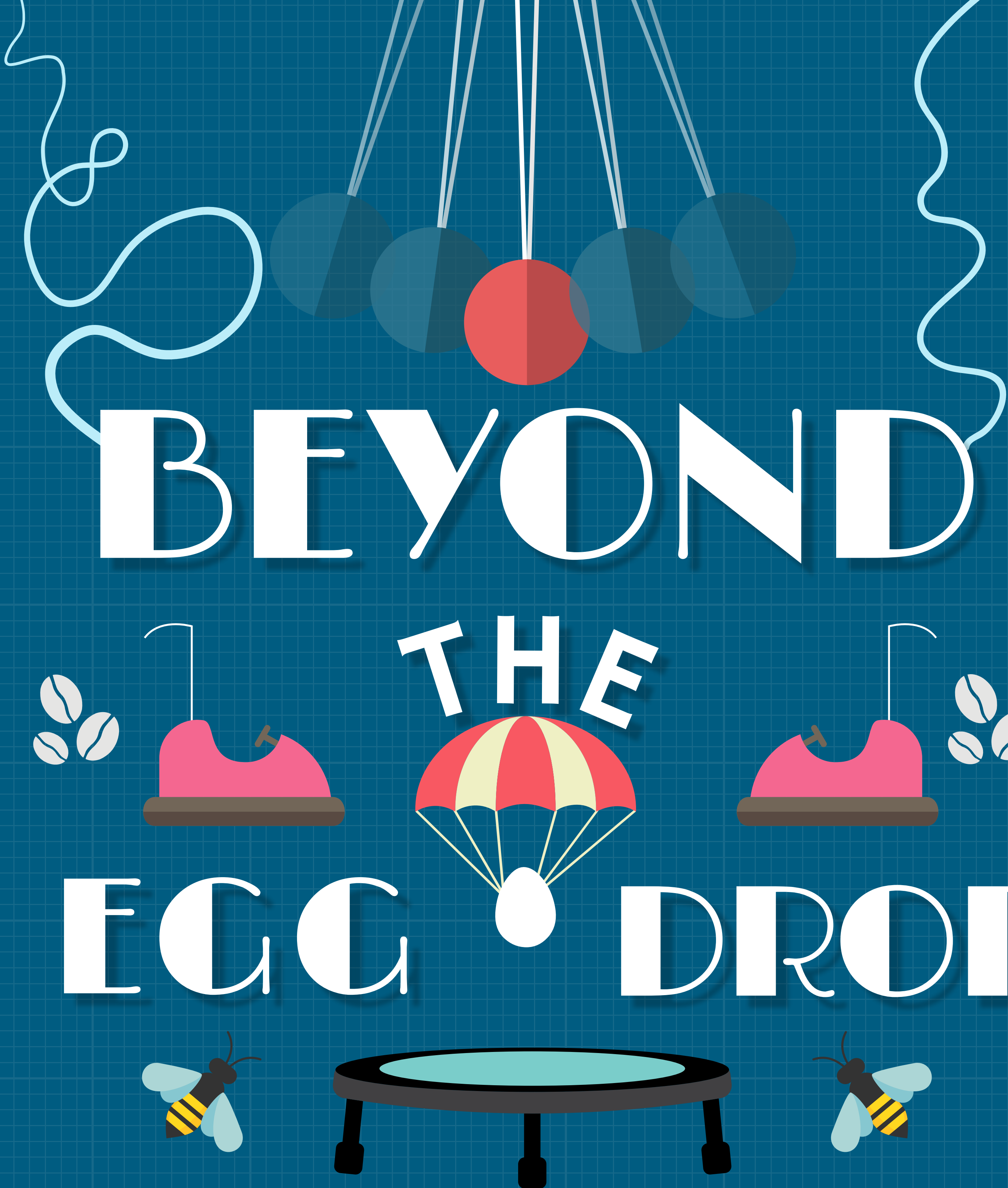

BEYOND THE EGG DROP

Infusing Engineering Into High School Physics

Arthur Eisenkraft
Shu-Yee Chen Freake
Editors

NSTA press
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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.

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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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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 • Analysis • 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 • 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 • Analysis • 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
	  o Weight versus deflection
	  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 • Torque ➔ drawing diagram	• Model of a real cantilever
Systems	• Sum of the net force = 0 N • The cantilever itself • Net torque = 0 N	• Attachment to table • 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 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. **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. **Elicit** **Evaluate**	• Work on Do Now questions individually then share with the class. • 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. • Suggest ways the cantilever could be redesigned to support more weight.	• Elicit students' prior knowledge and help them make connection from previous experience. • At this point, evaluate where students are.	• Properties of materials • Functionality • Aesthetics
5 mins. **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. • Clarify questions related to the task.	—
25 mins. **Explain** **Explore** **Evaluate**	• Work in groups on the cantilever construction.	• Coach students during group work (i.e., have them Explain) on materials testing. • Evaluate group dynamics, emphasizing exploring different design options. • 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. **Explain** **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.

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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.

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