game rules and strategies are oriented to a middle school–age audience.
- The game has at least two calculations of refraction attached to its schematic.
- The game demonstrates the students' understanding of the law of reflection

One way to add more context to the engineering aspect of this problem is to ask students to think about ways technologies use the laws of reflection and refraction to transmit information.

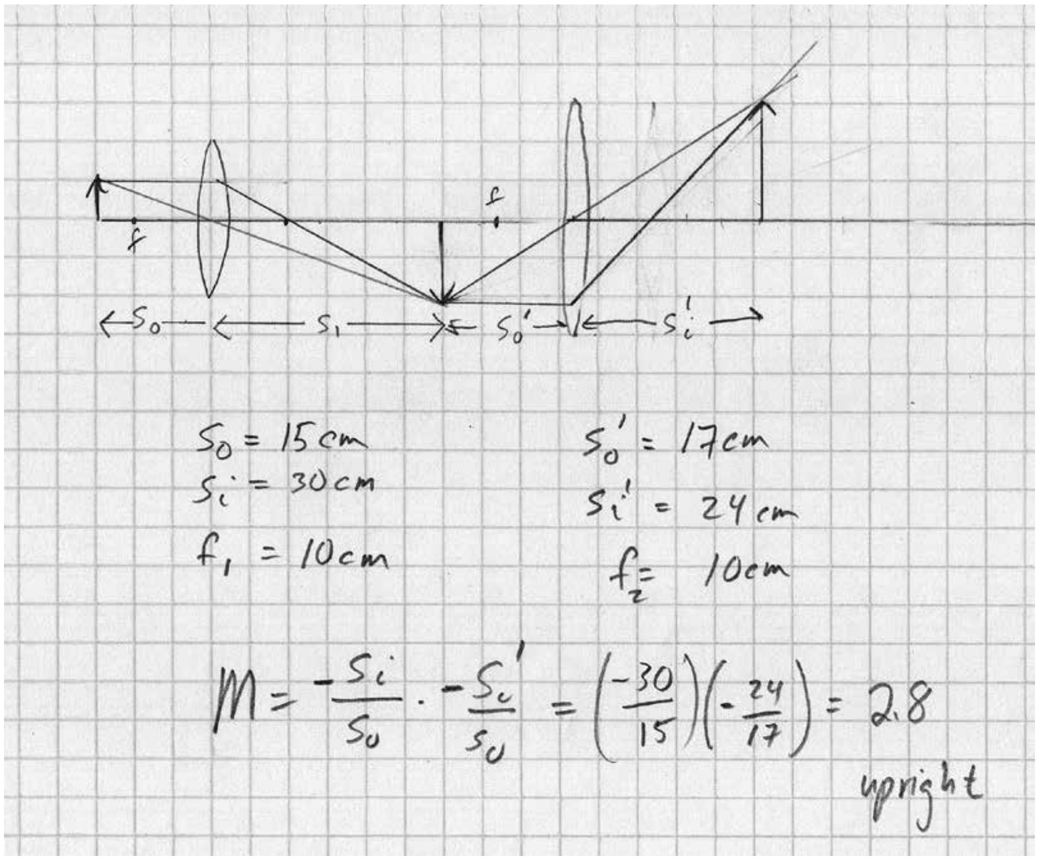
## BIG IDEAS

- **Physics**: Waves carry energy and can be transmitted across long distances.
- **Engineering:** Multiple technologies use wave properties in their interactions with matter to transmit information.

## Connections to the *Next Generation Science Standards*

### Performance Expectation

- HS-PS4-5: Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.




Students' plot of a graph of $1/S_i$ versus $1/S_o$ to determine the focal length of the lens

## Science and Engineering Practices

- Developing and using models
- Using mathematics and computational thinking
- Constructing explanations and designing solutions

## Disciplinary Core Ideas

- PS4.A: Wave Properties
- PS4.B: Electromagnetic Radiation
- PS4.C: Information Technologies and Instrumentation

### Crosscutting Concepts

- Cause and effect
- Energy and matter

| | Data Set | | | |
|---|---|---|---|---|
| | Object Distance (cm) | Image Distance (cm) | 1/Object Distance (1/cm) | 1/Image Distance (1/cm) |
| 1 | 10 | 10,000.00 | 0.100 | 0.000 |
| 2 | 15 | 29.00 | 0.067 | 0.034 |
| 3 | 20 | 21.00 | 0.050 | 0.048 |
| 4 | 25 | 16.00 | 0.040 | 0.062 |
| 5 | 30 | 15.00 | 0.033 | 0.067 |
| 6 | 35 | 13.80 | 0.029 | 0.072 |
| 7 | 40 | 12.75 | 0.025 | 0.078 |
| 8 | 45 | 12.50 | 0.022 | 0.080 |

**Data collected and manipulated to determine the focal length of the lens**

## Assessment: Determining Acceptable Evidence

### Formative

- Students practice problems and homework assignments.
- Students engage in class discussion and group interaction.

### Summative

- Final game design
- Student analysis and engineering notebook for the game design and calculations

## Materials and Preparation

### Materials (Groups of 3–4)

- Safety glasses or goggles for each student
- Recycled cardboard box lid
- Craft mirrors mounted on wooden blocks
- Small lenses or plastic containers to hold water
- Small handheld laser for light source (optional) or small flashlights for light source.

### Class Equipment

- Craft materials for game construction, including scissors, construction paper, tape, and so on.

## Safety

- Follow all general lab safety procedures.
- Use extreme caution when working with lasers. Never look directly at the laser light. Also remember not to look at reflected laser light! Laser light can cause severe damage to eyes!
- Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Immediately wipe up water that spills on the floor. This can create a slip-and-fall hazard.
- Keep water away from electrical receptacles as this is an electrical hazard.
- Use caution in working with sharps (scissors and so on), which can cut or puncture skin.
- Remind students to wash their hands with soap and water upon completing this activity.

### Game On! Lesson Plan for Day 1 (50-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **2 mins.**<br><br>**Elicit** | — | • Ask students to imagine a movie in which the action hero (e.g., James Bond, Jason Bourne, Katniss Everdeen) must avoid an intense laser beam. The path of the laser keeps changing because of mirrors, lenses, and glass placed throughout the surroundings. | — | — |
| **8 mins.**<br><br>**Elicit** | • Provide ways that the laser beam in the action movie could be altered with mirrors, lenses, glass, or other objects.<br>• With their groups, read the project handout silently and then list questions they have about the project. | • Push the students to explain in more detail how the laser beam will be affected.<br>• Clarify the project goals and criteria based on student questions. | — | — |
| **10 mins.**<br><br>**Explore** | • Watch an example of an optics-based game from a previous class or inspirational optics-based scenes from movies, then brainstorm ideas in their groups. | • Show simulations such as PhET-Geometric Optics, or a clip from movie such as *Goldfinger* (part of the James Bond series). | — | • Take a moment to discuss the client aspect of the project by thinking about the goals of the game. |
| **30 mins.**<br><br>**Explain**<br>**Evaluate** | • Develop a written plan for their game design. This plan should include a detailed diagram and a list of materials. | • Provide students with the engineering notebook format to follow. | • Snell's law of reflection<br>• Refraction<br>• Focal lengths | • While students are drawing their design, ask them to use the scientific models of reflection and refraction and communicate that through drawings. |
| **Evaluate** | **Homework:** Assign readings and reading questions: laws of reflection, laws of refraction, Snell's law, and so on | | | |

**Game On! Lesson Plan for Day 2 (50-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **50 mins.**<br><br>**Explore**<br>**Evaluate** | • Design and construct a board game based on their schematic diagram and materials list. | • Facilitate by making sure that students are on task, but ensure minimal interaction with students. | • Snell's law of reflection<br>• Refraction<br>• Focal lengths | • The design loop should include chances for iteration and allow students to test and perform analysis throughout the process.<br>• Ask students to break the complex systems into discrete components so they can troubleshoot specific pieces without affecting others. |
| **Evaluate** | **Homework:** Assign physics problem sets related to laws of reflection and refraction. | | | |

**Game On! Lesson Plan for Day 3 (50-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **20 mins.**<br><br>**Explore**<br>**Evaluate** | • Design and construct a board game based on their diagram and materials list. Also write down rules for the game. | • Facilitate group works.<br>• Elicit prior knowledge to determine student misconceptions and provide a prompt to help them move along. | • Snell's law of reflection<br>• Refraction<br>• Focal lengths | • After the design process, ask students to consider the client-interface piece of this design and write down clear instructions for communicating game rules. |
| **10 mins.**<br><br>**Explore** | • Present their game to others.<br>• Classmates rate the game according to agreed-on criteria. | — | — | — |
| **20 mins.**<br><br>**Elaborate**<br>**Evaluate** | • Perform required calculations for angle of reflection, angle of refraction, and focal length. | — | • Snell's law lens equation | • Students analyze their design using the scientific model. |

## Optional Modification and Extension (Extend)

- Instead of having students design different games, instructors can set up different entry and target locations on the box lid, asking students to design their own "museum mirrors" to reflect and refract the light to those target locations. For extension, each group will have a certain amount of time to "light" their museum floor plan, and then have to break it down and switch to a new museum floor plan and try a different configuration. This activity can also be used as the assessment of their understanding by providing students with paper or pen so they can draw out the paths of light without having to design it.
- Create a movie script that would incorporate the game. What factors would have to be taken into account if your game were expanded for a movie scene?

## Differentiated Instruction

### Special Needs

- Scaffold the parts of the exploration so students can focus on one task at a time. For example, ask students to work on only reflection from point A to point B for one day, then add the refraction the next day to help students get the light from point B to point C.

### English Language Learners

- Preteach any unfamiliar vocabulary terms such as *reflection* and *refraction.*
- Provide some culturally relevant board game examples for students to draw ideas from.
- Provide sentence frames for writing for rules and game strategies.

## Supplemental Material

- PhET-Geometric Optics, *https://phet.colorado.edu/en/simulation/geometric-optics*

9

# Engineering Infusion With Electricity and Magnetism

Open-ended engineering projects in the electricity and magnetism unit allow students to explore these invisible fields in a different way than traditional physics labs where students measure resistance or map out magnetic fields using compasses. In order for students to be successful in making a speaker or designing school memorabilia with light-emitting diodes (LEDs), they have to apply their understanding of physics principles to these meaningful experiences. Start the unit by having student design an LED zombie flashlight to teach them about terminals, insulators, conductions, and switches. Throughout the activity, introduce concepts of electrical components, current electricity, and even series and parallel circuits for an added challenge. Students will probably not forget to check for short circuits or polarity of the LEDs if they have failed a few times and have to perform failure analysis during the design process.

Although design is the essence of engineering activities, constructing a physical model or design is not always appropriate or necessary in the classroom. Start by asking students to do some paper and pencil "designs." In the Enter a Room design challenge, students have a higher degree of freedom so they often come up with more creative ideas to make a switch (think light beams!) compared with a project involving having to actually build a switch. Take about 30 minutes of class time or use the Magnetic Bees project as a homework extension. Students will read about the connection between asking a biology question about behavior, using physics principle of magnetism, and designing an instrument to manipulate bees for research. Table 9.1 (p. 334) provides basic curricular details for the activities in this chapter.

**TABLE 9.1. Chapter 9 Activities**

| Activity Name | Physics Concept(s) | Core Concepts | Class Period(s) | Brief Description |
|---|---|---|---|---|
| **Design a Speaker** | • Electromagnetism<br>• Sound waves | • Design<br>• Analysis<br>• Models<br>• Systems | 4 | Students build a functioning speaker using common household items. The winning speaker is determined by both the volume of sound and the quality of sound. |
| **LED School Spirit** | • Circuits | • Design<br>• Analysis<br>• Systems | 4–5 | Students design school spirit memorabilia using at least three LEDs, a battery, and a switch. |
| **Enter a Room** | • Circuits | • Design<br>• Analysis<br>• Models | 2 | Students use both schematic diagrams and a blueprint to sketch a light system that turns on when a person enters a room. |
| **Lights Out! Zombie Apocalypse Flashlight** | • Circuits | • Design<br>• Analysis<br>• Models<br>• Systems | 4 | Students use some simple household items to design a working flashlight that can be operated with one hand. |
| **Magnetic Bees** | • Magnetism | • Design<br>• Models<br>• Systems | 0.5 | Students read an article about using magnets to influence the behaviors of bees, and then consider the physics principles for this "magnet" instrument and what engineers must consider to design this apparatus. |

# ACTIVITY 9A: DESIGN A SPEAKER

**Contributors: Gita Hakerem Foster and Julie Mills**

**Time frame:** 4 class periods
**Physics focus:** Electromagnetism and sound
**Engineering focus:** Design, analysis, models, systems, iteration, and communication

## Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Test the electromagnetic: number of magnets, number of coils<br>• Frequency response | • Design a speaker using common materials that meets the constraints. |
| **Analysis** | • Volume of the sound<br>• Impedance matching<br>• Power calculation<br>• Magnetism equations | • Sounding board material analysis and attachment<br>• Analyzing sound quality<br>• Impedance matching<br>• The kinds of speakers that are better at amplifying certain sounds |
| **Models** | • Right-hand rule<br>• Newton's third law<br>• Simple harmonic motion<br>• Ohm's law<br>• Model of electromagnetic force<br>• Transfer of energy<br>• Model of a sound wave | • Physical model for a speaker |
| **Systems** | • Energy as a system<br>• Oscillating system | • Magnet and coil<br>• Mechanical attachment<br>• Electrical system<br>• Amplification |

## PROJECT OVERVIEW


A sample speaker designed using all recycled items

The speaker project works great as an introduction and activator for the unit on waves or as a culminating project for the electromagnetism unit. It can also be used as a bridging activity between the two units.

After students learn about electromagnetic induction, they are asked to create a working speaker out of household items and then to try to maximize the quality and quantity of the sound coming from the speaker. They have to physically design the speaker and experience the effects of a changing magnetic field on an electric current. In addition, the students gain a clearer understanding of how speakers work and how sound is created from vibrations. The information gained and the experiences from this project are referred to throughout the entire unit on waves.

The engineering design process is used but a special focus is on students reverse engineering a real speaker to help inform their design decisions, as well as the iterative design process.

## BIG IDEAS

- **Physics:** A changing magnetic field causes electric fields, which can be used to do work. A wave carries energy and can be transmitted across long distances.
- **Engineering:** Multiple technologies use wave properties in their interactions with matter to transmit information.

## Connections to the *Next Generation Science Standards*

### Performance Expectations

- HS-PS2-5: Plan and conduct an investigation to provide evidence that an electric current can produce a magnetic field and that a changing magnetic field can produce an electric current.
- HS-PS3-3: Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.

#### Science and Engineering Practices

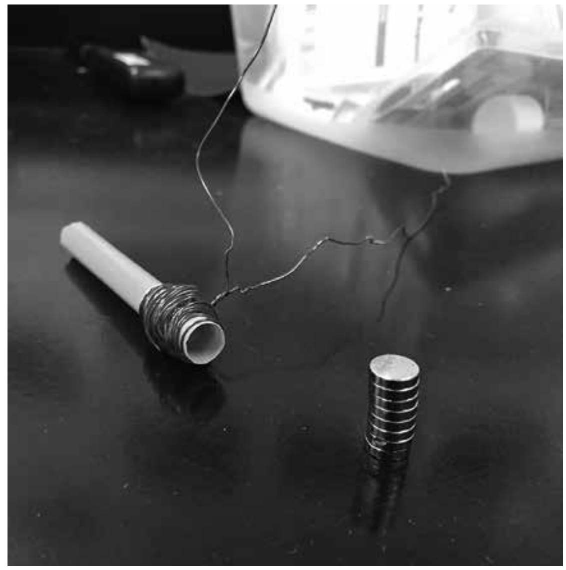
- Planning and carrying out investigations
- Constructing explanations and designing solutions

#### Disciplinary Core Ideas

- PS3.A: Definitions of Energy
- PS3.D: Energy in Chemical Processes and Everyday Life
- ETS1.A: Defining and Delimiting Engineering Problems

#### Crosscutting Concepts

- Cause and effect
- Systems and systems model
- Energy and matter



Students testing and experimenting with a simple electromagnetic and the permanent to produce sound wave

## Assessment: Determining Acceptable Evidence

#### Formative

- Student practice problems and homework assignments
- Class discussion and group interaction

#### Summative

- Final speaker design: quality of the speaker, volume of sound
- Engineering notebook
- Final student report

## Materials and Preparation

#### Materials (Groups of 4)

- Safety glasses or goggles for all students
- 1 stack of 3 permanent magnets

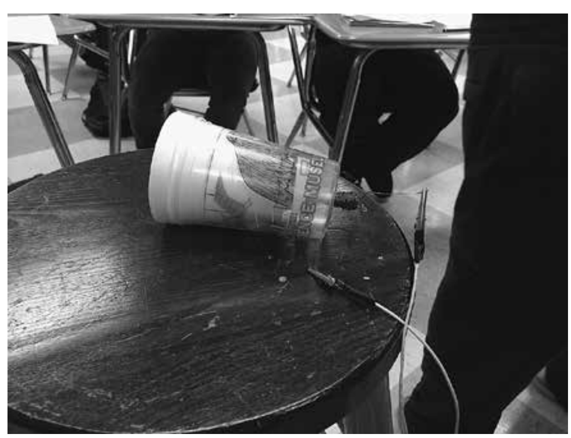
- Sound amplifier (this will plug into your personal music listening device with a normal 3 mm plug)
- Straws or homemade paper tubes to fit around the magnets
- Paper
- Tape
- 3 m magnet wire (thin copper wire)
- Household items (no more than $3 in value)
- Speaker output

### Class Equipment

- Utility or hobby knives
- Scissors
- Tape
- Hot glue
- Matches to burn off the enamel on the wire ends

## Safety

- Remind students about general lab safety procedures.
- All participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Use caution in working with sharps (scissors, knives, wire, and so on). These can cut or puncture skin.
- Use caution in working with hot objects (matches, glue gun, hot glue). These can burn skin.
- Students should not use a knife or glue gun until they are safety trained by a teacher. Remind them to follow all safety procedures.
- Students should wash their hands with soap and water upon completing this activity.



A group of students testing out the speaker design by playing music through the amplifier

### Design a Speaker Lesson Plan for Day I (50-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **2 mins.**<br><br>**Engage** | • Answer the question, “Have you ever been to a stadium concert?” | • Begin by telling students, “When Amadeus Mozart lived, there was no sound amplification and music was limited to what was played in small halls. Today, at some concerts, a wall of speakers amplifies the sound to 50,000 screaming fans in a stadium.” | — | — |
| **5 mins.**<br><br>**Elicit** | • Provide their prior understanding of how speakers work. | • Ask students, “How do you think a speaker works? What are the necessary components of a speaker? What limits the volume of a speaker?” | — | — |
| **30 mins.**<br><br>**Explore** | • Take apart a speaker to reverse engineer it, draw pictures of it, and make notes about the functions of the parts. Do online research. | • Encourage students to take notes and make guesses as to the function of each component. | • Electromagnetism<br>• Sound waves | • Break down the speaker system into components and analyze the function of each. |
| **8 mins.**<br><br>**Explain** | • Within their groups, read handout silently and create a list of their questions about the project. | • Clarify understandings based on student questions.<br>• Remind students to think about how different components need to work together but each component has its own purpose. | • Energy transformation | • Identify systems and relationships between each component.<br>• Analyze properties of different materials. |

Design a Speaker Lesson Plan for Day 1 (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins.**<br><br>**Elaborate**<br>**Evaluate** | • Show their engineering notebook to the teacher and ask questions. | • Quickly spot check students' engineering notebooks. | — | — |
| **Evaluate** | **Homework:** Students should bring materials from home and think about design ideas. Students do online research and answer preliminary questions related to the basic function and design of the speaker. | | | |

## Design a Speaker Lesson Plan for Days 2 and 3 (50-minute blocks)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **10 mins.**<br><br>**Explain** | • Brainstorm and sketch design ideas, make notes about different systems to consider, and share with group members. | • Ask student to focus on making a good sketch for communication of ideas. | — | • System<br>• Design<br>• Models<br>• Materials<br>• Analysis |
| **40 mins.**<br><br>**Explore**<br>**Evaluate** | • Build the coil, optimize the best configurations for the magnet and coil, and connect the coil to the amplification system they designed.<br>• Test and record test results and modifications throughout. | • Facilitate by making sure that students are on task, checking for understanding, and evaluating student conversations and progress. | • Electromagnetism<br>• Properties of sound | • Engage students in the entire design process.<br>• Emphasize how the components have to work together and the importance of iteration. |
| **Evaluate** | **Homework:** Students should begin working on their final report by recording all of their iteration and design process each day. | | | |

### Design a Speaker Lesson Plan for Day 4 (50-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **10 mins.**<br>**Elaborate Evaluate** | • Prepare their speaker for final testing and scoring and for presenting it to the class. | • Facilitate group work. | — | • Engineering design cycle |
| **40 mins.**<br>**Elaborate Evaluate** | • Present their speakers to the class.<br>• Record final testing.<br>• Work on documentation. | • Remind students to record the data during testing, compare their devices to others ‘ devices, and make notes about how different components of the speakers can be improved separately without changing too much about the other parts of the system. | • Electromagnetism<br>• Waveproperties | • Ask students to articulate different points where they used a model of analysis to inform their design. How did they control different components within the system? |
| **Extend** | **Homework:** Group members work together to finish the final report. | | | |

## Optional Modification and Extension (Extend)

- This project can be much smaller in scale if the teacher only wants to focus on the electromagnetic induction instead of asking students to manipulate the amplifier portion of the speaker. It can also be modified to only focus on sound and properties of sound wave—just give students premade coils to save time for the building.
- This project can also be used to emphasize competing criteria that might be important in engineering—having a smaller, more portable speaker versus having loud sounds. Ask students to determine what defines success and what is the acceptable range for meeting each criterion.
- Return to the questions asked at the beginning of the project:
  - How do you think a speaker works?
  - What are the necessary components of a speaker?
  - What limits the volume of a speaker?

## Differentiated Instruction

### Special Needs

- Scaffold the parts of the exploration so students can focus on one task at a time. For example, ask students to work on only reflection from point A to point B for one day, then add the refraction the next day to help students get the light from point B to point C.

### English Language Learners

- Preteach any unfamiliar vocabularies ahead of time.
- Provide prompts and sentence frames for written report.

## Supplemental Materials

- Handout 9A-1: How Can We Build a Speaker Using Common Household Items?
- Handout 9A-2: Instructions for Building the Speaker Coil and Magnet Setup
- Handout 9A-3: Design a Speaker Project Rubrics

# HANDOUT 9A-1: HOW CAN WE BUILD A SPEAKER USING COMMON HOUSEHOLD ITEMS?

## ENGINEERING–PHYSICS PROJECT

Electric current going through a wire creates a magnetic field *around* the wire. When the wire is coiled, that magnetic field can all be directed straight down or up through the coil. This in turn can affect nearby magnets.

Sound is a compression (longitudinal) wave. We hear sound because the air is compressed/expanded in our ears. We can create sound waves by talking, banging a drum, or otherwise making noise.

But we can also create a sound wave by transforming an electrical (transverse) wave into a sound wave using physical materials. The latter method involves a "speaker" that changes the electrical impulse into a physically moving wave that we can hear. That is what we will do in this project.

## SAFETY PRECAUTIONS

- Follow all general lab safety procedures.
- Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Use caution in working with sharps (scissors, knives, wire, and so on). These can cut or puncture skin.
- Use caution in working with hot objects (matches, glue gun, hot glue). These can burn skin.
- Do not use knife or glue gun until safety trained by teacher. Follow all safety procedures.
- Wash your hands with soap and water upon completing this activity.

## GOAL

Build a functioning speaker out of common household items. The winning speaker is determined by both volume of sound produced and quality of sound produced.

## CONSTRAINTS

- All groups will use the same materials to create the coil/magnet for the speaker.
- Household items brought from home should not cost more than $3 total.
- All speakers must have wire leads that are easily accessible to hook the speaker up to the amplifier.

## MATERIALS PER GROUP

- Safety glasses or goggles for all students
- 3 m of "magnet wire" (thin copper wire)
- 3 permanent magnets
- Sound amplifier (this will plug into your personal music listening device with a normal 3-mm plug)
- Matches to burn off the enamel on the wire ends
- Paper
- Tape
- Common household items: *You will provide these within a price constraint of $3 total, to make your speaker that will plug into the other side of the amplifier. The teacher will have limited supplies available in the classroom for use.*

## PRELIMINARY QUESTIONS

Using what you have learned in class, from reverse engineering a speaker and from the websites listed below, answer the following questions in your engineering notebook. Please use your own words in your answers.

### Websites

- *http://electronics.howstuffworks.com/speaker.htm*
- *http://electronics.howstuffworks.com/amplifier.htm*
- *www.physicsclassroom.com/class/sound*

### Questions

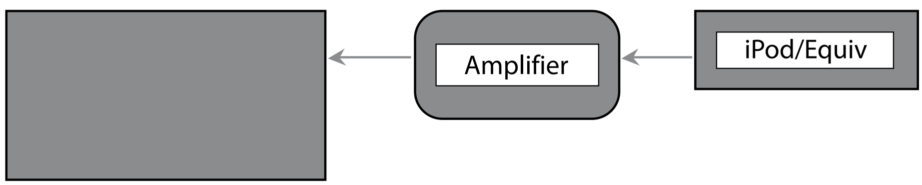
1. How does sound travel through the air?
2. What determines the pitch and loudness of a sound?

3. How does a basic speaker work? How is this the same as for a microphone? How is it different?

4. What are the purposes of the diaphragm, voice coil, magnet, and driver in a speaker?

5. What is the purpose of the amplifier in a speaker?

## SPEAKER TESTING SETUP




## PROCESS

1. Reverse engineer a speaker.

2. Research information.

3. Build the coil–magnet system.

4. Brainstorm the speaker.

5. Construct, test, and redesign.

6. Write a  report.

## SCORING YOUR SPEAKER

### Loudness Score

The loudness score (maximum 10 points) is $40 \times (1/x)$ = ________, where $x$ = the audio setting on the amplifier where the judge (a teacher) can hear it at a distance of 1 m when facing away from it. The audio on the iPod should be on the middle setting.

### Quality Score

The quality score is the average of five scores (of 1–10) given by teachers and students in the classroom.

### Total Score

The total score is the loudness score plus the quality score.

## FINAL REPORT

The final report will be co-written by all members of the group. It should be typed in Google Docs and should contain the following elements:

- Title of project
- Group member's names
- Goal
- Constraints
- Materials used in final design
- Annotated running log of iterations
  - Pictures
  - Description of each iteration
  - Results of testing of each iteration
  - What worked well and what didn't work with each iteration
  - Changes you made between each iteration (and why)
- Final design
  - Picture of final design
  - Description of final design
  - Description of performance of final design
- Data
  - Loudness score (show how it was determined)
  - Quality score (show how it was determined)
  - Total score (loudness + quality)
- Conclusion
  - What types of materials seemed to produce the loudest sound?
  - How did you decide what type of material to use for building the final design of your speaker?
  - Do you think your speaker is best at putting out high, medium, or low frequencies? What design choices contribute to this characteristic?

- Describe how your speaker produces sound.
- Discuss the main differences between the speaker you built and the speaker you took apart.

# HANDOUT 9A-2: INSTRUCTIONS FOR BUILDING THE SPEAKER COIL AND MAGNET SETUP

## SAFETY PRECAUTIONS

- All participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Use caution when working with sharps (scissors, wire, and so on). They can cut or puncture skin.

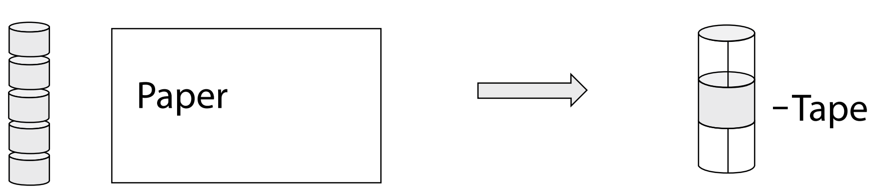
## MATERIALS

- Safety glasses or goggles for all students
- 5 rare-earth magnets
- 3 m magnet wire
- Plain white paper
- Thin, clear tape
- Thin marker
- Scissors

## PROCESS

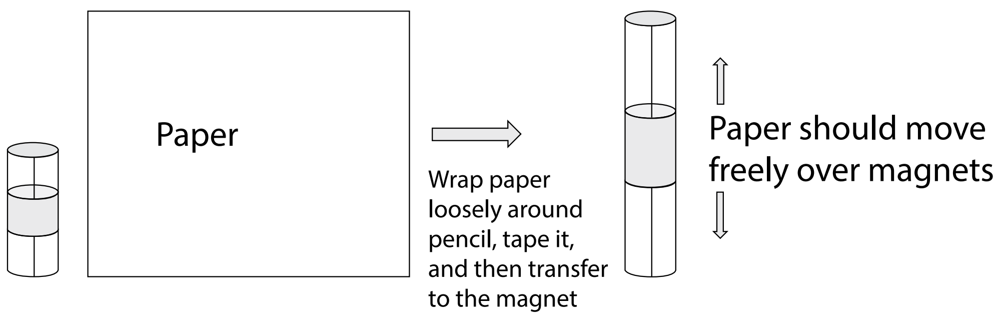
### Step 1

The first step is to stack the magnets and cut a paper strip to wrap around the magnet stack. The paper should be the same height as the magnet stack and long enough to completely wrap around the magnets with a little left over. Wrap the paper strip snugly around the magnets and tape it to itself.



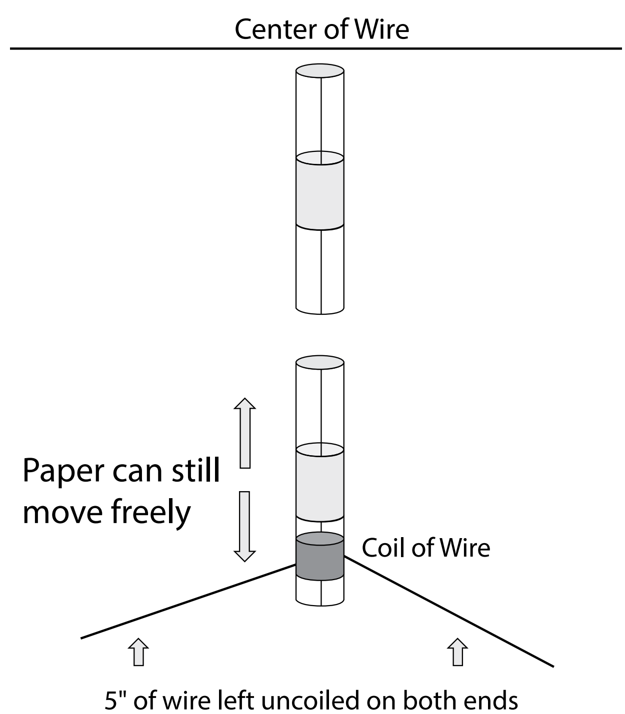
### Step 2

For step 2, cut another paper strip, this one at least three times as tall as the magnet stack so it will wrap around the stack with some left over. Wrap the paper strip around a pencil that is slightly wider than the magnet stack. The paper wrap should be loose enough to slide freely over the magnet stack but not so loose that it moves side to side. Tape the paper to itself and slide it off the marker.




### Step 3

In step 3, wrap the magnet wire around the outside paper over the magnet stack so it is flush with the magnets but not so tightly wrapped that it restricts the ability of the outside paper to move freely. *It might be easier to put the paper back onto the pencil for this next part, and then transfer the paper–coil combination back to the magnet stack when you're done.*




Start at the center of the wire and wrap from the center out to one of the ends, leaving about five inches of the wire not wrapped in the coil. Then repeat with the other half of the wire, again leaving about five inches unwrapped. The coil should be fairly neat and all of the coil should be positioned over the magnets once the paper is back over the magnets. (If the coil is higher up than needed, you can trim the excess paper below the coil so that the coil sits around the magnets. Again, check that the outer paper can still move freely and if it cannot, rewrap the coil less tightly. Tape the coil in place on the paper so that it stays coiled and doesn't slide around.

## Step 4

See the teacher to finish up the last few steps.

Name: ______________________________________________

# HANDOUT 9A-3: DESIGN A SPEAKER PROJECT RUBRICS

**Rubric for the Engineering Notebook (Individual Grade)**

| Notebook Element | Possible Points | Points Earned |
|---|---|---|
| Reverse engineering of speaker—sketch of actual speaker parts, hypothesis of role each part plays | 8 | |
| Research | 6 | |
| Brainstorming—several designs sketched and brainstorming of possible materials that could be used | 6 | |
| Design sketches of each iteration of design, including the results of testing of that design, explaining what worked well and what didn't work well with each design iteration | 10 | |
| Explanations of decisions and design choices, including the reasons behind the choice. This should be evident throughout the notebook entries. | 10 | |
| **TOTAL** | 40 | |

### Rubric for Typed Final Group Report (Group Grade)

| Report Part | Possible Points | Points Earned |
|---|---|---|
| Project Title | 1 | |
| Group Members' Names | 1 | |
| Project Goal | 2 | |
| Project Constraints | 3 | |
| Materials Used in Final Design | 3 | |
| Annotated Running Log of Iterations, including the Following:<br>• Pictures<br>• Description of each iteration<br>• Results of each iteration<br>• What worked and what didn't work<br>• What changes you made between each iteration | 15 | |
| Final Design<br>• Picture of final design<br>• Description of final design<br>• How the final design performed | 10 | |
| Data<br>• Loudness score and how it was determined<br>• Quality score<br>• Total score (loudness + quality) | 5 | |
| Conclusion<br>• What types of materials seemed to produce the loudest sound?<br>• How did you decide what materials you were going to use?<br>• At what frequency range does your speaker work best? What design choices contributed to that (if any)?<br>• Describe how your speaker produces sound.<br>• Discuss several differences between your speaker and the speaker that we reverse engineered. | 15 | |
| **TOTAL** | 55 | |

# ACTIVITY 9B: LED SCHOOL SPIRIT

**Contributor: Nora Paul-Schultz**

**Time frame:** Approximately 4–5 class periods
**Physics focus:** Series circuits, parallel circuits, and Ohm's law
**Engineering focus:** Design, analysis, models, and systems

## Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Measurement of resistance<br>• Power efficiency of LED versus other bulbs<br>• Illumination level and power consumption<br>• Varying voltage input<br>• Parallel versus series circuit | • Design an aesthetically pleasing "school spirit" piece of memorabilia that has at least three LEDs under constraints. |
| **Analysis** | • Analysis of circuit<br>• Use Ohm's law to determine resistance<br>• Threshold voltage<br>• Power<br>• Parallel versus series circuit | • Thermal analysis<br>• Using mathematical analysis to choose the resistances |
| **Models** | • Ohm's law<br>• Parallel versus series circuit<br>• Circuit diagrams<br>• Electron flow (analogy and so on)<br>• LED itself and how it works | • Toys<br>• LED clothing<br>• Keychains<br>• Mathematical models<br>• Circuit diagram as a model |
| **Systems** | • Circuit<br>• Energy (efficiency) | • Mechanical system<br>• Switch<br>• LED<br>• Wiring<br>• Decorative (art) piece<br>• Optics<br>• Heat dissipation (heating or cooling system) |

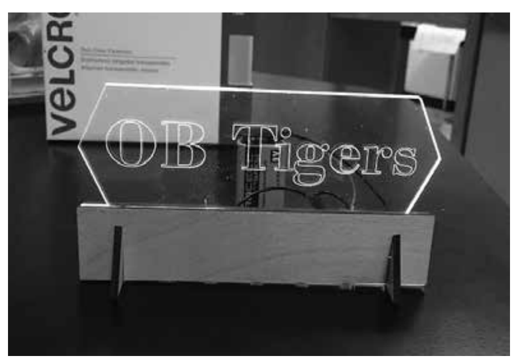
## PROJECT OVERVIEW

In this project, students design school-spirit themed memorabilia that include at least three LEDs, a battery, and a switch. This project allows a lot of flexibility in terms of the product created. Students could build flashlights, keychains, signs, or t-shirts. (*Note:* Detailed instructions are provided here for the school sign. A similar set of instructions can be created if students and the teacher decide to create flashlights or other memorabilia.)

Students begin by brainstorming possible products and narrowing down their choices. The second phase of the project is to design the circuits, including the number of LED lights, the color of the LED lights, and the placement of LEDs and switches. Students need to calculate the resistance necessary to limit current through the LEDs, choose whether to use a series circuit or a parallel circuit, and design a switch.

Once students have designed the circuit and have their diagram and calculations checked, they need time to construct the circuit and also construct the device that will be attached to the circuit.

The project can be scaffolded in different ways and inserted in different parts of the electricity unit. The goal of the entire unit can be to design this product while progressing throughout the unit; students learn the physics necessary to solve each portion of this engineering challenge. Alternatively, this can be the final project designed as the performance assessment of students' understanding of Ohm's law, Kirchhoff's laws, and series and parallel circuits. It might also be interesting to ask students to do "paper design" instead of the real one, or a smaller scale model on a breadboard of any Snap-circuit kits that might be lying around the classroom. These smaller scale models or paper models can be used to emphasize the importance of engineering modeling and also save money in the case of limited budget for classroom equipment.



Sample student-designed school spirit sign

## BIG IDEAS

- **Physics:** Circuits provide a path for electrical charges. The energy from the movement of electric current can be used to do work.
- **Engineering:** Engineers break down complex problems into systems and subsystems.

## Connections to the *Next Generation Science Standards*

### Performance Expectation

- HS-PS3-3: Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.

### Science and Engineering Practices

- Using mathematics and computational thinking
- Constructing explanations and designing solutions

## Disciplinary Core Ideas

- PS3.A: Definitions of Energy
- PS3.D: Energy in Chemical Processes and Everyday Life
- ETS1.A: Defining and Delimiting Engineering Problems

### Crosscutting Concepts

- Systems and system models

## Assessment: Determining Acceptable Evidence

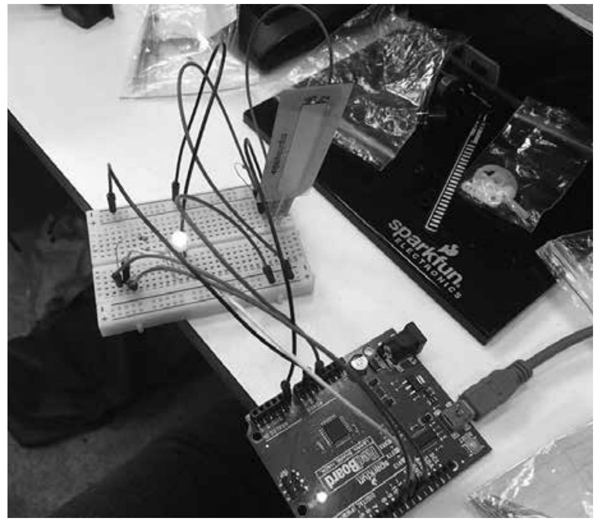
### Formative

- Ask students to explain their design decisions and the calculations that support them.
- Check engineering notebooks daily for the following: student records of what they tried during class, what worked, what did not work, and what they will work on during the next class period.

### Summative

- Engineering notebook (daily record of design work)
- Completed device—At least three LEDs powered by a 9-volt battery with a switch to turn them on and off
- Design report
- A description of the device, including a written description of the circuit and one or more drawings of the design that show the locations of the bulbs, battery, switch, and so on
- Circuit schematic

- Calculations for resistor values
- A description of how all of the systems (circuit, switch, base, and so on) interact
- The design choices that were made
- Reasoning to support the design choices (including physics analysis)
- Reflection questions
- What challenges did students face and how did they overcome them?
- If students had to do something differently, what would that be?
- What did students learn from this project?




Student using breadboard conduct preliminary tests

## Materials and Preparation

### Materials per Student

- Safety glasses or goggles
- Resistors
- 9V batteries
- LED lights (see Table 9.2)
- Solder (to connect the elements together)
- Switch materials:
- Paperclips
- Pins
- Mini-binder clips
- Brads
- Other random metal materials
- 9V battery clips

**TABLE 9.2. Table of LED Specifications**

| Color | Typical Voltage | Current |
|---|---|---|
| Red | 2 V | 24 mA |
| Orange | 2 V | 24 mA |
| Yellow | 2 V | 24 mA |
| Green | 3.2 V | 24 mA |
| Blue | 3.2 V | 24 mA |
| White | 3.2 V | 24 mA |
| Warm white | 3.2 V | 24 mA |
| Pink | 3.2 V | 24 mA |
| Ultraviolet (UV) | 3.2 V | 24 mA |

### Class Equipment

- Soldering iron
- Cardboard
- Poster board
- Scissors
- Tape
- Any other materials students could use to construct their device

## Safety

- Remind students about general lab safety procedures.
- All participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Use caution when working with sharps (scissors, pins, brads, wires, clips, and so on). These can cut or puncture skin.

**An alternative product for students to make instead of a school spirit sign**

- Use caution when working with hot objects (soldering iron). These can burn skin!
- Provide a short lesson on box soldering iron safety before beginning the building process.
- Students should not use a soldering iron until they are safety trained. Remind students to follow all safety procedures.
- Set up the soldering iron in a space separate from student work areas and make sure students go to that location to do their soldering. Instruct students to unplug the soldering iron when they are finished and to not leave soldering irons unattended. Also make sure there is appropriate ventilation to protect students from soldering fumes.
- Remind students to wash their hands with soap and water upon completing this activity.

### LED School Spirit Lesson Plan for Day 1 (~55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins.**<br>**Engage** | — | • Present the school spirit project and show websites with school-spirit novelty products. | — | — |
| **10 mins.**<br>**Elicit** | • Brainstorm memorabilia ideas in groups of two or three students, then share with the class. | • Have students brainstorm factors that will affect their designs. | — | • Reinforce the engineering design process: define the problem, brainstorm and research, design, prototype, test, and evaluate. |
| **20–30 mins.**<br>**Explore**<br>**Explain** | • Explore ideas, choose an idea, and then draw a picture of the chosen design. | • Ask students to share reasoning for their design decisions. | • Prompt students to think about what kinds of circuits they will need to build their project. | • Clarifying reasoning behind design decisions |
| **10–15 mins.**<br>**Elaborate** | • Translate their design drawing into a preliminary schematic drawing. | • Prompt students to think about series circuits versus parallel circuits and where the switch needs to be to operate all LEDs. | • Series circuits versus parallel circuits | • Modeling design as a drawing and schematic diagram |
| **Evaluate** | **Homework**<br>• Students reflect in their engineering journals about what they tried during class, what worked, what did not work, and what they will work on during the next class period.<br>• Students can also read Handout 9B-2: LED Circuits (p. 366) to learn to calculate the appropriate resistors so that they will be prepared for a mini-lesson during the next class. | | | |

### LED School Spirit Lesson Plan for Day 2 (~55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5–10 mins.**<br><br>**Explain** | • In small groups, share what they have chosen for their design and their preliminary ideas for their circuit. | • Check in with each group. | • Series circuits versus parallel circuits | • Students use the sketch as a model to explain their design to each other. |
| **10 mins.**<br><br>**Evaluate** | • Review LED School Spirit handout and makes notes. | • Teach mini-lesson about how to choose appropriate resistors for circuits. | • Series versus parallel circuits, Ohm's law | • Mathematical analysis for circuits |
| **30 mins.**<br><br>**Explore**<br>**Explain**<br>**Elaborate** | • Design circuits and do calculations to determine resistor values. | • Ask students to explain their calculations. | • Series versus parallel circuits, Ohm's law | • Analysis and modification of design based on results of calculations |
| **Evaluate** | **Homework:** Students modify schematic diagrams if necessary based on calculations. Students reflect in their engineering journals about what they tried during class, what worked, what did not work, and what they will work on during the next class period. | | | |

### LED School Spirit Lesson Plan for Days 3 and 4 (~55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins.**<br><br>**Engage**<br>**Elicit** | • Share what their next step is for their project and ask questions. | • Facilitate discussion. | — | • Students communicate ideas to each other. |
| **45 mins.**<br><br>**Engage**<br>**Explore**<br>**Evaluate** | • Have open-ended time to finish calculations, build circuits, and build their device. | • Prompt students about their design decisions and the evidence that supports them. | • Series versus parallel circuits, Ohm's law | • Construct final design based on analysis.<br>• Use iterative process and break the project into manageable components. (Systems thinking) |
| **Elaborate**<br>**Evaluate** | **Homework:** Students reflect in their engineering journals about what they tried during class, what worked, what did not work, and what they will work on during the next class period. | | | |

**LED School Spirit Lesson Plan for Day 5 (~55-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **20–30 mins.**<br><br>**Explore**<br>**Explain**<br>**Elaborate**<br>**Evaluate** | • Set up their devices for a class gallery walk. Half of class stands near projects to demonstrate while the other half observes. Then the groups switch. Students complete peer review worksheet. | • Ask clarifying questions while students are demonstrating. | • Students explain choices they made about their circuits. | • Students share their ideas and explain the design choices they made. |
| **20–30 mins.**<br><br>**Explain**<br>**Evaluate** | • Work on design report, clarifying questions with the teacher. | • Check in with students to answer any questions before students write their final reports. | • Students explain their circuit design and the reasoning for their choices using physics models | • Communicate, explain, and share. |
| **Elaborate** | **Homework:** Students complete design report and reflection. | | | |

## Optional Modification and Extension (Extend)

- If your school has a three-dimensional (3-D) printer, have students use Tinkercad to design and 3-D print products that will fit the LEDs.
- Students could create an advertisement for their memorabilia that is focused on a particular target audience.

## Differentiated Instruction

### Special Needs

- Use a graphic organizer for the design journal and design report.
- Provide sentence starters for the design journal and report.
- Provide a template for doing resistor calculations.
- Provide opportunities for frequent check-ins with the teacher.

### English Language Learners

- Preteach key vocabulary.
- Use a graphic organizer for the design journal and design report.
- Provide sentences frames for the design journal and report as necessary.
- Provide a model of a design journal.
- Allow student to partner with a native English speaker.
- Provide opportunities for frequent check-ins with the teacher.

## Supplemental Materials

- Handout 9B-1: LED School Spirit Signs
- Handout 9B-2: LED Circuits

# HANDOUT 9B-1: LED SCHOOL SPIRIT SIGNS

As a memento for this school year, you will use light-emitting diodes (LEDs) to make light-up-the-school spirit signs. The acrylic signs will be provided; you will have to design the other parts of the sign, including the lighting, the base, and the switch.

## LIGHTING

You will need to make decisions about the design of your sign. Some of these decisions should include the number of LED lights, color(s) of the LED lights, and the placement of the LED lights and switch(es). After making these decisions, draw a circuit schematic.

## BASE

You will need to design a base to hold your LED lights and sign.

## SWITCH

You will need to design a switch to turn the circuit on and off.

## DELIVERABLES

### Engineering Notebook

- Every day, record in your engineering notebook what you did. Write down everything you tried, what worked, and what did not work. At the end of each class, write down what will need to do next time.

### Design Report

- Circuit schematic
- Drawing(s) of the design showing the location of the bulbs, battery, switch, and so on
- Calculations for the resistor values
- A report that includes the following information:
- A description of the device including a written description of the circuit
- A description of how all of the systems (circuit, switch, base, and so on) interact
- The design choices you made

- Why you made the choices you did (including the physics behind all of the choices)
- Reflection questions
- What challenges did you face and how did you overcome them?
- If you had to do something differently, what would it be?
- What did you learn from this project?

## SAFETY PRECAUTIONS

- Follow all general lab safety procedures.
- All participants should wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Use caution when working with sharps (scissors, pins, brads, wires, clips, and so on). These can cut or puncture skin.
- Use caution when working with hot objects (soldering iron). These can burn skin!
- Do not use a soldering iron until you are safety trained. Follow all safety procedures.
- Set up the soldering iron in a space separate from student work areas and be sure to go to that location to do your soldering. Unplug the soldering iron when you are finished and do not leave soldering irons unattended.
- Be sure there is appropriate ventilation to protect participants from soldering fumes.
- Remind students to wash their hands with soap and water upon completing this activity.

## MATERIALS

Please be respectful of the materials. Do not waste materials or take more then you need. Materials provided include the following:

- Safety glasses or goggles
- Laser-cut signs
- Resistors
- 9V batteries
- LED lights (see Table 9.3)
- Soldering iron

- Solder (to connect the elements together)
- Switch materials
- Paperclips
- Pins
- Mini-binder clips
- Brads
- Other random metal materials
- 9V battery clips
- Base materials

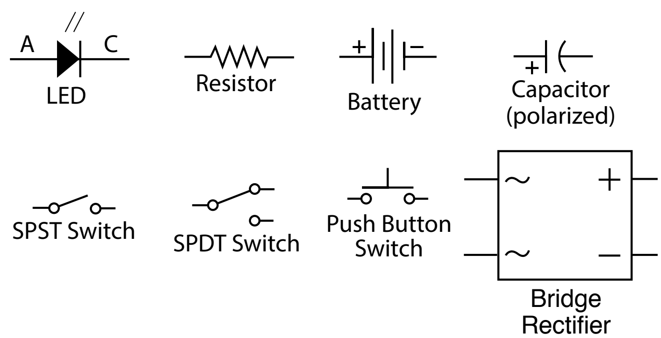
**TABLE 9.3. Table of LED Specifications**

| Color | Typical Voltage | Current |
|---|---|---|
| Red | 2 V | 24 mA |
| Orange | 2 V | 24 mA |
| Yellow | 2 V | 24 mA |
| Green | 3.2 V | 24 mA |
| Blue | 3.2 V | 24 mA |
| White | 3.2 V | 24 mA |
| Warm white | 3.2 V | 24 mA |
| Pink | 3.2 V | 24 mA |
| Ultraviolet (UV) | 3.2 V | 24 mA |

# HANDOUT 9B-2: LED CIRCUITS

This handout provides an overview of the basic types of circuits used to power LEDs (light-emitting diodes). The circuit diagrams—or schematics—that follow are drawn using industry standard electronic symbols for each component. Figure 9.1 shows the symbol definitions.

**FIGURE 9.1. Circuit Schematics Symbol Definitions**



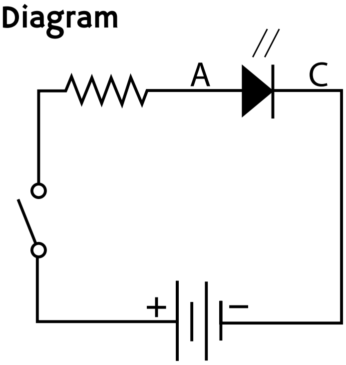

The LED symbol is the standard symbol for a diode with the addition of two small arrows denoting emission (of light). Hence the name *light-emitting diode*. The "A" indicates the anode or plus (+) connection and the "C" is the cathode or minus (–) connection. LEDs are strictly direct current (DC) devices and will not function using AC (alternating current). When powering an LED, unless the voltage source exactly matches the LED device voltage, a "limiting" resistor must be used in series with the LED. Without this limiting resistor, the LED will instantly burn out. In the circuits below, the battery symbol indicates a power source.

## BASIC CIRCUIT

The basic circuit (Figure 9.2) is the simplest circuit. The single LED circuit is the building block on which all of the following examples are based. For proper function, three component values must be known: the supply voltage ($V_s$), the LED device operating voltage ($V_d$), and the LED operating current ($I$). With these known, using a variation of Ohm's law, the correct limiting resistor ($R$) can be determined using the following formula:

In the schematic above, the limiting resistor and the switch are both connected on the positive (+) side of the circuit. This was done to be consistent with "standard electrical practices" in working with the "hot" (plus) side of the circuit rather than the minus (–), or "ground" side.

**FIGURE 9.2. Circuit Diagram**




**Basic circuit diagram showing the simplest connection to light up the LED using one limiting resistor**

## CIRCUITS WITH TWO OR MORE LEDS

Circuits with multiple LEDs fall into two general categories: parallel-wired circuits and series-wired circuits. A third type known as a series/parallel circuit is a combination of these.

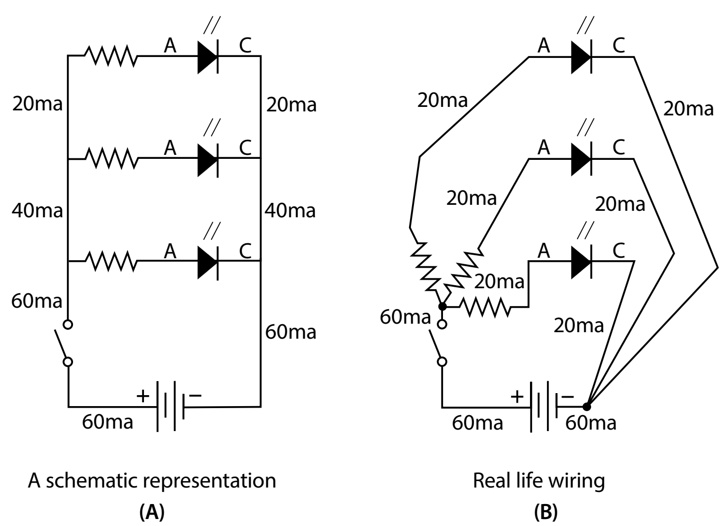
The general rules for parallel and series LED circuits can be stated as follows:

1. In a parallel circuit, the voltage is the same through all components (LEDs) but the current is divided through each.
2. In a series circuit, the current is the same through all components (LEDs) but the voltage is divided among the LEDs.
3. In a series circuit, the sum of all LED voltages should not exceed 90% of the supply voltage to ensure stable LED light output.
4. In a series circuit, all LEDs should have the same voltage and current properties.

## PARALLEL-WIRED LED CIRCUIT

Figure 9.3 shows two examples of the same circuit. Diagram *A* is a schematic representation of three LEDs connected in parallel to a battery with a switch to turn them on and off. Diagram *B* shows the real-life wiring for that schematic in *A*. In this circuit, each LED has its own limiting resistor and the supply voltage sides of these resistors are connected together and routed to the plus battery terminal (through a switch). Also, the cathodes of the three LEDs are connected together and routed to the negative battery terminal. This "parallel" connecting of components is what defines the circuit.

**FIGURE 9.3. Examples of the Same Circuit**

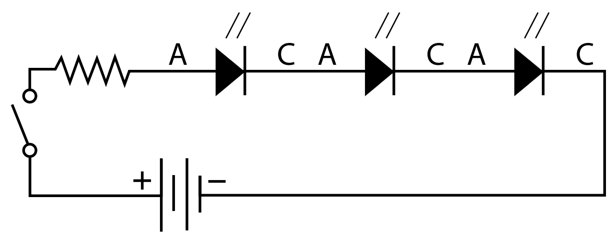



**A comparison showing how schematic diagram vs. actual wiring diagram in a sample parallel circuit arrangement**

## SERIES-WIRED LED CIRCUIT

The series-wired LED circuit (Figure 9.4) is a simple series circuit to power three LEDs. There are two main differences between this and the parallel circuit: All of the LEDs share one limiting resistor, and the LEDs are connected anode-to-cathode in daisy-chain fashion.

**FIGURE 9.4. Series-Wired LED Circuit**




**A schematic diagram showing one limiting resistor connecting to three LEDs in a series arrangement**

First, following rule 2 on the previous page, use the initial formula but vary it by adding together the LED voltages for the number of LEDs being used and then subtracting that value from the 9 V supply voltage as follows:

$$\frac{V_s - (V_d + V_d + V_d)}{I} = R$$

Then divide the result by the LEDs' device current (typically 20ma or 0.02) to get the resistor number. However, in this case, there are additional checks to make. You also must check that the LEDs' total voltage conforms with rule 3. So, multiply that combined supply voltage by 90% (0.9) and make sure that the sum of all device (LED) voltages doesn't exceed that value. Let's work through some examples using a 9 V battery or other 9 V power supply).

### Example 1

We want to hook up two LEDs in series. The LEDs are 3.6 V and have a device current of 20ma.

1. The LEDs' combined voltage is determined as 7.2 V by adding the voltages of the two LEDs together (3.6 + 3.6 = 7.2).

2. Check this total voltage to be sure it doesn't violate rule 3. So, 90% of 9 V is 8.1 V (0.9 x 9 = 8.1). We aren't over 90% so we can proceed.

3. Subtract this 8.1 amount from the 9 V supply voltage, which leaves 0.9. (This is $V_s - V_d$ in the formula.)

4. Then divide 0.9 by the device current, which is 20ma, or 0.02. The answer is 45. Since a 45 ohm resistor isn't standard, we'll pick the next highest value (50 ohm

or 60 ohm). This slightly higher resistance won't make any difference in the brightness of the LEDs.

## Example 2

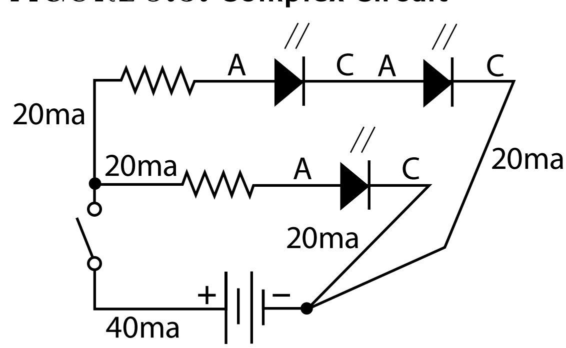
We want to connect four 1.7 V LEDs in series. The LEDs are 1.7 V and have a device current of 20ma. What resistor should be used?

1. For four LEDs, the total voltage would be 6.8 V (4 × 1.7 = 6.8).
2. Check to be sure this amount doesn't violate rule 3 in the "Circuits With Two or More LEDs" section (p. 367). So, 90% of 9 volts is 8.1 V (0.9 x 9 = 8.1). Because 6.8 is less than 8.1, it's okay.
3. Subtract the 6.8 V from the supply voltage (9 V), which leaves 2.2 V. (This is $V_s - V_d$ in the formula.)
4. Divide that 2.2 V by the device current of 20ma, or 0.02. This gives an answer of 110. Because 110 ohms is a standard resistor value, there's no need to pick the next higher value available. (*Note:* never choose a lower value!) So the correct resistor to use would be 110 ohm 1/8W1%.

## Example 3

We want to connect three LEDs together in series. The LEDs are 3.5 V and have a device current of 20ma.

**FIGURE 9.5. Complex Circuit**




**An example complex circuit showing three LEDs connected with limiting resistors**

1. For three of these LEDs, the total voltage will be 10.5 volts. This is a problem in two ways. First, that voltage violates rule 3 in the "Circuits With Two or More LEDs" section (p. 367) but it also exceeds the 9 V supply voltage. The LEDs wouldn't even light. Correcting the problem will require either using a power source of at least 11.67 V (i.e., 10.5 is 90% of 11.67) or connecting two of the LEDs in series and the third one separately with its own resistor. (This is known as a series/parallel circuit.) That case would have two circuit types con-

nected together at a common power source. The schematic would appear as in Figure 9.5 (p. 369).

2. To determine what limiting resistors are required, calculate each segment of the circuit separately. It doesn't matter which segment is determined first. Starting with the single LED, use the following formula:

$$\frac{V_s - V_d}{I} = R$$

The value for $V_s$ is 9 V. The value for $V_d$ is 3.5 volts and for $I$ is 20ma. So, 9 − 3.5 = 5.5 and 5.5 ÷ 0.02 = 275. That isn't a standard value resistor, so choose the next higher standard resistor—300 ohm.

3. Next, calculate the series pair of LEDs. The formula adjusted for two LEDs would be as follows:

$$\frac{V_s - (V_d + V_d)}{I} = R$$

So, 9 − (3.5 + 3.5) = 2, and 2 ÷ 0.02 = 100 ohm, which is a standard resistor value.

# ACTIVITY 9C: ENTER A ROOM

**Contributor: Derek van Beever**

**Time frame:** 2 class periods

**Physics focus:** Current electricity, electrical components, series and parallel circuits, and circuit diagram

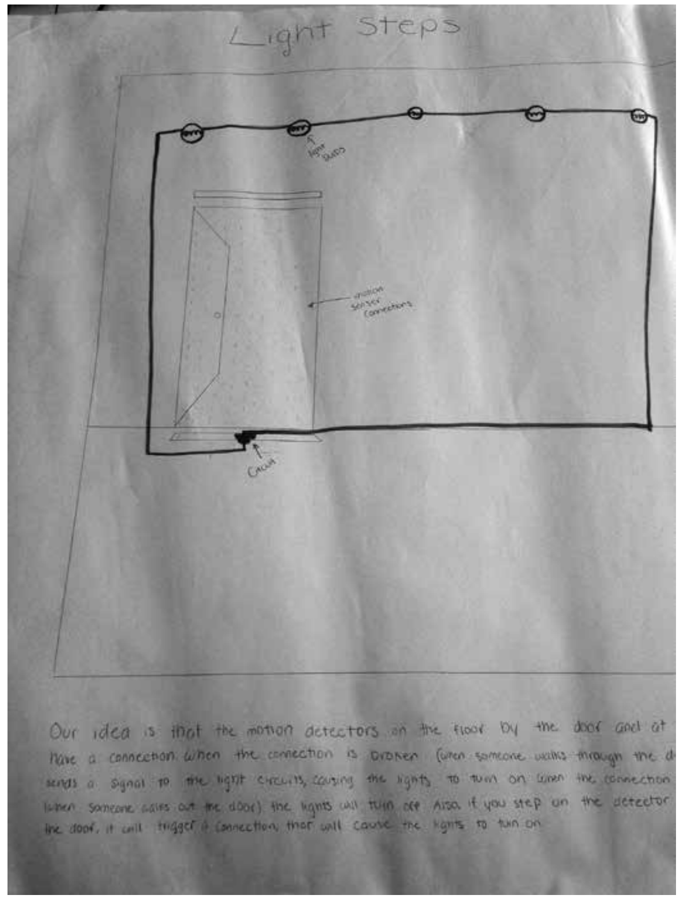
**Engineering focus:** Design, analysis, models, and systems

## Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Design an experiment that affects a sensor (speed of motion, volume of sound).<br>• Switch wired in series with rest of the circuit | • Can't have a physical switch<br>• Geometry and setup of the room<br>• Mechanism to turn the lights on<br>• Cost-sensitive material constraints |
| **Analysis** | • Complete circuit<br>• Tracing the current pathway<br>• Analyze motion and sound | • Testing whether it works<br>• Sensitivity<br>• Consistency<br>• Range of motion sensor or audio sensor |
| **Models** | • Electron flow model<br>• Circuit diagram<br>• Model of switch mechanism | • Circuit diagram<br>• Room blueprint<br>• Switch prototype/sketch |
| **Systems** | • Circuit<br>• Power system<br>• Output | • Room layout<br>• Electrical system<br>• Switch system<br>• Light holder<br>• Wiring |

## PROJECT OVERVIEW

This is a paper-and-pencil design activity in which students use schematic representations to draw how a light can be turned on when someone enters a room without the need of a person to turn on a switch. This lesson is a follow-up to the traditional introductory lesson on batteries and bulbs. In that brief introduction to the requirements of making a light bulb light up using just one battery, one wire, and one bulb, students often feel a sense of amazement and accomplishment to this challenge. Students may be asked to draw the four possible combinations in a journal or in their notes. This engaging experience is followed by a recap of the four possible combinations and an introduction to three basic schematic symbols. When the students have drawn the schematic representation under each drawing, move on to the design challenge.




**Sample student presentation showing schematic diagram and using a motion detector as part of the switch design**

Show one or two short videos to get the students thinking freely, inspire them, and open their minds to new ideas. One video is about an invisible bicycle safety helmet and the other is about a cardboard bicycle. Ask students to look at their definitions of DAMS (design, analysis, models, systems) before the videos and to note where they see examples of these concepts in the videos (a paper version is included here if viewing the videos is not an option). After watching the videos, most students feel somewhat inspired and are excited to discuss what they just saw. If students are encouraged to point out where the DAMS concepts arose, a much livelier discussion usually ensues. Limit this discussion to 5–10 minutes and then move on to the design challenge.

Students should work in groups of two or three to design a light system that turns on when a person enters a room, without the need for the person to flip a switch in the traditional way. Because there are no materials needed for this challenge—other than a pen and paper (large butcher paper is ideal for the final presentation)— there is no need to put any limits on what students can use or how the light turns on. At this point, they are usually raring to go and get all of their crazy ideas on paper.

The second part of this design challenge is for the groups to communicate their designs to the class. The only other requirement for this challenge is that students include each concept on their poster or presentation and be able to explain how that idea is addressed in their design idea. They should refer to their concept definitions and rather that copying them verbatim, try to explain how their idea exemplifies each concept. The final part is the group presentations and subsequent voting for the best idea.

## BIG IDEAS

**Physics:** circuits, circuit schematics, series, parallel, current

**Engineering:** The design of a system affects the function of the system. Individual components of a system must work together, each completing a function, for the entire system to work. There are multiple solutions to any problem.

## Connection to the *Next Generation Science Standards*

### Performance Expectation

- Not applicable

### Science and Engineering Practices

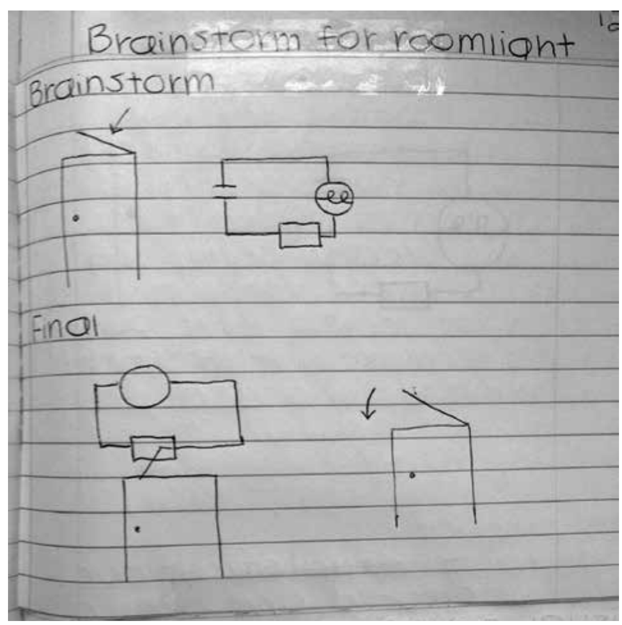
- Asking questions and defining problems
- Constructing explanations and designing solutions
- Engaging in argument from evidence
- Obtaining, evaluating, and communicating information

### Disciplinary Core Idea

- Not applicable

### Crosscutting Concepts

- Patterns
- Systems and systems models




**Sample student engineering notebook showing initial brainstorming process**

## Assessment: Determining Acceptable Evidence

### Formative

- Check in with students while developing design, asking guiding questions and evaluative questions of each group.

### Summative

- Final designs are presented and graded.

## Materials and Preparation

### Materials (Groups of 3)

- Safety glasses or goggles for all students
- Chart paper
- Markers
- Light bulbs
- Batteries
- Wires

### Class Equipment

- Projector for videos

## Safety

- Follow all general lab safety procedures.
- Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Use caution when working with sharps (wire and so on). These can cut or puncture skin.
- Use caution when working with bulbs. These can get hot and burn skin.
- Use caution when working with glass bulbs—they are fragile and can break and cut skin.
- Remind students to wash their hands with soap and water upon completing this activity.

### Enter a Room Lesson Plan for Day 1 (55-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **3 mins.**<br><br>**Engage** | — | • Start by telling students, “We take electricity and lights for granted regardless of whether they are in a flashlight, our homes, a stadium or an entire city. LED (light-emitting diode) lights are now saving millions of dollars a year as they continue to replace incandescent bulbs.” | — | — |
| **17 mins.**<br><br>**Elicit**<br>**Explore**<br>**Evaluate** | • Explore different ways to get light bulbs to light up using bulbs, batteries, and wires.<br>• Present and draw on the board different, unique circuits for discussion. | • Gather materials for bulb and battery activity. Hand out materials to students—one battery, one bulb, and one wire per student.<br>• Facilitate a class discussion about the similarities and differences between the different working circuits drawn on the board. | • Circuits | • Design and build solutions to solve a problem (light a bulb). |
| **10 mins.**<br><br>**Explain** | • Take notes as needed on circuit diagrams and circuit types. Students share these notes and diagrams. | • Whole class discussion and notes on circuit diagrams (introduce only symbols for wire, battery, and bulb) and types of circuits | • Circuits<br>• Circuit schematics<br>• Series circuits<br>• Parallel circuits<br>• Combination circuits | — |

Enter a Room Lesson Plan for Day 1 (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **15 mins.**<br><br>**Elaborate Evaluate** | • Watch videos for inspiration.<br>• While watching the video(s), look for ways that the engineers incorporate design, analysis, models, and systems in their design process and solution.<br>• As a class, discuss the DAMS concepts in the video(s). | • Show videos or hand out article.<br>• Facilitate a class discussion about how DAMS is seen in the videos. Include a discussion of what role creativity plays in the design process. | — | • Design<br>• Analysis<br>• Models<br>• Systems<br>• The role of creativity in engineering design solutions |
| **3 mins.**<br><br>**Explain** | • Work in small groups, discussing the challenge and any questions to make sure they understand the challenge and timeline. | • Explain the Enter a Room challenge to students and clarify the process and timeline for presentations. | — | — |
| **7 mins.**<br>**Explore Evaluate** | • Brainstorm as a group, writing ideas on scrap paper or butcher paper. | • Facilitate student brainstorming. | • Creating working circuits | • Brainstorming process is part of the engineering design process<br>• Different parts of a system and how they work together to create a solution |
| **Evaluate** | **Homework:** Students independently sketch a variety of options for the Enter a Room challenge and should be ready to present those options to the group tomorrow. | | | |

**Enter a Room Lesson Plan for Day 2 (55-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **30 mins.**<br><br>**Explain**<br>**Evaluate** | • Present their ideas to their group so their group can analyze and synthesize those ideas to come up with the best solution to the challenge. The chosen solution must then be drawn and explained on butcher paper or other paper to prepare for class presentation.<br>• As groups, be ready to explain and defend their design solution. | • Facilitate the design process, answering questions as needed and asking for clarification when drawing and explanations are not clear. | • Circuit schematics<br>• Types of circuits | |
| **15 mins.**<br><br>**Elaborate**<br>**Evaluate** | • Each group presents its design solution, giving reasoning for why it might be the best or most creative solution<br>• Vote for winning design. | • Facilitate presentations and grade presentations.<br>• Collect drawings for further grading. | — | • Communicating ideas |
| **10 mins.**<br><br>**Explain** | • Students should spend time summarizing the process, either on a separate sheet or in their engineering notebooks. They should address what worked well and what didn't work well with the process and provide the rationale for improvements or changes they would make to their design after seeing all of the other design solutions presented. | | | |

## Optional Modification and Extension (Extend)

- Add the criterion or restriction that the light must turn off once the person leaves the room.
- For groups that finish early, challenge them to create additional, more complex solutions to present. (The more complex and convoluted, the better.)

## Differentiated Instruction

### Special Needs

- Supply students with guided notes for circuit schematics and circuit types, or "cheat sheets" with schematic symbols and circuit types.
- Provide a format for the written explanation of their design solution.
- Provide guiding questions or a format for the written summary.

### English Language Learners

- Post important terminology in classroom: circuit schematics and types of circuits.
- Provide sentence framework for written explanations and summary.

## Supplemental Materials

- Article: "This $9 Cardboard Bike Can Support Riders Up to 485lbs," *www.fastcodesign.com/1670753/this-9-cardboard-bike-can-support-riders-up-to-485lbs*
- YouTube video: "This $9 Cardboard Bike Can Support Riders Up To 485lbs Co Design business + innovation + design," *www.youtube.com/watch?v=0Lwox-IAeGI*
- Article: "The Invisible Bike Helmet: An Airbag On the Go," *https://techcrunch.com/2012/08/15/invisible-bike-helmet*

# ACTIVITY 9D: LIGHTS OUT! ZOMBIE APOCALYPSE FLASHLIGHT

**Contributors: Danielle Raad, Matthew Anderson, Shu-Yee Chen Freake, and Michael Hazeltine**

**Time frame:** 4 class periods

**Physics focus:** Circuits, series and parallel circuits, circuit components and diagrams, insulator versus conductors, and Ohm's law

**Engineering focus:** Design, analysis, models, systems, and communication

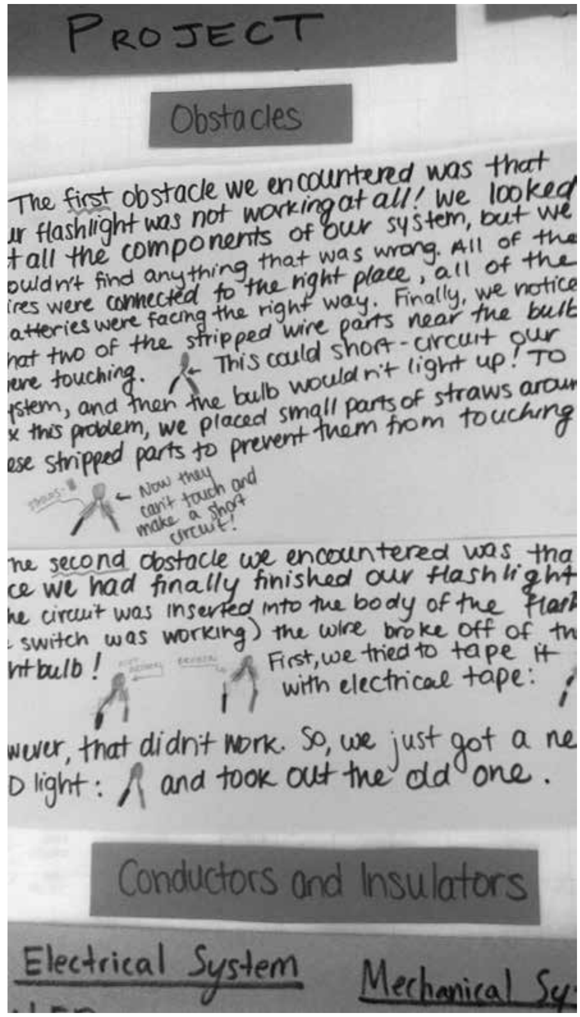
## Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • Experiment to test voltage, current, brightness<br>• Ohm's law | • Simple household items as the design constraint<br>• One-handed operation<br>• Sturdy and reliable<br>• Is the light bright enough to be considered working light?<br>• Can it double as a weapon?<br>• Hand-crank to recharge batteries |
| **Analysis** | • Ohm's law and power as tools for analysis | • Analyze brightness<br>• Optimize power<br>• Battery life<br>• Maximize efficiency<br>• Analyze how deep you can penetrate zombie head without damaging the flashlight!<br>• Durability<br>• Waterproof |
| **Models** | • Circuit diagram<br>• schematic diagram (sketch) | • A prototype for a flashlight that meets other criteria |
| **Systems** | • Conservation of charge<br>• Conservation of energy | • Electrical system<br>• Mechanical system |

## PROJECT OVERVIEW

This zombie flashlight project is designed as an introduction to circuits. Prior to this project, students have learned about electrostatics, but not moving electrical charges. The project serves as an engaging activity to familiarize students with circuits and to provide a common experience for students that can be referenced throughout the unit.

The premise of the project is that zombies have infiltrated the school, and it's up to the students to save the day by building flashlights and leading the school to safety. Students work with partners, and each pair is supplied with batteries and a pile of "trash" that includes clean items from the recycling bin (plastic bottles, cardboard boxes, and so on) as well as some strings of Christmas tree lights. They are required to keep a record of their design process in their engineering notebooks in case they are "taken by the zombies" and someone else needs to pick up where they left off.




**Sample student presentation that focuses on the iterative process of design**

Students are given time to brainstorm multiple ideas and then sketch a final design. This design is approved by the instructor and then time is provided for students to build their flashlight. During the build process, changes in the design typically arise and should be documented in the engineering notebook.

On the day of presentations, the class is split into two groups that consists of one person from each group pair. One group spends time viewing each of the flashlights while the members of the other group stand near their flashlight to aid in presentations. Then the two groups switch. After all flashlights have been presented and viewed, the class votes for the "Most Creative Flashlight Design" and the design "Most Likely to Survive the Zombie Apocalypse."

## BIG IDEAS

- **Physics:** Some materials allow electric current to flow more easily than others. Circuits must have a voltage source, a conducting path and a load. Each circuit component can be represented using a schematic diagram and is measurable.
- **Engineering:** Design is an iterative process that can be used to produce a product. Systems thinking allows the breaking down of design complexity and troubleshooting of certain components separately. Communication is essential for the design process.

## Connection to the *Next Generation Science Standards*

### Performance Expectation

- HS-PS3-3: Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.

### Science and Engineering Practices

- Developing and using models
- Planning and carrying out investigations
- Constructing explanations and designing solutions
- Obtaining, evaluating, and communicating information

### Disciplinary Core Ideas

- PS3.A: Definitions of Energy
- PS3.D: Energy in Chemical Processes and Everyday Life
- ETS1.A: Defining and Delimiting Engineering Problems

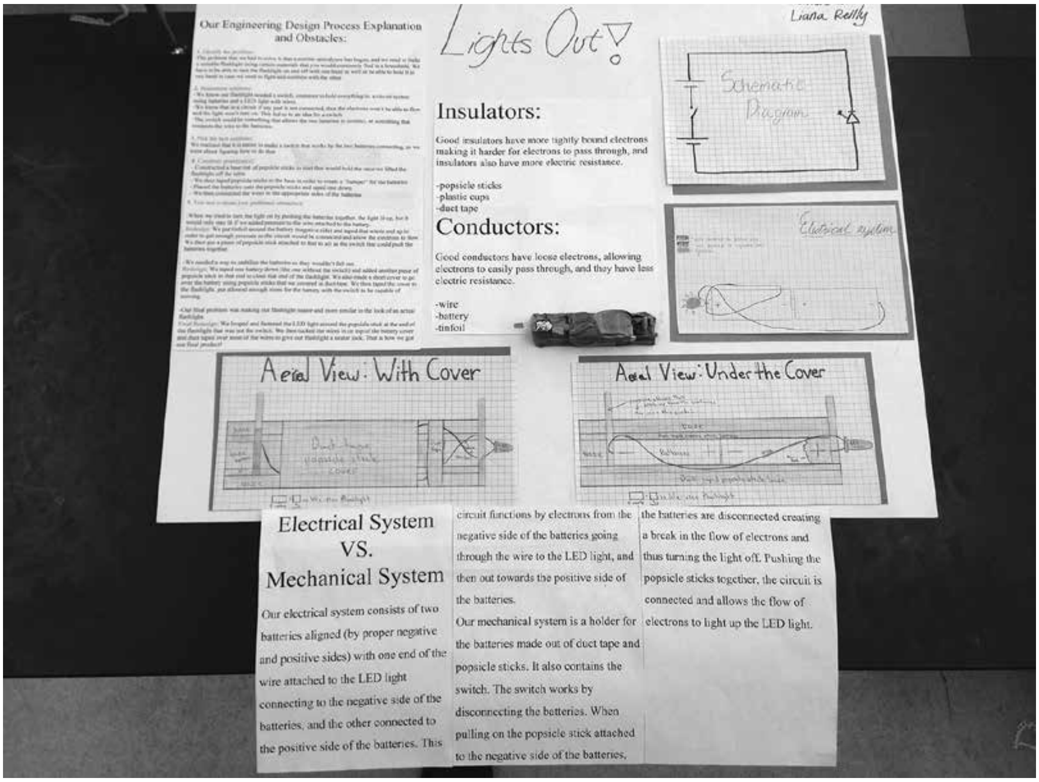
### Crosscutting Concepts

- Systems and systems models
- Energy and matter
- Structure and function

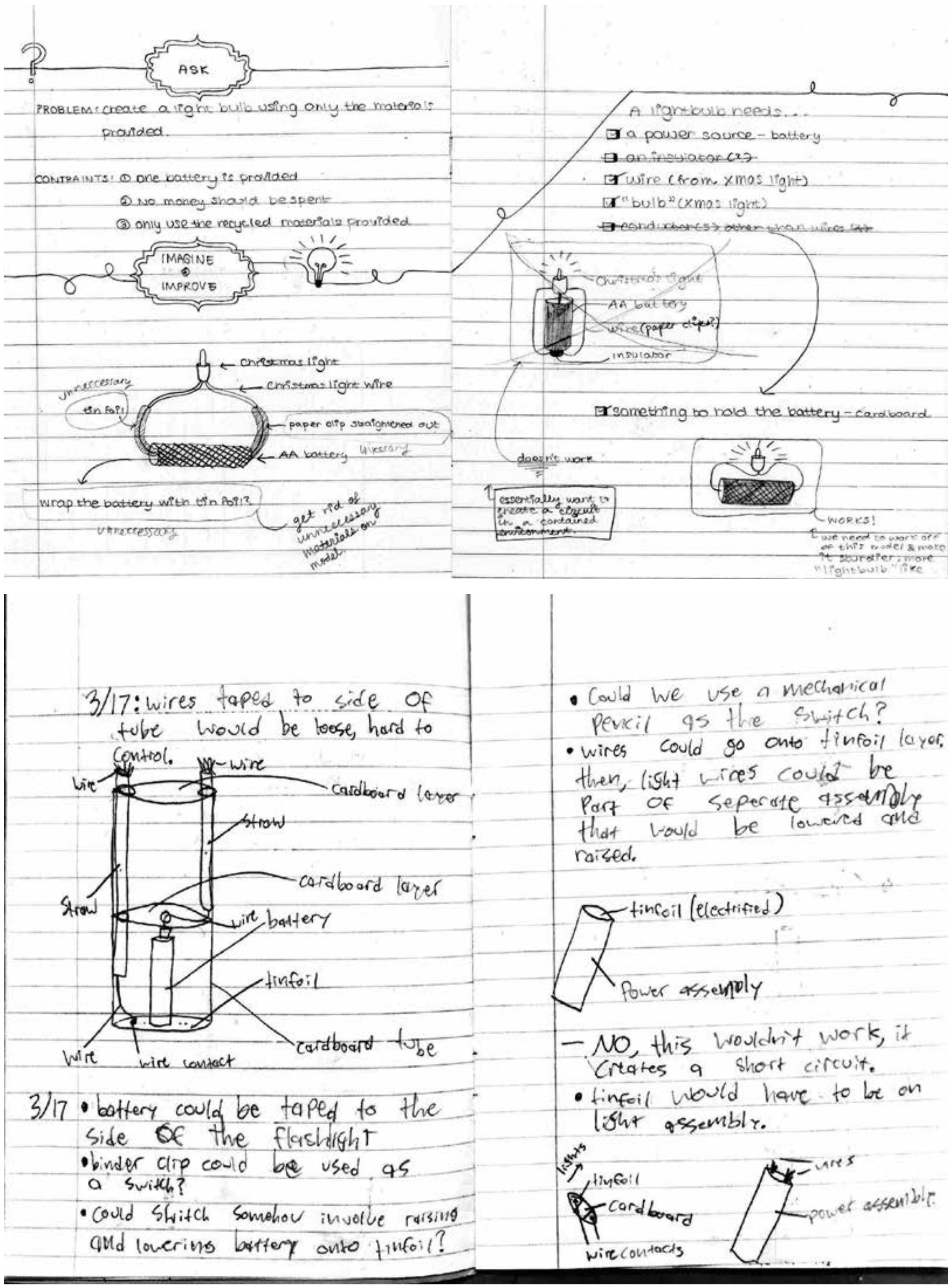
## Assessment: Determining Acceptable Evidence

### Formative

- Mini-conferences with groups
- Class discussion or chart discussion of constraints and final test requirements
- Do Now, class notes and discussions, homework assignments (spot check)




**Sample student group poster at the end of the flashlight project**




**Sample pages of students' engineering notebooks**

### Summative

- Individual: engineering notebook, homework assignments
- Group: Working flashlight that fits the criteria, poster (optional)

## Materials and Preparation

### Materials (Groups of 3)

- Safety glasses or goggles for all students
- 2 AA batteries
- 1 1-gallon zip-sealed bags (for project storage)
- Poster-making supplies
- LED lamps with leads OR small light bulbs

### Class Equipment

- Wire strippers
- Wire cutters
- Scissors
- Masking tape, duct tape, clear cellophane tape, and electrical tape
- Strings of Christmas lights
- Aluminum foil, stretchable plastic wrap, cellophane in different colors
- Recycled materials such as toilet paper, cardboard holders, yogurt cups, plastic and foam cups, straws, plates, and bowls
- Everyday school supplies such as brads, pins, and paper clips

## Safety

- Follow all general lab safety procedures.
- The teacher should do the soldering before giving students the light bulbs or LED lamps. In addition, during the testing phase, emphasize the importance of avoiding short circuits.
- Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Use caution when working with sharps (scissors, wires, pins, and so on). These can cut or puncture skin.
- Use caution when working with hot objects (soldering iron). These can burn skin!

- Provide a short lesson on soldering iron safety before beginning the building process.
- Students should not use a soldering iron until they are safety trained. Remind students to follow all safety procedures.
- Set up the soldering iron in a space separate from student work areas and make sure students go to that location to do their soldering. Instruct students to unplug the soldering iron when they are finished and to not leave soldering irons unattended. Also make sure there is appropriate ventilation to protect students from soldering fumes.
- Use caution when using hand tools (wire cutters, wire strippers, and so on). They can be a pinch hazard and cause skin injury.
- Use caution when working with light bulbs. They can get hot and burn skin, and if glass shatters, it can cut skin.
- During testing phase, avoid creating short circuits.
- Remind students to wash their hands with soap and water upon completing this activity.


**The table of "trash" halfway through the project, with student works-in-progress organized by class in large zip-sealed bags in the background**

### Lights Out! Zombie Apocalypse Flashlight Lesson Plan for Day 1 (50-minute block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins.**<br>**Engage** | • Read the Zombie Apocolypse handout and scenario. | • Explain the scenario and set the stage for the project.<br>• Provide students with the handout and project the engineering design process diagram on the board. | — | • Discussing the different steps of the engineering design process |
| **3 mins.**<br>**Elicit** | • As a class, discuss and create list of constraints. | • Ask the class to consider some constraints that might not be obvious. For example, ask students whether it's important for the flashlight to be operated easily with one hand. | — | • Identifying constraints on the problem |
| **40 mins.**<br>**Explore** | • With partners begin brainstorming. Identify the problem and the constraints and write them in their engineering notebooks. Look over the available materials but no calling "dibs" on any materials allowed and no building yet. Draw and plan out potential ideas in their engineering notebooks. | • Have a system for pairing up students.<br>• Distribute engineering notebooks to students.<br>• Have project materials organized and set out. | • Designing circuits with a battery, wire, and light bulbs<br>• Drawing circuits | • Coming up with a plan or design for a product<br>• Identifying materials to be used<br>• Coming up with multiple ideas to solve the problem |
| **Extend** | • **Homework:** Come up with one or two more flashlight designs and draw or explain them in their engineering notebooks. | — | • Designing circuits with a battery, wire, and light bulbs | • Coming up with a plan or design for a product |

**Lights Out! Zombie Apocalypse Flashlight Lesson Plan for Day 2 (50-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins.**<br>**Engage** | • In pairs, decide on a final plan. | — | — | • Choosing the best idea to pursue |
| **10 mins.**<br>**Explain** | • When ready, student pairs walk the teacher through their plan. Once the plan is approved, they receive one AA battery and a gallon-size zip-sealed plastic bag for storing their project at the end of the period. | • Listen to each group's plan and approve it. Students must show evidence of multiple ideas in the notebooks, not just the one plan. Send students back to come up with more ideas if there is just one plan. When their plan is approved, give students one AA battery and one gallon-size zip-sealed plastic.<br>• Do not tell students whether or not their circuit will actually work! | — | • Defending a proposal |
| **30 mins.**<br>**Explore** | • Begin to build their flashlight. | • Prompt students to keep track of their progress, tests, and changes in their engineering notebooks. | • Figuring out how to arrange materials to get a lightbulb to turn on | • Gathering materials, following the plan, and testing it out<br>• Troubleshooting |
| **5 mins.** | • Clean up their areas.<br>• Put their projects in the storage bag and then in a box designated for their block. | • Prompt students to clean up their space, return unused materials, replace tools in their correct locations, throw away trash, and store their work-in-progress. | — | — |
| **Extend** | • **Homework:** Brainstorm one or two additional ideas for improving the design. | — | • Additional ideas for circuits | • Modifying and improving a design |

**Lights Out! Zombie Apocalypse Flashlight Lesson Plan for Day 3 (50-minute block)**

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **45 mins.**<br><br>**Explore** | • Finish creating their flashlight. Try to make improvements. | • Remind students they must have a working flashlight by the end of the period or may come in after or before school to finish.<br>• Prompt students to keep taking notes in their engineering notebooks. | • Discovering how to wire bulbs in series circuits versus parallel circuits<br>• Making switches by breaking the circuit<br>• Troubleshooting short circuits | • Refining, modifying, and improving the product<br>• Keeping track of changes |
| **5 mins.** | • Clean up their areas. | • Prompt students to clean up their space, returning unused materials, replace tools in their correct locations, throw away trash, and store their completed flashlights. | — | — |
| **Extend** | • **Homework:** Students make sure they have included a final diagram of the product. | — | • Drawing the final, working circuit | • Diagramming the prototype |

### Lights Out! Zombie Apocalypse Flashlight Lesson Plan for Day 4 (50-Minute Block)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins.** | • In groups, make sure their flashlight is ready to present. | — | — | — |
| **30 mins.**<br><br>**Explain** | • One student from each pair stands by the flashlight while the other student moves around the room and checks out all the other designs. After 15 minutes, students swap roles. This gives each student a chance to explain their design to others and an opportunity to look at the other products.<br>• At the end of each session, students who were walking around cast their votes. | • Establish the procedure and set two 15-minute timers. Make sure each flashlight is working and take photographs of students with their designs. Establish rules for voting: can't vote for self, must vote for two different groups. Set out voting cards and voting box. | • Explaining to others how the circuit works | • Showing off features of the flashlight such as brightness, durability, and so on |
| **10 mins.**<br><br>**Expand** | • Take a survey on their smartphones or on a classroom laptop while the teacher tallies the votes. | • Have available two or three laptops for students who don't have smartphones.<br>• Prepare reflection and feedback survey on Google Forms.<br>• Tally votes while students work. Make slides with winners' names. Write names of winners on certificates. | • Reflecting on how much new knowledge about circuits has been learned | • Reflecting on the steps of the engineering design process.<br>• Identifying changes made along the way, and struggles that were overcome |

Lights Out! Zombie Apocalypse Flashlight Lesson Plan for Day 4 (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **5 mins.** | • Hold an awards ceremony. Announce third place, second place, and winners for the categories of "Most Likely to Survive the Zombie Apocalypse" and "Most Creative Design." | • To recognize the work of more students, announce the third- and second-place winners before the first-place winners. Clap for each announced group. Give winners certificates. | — | — |
| **Evaluate** | • Hand in notebooks. Students get to take home flashlights, or leave with the teacher as examples for next year. | • Collect engineering notebooks for summative assessment. | — | — |

**A variety of finished flashlight designs**

## Optional Modification and Extension (Extend)

- Weave this project into the current electricity unit, using it as an opportunity for students to explore concepts of current electricity, such as the schematic diagram, circuit components, series and parallel circuits, and Ohm's law. (See Handout 9D-2, p. 396, for a version of this project with content that is more physics-heavy.)
- Add on to this project by asking students to think about other electronic devices that are essential for basic survival and then asking them to design a new device for a specific amount of allotted wattage.
- Ask students to test both series and parallel setups during the second and third building days as a way to introduce series and parallel circuits.
- After spending some time teaching about circuits, Ohm's law, and series and parallel circuits, revisit the project and ask students how they can change the amount of current running through the flashlight. Ask them to do a paper design

of the flashlight with more than one light bulb and to calculate the current going through it.

- Have students redesign the flashlight as one that can be easily reproduced cheaply using minimal materials.

## Differentiated Instruction

### Special Needs

- Provide students with a checklist of daily goals.
- Use preprinted engineering notebook templates for students who need the structure for documentation.
- For students who might struggle with a handwritten engineering notebook, allow different types of documentation such as using a computer to type or phones or tablets to take pictures and then add captions.

### English Language Learners

- Have visuals around the classroom for the terms *engineering design process, current, resistance,* and *voltage.*
- Provide sentence frames and use technologies for students to record in their engineering notebook.

## Supplemental Materials

- Handout 9D-1: Zombie Apocalypse Flashlight
- Handout 9D-2: Lights Out! Zombie Apocalypse Flashlight (a modified version of the activity to be used by students daily during activities for main goals and objectives, Do Now questions, and key activities each day)
- Handout 9D-3: Light a Bulb—A Bright Idea! (a worksheet for the mini-lab to be completed before introducing the project)
- Handout 9D-4: Schematic Symbols for Electric Circuit Diagrams (a quick reference sheet for introductory physics students that summarizes the commonly used schematic diagram symbols)

# HANDOUT 9D-1: ZOMBIE APOCALYPSE FLASHLIGHT

**Oh, snap!** The zombies have taken over our high school and it's up to us brave physics students to use our ingenuity to save the day!

## SAFETY PRECAUTIONS

- Safety glasses or goggles are required for this activity. Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Use caution when working with sharps (scissors, wires, pins, and so on). These can cut or puncture skin.
- Use caution when working with hot objects (soldering iron). These can burn skin!
- Do not use a soldering iron until you are safety trained by a teacher. Follow all safety procedures.
- Set up the soldering iron in a space separate from student work area. Students should always go to that location to do their soldering. Be sure to unplug the soldering iron when you are finished and do not leave soldering irons unattended. Also make sure there is appropriate ventilation to protect students from soldering fumes.

- Use caution when using hand tools (wire cutters, wire strippers, and so on). They can be a pinch hazard and cause skin injury.
- Use caution when working with light bulbs. They can get hot and burn skin, and if glass shatters, it can cut skin.
- During testing phase, avoid creating short circuits.
- Wash your hands with soap and water upon completing this activity.

## PREMISE AND GOAL

You and your partner have managed to find one AA battery. Your task is to use this battery to design and build a working flashlight using only the trash that the zombies have left behind. Thankfully, although they have a penchant for eating humans, the zombies do take recycling very seriously and have left behind a number of clean recyclables. There are a lot of supplies in our classroom but you may also bring in materials from home, provided you spend no money on them and only use items considered trash, waste, recyclable, or disposable.

Each of you will receive an engineering design notebook, in which you will keep track of all steps of the engineering design process (see the image that follows) throughout the zombie apocalypse. It's very important to keep track of everything in your notebook, so that if you get eaten, all of your work is not lost! Once we've rescued the school, your notebooks will be collected, and assessed as a 25-point lab grade. Table 9.4 lists the zombie apocalypse survival criteria and serves as a rubric for grading on how you meet them.

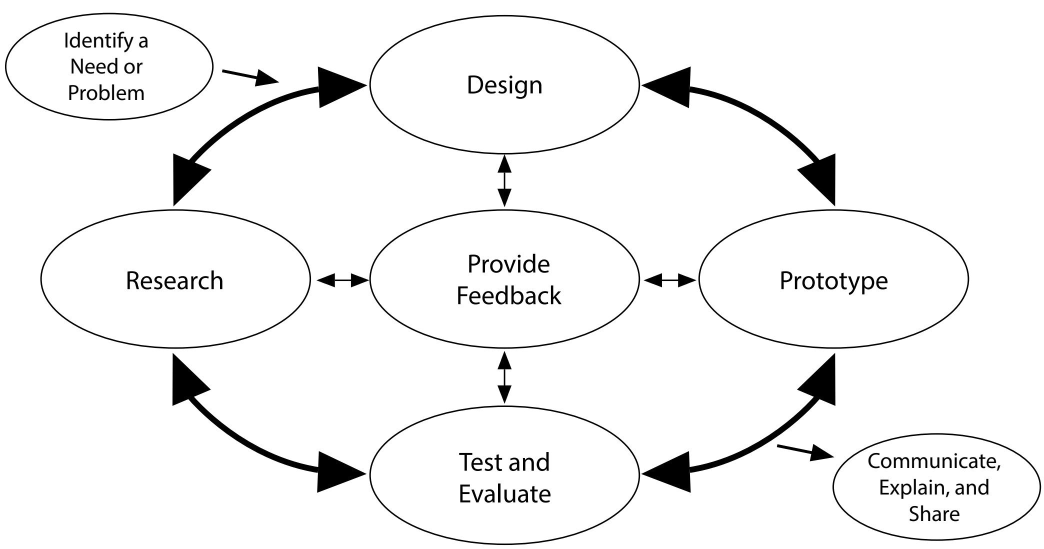



**Diagram of the engineering design process**

**TABLE 9.4. Rubric for Meeting the Zombie Apocalypse Survival Criteria**

| Step | Requirements | Your Points | Possible Points |
|---|---|---|---|
| **Ask** | • Identify the problem.<br>• Identify criteria and constraints. | | 5 |
| **Imagine** | • Brainstorm multiple ideas for the design.<br>• Select one idea to move forward with. | | 5 |
| **Plan** | • Draw a diagram.<br>• List necessary components and materials. | | 5 |
| **Create** | • Execute the plan.<br>• Test it out.<br>• Create a *working* flashlight. | | 5 |
| **Improve** | • Keep track of what worked and what didn't work.<br>• Record modifications made to the design along the way. | | 5 |

**TOTAL _______ / 25**

*Note:* The "ask," "imagine," "plan" and "improve" steps will be graded based on evidence, notes, and drawings in your engineering design notebook. Your points for the "create" step will be determined by the final built flashlight.

# HANDOUT 9D-2: LIGHTS OUT! ZOMBIE APOCALYPSE FLASHLIGHT

## SAFETY PRECAUTIONS

- Safety glasses or goggles are required for this activity. Wear personal protective equipment (eye protection) during the setup, hands-on, and takedown segments of the activity.
- Use caution when working with sharps (scissors, wires, pins, and so on). These can cut or puncture skin.
- Use caution when working with hot objects (soldering iron). These can burn skin!
- Do not use a soldering iron until you are safety trained by a teacher. Follow all safety procedures.
- Set up the soldering iron in a space separate from student work area. Students should always go to that location to do their soldering. Be sure to unplug the soldering iron when you are finished and do not leave soldering irons unattended. Also make sure there is appropriate ventilation to protect students from soldering fumes.
- Use caution when using hand tools (wire cutters, wire strippers, and so on). They can be a pinch hazard and cause skin injury.
- Use caution when working with light bulbs. They can get hot and burn skin, and if glass shatters, it can cut skin.
- During testing phase, avoid creating short circuits.
- Wash your hands with soap and water upon completing this activity.

## GOAL

Uh-oh, the zombie apocalypse has begun, and whoever was working at the power station has become lunch for the undead. We need light, and it's not coming from plugging in a lamp, so what can you do? you've got are some basic materials like batteries, tinfoil, plastic, an LED light, and some other stuff you'd find lying around the house. Home Depot and all the other home improvement stores have been overrun by CHUDs (cannibalistic humanoid underground dwellers, aka *zombies*) so you can't get any fancy stuff. It's up to you to create a functioning flashlight from these items.

- Engineering Design Process Define the problem.
- Generate solutions.

- Choose a solution.
- Build prototype(s).
- Analyze performance.
- Tweak and rebuild.
- Present results.

*Note:* All of your work should be documented in your engineering notebook. Please set up your engineering notebook.

## CONSTRAINTS

- You may only use the materials that is provided or easily found in a house. You may not use any preconstructed parts from a flashlight. (Check with your teacher if you are not sure about the materials you want to bring in.)
- The flashlight must be able to stay lit with one hand so you can also fight off the zombies if necessary.
- The flashlight must be able to be turned off and on.
- The flashlight meets the class-generated "test" conditions.

## DAILY LOG

In your daily log entries, please include the following: a heading (shown below as Day 1, Day 2, etc.), the date or dates of the work, your building documentation for each day, and answer to questions. Make sure to leave room for the teacher's initials or stamp.

## DELIVERABLES

### Individual

- To save others from becoming a midnight snack, you need to create some documents that will give others the information they need to create their own flashlights! The only way to accomplish that is by clearly and thoroughly documenting your solutions.

### Group

- A working flashlight that meets the goal and constraints
- A poster that includes the following:
    - Blueprint—to scale, showing how the light was designed and with insulators and conductors labeled

- Explanation of what parts constitute the electrical system versus the mechanical system in your blueprint. Explain how your group incorporated the two systems to make the final product.
- Circuit (schematic) diagram
- Paragraphs describing the thought and design process. (How did you end up with your final design?)
- "First we wanted to …"
- "We thought the switch should be like *x* so we …"
- Elaboration on *at least three* specific design decisions
- Description of at least two obstacles you encountered and how you worked around them or fixed them. (e.g., when we tried *x* it didn't work because …, so we tried *y* instead.)
- Explanation of how engineering is an *iterative* process and not just trial and error. What do you think is the difference between iteration and trial and error?

## DAILY OBJECTIVES AND QUESTIONS

### Day 1: Brainstorm, Design, Start Building, Work on Documentation

#### Physics Objective

Recognize that electric charge tends to be static on insulators and can move on in conductors.

#### Engineering Objective

Use the engineering design process. Understand that design is an iterative process conducted within specified constraints to develop products or systems to satisfy human needs and wants.

#### Do Now Questions

1. Draw one arrangement connecting one light bulb to one battery with one wire that makes the bulb stay lit.
2. How is current electricity different from static electricity?
3. What is a switch?

### Discussion Questions

1. Define the following terms: *circuit, simple circuit, short circuit, terminal, open switch*, and *closed switch*
2. Draw the direction of electron flow in a simple circuit.
3. What kind of test will we run to rank the flashlights?

### Engineering Challenge

By the end of class, you should include the following in the engineering notebook:

- A list of materials that are good insulators versus good conductors to be used in flashlight
- A list of materials that you would like to bring in from home
- Drawings and notes from brainstorming at least three different designs to turn the flashlight on and off
- Documentation for any test you did with materials today, including what worked and what didn't work
- Your teacher's signature or stamp.

### Homework

Bring materials from home.

## Day 2: Continue to Build, Test, Refine the Device, and Work on Documentation

### Physics Objective

Analyze simple arrangements of electrical components a circuit.

### Engineering Objective

Recognize that a system is a group of interrelated components designed collectively to achieve a desired goal.

### Do Now Questions

1. What is the material that provides voltage source in your designed circuit?
2. What are two types of system you really need to worry about in designing a working flashlight?

### Discussion Questions

1. Define the following terms: *voltage, current*, and *resistance*.
2. Define *electrical system* versus *mechanical system*.
3. Why do engineers use different systems?

### Engineering Challenge

By the end of class, you should include the following in the engineering notebook:

- Documentation of any test or work you did today, including what worked and what didn't work
- A labeled sketch of your current design
- The components of the mechanical system used to hold the flashlight in-place. (The mechanical system is the holder for the bulb and the flashlight housing and any other materials used.)
- The electrical system in your flashlight design
- Where on the flashlight voltage, current, and resistance can be measured
- Teacher's stamp or signature in your engineering notebook

### Homework

- Bring any other materials you might need.
- Read Handout 9D-4.

## Day 3: Refine the Flashlight and Complete the Documentation for Individual and Group Posters

### Physics Objective

Recognize symbols and understand the functions of common circuit elements (battery, connecting wire, switch, fuse, and resistance) in a schematic diagram.

### Engineering Objective

Use the engineering design process. Understand that design is an iterative process conducted within specified constraints to develop products or systems to satisfy human needs and wants.

### Do Now Questions

1. Using the schematic symbols, draw a circuit consisting of two batteries, one light bulb, and one closed switch that is connected with wire.
2. Using the schematic symbols, draw a circuit consisting of one battery, one resistor, and wire connecting them with an open switch.

### Discussion Question

What is the difference between a blueprint and a schematic symbol (circuit symbol)?

### Engineering Challenge

By the end of class, you should include the following in the engineering notebook:

- Completed documentation of any final changes to your design
- A drawing of a blueprint of your final design
- A drawing of a schematic diagram of your circuit
- Your teacher's signature and stamp
- The start of work on your group presentation poster

### Homework

- Finish the group presentation poster.
- Optional: Read about parallel versus series circuit online; explain how you could improve your flashlight design using more than one bulb.

## Day 4: Share Your Posters and Flashlight Design, Evaluation, and Work on Documentation

### Physics Objective

Analyze simple arrangements of electrical components a circuit.

### Engineering Objective

Create a visual model to represent in detail of an object or design.

### Do Now Question

Finish any last minute work on your poster or flashlight.

### Discussion Questions

Define the following terms: *source* and *load.*

### Engineering Challenge

We will be evaluating and voting for the best flashlight by the end of class. To help with the process, make sure you include the following in your engineering notebook for **three** different groups:

- A list of three pros for their flashlight design.
- A complete sentence describing why you think their design works well, using any of the following vocabulary; *circuit, short circuit, voltage, resistance, switch, source, load*.
- One recommendation for each group to consider
- Your teacher's signature and stamp.

### Homework

*Optional:* Calculate the resistance of their LED light by using a voltmeter and ammeter to measure and Ohm's law for calculation. Show your work!

## Day 5: Redesign and Extension Questions

*Note:* This step will be conducted later, after a short break from our flashlights.

### Physics Objectives

- Develop a qualitative and quantitative understanding of current, voltage, and resistance, and the connection among them (Ohm's law).
- Analyze simple arrangements of electrical components in series and parallel circuits.

### Engineering Objective

Use the concept of design, system, and models in an engineering solution.

### Do Now Questions (discuss in small groups)

1. Looking back in your flashlight project, how would you change the design to increase the amount of current in the flashlight?
2. If you have two LED lights, what are some ways you can connect them to your flashlight? Please explain the electrical system as well as the mechanical system.

### Engineering Challenge

By the end of class, you should include in the engineering notebook a drawing of a model of how your new flashlight would look if you want the most brightness while connecting two LED lights. Explain why you made this decision.

*Optional challenge question:* Draw a model to demonstrate a new design that would allow you to use switches to turn on one light, another light, or both lights.

## Rubric for How You Will Be Assessed

You will receive two project grades: one for individual work and one for group work.

| Grading Component | Points Possible | Points Earned |
|---|---|---|
| **Individual Grade: Working diligently each day (10 points possible)** | | |
| Day 1 | 2 | |
| Day 2 | 2 | |
| Day 3 | 2 | |
| Day 4 | 2 | |
| Day 5 | 2 | |
| **Individual Grade: Engineering Notebook Documentation (20 points possible)** | | |
| Day 1 | 4 | |
| Day 2 | 4 | |
| Day 3 | 4 | |
| Day 4 | 4 | |
| Day 5 | 4 | |
| **Group Grade: Working flashlight (8 points possible)** | | |
| Works | 2 | |
| Turns on and off | 2 | |
| Stays lit with one hand | 2 | |
| Class designed test | 2 | |
| **Group Grade: Poster (22 points possible)** | | |
| Blueprint | 2 | |
| Conductors versus insulator | 2 | |
| Electrical versus mechanical system | 2 | |
| Circuit diagram | 2 | |
| Engineering design process explanation | 10 | |
| Obstacles | 2 | |
| Iterative versus trial and error | 2 | |

**TOTAL ______ / 60**

# HANDOUT 9D-3: LIGHT A BULB—A BRIGHT IDEA!

Using one wire, one battery, and one small light bulb, light the bulb! It may not be as easy as you think—keep trying until you get it! Once you get it, find a second setup that also lights the bulb.

| | |
|---|---|
| **Draw and label a setup that lights the bulb. Include as much detail as possible.** | **Draw and label a setup that does not light the bulb. Include as much detail as possible.** |
| **Draw and label a different setup that also lights the bulb. Include as much detail as possible.** | **Draw and label a second setup that does not light the bulb. Include as much detail as possible.** |

## QUESTIONS AND THINGS TO DO

1. The lightbulb: To make the lightbulb light, you had to touch certain parts of it with the wire or battery.

   a. Draw arrows pointing to the parts of the lightbulb that had to be touched by the wire or battery.

   b. How many parts of the lightbulb needed to be touched for the lightbulb to light? ________

2. The battery: To make the lightbulb light, you had to touch certain parts of the battery with the wire or lightbulb.

   a. Draw arrows pointing to the parts of the battery that had to be touched by the wire or lightbulb.


   b. How many parts of the battery needed to be touched for the lightbulb to light? ____________

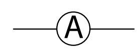
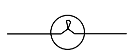
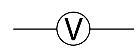
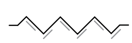
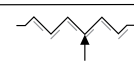
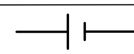
3. The battery or lightbulb becoming hot:

   a. Did you do anything that made the battery and/or lightbulb or wire become hot? _____________

   b. What did you do that made it become hot? Draw a picture to help with your explanation.

# HANDOUT 9D-4: SCHEMATIC SYMBOLS FOR ELECTRIC CIRCUIT DIAGRAMS

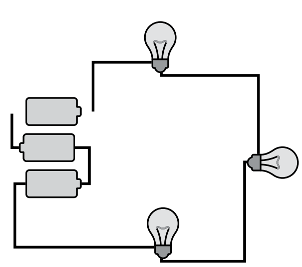
We will be using circuit diagrams to analyze different types of circuits. It is important for you to be familiar with what each symbol means. Below are some of the common symbols you might see in a circuit diagram and what they mean:

| Symbol | Meaning | Symbol | Meaning |
|---|---|---|---|
|  | wire |  | ammeter (measures the current) |
|  | light bulb |  | voltmeter (measures the electrical potential difference) |
|  | resistor |  | variable resistor |
|  | switch |  | source voltage (DC) |

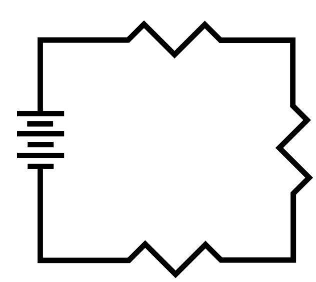
Here are some other examples of circuit diagrams, showing the diagram, description, and a sketch of the circuit:

Example 1: Three cells (batteries) are placed in a battery pack to power a circuit containing three light bulbs in series.

Drawing of Circuit

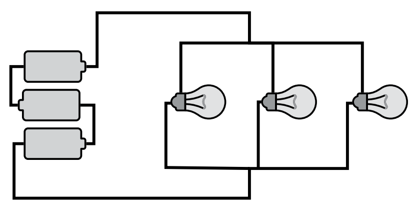


Schematic Diagram of Circuit

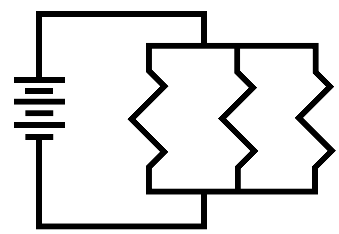


Example 2: Three cells (batteries) are placed in a battery pack to power a circuit containing three light bulbs in parallel.

Drawing of Circuit



Schematic Diagram of Circuit



# ACTIVITY 9E: MAGNETIC BEES

Contributor: Derek van Beever

**Time frame:** 15–30 minutes (or a homework assignment)

**Physics focus:** Magnetism, electromagnetism, and circuit

**Engineering focus:** Design, iteration, systems, models, and communication

### Opportunities for Science Versus Engineering Concepts

| Concept | Science | Engineering |
|---|---|---|
| **Design** | • How bees respond to different strengths and placements of magnets<br>• Trajectory of bees | • Mechanism to alter where bees go<br>• Number and strength of the available magnets |
| **Analysis** | • Strength of magnetic field and distance<br>• Current strength versus magnetic field | • Whether magnets affect other animals or systems in the environment |
| **Models** | • Magnetic field electron spindipole<br>• Magnetic domains<br>• Inverse square law | • Magnetic interference of electrical systems |
| **Systems** | • Bees<br>• Magnetic field of magnet<br>• Magnetic receptor of bees | • Bees' social system<br>• Ecological system around bees<br>• Where you want the bees to go<br>• Magnets and placements |

## PROJECT OVERVIEW

Not all infused lessons need to be multiday design challenges! Another way to infuse engineering into a physics lesson is to incorporate current events and ask probing questions that make the connection between physics and engineering visible. Fun and engaging articles or videos can be found by looking at news headlines, websites such as Makezine.com, or magazines such as *Wired*. It usually doesn't take much to make a short article into a quick engineering lesson. If you can find which aspect of the physics content is covered in the article or video, it can be amazing to see student responses to a question or two related to the physics aspects of the issue. This is an example lesson using an article, but keep in mind that the articles or videos that teachers personally respond to or find interesting will make the current-event mini-lesson more powerful to students and the classroom goals.

This magnetic bee article is just an example of how to infuse engineering without actually building, or spending too much time on a project. Students read an article that highlights how a specific instrument is designed for scientists to understand insomnia. The "insominator" utilizes scientific principles of magnetism to manipulate the movement of the bees. In a way, this article represents the important overlap between science and engineering goals and skills that one needs to solve a problem.

## BIG IDEAS

- **Physics:** Magnetic force, just like any other forces, has the ability to do work and change the system.
- **Engineering:** Engineers use scientific principles and models to design solutions to a problem.

## Connections to the *Next Generation Science Standards*

### Performance Expectation

- HS-PS3-4: Develop and use a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction.

### Science and Engineering Practices

- Developing and using models
- Constructing explanations and designing solutions
- Using mathematics and computational thinking

### Discplinary Core Ideas

- PS3.B: Conservation of Energy and Energy Transfer
- PS3.D: Energy in Chemical Processes and Everyday Life

### Crosscutting Concept

- Patterns

## Assessment: Determining Acceptable Evidence

### Summative

- Class discussion

### Formative

- Handout questions answered individually or in small groups, exit cards

### Magnetic Bees Lesson Plan for Day 1 (Less than one class period or for homework)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **2 mins.**<br><br>**Engage**<br>**Elicit** | • View picture on board or on handout and discuss the following questions:<br>○ "What do you see?"<br>○ "What do you think the device does?" | • Show the magnetic bees article illustration on the board or on a handout.<br>• Ask the students what they see in the picture.<br>• Ask students what they think the device does.<br>• Engage students by asking them to be descriptive and use think-out-loud protocols. | • Observation | • Communication |
| **3 mins.**<br><br>**Engage**<br>**Explore** | • Read the article silently. | — | — | — |
| **13 mins.**<br><br>**Explore**<br>**Explain**<br>**Elaborate** | • Participate in class discussion:<br>○ What were the researchers testing?<br>○ How did they control for their experiment?<br>○ From the picture, how do you think the researchers made the magnets move?<br>○ What do you think were some of the challenges in designing a way to test their research problem? | • Students can be confused about how controlled studies are done.<br>• A short discussion about the need to only test one variable at a time could be useful here. | • Not all metals are magnetic.<br>• Discussion of what makes certain materials magnetic<br>• Earth's magnetic field | • The mechanical system of the moveable track to create a changing magnetic field is crucial to this experiment working.<br>• A possible discussion about how to stick pieces of metal to bees without it affecting their behavior (materials science-adhesive that can stick to bees) |

Magnetic Bees Lesson Plan for Day 1 (*continued*)

| Time Allotted and 7e Model Stage(s) | Lesson Procedure: What Are the Students Doing? | Instructional Notes: What Is the Teacher Doing? | Physics Opportunities | Engineering Opportunities |
|---|---|---|---|---|
| **10 mins.**<br><br>**Elaborate** | • Answer this challenge prompt: "Suppose that the mechanical system was disturbing all the bees. Given a 10-minute time constraint, redesign the insominator without permanent magnets."<br>• Draw a sketch of their prototype and explain how it works." | • The teacher may have to be explicit about current-carrying wire creating the magnetic field.<br>• If students are finished in two minutes, challenge them to make another design. | — | • Individual brainstorming to create a design or multiple designs<br>• Mechanical system mentioned and pointed out in the design.<br>• Reiterate that this would be a first stage in the design cycle. |
| **2 mins.**<br><br>**Evaluate**<br>**Explore** | • Turn and talk with their neighbor and share their design with the class. | — | — | — |

## Optional Modification and Extension (Extend)

- What modifications may be made in the insominator to answer a research question of your own?

## Differentiated Instruction

### Special Needs

- Provide students with a list of definitions of the engineering core concepts.
- Have students work in groups so they can share ideas and explain to each other their understanding of the engineering and science concepts.

### English Language Learners

- Provide sentence frames for written work.

## Supplemental Materials

- Article: "Sleep Deprived Bees Do Weirder Waggle Dances," *www.wired.com/2014/11/berrett-klein-honeybees*
- Handout 9E: Magnetic Bees

# HANDOUT 9E: MAGNETIC BEES

## READING BACKGROUND

Article "Sleep-Deprived Bees Do Weirder Waggle Dances" by Leah Shaffer, *Wired*, November 13, 2014. *www.wired.com/2014/11/berrett-klein-honeybees*

## REFLECTION QUESTIONS

1. What physics principles do you see in this article?

2. What engineering principles do you see in this article?

3. What do you think are some of the challenges of this experiment? How do you think they were solved?

4. Describe how you could design an “insominator” if you did not have access to actual magnets.

5. Draw a picture of parts of your prototype and label it.

10

# Professional Development and Growth in Engineering Infusion

**Arthur Eisenkraft and Shu-Yee Chen Freake**

## HISTORY OF PROJECT INFUSE

Project Infuse began before the publication of *A Framework for K–12 Science Education* (the *Framework;* NRC 2012) and the *Next Generation Science Standards* (*NGSS;* NGSS Lead States 2013). Because both of those publications emphasized the need to have engineering as part of science curricula, interest in Project Infuse and the importance of our work took hold.

As described in earlier chapters, the leadership team of Project Infuse set out to look at the possibility of engineering infusion in high school science classes (as opposed to stand-alone engineering courses), looking specifically at teaching and articulating engineering concepts of design, analysis, model, and systems. Professional development was implemented with a two-summer commitment and school-year call back sessions in which teachers and trainers had the time and ample opportunities to share their expertise, experiences, and challenges with each other and problem solve together.

The first two summers of Project Infuse workshops included professional development training for 10 high school physics, engineering, and technology teachers. They gathered for two weeks each of two summers and introduced engineering during the school years following each summer. Dr. Arthur Eisenkraft and Dr. Kristen Wendell led the workshops focusing on developing visions and defining models of infusion that can be used in classrooms. The *Active Physics* curriculum and engineering activities were designed to inspire and jumpstart discussions. *Active Physics* is a project-based learning high school curriculum that has infused engineering concepts throughout each chapter of the book. As an organizing structure for infusing engineering, four anchor activities were introduced and used in the training period, and teachers were asked to consider electromagnetism units of the *Active Physics* curriculum to brainstorm ways to infuse each of the four core concepts (design, systems, analysis, and models) at a time and critique each other's lesson plans. Electromagnetism was chosen as the content focus rather than mechanics because most teachers' experience with engineering (if any) had to do with egg drops, catapults, or other mechanical devices. It was reasoned that a fresh perspective on engineering infusion would generate more learning if we moved away from teachers' engineering infusion comfort zone. In addition to learning about the four core concepts and attempt to add them into a physics curriculum, the workshop also provided teachers with case studies, videos such as IDEO Shopping Cart Project outlining an engineering company at work ("ABC Nightline - IDEO Shopping Cart" *www.youtube.com/watch?v=M66ZU2PCIcM*), and articles discussing engineering design, analysis, and the *NGSS* documents on physics content and science and engineering practices. In a seminar format, teachers discussed how each of these components represents different aspects of engineering concepts and how they could apply these components to their classroom.

During the first school year, teachers all developed and taught an engineering-infused lesson in the electricity unit and shared the process and results during the callback sessions. They were asked to develop at least one lesson, record the lesson, and have an outside evaluator come to observe the lesson. During the three callback sessions, teachers shared their lessons, students' works, successes and failures, and questions for the entire group to problem solve and fine tune the lesson plans.

The professional development for the second summer was focused on finding some common themes in how teachers implemented the lessons, and on discussions of assessments and further expansion of infusion across different topics of physics and physical science curriculum. In the second year, videos from the teacher's electromagnetic lessons were shared and critiqued. In the video critique protocol, teachers in groups of three were asked to view the entire lesson, examine how engineering concepts and practices were being taught explicitly, and provide suggestions using the Innovation Configuration (IC) Map (see Appendix A, p. 423) and *NGSS* science and engineering standards as guides. Other engineering activities such as anchor activities focused on design, predictive analysis, mathematical analysis, and differentiated materials were also presented by both the trainers and participants. Speakers were brought in from engineering schools to provide different perspectives on engineering education, science education, and ways to assess engineering in a classroom. The group of teachers also used a big portion of the second summer to focus on developing engineering infused lessons in other topics of physics and making an implementation plan for the year. There was enough time for feedback during the lesson designing process (in pairs) as well as in larger groups using protocols for small learning communities.

The following school year, each teacher implemented at least one lesson in a different topic of physics and shared his or her experiences in the callback sessions throughout the year. Most of the teachers reported implementing multiple lessons (beyond the requirement and expectation), and the sharing sessions allow some teachers to collaborate in designing and implementing lessons in different schools.

Much of the structure and components from the first cohort were found to be especially helpful in creating professional dialogues focusing on engineering concepts and practices in the classroom. Among those common core experiences, anchor activities were especially effective in helping us frame discussions and raise questions about how one understands and engages in engineering concept learning. For example, one day teachers used a small direct-current (DC) motor, a plastic cup, rubber bands, markers, and some craft sticks to design a simple robot that could draw on a piece of paper automatically after being connected. One simple activity that the training team thought was a good way to kick-start some engineering design turned out to be amazingly effective for our discourse on engineering infusion. Teachers ended up referring to it constantly throughout the two-week discussion. We discussed ways it can be used to teach about kinematics, electricity, and magnetism, and even the connection between art, culture, engineering, and science. This activity sparked conversations about assessments of engineering-infused lessons, dialogues about how one can conduct this lesson focusing on different aspects of engineering, and ways to encourages engineering-design thinking among the participants. We found that these types of activities (which we later named the anchor activities for cohort II) to be particularly successful in the professional development trainings. They provided both engaging hands-on pieces that are necessary when discussing engineering as well as eye-opening ways to focus on how different engineering concepts emerge in different activities. Some of these anchor activities have been modified to use by administrators and teachers to begin the school year as a way to discuss engineering concepts.

Supplementing the professional development with some totally different perspectives was also very helpful for broadening our conversation about teaching science and engineering. Sanjoy Mahajan, a professor at Olin College, Massachusetts, came to speak about the power of predictive analysis to solve interesting physics problems. Cory Culbertson, a high school engineering teacher at University High, Illinois State University, came to discuss assessments methods in engineering activities as well as the parallel between an engineering design–centered classroom and an inquiry-based science classroom. In addition, both cohorts worked with middle school and high school students from a summer enrichment program to test out ways to teach engineering process using different techniques or activities. All of these added experiences allowed for a richer conversation and broader imagination about how engineering infusion can work in a classroom.

The pilot two-year cohort was followed by a field-test two-year cohort of 20 teachers. When the second cohort gathered, two teachers from cohort I (Shu-Yee Chen Freake and Derek van Beever) joined the training team to bridge some of the experiences from the previous years. Having teachers who have struggled with similar questions of developing, implementing, and assessing engineering-infused lessons helped open up the discussions even more. Participants were able to learn from some of the success and challenges and to feel more comfortable trying different forms of the infusion model. Shu-Yee and Derek had two very different approaches to infusion, so they were able to present and help the cohort II teachers to come up with infusion methods that supplemented their own classrooms and teaching styles.

The second cohort followed a similar professional development approach as the first, with two-week workshops over two successive summers and the requirement of implementing lessons in the years following each summer. The recruitment for the second cohort yielded 20 experienced physics teachers, some of whom had engineering degrees. In fact, some of the teachers had been practicing engineers before beginning their teaching careers, and their wealth of experience offered a perspective of engineering that was beneficial for the entire cohort. Given the talents of the second cohort, it was agreed that we should try to share our experiences, and work on this book was initiated.

## RECOMMENDATION FOR PROFESSIONAL DEVELOPMENT

After four years of the project, we found that having teachers commit to only one lesson per year to start with was a good way to encourage engineering infusion without too much stress or change to a teacher's already established curriculum. This is the recommendation we have for anyone trying to infuse engineering into science classes. Some teachers naturally want to start by doing some small-scale design activities such as the anchor activities to introduce engineering and some physics concepts because those do not take much to carry out and can be used throughout the year without much interruption to the curriculum. Other teachers love to try an engineering project that helps students apply what they learned in physics, so they just add them on to the end of a unit. Still others might decide to replace the study of electricity with learning about all the features that contribute to lighting up a school spirit sign. All of these are valid forms of infusion. The journey of infusing engineering takes time and some planning, but it can all start with just one small change and seeing how that affects our students and our teaching. Most teachers from Project Infuse found themselves feeling more confident and excited about teaching engineering-infused lessons, so that they often did more than one lesson the second year. Some even decided to eventually transition their entire course so that engineering is embedded throughout.

In our attempt to find out what engineering infusion looks like, we were able to share ideas about teaching and learning with groups of teachers who are dedicated and excited to help students become independent learners and problem solvers. A few common themes emerged as a result of this project. One is that engineering infusion is doable in any type of physics classroom. In addition to some exemplar lessons to begin their infusion process, teachers need the time, structure, and support within their school or other connections to be effective in making changes.

## PROJECT INFUSE TAKEAWAYS

1. Using systems, design, analysis and models as a set of unifying and consistent themes of engineering is an effective means promoting better instruction. The DAMS (design, analysis, models, systems) choices from the published Delphi study provide a way of framing and assessing lessons and performance. The DAMS scheme used in this book provided a powerful way to organize thinking about engineering as a broader endeavor than designing and making.

2. There are multiple ways of infusing engineering into high school physics. These vary in approach and in time required. They range from readings about engineering to full-scale long-term engineering projects. In between these two extremes in pedagogy and time are paper-and-pencil approaches and activities. Engineering does not always have to involve a physical design, and teaching engineering in a science classroom is possible by looking at the different elements of engineering (specifically the four core concepts). Through the use of some building activities, mathematical simulations and modeling, case studies, and other forms of engineering activities, one can choose to emphasize different concepts of engineering and fit that into the curriculum.

3. Successful professional development requires an amount of discussion, planning, and implementation timelines that is reasonable for educator's schedule and commitment. Being product-oriented and having common planning and reflection times for teachers and the instructors to provide feedback after implementation were effective strategies. Having a collective deliverable or outcome, such as this book, really helped to motivate, structure, and organize teacher development work. The experience and expertise of the participating teachers and the dynamics of the teacher cohorts were a huge factor in the success of the program. Teacher leadership was a wonderfully powerful force.

4. There is a strong increase in the need for ways to infuse engineering into high school physics. This embrace of engineering for high school physics teachers probably is due to the emphasis placed on engineering in the *Framework* and *NGSS*. There is a clear sense of need for secondary science educators to learn and understand more about the engineering field and engineering concepts. In addition to using the anchor activities and discussion about the core concepts of engineering, there should be more emphasis on articulating the engineer's approach to problem solving and contrasting it with a novice's approach.

5. Assessment of engineering concepts and skills continue to be the most difficult portion of engineering-infusion discussion. A variety of assessment methods have been discussed, field-tested, and developed, but teachers still need ways to assess the students, their own lessons, and the activity. The IC Map can be a good tool if it is used in the right context (i.e., for the teacher as a guide but not as an assessment tool for an evaluator because some of the elements might not match with the goal of the particular activity.

6. Engineering infusion into high school physics is a credible means of acquainting students with engineering. Engineering can be infused across all the major topics of physics—mechanics, electricity and magnetism, optics, and thermodynamics.

## REFERENCES

Eisenkraft, A.. *Active Physics.* New York: It's About Time.

National Research Council (NRC). 2012. *A framework for K–12 science education.* Washington, DC: National Academies Press.

NGSS Lead States. 2013. *Next Generation Science Standards: For states, by states.* Washington, DC: National Academies Press. *www.nextgenscience.org/next-generation-science-standards.*

# Appendix A

## Assessment of Engineering Infusion

### PROJECT INFUSE INNOVATION CONFIGURATION (IC) MAP

### A. Curriculum Materials

The curriculum materials chosen by the teacher should include engineering concepts and an open-ended design challenge and be designed to facilitate the connection between engineering concepts and science learning. Materials should be standards-based and include a student-assessment component.

☐ If the curriculum chosen does not include engineering concepts, please check here and move on to Section B.

| a | b | c | d |
|---|---|---|---|
| A1. Curriculum targets engineering concepts articulated in science standards appropriate to the course. | Curriculum targets engineering concepts articulated in science standards, but the concepts targeted are not well-matched to the course or unit. | Curriculum targets engineering concepts, but the concepts targeted are not standards-based. | Curriculum does not target science and engineering standards. |
| **a** | **b** | **c** | **d** |
| A2. Materials chosen include at least one open-ended engineering design challenge that requires understanding of scientific concepts and an iterative process for optimal solutions. | Materials chosen include an engineering design challenge that requires understanding of scientific concepts for solutions, but the scientific concepts are not those targeted by the teacher (unit, standards). | Materials chosen include an engineering design challenge that can be solved simply by trial and error without understanding of science concepts. | Materials chosen do not include an open-ended engineering design challenge. |

| a | b | c | d |
|---|---|---|---|
| A3. Curriculum materials make explicit connections between engineering concepts and science learning. | Curriculum materials include engineering concepts, but connection to science learning is not explicit. | Curriculum materials include engineering concepts but present them in total isolation from science concepts. | Curriculum materials lack explicit engineering concepts. |
| **a** | **b** | **c** | **d** |
| A4. Materials include a standards-based student assessment that explicitly targets both science and engineering concept understanding in an authentic context. | Standards-based student assessment is included and targets engineering concepts, but coverage of engineering concepts is minimal or exclusively at the knowledge/ comprehension level. | Student assessment includes engineering concepts but is not in line with appropriate standards. | There is no evidence of student learning assessment that includes engineering concepts. |

## B. Teacher Practices: Design-Centered

The design challenge should be structured as an open-ended team-based activity in which each team is expected to generate a unique solution. When implementing the challenge, the teacher should take on the role of consultant and guide and should support student teams in the use of a rational design process. To support science learning, the teacher should make explicit connections to science concepts when supporting design teams, and routinely should ask students to provide science-based rationale for design decisions.

☐ If no engineering design challenge is used, please check here and move on to the Section C.

| a | b | c | d |
|---|---|---|---|
| B1. Teacher structures the design challenge as a team-based activity such that all team members contribute to the design solution. Checks and balances are in place to ensure that all students participate. | Teacher structures the design challenge as a team-based activity, but checks and balances are not always effective in ensuring that all students participate. | Teacher structures the design challenge as a team-based activity, but checks and balances are not in place to ensure that all students participate. | Design challenge is structured as an individual activity. |

| | | | |
|---|---|---|---|
| Examples of checks and balances include the teacher actively asking about participation while moving from group to group, assigning individual students to play specific roles during the design challenge, including a peer-rating system in students' report-out or grade and requiring each student to report out on results. | | | |
| **a** | **b** | **c** | **d** |
| B2. Teacher encourages a unique solution from each team and actively supports students in creating a unique solution during the design process. | Teacher encourages a unique solution from each team in the activity's introduction but does not actively support students in creating a unique solution during the design process. | Teacher does not provide direction to students regarding uniqueness of design solution. | Teacher actively directs students toward a single solution. |
| Open-ended design challenges have multiple solutions. In engineering, it is desirable for a design to have attributes that differentiate it from competitors. The word *unique* as used above is meant to capture this element of engineering design. In the best-case scenario, there would be some element or attribute to each group's design that is a bit different from all the others, something that differentiates it and makes it unique. | | | |
| **a** | **b** | **c** | **d** |
| B3. Teacher actively checks on group progress and provides individual coaching to groups by making specific suggestions for additional considerations or next steps. | Teacher actively checks on group progress and provides general coaching to the class as a whole rather than on an individual group basis. | Teacher observes group work to check on progress but does not provide coaching at either the class or individual group level. | Teacher neither checks on group progress nor offers coaching to support group work. |
| **a** | **b** | **c** | **d** |
| B4. Teacher requires students to engage in an iterative design process with at least one opportunity for redesign, testing, and analysis. | Teacher requires one cycle of redesign on paper but does not include testing or analysis of the new design. | Teacher requires students to briefly document what they would do differently if allowed to redesign. | There is no evidence of redesign. |

## C. Teacher Practices: Engagement With Engineering Concepts

Teachers should make explicit connections to engineering concepts throughout the lesson or unit and routinely use appropriate engineering terminology. Teachers should explicitly connect science concepts with real-world engineering applications and describe these applications as a rationale for the learning of science.

☐ If no engineering concepts are included, please check here.

| a | b | c | d |
|---|---|---|---|
| C1. Teacher makes explicit connections to engineering concepts throughout the lesson/unit (i.e., in the lesson introduction, primary activity, and wrap-up). | Teacher makes explicit but sporadic connections to engineering concepts. | Teacher makes implicit connections to engineering concepts. | Teacher does not make connections to engineering concepts. |
| **a** | **b** | **c** | **d** |
| C2. Teacher uses engineering terminology correctly and provides explicit instruction on terminology to students. | Teacher uses engineering terminology correctly but does not provide explicit instruction to students. | Teacher uses engineering terminology but sometimes uses terms incorrectly. | Teacher does not use engineering terminology. |
| **a** | **b** | **c** | **d** |
| C3. Teacher provides rationale for science learning throughout the lesson by using real-world engineering application(s) OR focusing on the science needed to solve a real-world engineering challenge. | Teacher provides rationale for science learning using real-world applications but significant “missed opportunities” are evident. | Teacher sometimes mentions real-world applications but those examples are not related to the rationale for science learning. | Teacher does not mention real-world applications of science concepts. |
| **a** | **b** | **c** | **d** |
| C4. Teacher routinely asks students to provide scientific or engineering rationale for design decisions and supports students in developing detailed, correct responses. | Teacher sporadically asks students to provide scientific or engineering rationale and supports students in developing detailed, correct responses. | Teacher asks students to provide scientific or engineering rationale but accepts superficial or incorrect responses. | Teacher does not ask students to provide scientific or engineering rationale for design decisions. |

# PROJECT INFUSE IC MAP (CONDENSED VERSION)

## A. Curriculum Materials

The curriculum materials chosen by the teacher should include engineering concepts and an open-ended design challenge and be designed to facilitate the connection between engineering concepts and science learning. Materials should be standards-based and include a student assessment component.

| A1 | A2 | A3 | A4 |
|---|---|---|---|
| Curriculum targets engineering concepts articulated in science standards appropriate to the course. | Materials chosen include at least one open-ended engineering design challenge that requires understanding of scientific concepts and an iterative process for optimal solutions. | Curriculum materials make explicit connections between engineering concepts and science learning. | Materials include a standards-based student assessment that explicitly targets both science and engineering concept understanding in an authentic context. |

## B. Teacher Practices: Design-Centered

The design challenge should be structured as an open-ended team-based activity in which each team is expected to generate a unique solution. When implementing the challenge, the teacher should take on the role of consultant and guide and should support student teams in the use of a rational design process. To support science learning, the teacher should make explicit connections to science concepts when supporting design teams and routinely ask students to provide science-based rationale for design decisions.

| B1 | B2 | B3 | B4 |
|---|---|---|---|
| Teacher structures the design challenge as a team-based activity such that all team members contribute to the design solution. Checks and balances are in place to ensure that all students participate. | Teacher encourages a unique solution from each team and actively supports students in creating a unique solution during the design process. | Teacher actively checks on group progress and provides individual coaching to groups by making specific suggestions for additional considerations or next steps. | Teacher requires students to engage in an iterative design process with at least one opportunity for redesign, testing, and analysis. |

## C. Teacher Practices: Engagement With Engineering Concepts

Teachers should make explicit connections to engineering concepts throughout the lesson or unit and routinely use appropriate engineering terminology. Teachers should explicitly connect science concepts with real-world engineering applications and describe these applications as a rationale for the learning of science.

| C1 | C2 | C3 | C4 |
|---|---|---|---|
| Teacher makes explicit connections to engineering concepts throughout the lesson/unit (i.e., in the lesson introduction, primary activity, and wrap-up). | Teacher uses engineering terminology correctly and provides explicit instruction on terminology to students. | Teacher provides rationale for science learning throughout the lesson by using real-world engineering application(s) OR focusing on the science needed to solve a real-world engineering challenge. | Teacher routinely asks students to provide scientific and/or engineering rationale for design decisions and supports students in developing detailed, correct responses. |

# Appendix B

## Handout for Students Setting Up Their Engineering Notebooks

### WHY DO I NEED AN ENGINEERING NOTEBOOK?

The goal of an engineering notebook is to document all of the important details of a project. It serves two major purposes: (1) to record experiments and the progression of the project and (2) to provide detailed dates for verification and legal information should a project be sought. Therefore, is it essential that you start developing and practicing the skills of recording information that demonstrates the progression of your project throughout all of the engineering challenges this year.

### WHAT DO I NEED FOR AN ENGINEERING NOTEBOOK?

- 1 bound notebook dedicated to use for your engineering challenges for physics class
- Your full name, your period, and your teacher's name written on the front on the notebook

### WHO IS RESPONSIBLE FOR RECORDING IN THE NOTEBOOK?

In general, you are! In most cases, we will work on this project in class, and you will be responsible for writing in your own notebook. Sometimes I will collect an official "report" from your group at the end of the project where you can work together to type up the important steps of your engineering process. When that happens, all of your notebooks serve as important rough drafts for your final report.

### WHEN WILL THE NOTEBOOK BE GRADED?

I will collect the notebooks at random times throughout projects this year. Sometimes I will just spot check certain section of your notebook DAILY and give you a stamp for completion, sometimes I will collect and grade your notebook at the end of the whole project.

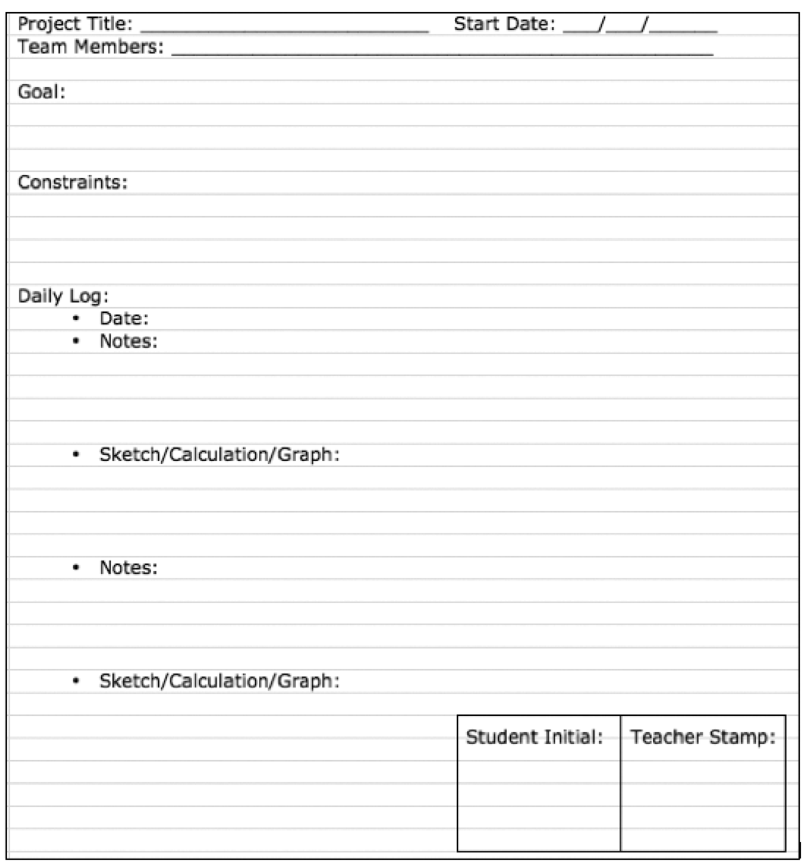
## HOW SHOULD I RECORD THE NOTES?

In general, you should aim to provide enough detail so someone else (who is not on your team) can understand the project. Think of it this way: In a team of three engineers, one of your team members was sick and absent from school yesterday. She came back and found both of you were out because of a field trip! She should be able to pick up one of your engineering notebooks and step in and continue the work without any questions.

Write legibly! Label any sketches, chart, or calculation you have. Because this is a running notebook, you should write EVERYTHING DOWN! If you made a mistake, you should just cross out the words. The notebook may help you remember the mistakes or issues in the design process so you do not repeat the same tests again without reason.

Here is a template of how I recommend you set up the notebook. You may add more headings if you find it useful for your organizational purposes.

1. Leave two pages in the front for a Table of Contents.
2. Here is a sample layout of a notebook page:


Project Title: ______________________ Start Date: ___/___/_____
Team Members: ________________________________________

Goal:

Constraints:

Daily Log:
- Date:
- Notes:

- Sketch/Calculation/Graph:

- Notes:

- Sketch/Calculation/Graph:

| Student Initial: | Teacher Stamp: |
|---|---|
| | |

# Appendix C

## Concept Definitions, Standards, and Performance Expectations

**Project Infuse, January 17, 2012**

## CONCEPT DEFINITIONS

The following process was employed to define the conceptual base for engineering at a level appropriate for secondary-level science education. Three stages of the process were conducted to ensure a systematic process that was rooted in the research literature and standards so that the concepts and definitions were appropriate for the secondary level. The graphic below outlines the key components of each of the stages.

**Identifying the Concepts**

- 18 main concepts and 16 subconcepts
- 2 concepts defined using a systematic process

→

**Refining the Concepts**

- Design
- Analysis
- Models
- Systems

→

**Defining the Concepts**

- Review engineering textbooks and standards.
- Identify or create "best" definition.
- "Audit" definitions against the NRC framework.

### Stage 1: Identifying the Concepts

Inputs to this process were two studies: Custer, Daugherty, and Meyer (2010) and Rossouw, Hacker, and de Vries (2010). Custer, Daugherty, and Meyer (2010) provided an in-depth analysis of a broad range of engineering-related literature and focus groups with engineering educators and engineers to identify core engineering concepts. Four types of documents were reviewed including: (a) engineering and technology philosophy writings, (b) curriculum materials focused on secondary-level engineering, (c) curriculum standards documents developed for the STEM disciplines and National Academy of Engineering reports, and (d) survey research studies relevant to K–12 engineering. A series of focus groups was also conducted, involving 21 engineers and engineering educators. This research process resulted in a set of 13 concepts: analysis, constraints, design, efficiency, experimentation, functionality, innovation, modeling, optimization, prototyping, systems, trade-offs, and visualization.

Rossouw, Hacker, and de Vries (2011) conducted a Delphi study and panel meeting to generate concepts and contexts that can be used for developing curricula. Three rounds were conducted. Throughout the three rounds, 32 experts were asked to generate concepts and rate each one for importance. In addition, they were provided with a draft list of concepts and definitions and asked to rate importance on a 1–5 Likert scale. From this process, the researchers narrowed the list to the following main concepts: designing ("design as a verb"), systems, modeling, resources, and values. The subconcepts were optimizing, trade-offs, specifications, invention, product life cycle, artifacts ("'design as a noun"), structure, function, materials, energy, information, sustainability, innovation, risk/failure, social interaction, and technology assessment.

To inform the process for defining the conceptual base from the lists developed by these two studies, a graduate student researcher reviewed a variety of texts to identify definitions for two concepts—*design* and *analysis.* The texts consulted included introduction to engineering textbooks (used primarily with freshmen engineering students), standards documents, and philosophy of engineering literature. Definitions were documented if they were specific to the engineering domain but in a broad conceptual way (not to a specific engineering discipline). The definitions were recorded verbatim, as well as any supporting text that further elaborated on the concept. This information was presented to the Project Infuse leadership team.

## Stage 2: Refining the List of Concepts

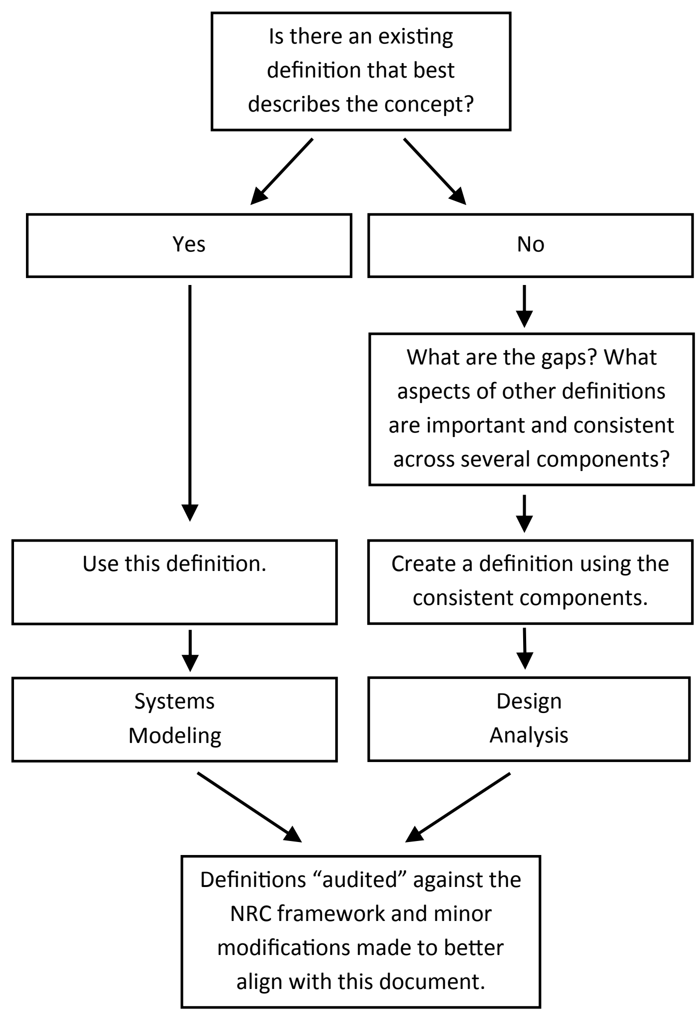
From the lists of concepts identified in the two studies, the Project Infuse leadership team discussed the merits of each of the studies and discussed the outcomes of each. In addition, the team reviewed the definitions of the two concepts (design and analysis). Based on this information, the team decided that there were too many concepts identified between the two studies to use all as the conceptual base for the project, have each defined in the literature, and assessed on one instrument. It was determined that a more manageable number was required. The team decided to focus on a smaller set of primary concepts that are central to engineering, important at the secondary level, and can provide strong links to science education. From these criteria, four primary concepts emerged and subconcepts were identified under these concepts serving to highlight key components. The concepts and subconcepts are:

- Design (constraints, tradeoffs, optimization, prototyping)
- Analysis (life-cycle, cost–benefit, risk)
- Modeling (visualization, prototyping, mathematical models)
- Systems (structure, functions, interrelationships)

## Stage 3: Defining the Concepts

With *design* and *analysis* already defined (at the end of stage 1), the graduate student then compiled definitions of *systems* and *modeling* and their subconcepts of *constraints*, *trade-offs*, *optimization*, *prototyping*, *mathematical modeling*, and *visualization* following the same process (consulting primarily engineering textbooks and standards documents). From these collated definitions, two members of the Project Infuse leadership team read through the definitions and selected the definition that best represented the concept and should be used in the project.

A decision matrix was followed in reviewing the definitions to identify the best definition. A definition was considered to be best if it described the concept using natural language appropriate for the secondary level. In addition, important themes and ideas represented across the definitions were noted. For example, with design, the notion of iteration was included in several of the definitions. If an existing definition did not include all of these important elements, one definition that best met them was modified to include the missing components.




Because of the project's goal of infusing engineering into science, the definitions were compared with the definitions and statements about the concepts within the National Research Council report *A Framework for K–12 Science Education* (the *Framework;* NRC 2012). The *Framework* identifies crosscutting concepts and practices within engineering and references the four concepts throughout the document. The same graduate student collated all references to the concepts in one document; the definitions were compared against these statements. Minor modifications in wording were made to better align with the document.

## Observations Regarding the Concept Definition Process

The graduate student noted that for "design" there was a plethora of definitions available but that for "systems," definitions were scarce. In addition, definitions for modeling were difficult to locate so the search was expanded to include the terms *model, analytical modeling,* and *solid modeling.*

The process used to select the best definition resulted in two approaches to determine the final definition. For *design* and *analysis,* no one definition was sufficient, so the two leadership team members created a definition using consistent components from the other definitions. For *systems* and *modeling,* one definition did emerge as being the best definition and was selected.

The table that follows outlines the number of definitions compiled for each of the concepts and the selected definition presented to the leadership team.

| Concept | Number of Definitions | Definition Selected or Created |
|---|---|---|
| **Design** | 15 | Design is an iterative process conducted within specified constraints to develop products or systems to satisfy human needs and wants. Design typically includes components such as problem definition, data analysis, modeling, and solution refinement and has both technological and social components. |
| **Analysis** | 8 | Using tools such as physical, graphic, and analytical models, empirical equations, and experience to analyze data and predict the performance or behavior of an object or system throughout the life of the design process. |
| **Models** | 5 | Creating a visual, mathematical, or three-dimensional representation in detail of an object or design, often smaller than the original. Modeling is often used to test and communicate ideas, make changes to a design, visualize and analyze systems, and to learn more about what would happen to a similar real object. |
| **Systems** | 9 | A system is a group of interrelated components designed collectively to achieve a desired goal. Systems should be studied in different contexts, including the design, troubleshooting, and operation of both simple and complex systems. |

# STANDARDS AND PERFORMANCE EXPECTATIONS FOR THE CONCEPTS

## Design Standards

Design is an iterative process *typically including components such as problem definition, data analysis, modeling, and solution refinement.* Engineering design is conducted within specified constraints to develop products or systems to satisfy human needs and wants and has both technological and social components.

- Design is an iterative process involving refinements, informed trial and error, and redesign rather than a set of steps done in linear fashion.
- The engineering design process typically involves defining problems, collecting and analyzing data, modeling, and refining solutions.
- Engineers develop designs within a specified set of requirements and constraints. Typical constraints include functionality, cost, appearance, durability, and manufacturability. Individuals should be able to develop designs given requirements and constraints. Test takers will be able to identify how constraints affect a specific design.
- Engineering designs have both technological and social dimensions. Some designs must be marketed to generate demand, whereas other designs are developed in response to social or economic demands and needs.
- Engineering designs typically draw on a range of knowledge including science, mathematics, and engineering experience. Individuals should know that engineering draws on a range of knowledge to do designs.

### Design Performance Expectations

- Describe an engineering design approach to developing products or systems and explain how that approach is similar to and different from from trial and error.
- Given an example of a design problem, identify its requirements and constraints, and explain how those constraints could impact the product, including how they might affect one's ability to optimize all requirements.
- Given a design case study, identify how engineers identified and refined the problem and used the analysis of data to modify and refine the solution.
- Identify or describe the technological, social, and economic dimensions of a specific engineering design.

- Describe the interdisciplinary nature of generating solutions to engineering design problems, including what kinds of knowledge are required to solve typical engineering problems.
- Engage in the design process to develop the best solution to a given problem within the constraints of the situation.

## Analysis Standard

Using tools such as physical, graphic and analytical models, empirical equations, and experience to analyze data and predict the performance or behavior of an object or system throughout the life of the design process.

- Engineers use analysis for a variety of purposes, including risk and benefit analyses, predicting the behavior of designed systems, and verifying the quality of design solutions.
- Engineering design analysis involves the use of mathematical tools and scientific knowledge as well as physical and graphic models.
- Engineers use knowledge obtained from experience with designing, testing, evaluating, and using products and systems to analyze future design solutions.
- Engineering analysis examines the extent to which design requirements have been met.

### Analysis Performance Expectations

- Identify situations in which engineers use analytical techniques to evaluate risks and conduct cost–benefit analyses.
- Describe the kinds of tools, models, and techniques that engineers use to predict the behavior of designed systems.
- Given an engineering design problem example, identify and describe the kinds of knowledge and techniques used to evaluate the quality of the design before its implementation.
- Explain how the analytical methods used by engineers are different from those used by scientists.
- Analyze a prospective design using an analytical model, an equation, or experience to predict the level to which the design meets the design requirements.

## Modeling Standard

Modeling involves creating a visual, mathematical, or three-dimensional representation of an object or design, often smaller than the original. Modeling is often used to test *and communicate* ideas, make changes to a design, *visualize and analyze systems*, and to learn more about what would happen to a similar real object.

- Engineers develop models to test the quality, viability, and performance of design solutions.
- Engineers use mathematical and scientific models as design tools.
- Models used and developed by engineers take many forms, including physical, visual, and mathematical.
- Models are designed to examine and test engineering design solutions in advance of their development.
- Models are used to help engineers visualize and communicate their design solution ideas.

### Modeling Performance Expectations

- Identify and describe the various kinds of tools that engineers use to model designs in advance of implementation.
- Describe the various uses of modeling in the engineering design process and the value of modeling for engineers as they solve design problems.
- Given a design model, identify and describe the kinds of modeling procedures that could be used to visualize, test, and refine the design.
- Discuss how modeling differs when developing physical artifacts vs. non-physical designs (e.g., software development and electronic or chemical solutions).
- Create a model of a design solution.

## Systems Standard

A *system* is a group of interrelated components designed collectively to achieve a desired goal. Systems should be studied in different contexts, including the design, troubleshooting, and operation of both simple and complex systems.

- Engineers design systems and components of systems.
- Engineering designs function within larger social and technological systems and contexts.

- Engineers engage in a variety of activities with systems, including designing, testing, evaluating, troubleshooting, and improving them.
- Engineering systems may be very simple or very complex.
- Designed systems are engineered within specified constraints and requirements.

### Systems Performance Expectations

- Identify examples of a simple and a complex system that is a result of an engineering design.
- Given a technological system, identify the system's subsystems and components and describe how these components interact with one another.
- Given a systems engineering design scenario, identify what engineers would do to test, evaluate, and improve the system.
- Describe how social values and priorities influence engineers as they develop solutions and systems.
- Discuss why it is important for engineers to work at the systems level rather than focusing on the design of components and subcomponents.

## REFERENCES

Custer, R. L., J. L. Daugherty, and J. P. Meyer. 2010. Formulating a concept base for secondary level engineering: A review and synthesis. *Journal of Technology Education* 22 (1): 4–21.

National Research Council (NRC). 2012. *A framework for K–12 science education: Practices, crosscutting concepts, and core ideas.* Washington, DC: National Academies Press.

NGSS Lead States. 2013. *Next Generation Science Standards: For states, by states*. Washington, DC: National Academies Press. *www.nextgenscience.org/next-generation-science-standards*.

Rossouw, H., and M. J. de Vries. 2011. Concepts and contexts in engineering and technology education: An international and interdisciplinary Delphi study. *International Journal of Technology and Design Education* 21: 409–424.

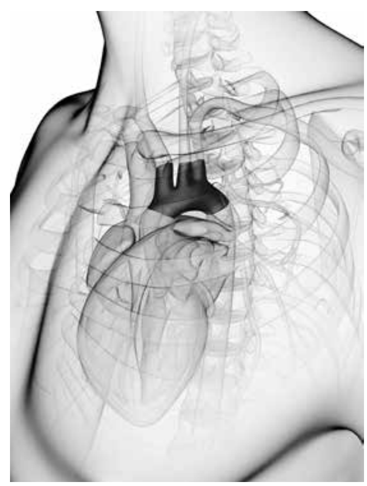
# Appendix D

## Case Studies

The following five case studies of engineering were developed by Cory Culbertson for Project Infuse.

## CARDEON: THE RISE AND FALL OF A MEDICAL STARTUP

Heart bypass surgery has saved the lives of thousands of people around the world. The procedure involves stopping the heart to reroute blow flow around blocked blood vessels, and it is one of the triumphs of modern surgical technique. However, it is also a procedure that is very stressful to the body. Serious complications after surgery are common. Even though the procedure takes place in the patient's chest, many patients experience brain injuries ranging from minor memory loss to life-threatening strokes.

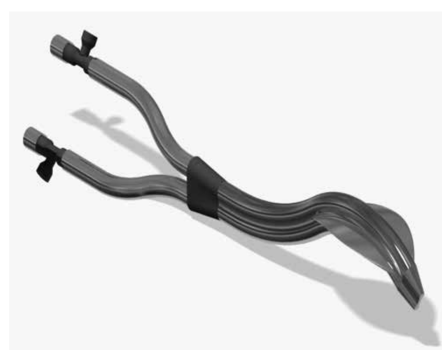

**Aortic arch**

Initially, these brain injuries were a mystery. However, in the 1990s it became clear that brain injuries were linked to small debris particles that blocked blood vessels in the brain, causing a condition known as embolism. These particles –mainly calcium and fat—normally collected on the walls of blood vessels, but were dislodged during bypass surgery. Researchers realized that reducing post-operative brain injuries meant that they needed to find a way to prevent these debris particles from entering the brain, at least long enough for them to be collected somewhere else.

A group of medical professionals hit upon an idea that was amazingly simple in theory, but very complex to execute in practice: place a "roadblock" in the patient's aortic arch at a point where the carotid arteries branch off to take blood to the brain. Then, blood circulating through the body could not carry debris up into the brain. However, such a barrier would have to be fairly large—larger than could fit through the blood vessels that doctors use to access the aorta. There would also have to be a way to supply the brain with clean, filtered blood while its supply arteries were blocked off. These medical professionals thought they had a way to solve these problems, but needed a team of engineers to develop the idea into a working medical device. In 1996, they attracted investment funds, formed a company known as Cardeon, and set to work developing a device.

Cardeon's engineering team was not starting from scratch. For many years, surgeons have used a device known as a catheter inside blood vessels. Many of the engineers at Cardeon had designed different types of catheters before. What was different now was the function of the device at the end of the catheter. The plan was to develop a baffle that could be rolled up, and then expanded when in the proper place in the aorta. The catheter would also contain a blood delivery tube that would supply clean filtered blood directly to the the patient's brain. Because the shape of the baffle at the end of the long catheter resembled a cobra's hood, they named the device the Cobra Catheter.

There were many challenges in designing the Cobra Catheter, particularly in the specially-shaped baffle at the end. Other companies had already patented a flexible "roadblock" baffle and a mesh "sieve" baffle that could block debris in the aorta. Cardeon's design would have to be different. Cardeon's engineers decided to design a baffle that would use extra blood flow on the brain side to push debris back out into the aorta. Engineers spent many hours trying to prefect the location of the blood delivery vents and the amount of blood flow. They tested their designs on a model of the human aorta made out of polyurethane plastic. Over and over, they simulated blood circulating in the aorta and measured the level of debris getting to the brain. The original design turned out to be very inefficient, and a complete redesign was required. Eventually, one engineer was able to design a baffle that pushed almost all of the debris away from the brain. It worked perfectly on the model aorta. Would it work on a real patient?



**A conceptual CAD model of the Cobra Catheter (image credit: C. Culbertson)**

In 2001, Cardeon had a prototype ready for testing. For safety, the first patients would not be humans. Instead, 16 pigs were the first test subjects. Each one underwent heart surgery, eight with the new Cobra catheter, and eight without. The device was a clear success: 89% of the particles in the blood stream were prevented from reaching the brain.

The Cardeon team felt that they had a good solution to the problem of brain embolism following cardiac bypass surgery.

However, the road ahead was still long and hard. Medical devices used in the United States must be approved by the Food and Drug Administration. The FDA's approval process would require careful clinical tests. In addition, the FDA required that the entire manufacturing process used to make the Cobra Catheter be carefully planned and then strictly followed. Any defects in the products would need to be analyzed, and then eliminated by changing the manufacturing process plan. All of these steps meant that Cardeon would have to hire a new crew of support personnel. Cardeon would also have to create a marketing team to promote the product and convince surgeons that it was worth using. Medical research and design is an expensive process. The company had already spent millions of dollars to get to this point, and had yet to sell a single Cobra Catheter. The promising surgery results were enough to raise more funding from the company's investors, but this was make-or-break time for the company. Success depended on positive clinical trials and quick approval of the company's manufacturing process.

It didn't happen. The Cobra Catheter was tested on more than 1,300 patients, and these patients responded well. The FDA appeared ready to approve the Cobra Catheter. However, the investors backing Cardeon wanted to see clear neurological benefits—backed up by statistical analysis—that the Cobra Catheter was a complete success. Unfortunately, Cardeon could not prove these clear benefits. Both surgeons and investors can be very conservative, and these mixed results weren't enough to convince them that the Cobra Catheter was worth taking to market. In addition, other ways of minimizing bloodstream debris were starting to show promise, including a way of doing minimally-invasive heart surgery that did not produce as much debris in the first place. Without a source of funding, Cardeon ceased operations in 2005. Many employees went on to other medical device companies, where they set to work designing and building the next device to revolutionize modern medicine. The Cobra Catheter never became the surgical miracle that its inventors hoped for, but it remains a brilliant example of engineering at the limits of medical knowledge.

## DISCUSSION QUESTIONS

1. Outline the major steps in the design process for the Cobra Catheter.
2. Describe the constraints that were involved in the design of the Cobra Catheter.
3. How did iteration play a role in the design process?
4. What different purposes were the catheter prototypes used for?
5. Medical device design is a world where engineers must often innovate rapidly, but surgeons must often exercise caution and conservative judgment in which

devices to use. What explains the difference in the perspective of these two groups?

6. What influences, both positive and negative, does governmental regulation exert on the design process for medical devices?

7. Medical device design is like many areas of engineering, in that much time and expense is spent on designs that ultimately do not succeed. Is this method of design appropriate? Why or why not?

# KEEPING FALLINGWATER FROM FALLING

Frank Lloyd Wright is America's best-known architect, and perhaps no other building better represents Wright's iconic style than Fallingwater in Mill Run, Pennsylvania. Built in 1936, Fallingwater was commissioned by the Kaufmann family to be a vacation house with a view of the beautiful waterfall on their property. Instead of building the house *next* to the waterfall, Wright boldly decided to place the house *over* the waterfall. Its broad flat lines echo the stone ledges around the waterfall. Fallingwater is considered an architectural masterpiece for the way it not only complements the natural surroundings but even enhances them.

Frank Lloyd Wright's Fallingwater (image credit: Ron Shawley, Wikimedia Commons, CC BY 3.0, *https://commons.wikimedia.org/wiki/File:FallingWaters_fall_colors_-_panoramio_(19).jpg)*

However, Wright's design stretched the limits of structural engineering in his day. The home's wide terraces stretched over the falls, supported only at one end, in an arrangement known as a cantilever. While graceful, the cantilevered terraces were under enormous stress at their support points. Wright chose to use reinforced concrete as his building material. Reinforced concrete is a durable and versatile material that allowed him to create the forms he envisioned. However, concrete does best when stressed in compression, not tension. The cantilevered terraces had areas of high tension that posed a real challenge for Wright's engineers. Their design called for inverted T-shaped beams to support the terraces, with a small number of steel bars in the top of the beams to resist tension forces. Careful analysis of the building's loads allowed them to create a design in which the tension loads were within the safe limits of the concrete and steel. However, Wright felt that their analysis was too conservative. He also sharply disagreed with an outside engineering firm that recommended a large increase in the amount of reinforcing steel in the terraces.

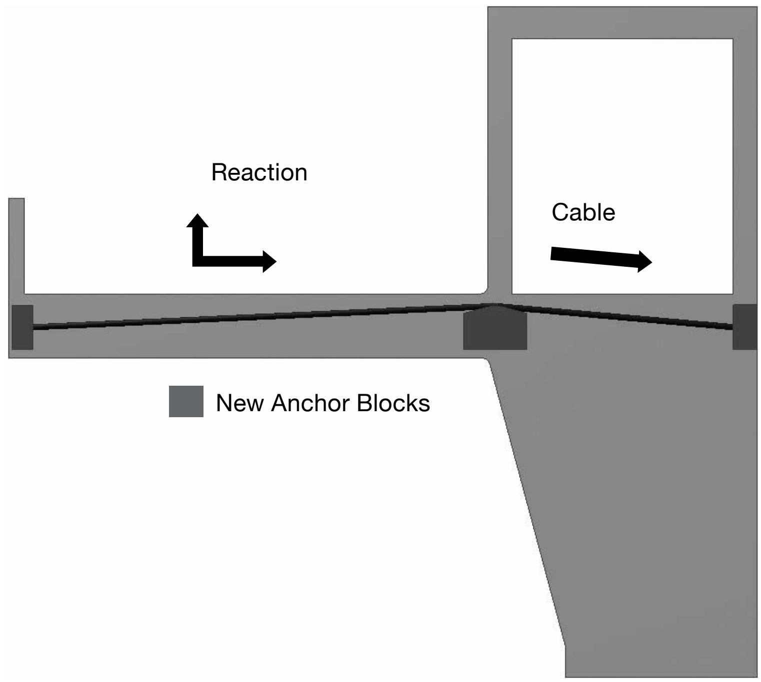
Soon after construction, the terraces began to sag noticeably. Later, cracks began to appear at the stress points. It appeared that the concrete would not be able to resist the tension forces indefinitely. Stopgap repairs were made for decades, but it was clear that


**Computerized stress analysis of a cantilevered terrace similar to that at Fallingwater. Red shows areas of high tension. Blue shows areas of high compression. (image credit: C. Culbertson; full-color version available at *www.nsta.org/eggdrop*)**

the problem was in the original design. In 1995, Robert Silman Associates was hired to investigate. By using new computer modeling techniques and radar images of the interior of the concrete, RSA discovered that the terraces were dangerously close to failing. It was time to finally correct the problem. The challenge was not only to fix the damaged structure but to find a way to reduce the stresses in Wright's original design without altering its historic appearance.

RSA's engineering team came up with a solution that placed a hidden support structure inside Wright's famous terraces. The key to the new design was the use of the same reinforcing material that Wright had originally undervalued—steel. Unlike concrete, steel is able to resist high tension forces. In fact, suspension bridges make dramatic use of steel tension cables to support their high-flying structures.

Unlike a suspension bridge, though, Fallingwater could not have its new steel cables strung up for the world to see. They had to be hidden inside the existing terrace floors and walls. This presented the engineers with a new problem: as the angle of the support cables became closer to horizontal, the amount of vertical load that they could support decreased significantly. At such a shallow angle, the steel cables would be stressed




**Placement of one of the steel cables within the terrace. As the angled cables are tensioned, the reaction forces pull the outer edge of the terrace inward and upward. (image credit: C. Culbertson; full-color version available at *www.nsta.org/eggdrop*)**

almost to their limits. Once again, Fallingwater engineers found themselves doing careful load analysis to keep their structure within safe limits of material stress.

The final design took advantage of the best properties of steel and concrete—steel to resist tension forces, and concrete to resist compression forces. The steel cables were carefully anchored into blocks buried inside the terrace floors. Then, they were slowly pulled into tension. The engineering team watched carefully as the lip of the main terrace rose by almost an inch. By careful placement of the new reinforcements, the engineering team had provided a much greater margin of safety and a longer life for the house.

Of course, visitors to Fallingwater will not see any of this. Instead, they will see Frank Lloyd Wright's house as it originally appeared when it was built. Only now, this architectural masterpiece will be able to majestically float over its waterfall for many more years to come.

## DISCUSSION QUESTIONS

1. Identify some points where engineering analysis played a critical role in the history of Fallingwater.

2. If engineering analysis is largely based on mathematics, how can there be disagreements over whether it is accurate or not?

3. Design is often described as an iterative process. However, few buildings are reworked until they are satisfactory, as Fallingwater was. Does the concept of iterative design apply to large structures and other one-time designs? If so, then how?

4. Steel-reinforced concrete was a relatively new material in Frank Lloyd Wright's time, and it was not as well understood as it is now. Does Wright deserve blame for using a material that was still somewhat unproven? Describe more recent examples of situations in which somewhat unproven materials have been used.

5. Wright's vision for Fallingwater sometimes conflicted with the more conservative desires of both his clients and his structural engineers. Does the engineering design process have room for highly innovative, visionary people? What benefits and costs are associated with highly innovative design?

# PAY-AS-YOU-GO SOLAR

Marakaru is a small farming village in the lush green highlands of western Kenya near Lake Victoria. A visitor to the area might see the residents out working, hand-cultivating the fertile fields of corn, sweet potatoes, tomatoes, coffee, and vegetables. At night, a Marakuru farmer might retire to his home, light a smoky oil lamp to see by—and pick up a cell phone to contact a buyer for his crop.

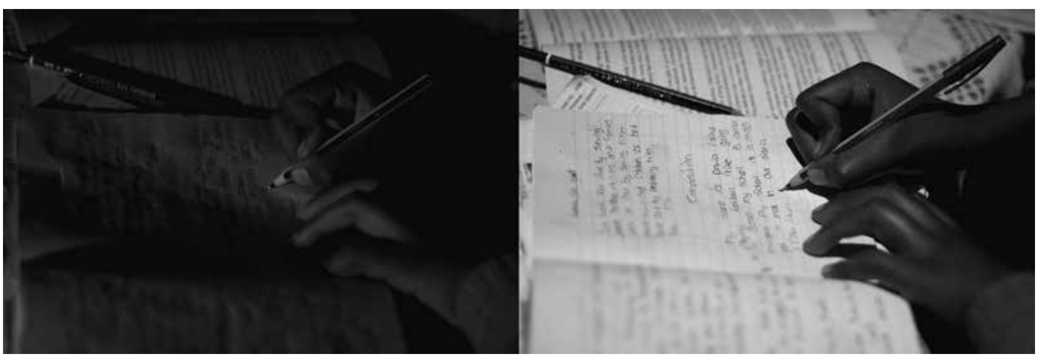
Marakaru, like most of rural Kenya, has mobile phone coverage. But like most of rural Kenya, the village lacks any source of electrical power. This seemingly strange arrangement makes sense in rural Africa, where raising mobile phone towers is realistic, but stringing electrical lines to every village would be an impossible luxury. Still, Marakaru residents have come to rely on mobile phones for communication, and the lack of electrical outlets means that recharging a phone can become a major chore: an hour walk to the nearest town with electricity, a long wait and expensive fee at a recharging kiosk, and another hour walk back home.

A company called Azuri Technologies sees this hassle as an opportunity. It has developed a solar charging system called Solar Home that promises to provide a small, inexpensive source of electricity for people like the residents of Marakaru. The system has a solar panel, battery/control box, two white LED lamps, and a phone charging cord with adapters for the most common cell phones in Africa. The LED lamps help reduce another expensive inconvenience for rural Africans, since the only light sources in many rural homes are smoky kerosene-burning lamps.

The use of solar panels in rural African areas is not a new idea. Many universities and private companies have tested solar power in Africa, with varying degrees of success. The Azuri system shows promise for two reasons, one technical and one economic. On the technical side, Azuri has found ways to maximize the amount of light that their customers have available at night. The LED lamps in the system had to be bright enough

**The Azuri Solar Home system, including charger, LED lamps, and phone adapters, is shown. (image credit: Azuri Technologies Ltd / used with permission)**

to replace the old kerosene lamps, but increasing the brightness means that the light will not last as long before the battery runs down. A larger battery could be used, but would add a great deal of weight and require a larger solar panel to charge it each day. To get the most light out of the limited energy stored in the battery, Azuri developed a "smart" electronic controller. The controller remembers how long a customer typically uses the LED lights at night. Each evening, it calculates how much energy the solar panel generated during the day and then automatically adjusts the brightness of the lights so that they will last as long as the customer needs. While the controller adds some extra expense and complexity to the system, Azuri considers this a good tradeoff to provide a more useable system for its customers.



**Studying is much more comfortable with LED lighting (right) instead of kerosene lighting (left). (image credit: Azuri Technologies Ltd / used with permission)**

When designing the Solar Home system, the product development team had to make choices for the solar panel, battery, and lights that they felt represented the best balance of cost, size, power, and other criteria. However, the engineering team also realized that one specification point would not fit all customers, and designed other versions of the system with different combinations of features.

Despite all this clever engineering, Azuri's largest innovation may be its business plan: "pay as you go solar." Even the most basic solar electric system is too expensive for most rural Africans to purchase, and there is no bank willing to give loans. Instead, Azuri will sell the solar power systems at a small fraction of their actual price. To use the system, customers will send a payment via cell phone, a system that is already common in Africa. They will then receive a text message containing a code that will activate the system for a set number of days. While pay-as-you-go plans sometimes get a bad reputation, this one is intended to be a win-win for the company and its customers. The company can sell units at an attractive price and generate repeat business. In exchange, the customer gets a solar electric system without going into debt, and can pay for as much or little electricity as needed. Most importantly, once the full cost of the solar power system is paid, the customer owns it and can use it freely without having to purchase any more access codes.

It is clear that a need exists for better sources of light and electricity for rural Africans. Time will tell whether Azuri's Solar Home system has the right mix of features to successfully fill this need.

Solar panels are being installed on a home. (image credit: Azuri Technologies Ltd / used with permission)

## DISCUSSION QUESTIONS

1. How did technical constraints limit the design of the Solar Home system?
2. How did economic constraints limit the design of the system?
3. Besides those listed, what other design tradeoffs might Azuri's designers have had to make?
4. How would the design specification point (battery size, lamp power, and solar cell) have to change for use in different locations—such as Greenland, Indonesia, or rural New Mexico?
5. Do you predict that the pay-as-you-go model will be successful? Why or why not?
6. What are some possible societal changes that could occur if most rural African homes had access to better lighting and cell phone power?

# MAKERS

*Limor Fried graduated from MIT in 2005 with a master's degree in electrical engineering. She is a young woman who is well-known by her screen name* ladyada, *and who has been known to wear a lip ring and stoplight-red hair. She is also the CEO of an influential electronics company, a pioneer who has been hailed as the "queen" of her field, and a minor celebrity who has graced the cover of* Wired *magazine. Which of these characteristics don't fit with the normal concept of an engineer?*


Limor Fried (image credit: TechCrunch, Flickr, CC BY 2.0, *https://flic.kr/p/efCWuM*)

*Limor Fried is one of the driving forces behind the rising "maker" movement in electronics and robotics. If any of the above descriptions seem out-of-place, it probably has more to do with the eclectic nature of the maker movement than anything else.*

*Makers* is the current term for a loose-knit group of enthusiasts who use modern electronic technology to create designs for their own personal use and to share with others. Some makers are immersed in the technical side of designing, and relish a challenge like reverse engineering the Microsoft Kinect box. Other makers are more interested in the artistic aspect of design, and gravitate toward projects like using colored LEDs to create portraits on the side of buildings. Some makers are hard to categorize, such the one who built a solar-panel covered swimsuit for charging a cell phone at the beach.

It can be easy to dismiss the maker movement as an interesting hobby for technically-minded people. Many maker web sites are full of amateurish contraptions that do neat things, but are too unique, personal, or totally weird to have any chance of hitting the mainstream. Not many people have a yearning to own a solar-panel swimsuit. For most makers, though, following personal interests is the key to true innovation. As maker Eric Stackpole points out in an interview on Metroactive.com: "When people follow their passion, they try things businesses that rely on market research never would."

In a sense, makers are like chefs than can create interesting new dishes from the ingredients available in any grocery store. Electronic components like chips and resistors are very difficult to manufacture, but they are cheap to buy and there are thousands of different varieties. It is easy for a maker to buy a handful of components, connect them together, and create a new product that has never been imagined before. Internet sites such as Limor Fried's adafruit.com support these inventors by providing information, components, and even discussion forums to help solve difficult design problems.

**Makers frequently rely on soldering and other electronics prototyping skills**

Limor Fried leads the maker movement as both an innovator and a collaborator. Some of her designs like the MintyBoost (a cell phone charger built into an Altoids tin) are among the most popular projects for beginning makers. However, it is her ability to


**Portable electronic devices like the MintyBoost charger are popular projects with many makers (image credit: Agrohmann, Wikimedia Commons, CC BY 4.0, *https://commons.wikimedia.org/wiki/File:2016_09_UJ_Meet_Up_Makerspace_(c)_Lukas_Boxberger.jpg*)**

communicate and collaborate that truly led to her success. Fried has filled her web site with detailed descriptions, photos and diagrams of her designs, and she frequently posts on discussion forums to help other makers with their projects. The web site began just as a way to share ideas, but when her projects became more popular, Fried began to sell ome of the harder-to-find electronic components to help her fellow makers. Now, Fried's company, Adafruit Industries, sells a wide variety of electronic hardware. The design help is still provided for free.

Modern makers like Limor Fried carry on the tradition of innovation and collaboration that has long been part of the electrical engineering world. Over thirty-five years ago, one of the first maker groups started meeting in Menlo Park, California. Called the Homebrew Computer Club, it was a place for people to work together and share ideas about the then-unheard-of idea of personal computers. The club meetings often were the spot for the unveiling of new inventions. In 1976, Steve Wozniak and Steve Jobs attended a meeting of the Homebrew Computer Club and demonstrated their newly-built computer. It was called the Apple 1.

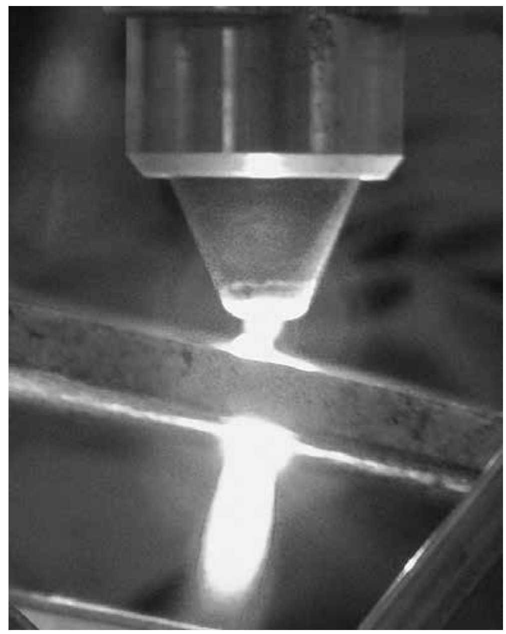
## RESOURCES

- *Wired* interview with Limor Fried: *www.wired.com/magazine/2011/03/ff_adafruit/all/1*
- *Economist* article on the maker movement: *www.economist.com/node/21540392*

## DISCUSSION QUESTIONS

1. In what ways is the maker movement "engineering?" In what ways is it not?
2. Do makers follow a design process? How is it similar to or different from the process followed by a professional engineer?
3. Which stereotypes of an engineer does Limor Fried break? Are there any stereotypes that she reinforces?
4. Besides electronics, are there other areas of engineering in which amateur designers can be highly innovative? If so, which areas?
5. What constraints do makers face that professional engineers do not? What about the other way around?
6. One popular maker slogan is "If you can't open it, you don't own it." What attitude toward technology does this sentiment reflect?
7. Some makers consider their goal to be making engineering into an activity for everyday people, instead of an activity that is only for professionals in major corporations. Is this goal reasonable? Why or why not?

# ZAPPING TRASH



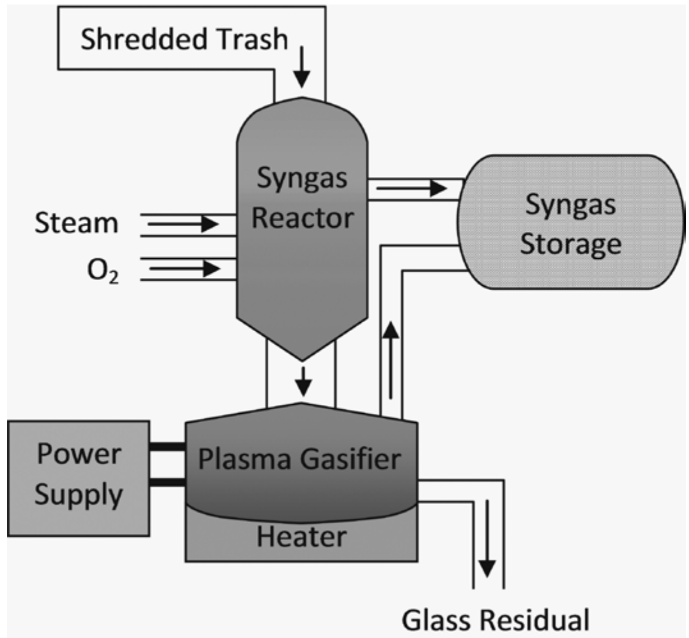
Plasma can be used to melt or even vaporize materials, as in this demonstration of a plasma cutting torch. (image credit: Submarine007, GNU Free Documentation, *https://commons.wikimedia.org/wiki/File:Plasma_drilling.JPG*)

For thousands of years, people have been doing the same thing with their trash: digging a hole and putting it out of sight. But with billions of people now needing room to live on our planet, burying trash has become much less attractive than it used to be. Waste landfills require huge areas of undeveloped land, and they emit tons of greenhouse gases as the refuse decomposes. Landfills also don't solve the problem of toxic chemicals in our trash. The toxins are merely hidden away, still holding the potential for serious land and water contamination in the future.

Incineration is another potential solution for dealing with garbage. Burning trash can drastically reduce the volume of waste, and possibly even generate some energy at the same time. Yet incineration has some strong opposition due to actual and perceived environmental hazards. Even though modern incinerators are much cleaner than almost any other form of combustion, the public has generally remained skeptical that toxins are truly being kept out of the air.

Engineers at a startup venture called InEnTec hope to solve the technical and image problems of garbage incineration. If successful, InEnTec engineers may even be able to turn trash into a profitable resource instead of a liability. The key component of their strategy is a technology called *plasma gasification*. While normal incinerators burn most of the easily-combustible materials in trash, many other compounds are left untouched. Plasma gasification goes further – thousands of degrees hotter – to break apart almost every known compound into its basic atomic building blocks. At these temperatures, toxic compounds are completely broken apart. The output of a plasma gasification unit is simple elements such as carbon, oxygen, and iron.

However, two big challenges stand in the way of simply turning our trash into plasma-induced atomic flux. The first is that plasma gasification requires immense




A schematic representation of the InEnTech waste treatment system. (image credit: C. Culbertson)

amounts of energy, making it an expensive form of waste disposal. The second challenge is that household trash contains a wide and unpredictable variety of materials. Some of them are easy to process, but others will remain toxic even after plasma gasification. For example, toxic metals like lead and cadmium pass though the gasification chamber completely unchanged.

InEnTec's solution to these challenges is to create an entire waste-treatment system, not just a single device. In this system, trash is first delivered to the InEnTec processing facility via truck and shredded into easily-combustible chunks. From there, it goes into a reaction chamber that heats the shredded garbage and mixes it with steam and oxygen. The steam and oxygen react with organic compounds in the trash to produce syngas—a valuable commodity that can be used to make natural gas. Syngas production is the key to making the whole system economically feasible. By vaporizing the organic part of the trash, the syngas reactor vastly reduces the amount of trash and creates a revenue source at the same time.

After the syngas is extracted, the remaining trash is fed into the plasma gasification chamber. Here, it is hit with an electric arc that is essentially a manufactured lightning bolt. The intense blast breaks apart the compounds in the trash stream, vaporizing most of what is left after syngas production. The challenge at this step is to process as much trash as possible, but to insure that all of the trash receives sufficient heat to be fully atomized.

After most of the trash has been vaporized, the remaining heavy atoms fall to the bottom of the chamber, where a final heating system turns them into a thick, molten soup. This tough trash is extracted and cooled into glass-like chunks. While these leftover chunks contain some toxic elements, they are encased in a solid glass form which keeps them inert and out of the environment. This glassification process is considered one of the safest options for handling hazardous materials.

**InEnTec's waste treatment system has attracted investors such as Waste Management Inc., which operates 273 landfills in North America. (image credit: Redwin Law, Flickrs, CC BY 2.0, *https://tinyurl.com/ycf8t483*)**

InEnTec has already built a large test system at a landfill in the northwest US, but the company still has more engineering development to do. To be profitable, the plasma gasification system must come close to maximizing the amount of syngas produced per pound of trash, while minimizing the energy input into the plasma arc. Engineers at InEnTec are still working to find the best balance of mass and energy inputs into the syngas reactor and the plasma gasification chamber. These engineers also need to balance many other system variables. For example, higher plasma temperatures can guarantee that even the toughest compounds are broken apart, but high temperatures require more energy input and shorten the life of the reactor. Developing a system that is both technically and economically successful is still a future goal.

If the engineers at InEnTec succeed, our society may finally have a modern solution to an age-old problem.

## DISCUSSION QUESTIONS

1. What are the main subsystems of the InEnTec design?
2. Are these subsystems modular? That is, can they be altered without significantly affecting the design of the overall system?
3. Suppose you were a potential customer for a waste treatment system such as this one. What would be some of your requirements for its successful operation?
4. If the InEnTec design is successful, how will it fit within large-scale waste management and energy systems in the United States?
5. Landfills are usually sited far away from urban areas so that they can use less-expensive land. Would the InEnTec system change this practice? If so, how?
6. Will a plasma gasification system be able to overcome the perception of incineration as a "dirty" technology? Why or why not?

# More About the Contributors

**Robert Aldape** has been teaching high school science since 2005 and is in his ninth year at Greater Lawrence Technical School in Andover, Massachusetts. He enjoys collaborating with terrific colleagues in his science department and helping his wonderful students connect physics concepts to their career areas. Aldape is a career changer—moving to the greener pastures of education after significant contributions as a molecular biologist at Vertex Pharmaceuticals for 14 years. He reports that infusing engineering into his teaching practice has added an engaging dimension.

**Alexandra Allaire** is an accomplished educator who holds a BS in theoretical physics from the University of Puerto Rico and an MA in teaching secondary science from Northeastern University. Her teaching career began in Nashua, New Hampshire, in 2005 at Nashua High School. Allaire would later join Burlington High School, in Burlington, Massachusetts, where she has been for 10 years. Her classroom approach is focused on implementing real-world context. Inspiration has been drawn from her publications at the Massachusetts Institute of Technology (MIT) Haystack Observatory's Research Experiences for Teachers program on demystifying scientific data, along with her work at UMass on incorporating engineering in the physics curriculum.

**Paul Aylward** is one of 11 children, with early exposure to athletics, boating and fishing, and many family gatherings. His education background reflects his wide variety of experiences and interests: Melrose High School; Bunker Hill Community College to study fire science and receive his EMT certificate; Salem State College to study violin; Massachusetts Maritime Academy for Marine Engineering to attain a USCG Unlimited Horsepower Motor and Steam license and a Massachusetts Second Class Steam Fireman shore side license; MEBA Calhoun School to learn welding, machine shop, and advanced firefighting; University of New Haven and Worcester Polytechnic to study digital electronics; UMass Boston to participate in COMIC Project, Infusing Engineering Into Physics; Peterson School of Engineering to take a training course for Third Engineer; and Fitchburg State University to receive his MEd. His previous experiences and hobbies include being a high school physics instructor and a heavy equipment operator, a member of the Boxing and Monomy Teams, and playing the violin.

**Jacob Backon** teaches physics and math at St. Mark's School in Southborough, Massachusetts. He has taught multiple levels of physics for the past 10 years and has been incorporating elements of the engineering design cycle into many of those classes since beginning work with Project Infuse four years ago. Backon studied physics at Bard College and although he has no formal engineering training he found the model developed with Project Infuse to be extremely helpful for diversifying his teaching and helping students apply their physics knowledge in new ways.

**Kevin Brosnan** currently teaches physics at Newton North High School (NNHS) in Newton, Massachusetts. He has been teaching at NNHS since 2008 and at various times has also taught engineering, robotics, and fashioneering. Before entering the teaching field, Brosnan was a mechanical and manufacturing engineer for companies such as GTE and American Science & Engineering.

**David Carbonneau** is an esteemed contributor to this book.

**Nivedi Chandrasekaran** has been teaching high school physics in Sharon, Massachusetts, since 2007. Although she graduated from Cornell University with a degree in mechanical engineering, Chandrasekaran never actually worked as an engineer. Upon graduation, she joined the Mississippi Teacher Corps, a state-funded program that places recent college graduates in impoverished schools in the Mississippi Delta. She fell in love with teaching physics during those two years, and went on to earn a master's degree in curriculum development from the University of Pennsylvania, teach in private schools, work for nonprofits, and raise three children with her husband, before finally returning to public school in 2007.

**Shu-Yee Chen Freake** has been teaching physics and biology at NNHS since 2005. She has a BS in biology, with minors in physics and education, from Brandeis University. She also holds an MEd from Northeastern University. At NNHS, she has taught a wide range of levels in both physics and biology. As a secondary educator, she is constantly looking for ways to engage students, focusing mainly on scaffolding learning experiences that promote student science and engineering skills that are necessary to solve problems in novel situations. She field-tested the NSF-funded Energizing Physics curriculum, which led to her interest in incorporating engineering pieces into the physics curriculum. In 2014, she was part of a team that developed videos to demonstrate reflective teaching through a grant funded by the Massachusetts Department of Elementary and Secondary Education. In this project, she taught and revised a physics and engineering lesson as part of a professional learning community. Since 2012, she has been involved in the Project Infuse program as a participant for the first cohort and then a co-trainer for the second cohort. She has presented at National Science Teachers Association (NSTA) conferences and helped in the planning and writing of this book.

**Blair Cochran** currently teaches at Melrose High School in Melrose, Massachusetts, where he gets the privilege of teaching with great physics teachers. He teaches all levels of physics and astronomy when requested, and has taught for more than 20 years at the high school level. He started doing engineering projects in his first year teaching after being inspired by his cooperating teacher during his student teaching. Cochran is a graduate of Gordon College, where he still serves as an adjunct in the education department.

**Emma Dalton** is a physics teacher and FIRST Robotics Competition coach in southern Maine. She holds degrees in subjects ranging from engineering science to imaginative education, and she has taught engineering concepts to students from eighth grade up through AP Physics seniors. In her spare time, she enjoys doing data science projects, biking everywhere, and designing her house.

**Marna Eckels** teaches physics and engineering in the Boston Public Schools at the Dearborn STEM Academy. Before becoming a teacher, she worked as an electrical engineer and quality assurance engineer on projects that included an implantable artificial heart, satellite communication systems, and airfare search engines.

**Arthur Eisenkraft, PhD,** is the distinguished professor of science education, professor of physics, and director of the Center of Science and Mathematics in Context at the University of Massachusetts (UMass) Boston. He is past president of NSTA and is past chair of the Science Academic Advisory Committee of the College Board. Eisenkraft is also project director of the National Science Foundation–supported Active Physics and Active Chemistry curriculum projects, which introduce high-quality, project-based science to *all* students. In addition, he is chair and co-creator of the Toshiba/NSTA ExploraVision Awards, involving 15,000 students annually. Eisenkraft also leads the Wipro Science Education Fellowship program, which is bringing sustainable change to 20 school districts in Massachusetts, New Jersey, New York, and Texas, and he has recently been supporting novel educational initiatives in Thailand and India.

His current research projects include investigating the efficacy of a second-generation model of distance learning for professional development—a study of professional development choices that teachers make when facing a large-scale curriculum change—and assessing the technological literacy of K–12 students.

He has received numerous awards recognizing his teaching and related work, including the National Public Service Award, the Presidential Award for Excellence in Mathematics and Science Teaching, the American Association of Physics Teachers Millikan

Medal, the Disney Corporation's Science Teacher of the Year, and the NSTA Robert H. Carleton Award. He is a fellow of the American Association for the Advancement of Science, holds a patent for a laser vision testing system, and was awarded an honorary doctorate from Rensselaer Polytechnic Institute.

**Gita Hakerem Foster** has been a physics teacher in Massachusetts for 30 years. She currently teaches at Weston High School in Weston, Massachusetts. She earned her BS in physics at the University of Rochester, her MEd at the UMass Amherst, and her EdD at Boston University.

**Ashley Freeman** teaches physics and engineering at Malden High School in Malden, Massachusetts. She has a BA in physics from Wellesley College and an MEd from UMass Boston. In her spare time, Freeman makes e-textiles in Malden's makerspace, Nedlam's Workshop.

**Boris Gokhfeld** is a physics teacher at Waltham High School in Waltham, Massachusetts, where he has taught since 2009. He is the coach of the high school's robotics team and has supervised STEM summer camps within the district. Gokhfeld collaborated with a local university to start a makerspace in the high school that is now used by several clubs. He has also interned at the global technology company Dassault Systèmes, where he developed STEM instructional materials that he presented at the American Society for Engineering Education. Gokhfeld holds a BA from Harvard University and an MEd from UMass Boston.

**Andrew Goodman** is an esteemed contributor to this book.

**Michael Hazeltine** has been teaching science at NNHS since 1995. He has a BS in physics from Stevens Institute, an MS in electrical engineering from Northeastern University, and an MEd from UMass Amherst. He teaches both freshmen and seniors in addition to being the physical science teacher at Springboard, one of NNHS's alternative education programs. He is the science methods instructor for the Newton Teacher Residency program, a Massachusetts Department of Elementary and Secondary Education–accredited teacher education program. He is also a science methods instructor for Lesley University. Before teaching at NNHS, he was an electro-optics engineer and program manager at Raytheon for 14 years, in addition to being an adjunct lecturer at Northeastern and Boston University, where he taught graduate-level courses in electro-optics. He enjoys the outdoors and is a certified sea kayaking instructor.

**Neil Kenny** teaches physics and biology at Pembroke High School in Pembroke, Massachusetts.

**Julie Mills** resides in Southeastern Massachusetts and is married with three lovely children. She is a 20-year teaching veteran, currently teaching at Apponequet Regional High School in Lakeville, Massachusetts, and also serving as the high school science curriculum leader. Although Mills has no formal engineering background, she learned much through participation in Project Infuse, and fully embraces the engineering infusion model in her classroom, witnessing firsthand the awesome learning that takes place with this teaching model.

**Norman Mitchell** holds degrees in education and physics from the State University of New York and from Clarkson College; however, he is more the product created by nearly 50 years of teaching all levels of high school physics. He tries to engage beginning students in both theory and application with the intent that seeing, touching, and thinking contribute to learning. Each term, his students receive nearly 20 lab exercises ranging from easy to full honors analysis and reporting, and he most enjoys the creativity that explodes when theory meets engineering proposal and process.

**Catherine Haberkorn Newman** earned her BS in physics and geophysics from McGill University. She started her teaching career at the South Shore Charter Public School in Norwell, Massachusetts, primarily teaching physics while also teaching electives in science and engineering. She accepted her current position as a physics teacher at Medford High School in Medford, Massachusetts, in 2008 and subsequently earned her MA in science teaching from Northeastern University. Catherine also worked with Dr. Arthur Eisenkraft over the course of several years as a physics instructor supporting content instruction for K–12 science teachers.

**Kristin Newton** earned certification to teach physics and math while pursuing a mechanical engineering degree at MIT. For her senior thesis project, she developed a high school design competition modeled after the MIT 2.70/2.007 competition and, for several years, teams of students from Cambridge Rindge and Latin School (CRLS) and Boston Latin School met for a yearly championship. Since graduating MIT, Newton has been teaching physics at CRLS in Cambridge, Massachusetts, and has been involved in several major physics curriculum revision projects. She currently teaches ninth-grade physics, AP Physics 1, and is the coach of the CRLS Science Team.

**Nora Paul-Schultz** currently teaches physics and engineering at the John D. O'Bryant School of Mathematics and Science, which is a Boston Public School. She has spent five years teaching physics in Boston and Chelsea, Massachusetts. She also helps out with her school's Engineering Club, First Robotics Team, and Knitting Club. Before becoming a classroom teacher, she spent three years teaching experiential environmental education. She has a BS in engineering science from Smith College and a master of arts in teaching in secondary science education from Tufts University.

**Danielle Raad** is a fifth-year high school science teacher with experience in physics, chemistry, earth science, engineering, and archaeology. She earned an MS in materials science and engineering from MIT, with a focus on archaeological materials. Her thesis work was the inspiration behind developing a high school archaeology curriculum. She also holds a BS in chemistry from Brown University, an MA in chemistry from Harvard University, and an MEd in high school education from Lesley University. When she's not teaching, Raad can be found taking photos or writing letters to pen pals.

**David Scott** has been teaching for 11 years and for the past 8 years has been teaching physics and chemistry at Duxbury High School in Duxbury, Massachusetts. He has a BS in mechanical engineering and a master's degree in teaching physics. Before becoming a teacher, Scott spent 30 years working in the electrical power generating industry as a mechanical engineer and later as the general manager of a nuclear engineering consulting company.

**Valentina Sountsova** is an esteemed contributor to this book.

**Peter Spiers** is an esteemed contributor to this book.

**Derek van Beever** is a physics teacher at Newton South High School in Newton, Massachusetts. When he is not teaching, he enjoys spending time with his three boys and playing music with the rock band Sleepyhead.

**Kristen Wendell, PhD,** is an assistant professor of mechanical engineering and adjunct assistant professor of education at Tufts University in Medford, Massachusetts, where she conducts research on engineering learning at the Center for Engineering Education and Outreach. Previously, she taught science and engineering teaching methods at UMass Boston. While working on her PhD in STEM education, she developed and studied an engineering design–based science curriculum for the elementary grades. She has an MS in aeronautics and astronautics from MIT, where she focused on advanced spacesuit design, and a BSE in mechanical and aerospace engineering from Princeton University.

**Amy Winston** is the vice principal at NNHS. She started her career as a physics teacher and then spent 10 years as the department head for science and technology/engineering at NNHS. As department head, she led professional development that focused on infusing engineering content and skills into all science classes at NNHS. This infusion focused on equitable access to engineering for all students while also exciting students about the engineering course offerings at NNHS. The engineering program quadrupled in size under her leadership. Winston has a BA in physics from Wellesley College and an MEd in education from Tufts University.

## CASE STUDIES CONTRIBUTOR

The editors wish to acknowledge **Cory Culbertson** (an outstanding teacher and engineer) for his work in developing the case study materials. He holds an MS in technology education and a BSE in mechanical engineering. Cory teaches engineering classes at University High School, which is a secondary-level lab school at Illinois State University in Normal, Illinois.

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Page numbers in **boldface** type refer to figures, tables, or images.

# BEYOND THE EGG DROP

## Infusing Engineering Into High School Physics

*How can we interweave opportunities to learn engineering concepts and skills in an already-packed science curriculum?* That was the problem that 30 Boston-area high school physics teachers aimed to solve when they took part in Project Infuse, a National Science Foundation study. Discover their practical solutions in this book, *Beyond the Egg Drop*, which is designed to enable physics teachers to expose students to engineering as they teach physics.

*Beyond the Egg Drop* is a user-friendly resource that does the following:

- Answers the *Next Generation Science Standards' (NGSS's)* call to add an engineering focus to your lessons so students can take part in authentic STEM experiences.
- Provides a thorough discussion on the rationale, justification, meaning, and implementation of integrating engineering into your science curriculum.
- Offers 24 engineering-infused physics lessons that include examples of student work; cover assessment, teaching, and student learning; and connect to the major content areas of physics, *A Framework for K–12 Science Education,* and the *NGSS.*
- Covers mechanics, optics, electricity, and thermodynamics in lively lessons with engaging titles such as "Bungee Jumping Cord Design" and "Lights Out! Zombie Apocalypse Flashlight."

And here's another problem-solving feature you're bound to appreciate: The lessons vary in length, so you can use them to fit the needs of your own classes. Some require part of a class period; others can take days or weeks. Some are activators that are best used before any discussion of physics principles; others work as capstones. All of the lessons are teacher-tested, so you can be sure they'll include engineering concepts and skills without making you restructure your existing physics curriculum.

**Grades 9–12**

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