HIGH SCHOOL ENGINEERING

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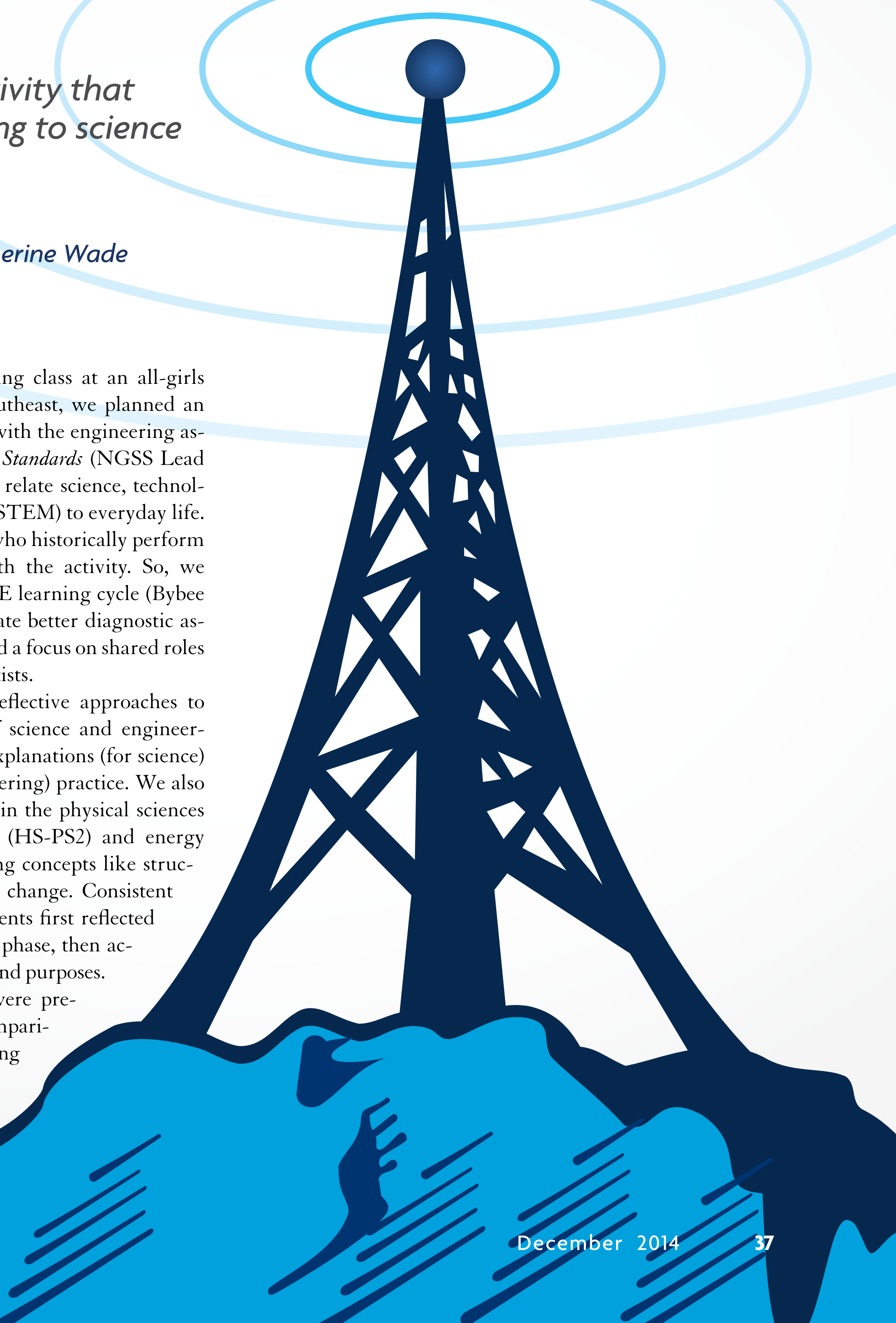
AN ENGINEER DOES WHAT NOW?

A 5E learning activity that compares engineering to science

Amy Gilbert and Katherine Wade



For an introductory engineering class at an all-girls urban high school in the Southeast, we planned an experience that would align with the engineering aspects of the *Next Generation Science Standards* (NGSS Lead States 2013). Our goal was to better relate science, technology, engineering, and mathematics (STEM) to everyday life. We expected our at-risk students—who historically perform below grade level—to struggle with the activity. So, we modified the activity, based on the 5E learning cycle (Bybee 2013), from the previous year to create better diagnostic assessments, more realistic contexts, and a focus on shared roles and processes of engineers and scientists.

Our activity uses explicit and reflective approaches to teach the practices that are part of science and engineering, particularly the Constructing Explanations (for science) and Designing Solutions (for engineering) practice. We also wanted students to learn core ideas in the physical sciences about motion, forces, and stability (HS-PS2) and energy (HS-PS3) and investigate crosscutting concepts like structure and function and stability and change. Consistent with the 5E learning cycle, our students first reflected on their own thinking in the *engage* phase, then actively *explored* engineering processes and purposes. In the *explanation* phase, students were presented accurate concepts of and comparisons between science and engineering processes. Students participated in a new, realistic engineering task as a means of *elaboration*.

Finally, students underwent *evaluation* based on how well they described the processes of designing a solution, including testing, redesigning, and forming a budget.

Engage: An engineer does what now? (45 minutes)

Instructional strategy: Card sort with think-pair-share. It has been well documented that students are confused about the unique and shared features of science and engineering (Fralick et al. 2009). In this phase, students were given 12 cards printed with science and engineering descriptors. Students individually reflected on these descriptors and then categorized them as science, engineering, or both (Figure 1A; see "On the web" for an answer key). After initial reflections, students were asked to compare responses with a partner, discuss commonalities, and resolve differences. Then, through whole-group discussion, students shared their categorizations and rationales. (Figure 1B is a table showing a similar comparison of science and engineering drawn from the *NGSS.)*

The group discussion showed that our students understood many of the shared features of science and engineering but struggled with how the meaning of *experimentation* varied between the two. For example, more than half of our students thought engineers only experimented with the strength of materials. Additionally, our students struggled with understanding how constraints affected the work of engineers and scientists. Their understanding was limited to such physical restrictions as the ocean depths, where indirect observations are the primary source of empirical data.

Explore: Protect Our Food! (45 minutes)

Instructional strategy: Contextualized performance task in teams. We told students that the exploration phase offered them the chance to work like engineers to design a model of a structure to protect community food supplies. We asked, "What do you think that means?" Students accurately responded with, "We will work with other people." "We will try to resolve a problem of some sort." "We will need to write down everything we figure out so that we can share with everyone at the end." We stated that because there was confusion about the role of experimentation and constraints in engineering, our focus was to help them distinguish these features in the engineering design processes.

A handout set parameters for the exploration (a shortened version is shown in Figure 2 (p. 40); for the full version, see "On the web"). We asked students to read the task description, underline important details, and ask questions to clarify the task. Then, students were told to group themselves into teams of four that would combine different self-identified strengths. For example, we told them, "One of you might be good at note taking. Another might be good at measuring and calculating. Another student might have lots of ideas."

Once students were in teams, and the timer had been set for 18 minutes, our role was to monitor each group and ask questions to encourage students to reflect on the process. We asked such questions as:

- What is your goal? How is this type of goal unique to engineering? Is this something scientists would pursue?
- What are your constraints? Is everyone remembering to fulfill his or her responsibilities? What might benefit your team?
- Is this a controlled experiment you are performing? Do you have specific variables you are manipulating or that might be considered an independent variable?

Explain: Engineering design process versus scientific processes (90 minutes)

Instructional strategy: Reflective, explicit concept replacement. This phase continued to focus on how engineers work with constraints as well as features unique to engineering and scientific practices. Students' reflections were guided through specific prompts (Figure 3, p. 41). Many students listed planning as their first step, whether in the form of discussion, brainstorming, or sketching ideas. Several groups mentioned testing smaller, temporary structures to see if they would hold the "food." Almost all groups mentioned a redesign phase, where testing led to changing their plans. Repeated testing and multiple iterations are essential in the engineering design process.

Students' reflections were then used to present typical engineering design processes (Figure 4, p. 41). We pointed out that students' intuitive approach was consistent with such processes, which often address a current problem. When asked how this might differ from science practices, students correctly responded that science does not always address something currently relevant or "do something for people" but often more broadly involves a search for understanding. Most students agreed that the work of engineers was always currently relevant, citing, for example, the engineers working on a deteriorating bridge near the school.

On the board we then wrote engineering-specific vocabulary such as *problem statement, specifications,* and *constraints*. We prompted students to discuss the constraints they encountered in the Protect Our Food challenge, and we added to the discussion other constraints that engineers face, such as budgets, time, and resources. Students were most troubled by how the materials we gave them to make a model were so inadequate. However, they agreed that once they embraced the challenge, they were able to determine a possible design to address the farmers' needs.

Next we listed the remaining features of engineering design processes in these broad categories:

- *problem identification*

FIGURE 1

A. Prompts for the Engage phase.

Below (or on the handout cards) are statements, or descriptors, about science, engineering, or both. Think about each carefully, then categorize the statements, writing the number of the statement in the column where it best fits.

Science	Both Science and Engineering	Engineering

1. Conduct experiments
2. Run tests, or trials
3. Work with restrictions
4. Solve problems
5. Help society
6. Repair things
7. Use math
8. Explain nature
9. Use creativity and innovation
10. Write down everything
11. Invent, or re-design, things
12. Communicate findings
13. Work in teams
14. Seek to understand the world

B. Science and Engineering Practices (from the *NGSS)*

Science practices	Shared practices	Engineering practices
1. Asking questions		1. Defining problems
	2. Developing and using models	
	3. Planning and carrying out investigations	
	4. Analyzing and interpreting data	
	5. Using mathematics, information and computer technology, and computational thinking	
6. Constructing explanations		6. Designing solutions
	7. Engaging in argument from evidence	
	8. Obtaining, evaluating, and communicating information	

FIGURE 2

Student handout for Protect Our Food activity.

Situation

Peanut and soybean crops stored in holding containers in a rural community are being eaten by deer and rabbits. Farmers suffering these losses are using containers made of a semi-permeable material that's quickly corroding. The containers sit directly on the ground. The farmers determined:

- New structures are needed to store future harvests.
- Temporary structures are needed for the harvests already in the corroding containers.

Materials

- 20 sticks of uncooked spaghetti
- 1 meter of masking tape
- 1 meter of string,
- 1 large marshmallow,
- 10 mini marshmallows

Challenge

Teams have 18 minutes to design, construct, and test models that can help solve this problem. The large marshmallow represents the already harvested crops. The smaller marshmallows represent the yet-to-be harvested crops. Teams must build both types of structures (permanent and temporary), which must be positioned above "sea level" (above the surface of the classroom table).

(For a longer version of this handout, see "On the web.")

- *research/brainstorming*
- *idea/prototype development*
- *testing,* and
- *redesigning.*

To draw students into the discussion, we asked such questions as: "Did your team complete each step once and in order, as described on the board?" Many groups responded that they did not complete them in this order but had completed most of the process. This gave us a chance to show students the flexibility associated with engineering processes. As seen in Figure 4, additional arrows represent the many different ways the process can be completed; there is no one linear process to follow.

For a formative assessment, we gave students cards with descriptors associated with engineering processes and asked them to create a visual that represented how they now understand the nature of engineering. Students' visuals were consistently accurate, presenting a cyclical process in which some back and forth occurred in phases such as testing prototypes, developing ideas, and redesign. Then, to address features of scientific processes, we handed out a different set of cards to use in visually representing how they understand scientific processes. On these cards we wrote descriptors such as *discovering, engaging in inquiry, hypothesizing, developing a controlled experiment, revising a hypothesis, communicating findings, analyzing results from experiment, redesigning controlled experiment, generating community analysis and feedback.*

We concluded our discussion by comparing their visual representations, highlighting those processes that were represented more accurately than others and the distinct features of scientific processes in comparison to engineering processes.

Elaborate/evaluate: Cell phones (360 minutes)

Instructional strategy: Contextualized performance task in teams. In the elaborate phase, students were first asked to consider their mistakes in the Protect Our Food activity. Students reported that the most damaging assumption was that marshmallows, like soybeans and peanuts, were lightweight and needed very little support from their structures. This assumption led to a class discussion on the importance of the base, different materials, and geometric shapes (e.g., triangles) in the design. Then, referring to the PBS force lab (see "On the web"), we presented students with specific civil engineering vocabulary along with related images and simulations. As a means of quickly and formatively assessing the students' understandings, we challenged them to use this vocabulary to diagram different pictures of towers. Their diagramming was projected using a document camera and peer evaluated through whole-class discussion. Accurate labels were commended and missing labels identified. We told students they would apply these civil engineering concepts in their final project.

Challenge: Cell Tower

Students assumed the role of a team of engineers working for EAE, a fictional engineering firm hired by a cell phone company to design a new cell phone tower. Students had to prepare a formal proposal for the phone tower, understanding that the contract would be awarded to the team who maximized height while minimizing cost. Budgeting was an exciting new challenge for the teams. Students were allowed to "buy" as much spaghetti, string, and tape as their $100,000 budget

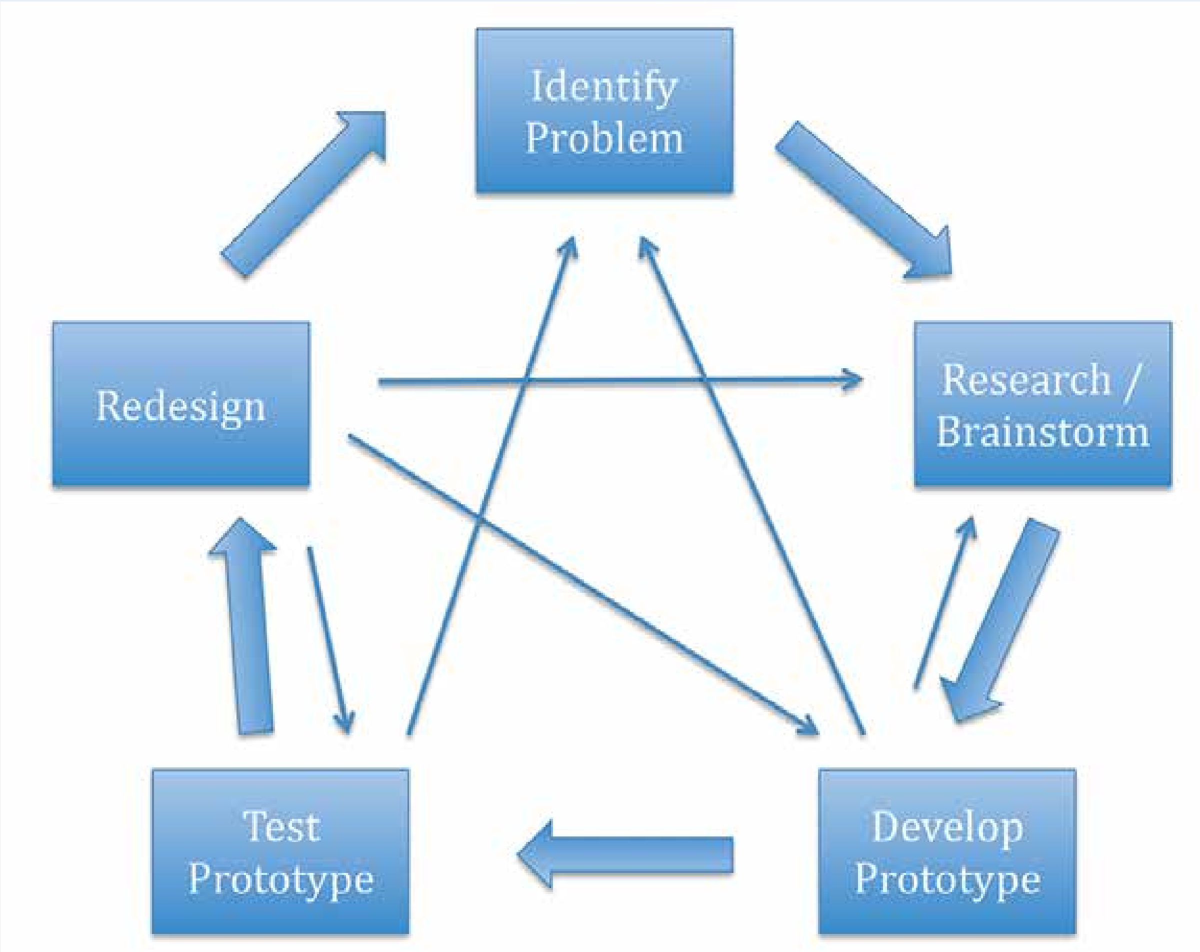
FIGURE 3

Reflection prompts for students.

Our actions (in the sequence they occurred)	**Our restrictions** (within this sequence)	Generally speaking, does your process seem consistent with scientific processes? ❐ Yes ❐ No Explain your thinking:

FIGURE 4

Typical design process, with additional arrows to indicate multiple approaches.



allowed. Spaghetti costs $10,000 per noodle; string costs $1,000 per 15 centimeters; and tape costs $1,500 per 5 centimeters.

As the student teams worked on their designs, we offered guidance, asking such questions as:

- What phase of the design process are you working on?
- What is the purpose of this phase?
- Is this something a scientist would do?
- How will you know when to move on to the next phase?

Through the students' responses, involvement, and outcomes, we ascertained that they accurately understood the features associated with engineering practices and how this compared to scientific practices. Students were highly engaged during prototype development, testing, and redesigning. A few groups were discouraged when prototypes didn't stand erect for long and wanted to completely start over. We encouraged them to consider where their prototypes failed and how they could modify them instead of developing a new plan. Throughout the process students were reminded to document their process in their engineering notebooks, which students use to keep detailed records of their engineering work, including documenting ideas and questions, sketching ideas, and recording testing data. Details recorded for this project included the use of mathematical/geometric principles in their design, forces involved, results of each prototype, and evidence of the different steps of the design process. Additionally, teams were reminded that they were working under the constraint of a deadline: two class sessions for teamwork and a final class session for writing their individual proposals.

Performance evaluation (90 minutes)

Students were provided one class session to individually write a final, polished version of their formal engineering proposal, guided by a rubric (see "On the web"). The purpose of the proposal was to allow students to demonstrate their understanding of the engineering design process, including choosing and justifying a final design, and the appropriate use of engineering and design principles. Many students completed their proposals successfully.

Conclusions

We found that our activity proved valuable throughout the course and was revisited each time engineering concepts were taught. For example, when building electrical models later in the semester, students went through several prototypes, testing each one, using data and research to inform their decisions. Students were leading discussions, clearly communicating distinctions in their practices as scientific or engineering (or both). This, along with the success students achieved with the activity's final performance task, led us to conclude that this explicit, reflective approach to teaching about scientific and engineering practices is effective. Teachers can modify it to fit their own students' needs, including asking different types of questions once students break into small groups or changing the context of the performance tasks. ■

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On the web

Cell tower proposal rubric; Figure 1A answer key; handout for Protect Our Food activity: *www.nsta.org/highschool/connections.aspx*

PBS Force Lab: *www.pbs.org/wgbh/buildingbig/lab/forces.html*

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Fralick, B., J. Kearn, S. Thompson, and J. Lyons. 2009. How middle schoolers draw engineers and scientists. *Journal of Science Education and Technology* 18 (1): 60–73.

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Career of the Month

December 2014, Based on Interviews With Professionals Using Science in the Workplace *Luba Vangelova*

Biomedical Engineer

Biomedical engineers "look at the body as an engineering system with a structure and mechanical forces going through the bones," says Paul DeVasConCellos. They apply their knowledge of both medicine and engineering to develop diagnostic and treatment devices such as prosthetic limbs, pacemakers, and magnetic resonance imaging machines. DeVasConCellos works for SIGN Fracture Care International, a nonprofit that develops practical and cost-effective orthopedic implants that are provided free of charge to injured, low-income individuals in developing countries.

SIGN (BOTH PHOTOGRAPHS)

Work overview.

We make over 20,000 orthopedic implants a year to help people in third-world countries. This is a small company, so I do a little bit of everything. The most fun part of my job is designing new products. The company's founder travels around the world and tells us what kind of implant or instrument would be useful to people in different countries. It's up to us to come up with a design to solve people's problems and then interface with our machine shop to make the parts.

Third-world countries present an unusual challenge. There are a lot of high-impact fractures from traffic accidents, and these can cause a bad break that can't be set right away. People who live in rural areas often don't get to a hospital for weeks or months. By then the bone has already started healing incorrectly, so you have to straighten it out.

The company's main product is an improved tibia nail, which is a rod implanted down the middle of the tibia bone, held together by screws. It holds together pieces of broken bone so they can align and heal. Our version can be implanted without an x-ray machine and is solid, which gives it a strength advantage and reduces the infection rate.

One of the products I've worked on personally is a pediatric nail, which is typically used in the femur. We borrowed a lot of features from the adult nail and made a few adaptations. The pediatric nail has a more flexible portion to accommodate changes in bone curvature as the child grows. Instead of screws, our nail has a fin on one side that wedges to the side of the bone. Because it's not locked mechanically like a screw, it gives the bone rotational stability, and it doesn't hinder growth, because the bone can grow over it.

Right now, we're working on implants to treat tibia plateau fractures at the bottom of the knee. I've also worked on a hip construct, which is used to treat femoral neck fractures where the femur enters the hip.

For every project, we have to do background research first. Books are often a good place to start, and then we do online searches for new advances in the field and read any new journal articles. We develop a hypothesis of what might work well, then sketch out features and rough dimensions for a model. We talk about the sketch and then make a 3-D model of one or two designs using our 3-D printer. Later the shop makes a metal prototype, and we test it.

We start with mechanical testing, using a machine that does axial testing to check tension, compression, and torsion and a fatigue machine that simulates walking *(below)*. We use fractured synthetic bones that are as strong as real bones. We put them in the walking machine, tell it how much weight to put on, and it starts "walking." After the prototype stage, the product usually goes for Food and Drug Administration (FDA) clearance.

We keep track of the surgeries done using our products, and the overall picture is that our implants do really well. We're always trying to figure out how to manufacture products more cost effectively and how to make them more efficient.

Career highlights.

The highlight so far has been getting FDA clearance for the pediatric nail. The patent won a Patents for Humanity

The "walking" machine.

award given by the United States Patent and Trademark Office.

Career path.

When I was really young, I wanted to be a veterinarian or a doctor, but I also liked to take things apart and see how they worked. During my first year of college, I learned about both medicine and engineering and became more interested in combining the two. Biomedical engineering was a natural combination.

During graduate school, I worked with SIGN on an antimicrobial coating for implants to prevent infection. After I finished my degree three years ago, I came to work for SIGN full-time.

Background needed.

You need a good background in mechanical forces. A knowledge of anatomy also helps. You should know how to run testing machines and write reports. You should also know about 3-D modeling, which is the best way to convey ideas. Communication is also important, because the problem you need to solve is not always clear.

Advice for students.

Don't slack off on math or science; they're important for getting an engineering degree. I found graduate school was a pretty valuable experience. I also had an internship. Usually the classroom teaches you basic skills, but it's always good to do something beyond the homework assignment.

BONUS POINTS

DeVasConCellos's education:
Education: BS in bioengineering, with minors in math and Spanish, and MS in mechanical engineering, Washington State University

On the web:
http://signfracturecare.org

Related occupations:
Mechanical engineer, manufacturing engineer

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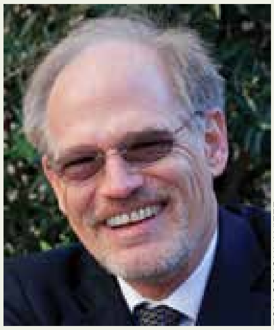
Career of the Month

February 2016, Based on Interviews With Professionals Using Science in the Workplace *Luba Vangelova*

Electrical Engineer

Electrical engineers deal with machines and machine components that rely on electric current or electromagnetic fields. They may work in any industry but are most heavily concentrated in the electronics sector. Tom Coughlin specializes in magnetic recording devices and has worked on flexible tapes, floppy disks, and hard disks. He is now the president of Coughlin Associates, his own data storage consulting company.



TOM COUGHLIN/IEEE

Work overview.

I consult for various companies and individuals and organize digital storage conferences, including one specifically for the entertainment industry. I write reports on technology trends in digital storage and applications.

To figure out industry trends, I confer with others and read a lot. Currently, new devices and new processing and memory capabilities are driving the industry. Digital storage in the cloud, making data accessible through the internet, has led to enormous changes in how we can use machines.

For my consulting work, I sometimes test storage devices and analyze problems, such as corrupted data on the device or damaged *firmware*, a software program on a hardware device. I may try to recover missing or damaged data, which requires specialized equipment, interfaces, and software. Sometimes I use an electron microscope to do materials analysis.

BONUS POINTS

Coughlin's education:
BS in physics, University of Minnesota; MS in electrical engineering, University of Minnesota; PhD, electrical engineering, Shinshu University (Japan).

On the web:
ww.ieee.org, www.tomcoughlin.com/techpapers.htm

Related occupations:
Embedded systems engineer, computer scientist, and photonics engineer.

Career highlights.

I like the sense of discovery that comes with understanding something and seeing how different parts work together. I've made many successful storage devices and am the author of six U.S. patents. It's satisfying to be able to make money off something you made.

I also enjoy writing. I wrote a book about digital storage and consumer electronics and blog about storage for *Forbes.com*.

Career path.

When I was a kid, I read a series of biographies. The people working in technology seemed so cool because they were making products that could change lives. And they were doing that by knowing about how the universe works.

In high school, I saw my first electron microscope when I visited a fossil collector's lab. I later got a bachelor's degree in physics at the University of Minnesota and then spent a year at Honeywell Research in the Twin Cities, working on magneto-resistive devices for sensor applications. I wanted to use equipment at the University of Minnesota, so I decided to go back to get a master's degree in electrical engineering, with a minor in materials science. Later, I got a PhD.

For a few years after college, I worked on magnetic recording on floppy disks for 3M and then for another company that made magnetic recording heads. After that, I developed storage media for an electronic camera at Polaroid. I then spent the next 20 years or so in California working at various hard-disk-drive companies, where I developed magnetic recording technology as an engineer and manager. After my last employer went bankrupt, I started my own company.

Knowledge, skills and training needed.

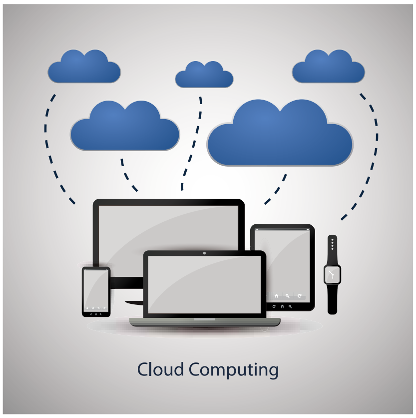
My electrical engineering training is useful for understanding what's going on in a device, how it operates logically, and what issues can occur with erasure or corruption. It's good to understand software and common debugging techniques, because few things work right the first time.

It's helpful to know physics principles and material science. Math subjects such as matrices and calculus are good to know. And having a geometrical view is helpful to visualize how things work. It's important to have some knowledge of communications. Encoding and decoding information is useful, as is understanding the general architecture of systems. And it's good to be comfortable meeting people and talking to them so you can learn from them.

Advice for students.

Find something that fascinates you, and explore it as deeply as you can. Find people who know more about it than you do, and learn what they know and what they would recommend for learning even more.

If you look at something from a multifaceted view and examine every possible interaction, you will learn a lot about the world, and you will develop good concentration and other skills useful throughout your career.



DON'T SHORT CIRCUIT STEM INSTRUCTION

Exploring the goals of engineering and science

Crystal Bruxvoort and James Jadrich

Science students should undertake engineering design projects and carry out scientific investigations, as recommended by the *Next Generation Science Standards* (NGSS Lead States 2013) (see box, p. 28). However, studies show that students misconstrue the goals of science and engineering and are uncertain about their respective practices (Gilbert and Wade 2014; Harkema, Jadrich and Bruxvoort 2009, 2012; Jadrich and Bruxvoort 2013). This article describes an electric circuits lesson to teach about the goals and practices of science and engineering to physics students.

Lighting a bulb

This two- to three-day lesson has two main learning goals—to understand the fundamentals of a complete circuit and to understand engineering and science's related but differing purposes. We provide student pairs with a small lightbulb, insulated wires, and a 1.5-volt battery and challenge them to light the bulb. Students sketch their successful and unsuccessful configurations (Figures 1A and 1B, p. 24) to help them document their progress and foster later class discussions. (**Safety note:** Instruct students to cautiously manipulate the batteries, wires, and bulbs. If at any time students' fingers sting or feel hot, they should immediately release their hold on the equipment [Roy 2010]).

Generally, even students who have previously studied electricity can't easily light the bulb. The predominant problem-solving strategy is to try every conceivable combination of wires and connection points randomly. We challenge students to reflect on this unsystematic, trial-and-error approach as we proceed with the lesson and present the purpose and methodologies considered normative in engineering.

A "tinkering only" approach

After all student pairs have successfully lit the bulb, we initiate a large group discussion that focuses on our two main learning goals. We ask students to examine their circuit sketches (successful and unsuccessful), identify the connections that seem necessary to light the bulb, and think about how they approached the task of getting the bulb to light. We ask: "How did you and your partner light the bulb?" and "What were you thinking about as you worked to light the bulb?"

When asked to reflect in this way, students admit, sometimes sheepishly, to trying lots of different configurations of wires and connections until they lit the bulb. This "confession" usually yields supporting comments from other groups such as: "We just messed around until we saw the bulb light up" and "It was sort of like trial and error."

Students' answers allow us to begin explaining the purpose of engineering and its associated methodologies. According to the *A Framework for K–12 Science Education* (NRC 2012), engineering encompasses all manner of societal and technological problem-solving to meet human needs and wants. The *Framework* and *NGSS* (NGSS Lead States 2013) also point out that engineering design typically involves researching or developing relevant scientific models and systematically applying those models to design a carefully considered solution. In this respect, "messing around" or "trial and error" is an inadequate portrayal of standard engineering practice. At times, engineers (and scientists) use trial and error or *tinkering* as practicing engineers commonly refer to it, but tinkering alone doesn't represent normative practice for engineers.

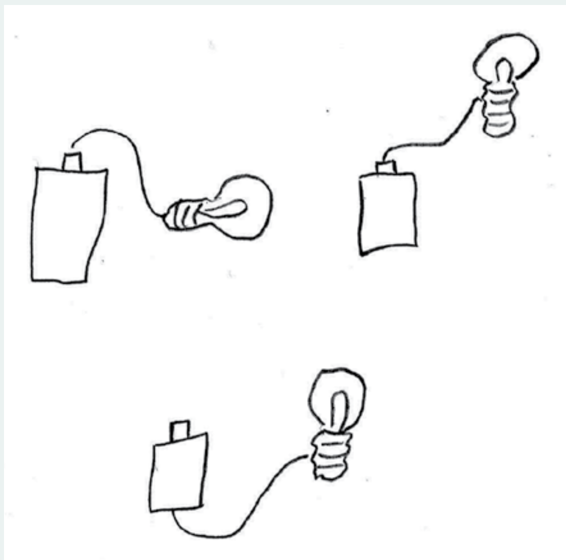
We explain this idea further in the next two phases of the lesson.

FIGURE 1A

A typical student drawing of the circuits that light a bulb.

FIGURE 1B

A typical student drawing of the circuits that don't light a bulb.



Developing a scientific model for a complete circuit

Students next develop a model to account for electricity flow in a circuit. Given time constraints, we present students with four possible scientific models (Figure 2) that represent students' most common responses to how an electric circuit works (Osbourne and Freyberg 1985).

We begin by describing the subtle differences among the four proposed models. Then, working in small groups, students test and determine which model best explains how a complete circuit works, keeping in mind that no scientific model completely explains everything.

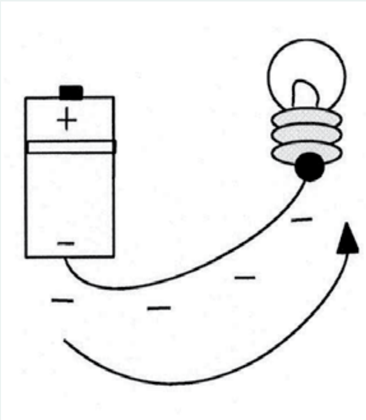
Having taught this lesson for many years, we can state how students typically work through this section of the lesson. Students quickly reject Model A, recognizing that they tested this model when they tried to light their bulbs. At first glance, Models B, C, and D appear identical to most students. We encourage them to inspect each model closely and, with prompting, they eventually notice some important differences:

- Model B depicts positive and negative charges combining to make the bulb light.
- Model C proposes that charges are used up as they pass through the bulb.
- Model D proposes that charges leave one side of a battery, pass through the bulb, and return to the battery.

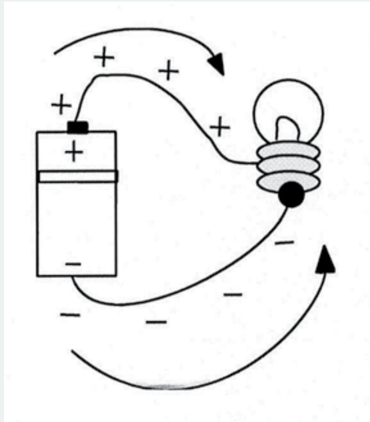
We provide students with additional equipment (i.e., extra batteries, bulbs, bulb holders), and they build test circuits to evaluate the models. We encourage them to compare what they observe in their test circuits with what they predict should happen. Depending on group progress, we may even suggest that students construct a particular test circuit

FIGURE 2

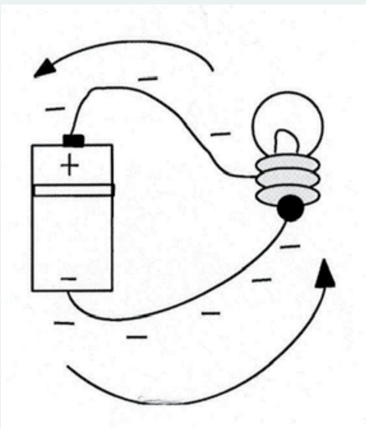
Four possible models for electric current.



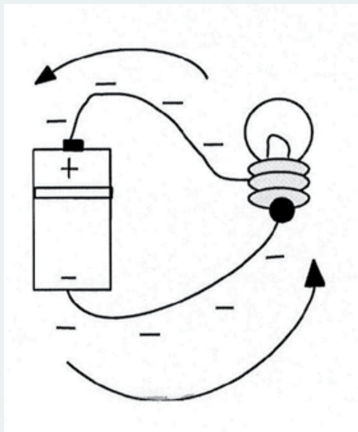
Model A: Negative charge comes out of the battery, goes into the bulb, and produces light.



Model B: Positive charge comes from the positive side of the battery, and negative charge comes from the negative side. The charges meet in the bulb and produce light.



Model C: Negative charge comes from the battery. Some of this charge gets used up in the bulb to produce light, and the rest goes back into the battery.



Model D: Negative charge comes from the battery. All of this charge goes back into the other end of the battery.

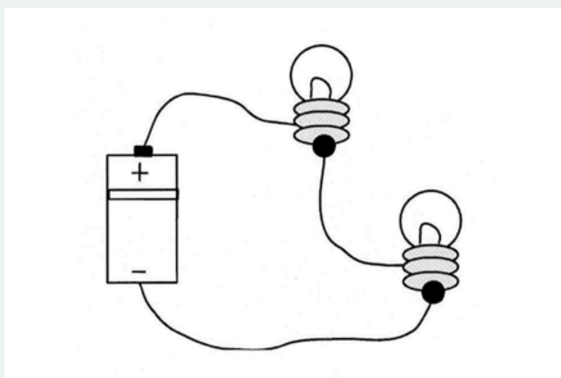
(Figure 3), and we talk through how this setup will help make and test predictions.

Below we offer a summary of the test circuits along with students' predictions and analysis as they evaluate Models B, C, and D.

- *Model B:* According to Model B, negative and positive charges come together and combine to make a bulb light. If that is so, Model B is unclear as to what should happen if students wire two bulbs as in Figure 3. Will only one of the two bulbs light (presumably the bulb where the charges combine) or will both bulbs remain unlit because the charges combine somewhere inside one of the wires? Model B is ambiguous as to what would happen in these cases, and thus it doesn't seem to support the fact that both bulbs light up. This prompts students to reject Model B.
- *Model C:* According to Model C, some charge is used as current passes through a bulb. If multiple bulbs are

FIGURE 3

Examining two bulbs in series helps to shed light on how current flows in an electric circuit.



connected (e.g., Figure 3), one bulb would be dimmer than the others as some charge is used up from one bulb to the next. When examining their results, students see that the bulbs in the series are equally bright and subsequently reject this model.

- *Model D:* According to Model D, charges leave one end of the battery, move through the bulb, and return to the other end of the battery. In this case, when observing two bulbs in series, both bulbs appear equally bright. Because this observation is consistent with the prediction, Model D appears to be the best of the four models.

Despite these results, many students remain uncomfortable with Model D. They argue that if all the charges return to the battery, then batteries would never die. This concern leads to a discussion about the nature of scientific models. Scientific models are never fully complete: They all have limitations in how accurately or completely they represent the physical world (Jadrich and Bruxvoort 2011; Gilbert 1991). In this case, a more complete model would have to include many more details, such as how batteries operate and why they eventually lose the ability to push charges through a circuit as the chemical reactants deplete. Scientists are constantly working to increase the accuracy and completeness of scientific models. This practice distinguishes science as a field of study.

We emphasize that Model D isn't wrong but incomplete. It doesn't explain why charges go around and eventually stop in a circuit, and there is no way of knowing if those charges are positive or negative. The model does, however, provide a good explanation for how circuits could work.

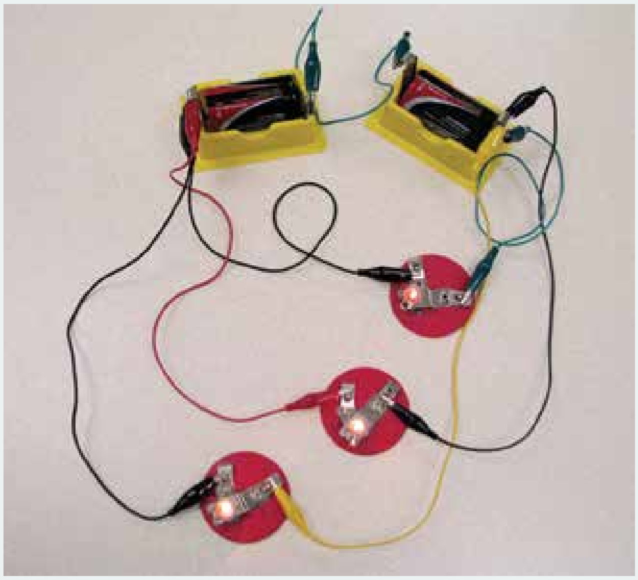
Solving circuit design problems

After students develop a scientific model for electric circuits, we assign problem-solving activities in which they design circuits to perform specific functions. We give students access to additional batteries, battery holders, bulbs, bulb holders, wires, and a variety of switches. Examples of problem-solving activities include

- Design an alarm system that sounds a buzzer or turns on a light when an intruder steps on a doormat.
- Design a circuit involving a toggle switch so that a bulb lights when the switch is "closed" and turns off when the switch is "open."
- Design a circuit with two bulbs and a switch so that one bulb is on and the other is off when the switch is in one position and the reverse happens when the switch is in the opposite position.

FIGURE 4

A student solution to a design problem in which the bulb(s) stay lit even if other bulb(s) are removed from the circuit.



- Design a circuit with three lightbulbs so that one bulb can be removed while the others stay on (e.g., Christmas tree lights). Figure 4 shows a student solution to this problem.

While students work on these design challenges, we remind them to use the model they previously developed. To dissuade students from reverting to the tinkering approach, we require them to sketch circuit designs they think might work and provide oral explanations describing their models. As students work, we ask them to justify their designs, asking questions such as: "Tell me how you are using the idea of a complete circuit" and "Trace how you think current would flow."

Students could solve these circuit problems more quickly if they didn't have to reflect on and justify how a scientific model informed their work. However, allowing random tinkering reinforces the misconception that engineering is just tinkering and obscures the essential interdependence of science and engineering.

Distinguishing the purposes of science and engineering

We open the final discussion by emphasizing that the purpose of science is to generate and test scientific models to determine which models best explain and predict natural phenomena (Boesdorfer and Greenhalgh 2014; Gilbert 1991; Harkema,

FIGURE 5

More examples of scientific and engineering pursuits.

Scientific questions:

- In a lever, what is the relationship between load position and effort?
- Why do slow-moving rivers meander more than fast ones?
- What is the effect of temperature on chemical reaction rates?

Engineering questions or problems:

- Make a toothbrush to clean hard-to-reach back teeth.
- Design a school composting and recycling system that reduces waste by 50%.
- What is the most efficient way for passengers to board an airplane?

Jadrich, and Bruxvoort 2009, 2012; Jadrich and Bruxvoort 2011, 2013; Seok Oh and Jin Oh 2011). In contrast, engineering's main goal is to generate desired outcomes to meet specific needs and wants, such as solving a societal problem or assisting the scientific community (Boesdorfer and Greenhalgh 2014; Harkema, Jadrich and Bruxvoort 2009, 2012; Jadrich and Bruxvoort 2013; Landis 2007). Figure 5 provides examples of both scientific and engineering projects.

Students are asked to identify where in this lesson they pursued engineering goals and where they pursued scientific goals. They readily identify that they tested Models A, B, C, and D for a scientific goal and that the design challenges were consistent with engineering. The initial problem students solved (i.e., lighting a bulb) is engineering, but we reinforce that their tinkering approach isn't generally normative.

Science and engineering aren't always clearly distinct. Sometimes practicing scientists pursue engineering goals, and vice-versa. If few relevant models are at hand, engineers must first do some model testing to derive potentially relevant models, as scientists would do. Similarly, scientists often have both a scientific and an engineering goal in mind, such as when they generate a new model for antibiotic resistance and then work on the production of molecules for that purpose.

Conclusion

The *NGSS* charge science teachers to teach the goals and practices of science and engineering. We use this electric circuits lesson to compare and contrast the primary goals of science and engineering and reflect on how they are integrally related. Because students tend to rely on an unsystematic, trial-and-error approach when pursuing engineering problems, we emphasize that tinkering isn't the dominant engineering strategy. Rather, engineering is primarily dependent on using models to problem solve. ■

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Acknowledgments

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Connecting to the *Next Generation Science Standards* (NGSS Lead States 2013).

<table>
<tr><td colspan="3">Standard
HS-PS3 Energy</td></tr>
<tr><td colspan="3">Performance Expectations
The materials/lessons/activities outlined in this article are just one step toward reaching the performance expectations listed below.
HS-PS3-2. Design 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.</td></tr>
<tr><td>Dimension</td><td>Name and NGSS code/citation</td><td>Specific Connections to Classroom Activity</td></tr>
<tr><td>Science and Engineering Practices</td><td>Developing and Using Models
• Use a model to provide mechanistic accounts of phenomena. (HS-PS3-2)

Constructing Explanations and Designing Solutions
• Design, evaluate, and/or refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations. (HS-PS3-3)</td><td>Students test four models—each of which attempts to account for how electricity works in a closed circuit.

Students are tasked to apply a model for electricity to explain why certain circuits work as desired and others do not.</td></tr>
<tr><td>Disciplinary Core Ideas</td><td>HS-PS3.A: Definitions of Energy
• At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, sound, light, and thermal energy. (HS-PS3-2, HS-PS3-3)</td><td>Students develop and test a model for electricity. Ultimately, this model is used to develop circuits according to certain specifications.</td></tr>
<tr><td>Crosscutting Concepts</td><td>Energy and Matter
• Changes of energy and matter in a system can be described in terms of how energy and matter flows into, out of, and within that system. (HS-PS3-3)
• Energy cannot be created or destroyed—only moves between one place and another place, between objects and/or fields, or between systems. (HS-PS3-2)</td><td>Students design circuits where various energy transformations occur to generate the desired outcome(s) (e.g., stored chemical energy to electrical energy to heat energy to light energy).</td></tr>
</table>

<table>
<tr><td>Connections to Engineering, Technology, and Applications of Science:
• Modern civilization depends on major technological systems. Engineers continuously modify these technological systems by applying scientific knowledge and engineering design practices to increase benefits while decreasing costs and risks. (HS-PS3-3)</td><td>Discussions throughout this lesson focus on two important aspects related to the natures of science and engineering:
• The purpose of science is different from the purpose of engineering.

• Good engineering practice does not end with only a tinkering approach, rather effective engineering practice also involves applying scientific models to achieve certain outcome(s).</td></tr>
</table>

Connecting to the *Common Core State Standards*

Mathematics: MP.2 Reason abstractly and quantitatively. (HS-PS3-3)

The fundamental model for electricity students are developing and testing requires abstract thinking on the level of charges, charges moving, etc.

MAKE ROOM FOR ENGINEERING

Strategies to overcome anxieties about adding engineering to your curriculum

Sarah Boesdorfer and Scott Greenhalgh

The *Next Generation Science Standards* (NGSS Lead States 2013) urge science teachers to include engineering practices and ideas in their already full science curriculum. But many teachers don't know where to start. Only 7% of high school science teachers report feeling "very well prepared" to teach engineering. The apprehension level may be higher for those who don't teach physics—28% of physics teachers have taken an engineering course compared to only 10% of other science teachers (Banilower et al. 2013). In this article, we describe the engineering design process and how it parallels scientific practices. Then we suggest ways science teachers can begin to incorporate engineering design into their current classroom curricula.

How science and engineering are similar and different

Engineering education parallels and complements science education. Similar to some goals of science education, a goal of engineering education is to promote engineering "habits of mind" in addition to preparing the next generation of scientists, engineers, and related STEM professionals. Engineering education provides students with skills in creating and evaluating the built (technological) world, just as science education provides skills in understanding the natural world.

Although scientists and engineers use similar practices, such as

- developing and using models,
- planning and carrying out investigations,
- analyzing and interpreting data,
- using mathematical and computational thinking,
- engaging in arguments from evidence, and
- obtaining, evaluating, and communicating information (NRC 2012 p. 49),

they use these practices to achieve generally different outcomes. Scientists typically work to understand natural phenomena while engineers try to design a solution to a problem. This similarity in practices of scientists and engineers has led to two common categories of science class activities: *science model* and *engineering model* (Harkema, Jadrich, and

Bruxvoort 2012; Schauble, Klopfer, and Raghavan 1991). Science model activities ask students to collect and use data to find relationships or understand what occurs in an observed phenomenon. For example, students could discover and explain the relationship between the pressure and volume of a gas or identify the environmental conditions that seeds require to sprout. In science model activities, students ask questions and collect data to understand and explain.

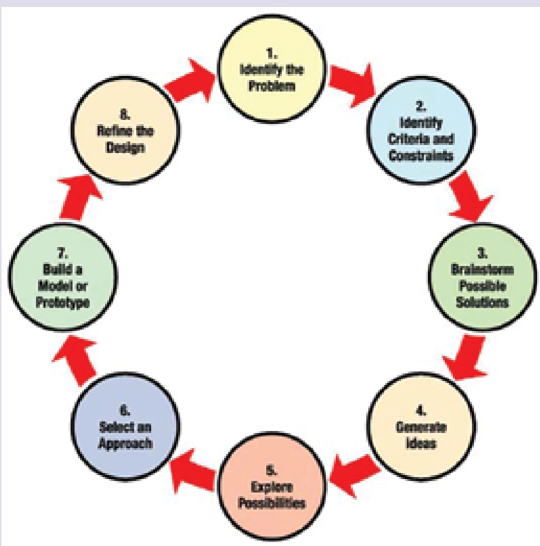
Engineering model activities, on the other hand, ask students to develop a product, process, or system to meet a challenge or solve a problem. For example, students could design a zoo habitat for an animal based on its specific adaptations, or students could use their knowledge of stoichiometry to design a process that consistently produces 5.0 g of zinc chloride by reacting zinc and hydrochloric acid. These activities are engineering model investigations because a problem is defined, a solution (product) created, and a need fulfilled. The science activities result in "universal" knowledge and understandings, while engineering activities result in solutions that are context specific.

The engineering design process

Just as there is no singular "scientific method" that all scientists follow, there is no singular path for engineers. However, like the "scientific method," engineers *generally* follow a technological and engineering design process or loop (Figure 1). This loop identifies the steps that lead to the development of a new product or system and emphasizes the importance of

FIGURE 1

Secondary engineering and technological design loops.



DAUGHERTY AND CUSTER 2003

multiple iterations in design: Rarely do engineers or designers work through each step only once on their way to a final solution. Many technological products are consistently being improved through the design process. Engineering shares practices with science—like experimenting, analyzing data, modeling, and communication—that are part of the process of brainstorming, testing models/prototypes, and improving designs along with other aspects of the design loop. This provides opportunities to highlight the complementary roles of scientific practices in the design process and to incorporate engineering into a science curriculum in addition to addressing the *NGSS* engineering design standard (HS-ETS1) and the links among engineering, technology, science, and society (ETS2) (NGSS Lead States 2013).

Four ideas for fusing engineering into your existing curriculum

1. Rework engineering model experiments to explicitly include engineering context, ideas, and terminology.

As mentioned above, many science investigations are actually engineering tasks, but students often do not see the difference between the two types of investigations (Harkema, Jadrich, and Bruxvoort 2012). To help students distinguish between the practices of engineers and scientists, provide a context for an engineering model activity using engineering terminology in the activity description, purpose, and/or procedure description. See "On the web" (Table of Engineering Terminology). For example, in an Earth science or environmental science course, students might currently be asked to compare different types of packing materials and choose the one that best limits environmental impact yet protects fragile materials during shipping. Figure 2 provides a "revised" version of this traditional activity that explicitly includes engineering concepts along with the context for the activity. Pre/post analysis questions could be added to make the engineering content more explicit. For example, students could be asked to "Identify the criteria and constraints that must be met to successfully complete this activity."

2. Remember engineering does not just mean building something.

Engineering encompasses more than the building of a bridge, building, car, or other product. Engineering outcomes also include processes and systems. Engineers improve or innovate processes to increase efficiency, thus solving a problem or creating an opportunity. This process of moving toward the best, or most efficient, product, process, or system is called optimization.

Students and engineers approach optimization through two methods: *guess and check* and *predictive analysis* (modeling), which students tend to underuse (Becker et al. 2012). To promote the use of scientific concepts in engineering, a teacher can use context and constraints to encourage predictive analysis. For example, in the Get the Salt activity (see "On the web"), students are asked to engineer or design a process that will separate 98% of the salt from a mixture of salt, sand, and iron filings. By making a single trial a constraint—as it is in real-world engineering design when prototype testing is not possible—students must justify their proposed process with data and apply their science knowledge, instead of simply using trial and error. This provides the opportunity to assess science content knowledge along with teaching engineering concepts. Constraining the time on task reflects real engineering problems where trials and experiments may be expensive, unsafe, or environmentally hazardous. Other ideas include asking students to create the best conditions for a chemical reaction or biological process (growing plants or anaerobic respiration of yeast) or developing an energy-efficient process for snow removal.

FIGURE 2

Experiment with engineering terminology and a context explicitly added.

Earth Science

Design brief: Environmental Packing Design

Context
You are part of a team of engineers at a glass beaker factory. The company you work for takes pride in producing environmentally friendly products and wishes to ship those products to schools.

Challenge
Your team must research and develop a cost-effective and environmentally friendly way to ship glass beakers to schools.

Resources
Your team will have one beaker supplied by the teacher. All classroom resources including tablets, computers, and the internet are available for research. Cotton balls, foam, packing peanuts (biodegradable and Styrofoam) paper towels, newspaper, cardboard, and bubble wrap are available for student use. Students must obtain for themselves any other materials they may wish to use.

Constraints
Your team must design a solution that costs less than $.50 per unit for packing materials (not including the box or shipping). To judge how well the beaker is packed, it must not break from a 1 m fall. Your team must also provide a two-page report of how your selected process is environmentally friendly in production, use, and disposal. Additionally, the report must include an estimated per unit cost for packing materials. The project will last two days. Day 1 will be devoted to research and planning. Day 2 will be devoted to assembly and testing. Safety note: Students should wear safety goggles and take care if handling broken glass.

Evaluation summary
Your team will be evaluated on the design sketches, research report, and design reflection. Additional evaluation will be given for meeting the constraints of budget, sustaining no damage in a fall, and completion deadline.

3. Use the design loop as a tool for creating activities.

The design loop can provide a scaffold to create activities for students. The design loop provides a systematic problem-solving strategy used to develop many possible solutions to a problem (ITEA 2007). Students can be asked to perform a task in which they must go through the entire process, or a task could be designed to focus on just part of the process, e.g., identifying the problem and criteria and developing possible solutions, or simply testing and improving a design.

For example, students could go through the entire design loop if asked to design a plan to improve a local outdoor space. In the Improving Your Environment activity (see "On the web"), students justify their plan, including addressing the environmental impact, and then assess their improvement and its impact on humans and the environment. Alternatively, activities might use only a portion of the design process. The activity in Figure 3 requires students to use the later portions—by testing and improving a prototype/design that already exists for keeping carbonated beverages from losing their fizz. Another activity might require students to use the first part of the design process; identify the problem, constraints, and criteria and then create a design. Students communicate their design, justifying it with their science knowledge; an example is the Heating Water with the Sun activity (see "On the web"). Using activities that focus on different aspects of the design loop allows students to learn, improve, and understand different engineering practices, and provides teachers several options to connect engineering to the curriculum. Students at times are provided with data rather than collecting it themselves so they can focus on the skill of making claims from data.

Using activities that focus on different aspects of the design loop allows students to learn, improve, and understand different engineering practices and provides teachers several options to connect engineering to the curriculum.

4. Create a design brief

Present students with a design brief—a written plan that identifies a problem to be solved, its criteria, and its constraints (ITEA 2007). The design brief encourages thinking about all aspects of a problem before attempting a solution and provides the context and the reasons the problem needs solving. A design brief should include

1. the situation (the context);
2. the problem;
3. the materials/resources available for the students;
4. the constraints of the project, including time; and
5. the criteria for evaluation.

Assessment

A template rubric reflecting the processes of the engineering and technological design loop described in this article is available online, as are simple rubrics for the "Get the Salt" and "Heating Water with the Sun" activities (see "On the web").

Conclusion

Engineering tasks require students to meet a challenge, perform a specific task, create an opportunity, or solve a problem. For science educators, it is important to remember the objective is learning an open-ended problem-solving process in which students use and demonstrate their knowledge of science core ideas and gain experience with science and engineering practices. It is easy for teachers and students to be caught up in the individual task and products. Often,

FIGURE 3

Activity in which students use part of the design process.

Chemistry

Design brief: Retain the Fizz

Context

The Sodas 'R' Us company just purchased the Pop's Our Game company. Among the company's inventory, they found some small plastic devices labeled as CO_2 Keepers. Sodas 'R' Us believes it is a device to keep the soda from losing its carbonation (going flat) after it has been opened. However, there are no instructions with the devices. They don't know how the device works and how to use it to its fullest potential. They have called in a team of engineers (you) to investigate and develop the process by which the device can be used to maintain the carbonation in the soda the longest.

Challenge

Create a set of instructions for the CO_2 Keepers that allows them to keep soda "fresh" the best. You must present your instructions to the company representatives. Your presentation must include an explanation of how the CO_2 Keeper works, your instructions, the results of your instructions (and how you define "best"), and data to support your instructions.

Resources

You will get 1 CO_2 Keeper and three 20 oz. bottles of soda along with any lab equipment you want or need, which includes CO_2 sensors and gas pressure sensors from our probeware. You will also have internet/computer access as needed. If you need more soda, you may provide your own.

Constraints

You have three class periods to plan, experiment, collect data, and create your presentation. Some presentation work may be done outside of class. You may collaborate with other groups for data collection, but each group should create its own presentation.

Evaluation summary

Your team will be evaluated on the quality of your presentation, which includes the use of data to support your findings. See the rubric for specific details about the evaluation of the presentation.

students (and maybe teachers) do not realize that these activities require students to use engineering practices.

We hope this article helps teachers to make engineering practices and design more explicit in science instruction and to improve student understanding of engineering and how it relates and strongly overlaps with the practice of science. *NGSS* asks science teachers to include engineering design in our science teaching. The ideas presented here should help reduce the anxiety that comes with adding something new to a curriculum. ■

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On the web

Design brief template, Get the Salt activity description, Heating Water with the Sun activity description, Improving your Environment activity description, table of engineering terminology, template for a design loop rubric: *www.nsta.org/highschool/connections.aspx*

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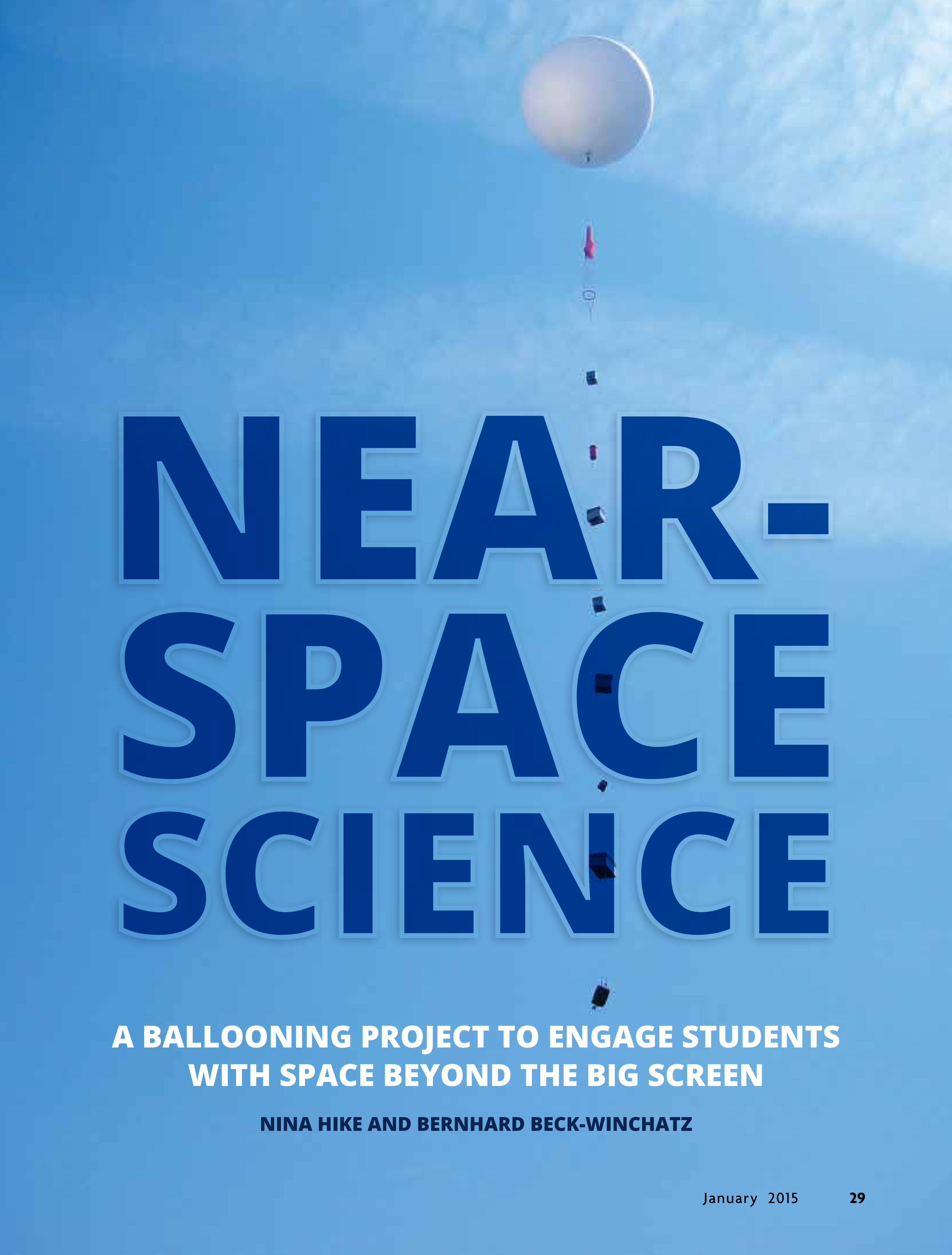


NEAR-SPACE SCIENCE

A BALLOONING PROJECT TO ENGAGE STUDENTS WITH SPACE BEYOND THE BIG SCREEN

NINA HIKE AND BERNHARD BECK-WINCHATZ

Many of your students probably know something about space from playing computer games or watching movies and TV shows. But you can expose them to the real thing by launching their experiments into near space on a weather balloon.

This article describes how to use high-altitude ballooning (HAB) as a culminating project to a chemistry unit on experimental design, gas laws, and air pollution. We describe how to design an instructional unit and perform a balloon launch, and we provide examples of student projects. We hope your students enjoy this real-life taste of space as much as ours did.

Ballooning background

HABs are filled with helium or hydrogen and released into the stratosphere (for student projects, only helium is acceptable, due to hydrogen's flammability); scientists often use a weather ballon (a type of HAB) to conduct experiments in near space—at altitudes above 99% of Earth's atmosphere. Many research projects require scientists to collaborate with engineers to develop the technology they need for such experiments. For example, when NASA launches a new space mission, the scientists tell the engineers what data the spacecraft should collect, and the engineers tell the scientists the design constraints of their instruments, such as limits on size, weight, and power consumption.

Ballooning engages high school students in a similar interaction and thus aligns with the *Next Generation Science Standards' (NGSS)* emphasis on science and engineering practices (NGSS Lead States 2013); the project is inherently interdisciplinary and can cover the range of *NGSS* disciplinary core ideas and crosscutting concepts.

Our near-space adventure

We undertook our own HAB project in spring 2013 as part of an International Baccalaureate Middle Years Programme chemistry course at Curie Metro High School in Chicago. Eighty percent of the students are Hispanic, and 95% come from low-income families.

More than 80 students in three sections of the course participated in our project. The textbook we use, the American Chemical Society's *Chemistry in the Community* (ACS 2011), worked well because it allowed us to integrate ballooning as part of a Putting It All Together Project (PIAT)—something the textbook includes at the end of each unit. We selected "Unit 2—Air: Designing Scientific Investigations" because it covers many concepts that are relevant for balloon experiments, such as

- experimental design,
- gas laws,
- kinetic molecular theory,
- atmospheric properties, and
- air pollution.

Students designed and launched 12 different experiments based on their understanding of these concepts. For example, one group investigated the effect of changing atmospheric conditions on the propagation of sound waves. They played a single-frequency tone using an MP3 player connected to a speaker and measured its volume using a sound level meter. The following sections describe the project in more detail.

Project breakdown

We divided the project into five segments:

- review of literature,
- experimental design,
- collecting and presenting data,
- conclusions and evaluation, and
- oral presentations.

The time requirements shown in Figure 1 are based on a two-week PIAT project and can be adapted to other time frames.

Review of literature

At the end of Unit 2—Air: Designing Scientific Investigations, students formed their own PIAT teams, selected research topics, and developed research questions. Their questions included:

- How do different liquids cool and freeze when exposed to the low temperature in the upper atmosphere?
- How does the ozone layer affect ultraviolet light intensity?
- Does the ideal gas law hold true in Earth's upper atmosphere?

Each student team then conducted a literature review and summarized key results of previous research related to their research question. In the first class period, they created outlines for their reviews. We then assigned each student a specific topic about which he or she had to write one paragraph using the graphic organizer, MEL-Con (see "On the web"). Students used internet search engines and online databases to find relevant articles and websites, then wrote their literature reviews in class. To learn how to properly cite others' work

FIGURE 1

Project timeline.

Each class period is 52 minutes long.

Segments	Activities	Required time	*NGSS* Science and Engineering Practices (NGSS Lead States 2013)
Review of literature	• Develop Review of Literature outlines. Conduct internet research and review class notes for scientific concepts and ballooning procedures. • Write group Review of Literature.	Two class periods	**Practice 8:** Obtaining, evaluating, and communicating information
Experimental design	• Finalize research questions. • Construct hypotheses and experimental design tables. • Develop and practice procedures. • Address safety issues.	Three class periods	**Practice 1:** Asking questions and defining problems **Practice 3:** Planning and carrying out investigations **Practice 6:** Constructing explanations and designing solutions
Data collection and presentation	• Construct payloads. • Launch balloon. • Generate data tables and graphs.	One school day (7 a.m.–5 p.m.) Two class periods	**Practice 2:** Developing and using models **Practice 3:** Planning and carrying out investigations **Practice 4:** Analyzing and interpreting data **Practice 5:** Using mathematics and computational thinking
Conclusions and evaluation	• Draw conclusions. • Evaluate experimental designs.	One class period	**Practice 6:** Constructing explanations and designing solutions **Practice 7:** Engaging in argument from evidence
Presentations	• Present results to peers, teacher, and assistant principal.	One class period	**Practice 8:** Obtaining, evaluating, and communicating information

according to the American Psychological Association (APA) style guide, students used the Son of a Citation Machine website (see "On the web").

Experimental design

We gave students three class periods to plan their experiments, finalize their hypotheses, and design their payloads. (The Federal Aviation Administration [FAA] imposes a 12 lb. [5.4 kg] weight limit on a weather balloon's payload [U.S. GPO 2014].) An experimental design table (example, Figure 2, p. 33) provided students a framework for developing experimental procedures. Students also completed a tethered launch—without actually releasing the balloon—on the school's athletic field to practice filling the balloon, attaching payload containers, and using the tracking software.

Ballooning logistics: A how-to guide.

Launch and landing

You can launch a weather balloon from a park, athletic field, or parking lot with enough space for the balloon to ascend without catching in a tree or other obstacle. Avoid densely populated areas and airports. You can predict the landing site to within a few miles by using prediction software (see "On the web").

A balloon will typically ascend for about 90 minutes to altitudes of 27–30 km before it bursts. Descent of payloads on a parachute takes about 30 minutes. The horizontal distance between launch and landing sites varies from a few kilometers in spring, summer, and fall to over 150 km during the winter months.

The flight track for our project.

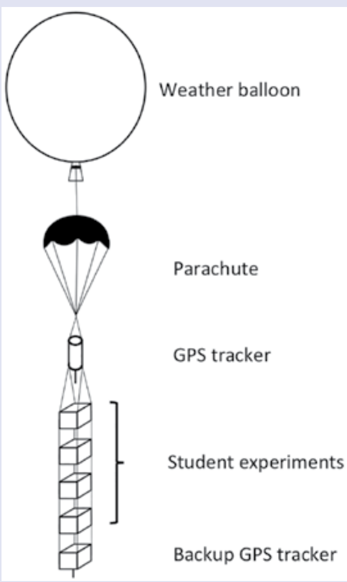
Regulations and safety

Comply with all FAA regulations (U.S. GPO 2014) and follow common-sense safety precautions for student transportation, launch, and payload recovery from difficult locations such as trees. Helium tanks should be properly secured for transport, strapped to a wheeled cart or dolly when moved, and kept upright. Never allow students or adults to inhale helium, as this can cause asphyxiation. Trained adult supervision should be provided at all times.

Costs and materials

The figure below shows a typical flight system, and the table lists the various costs associated with the project. Consumables for each flight include the balloon, helium, and miscellaneous other supplies that are approximately $200–400. Because our high school is located in a densely populated urban area, we rented a school bus to provide student transportation to the launch site and during the chase. The cost of the reusable equipment for this project is about $1,000 and consists of both a parachute and a HAM radio tracking system.

A typical flight system.



BERNHARD BECK-WINCHATZ

Equipment and costs.

Part	Purchase information	Approximate cost
1,200 g or 1,500 g balloon	*Kaymontballoons.com:* Part HAB-1200 or HAB-1500	$100–120
Helium size 300 cylinder	Purchase from welding supply stores or other gas supplier	$100–200
Miscellaneous consumables	Mason line, duct tape, cable ties, payload containers, and batteries	$50–100
Global Positioning System (GPS) tracker	*BigRedBee.com:* Part BLGPS2MHP with case and antenna	$280
Parachute (6 ft. [1.8 m])	*The-RocketMan.com*	$55
Tracking radio for chase vehicle	*Universal-Radio.com:* Part Kenwood TH-D72 with vehicle antenna	$650
Tracking software	*APRSPoint.com*	$77

FIGURE 2

Experimental design table.

Students conducting the sound-intensity experiment created this table.

Question:	Does sound intensity in Earth's atmosphere change with altitude?
Hypothesis:	Sound waves are mechanical waves that require a medium (e.g., air). As the density of the medium decreases, the sound waves will not be able to propagate as well and the sound intensity will decrease.
Independent variable:	Altitude (A). The altitude is expected to range from 200 m at launch and landing to approximately 30,000 m at burst.
Dependent variable:	Sound intensity (I) (sound energy per unit area and time).
Controlled variables:	Distance between sound-level meter and MP3 player; level of the tone; volume of the box.
Control tests:	Measure sound intensity in a vacuum jar.

FIGURE 3

Diagram and photograph of the sound-intensity payload container.

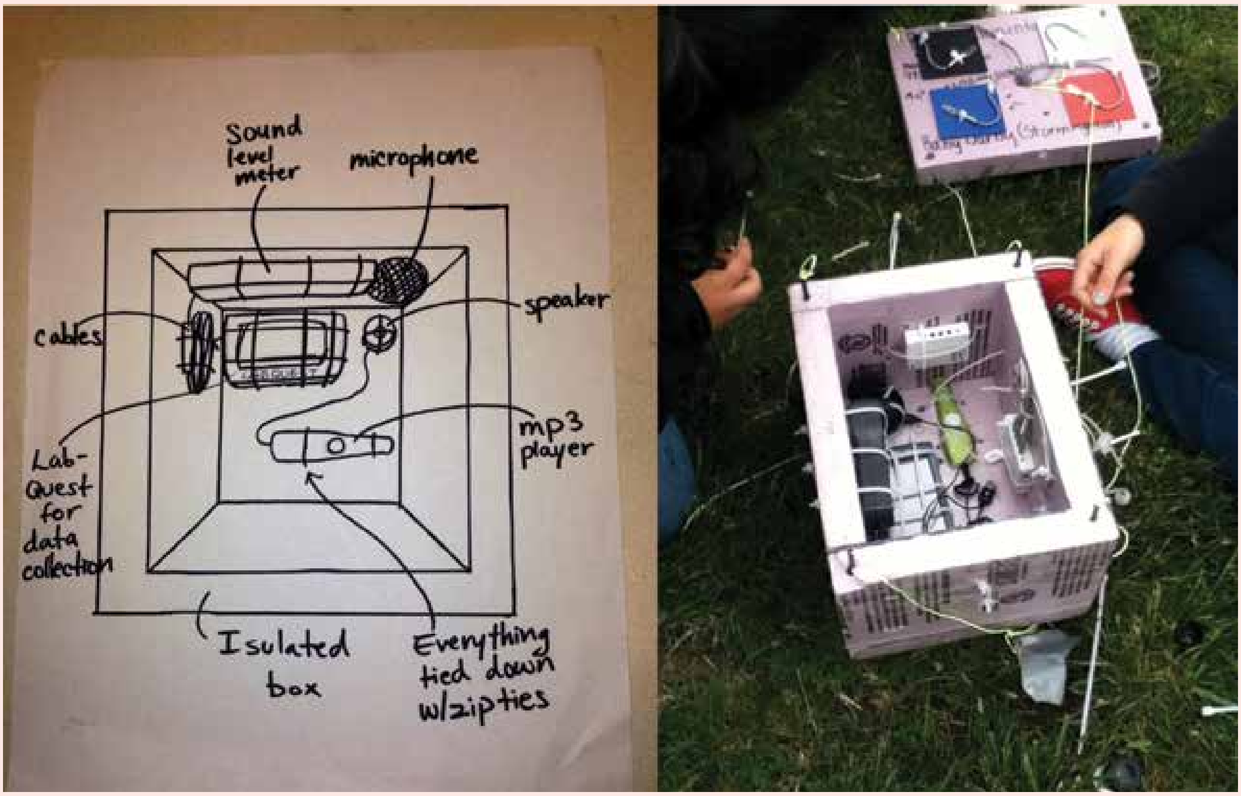


ILLUSTRATION: CRYSTAL TAN; PHOTOGRAPH: PAUL RITTER

Collecting and presenting data

On launch day, before leaving for the launch site on a school bus, students predicted the approximate flight path of the balloon with an online flight predictor (see "On the web"). Upon arrival at the launch site (another athletic field), each team had to complete its own preflight procedures (Figure 3, p. 33, and Figure 4), often coordinating with other teams that shared their payload containers. Students set up equipment to track the balloons' flight pattern and landing. They attached a parachute and two GPS trackers to the neck of the balloon (see sidebar, p. 32). Students had previously calculated how much lift was required for an ascent rate of 5.5 m/s, using an online ascent calculator (see "On the web"). Students posted updates and pictures on social media.

After two hours of preparation, students released the balloon and jumped on the bus to start the chase. They used mapping software on laptop computers to monitor the position of the balloon and give directions to the bus driver. The balloon ascended for 83 minutes and burst at an altitude of 27.5 km. The payload took another 27 minutes to descend back to Earth on the parachute. We arrived at the landing site in a farm field a few minutes after touchdown. After getting permission from the landowner, a small group of students and chaperones retrieved the payload, which took about 45 minutes (Figure 5).

During the following week, we gave students two days in the computer lab to generate data tables and graphs in spreadsheets. Figure 6 provides examples of the temperature, atmospheric pressure, and sound-level graphs they created.

FIGURE 4

Preparing experiments for flight.

NINA HIKE

Evaluation

During the final two class periods of the project, students evaluated their hypotheses, proposed alternative explanations, and revised their experimental designs.

For example, the sound-level team concluded that the data supported their hypothesis that the low-pressure, low-density air in the upper atmosphere would not transport sound energy as efficiently as the denser air on the ground. Their revised experimental design included several tones, instead of just one, to determine if the decrease in sound level depended on frequency.

Presentations

At the end of the project the students were excited to present their near-space experiments to their peers, teacher, and assistant principal. Each team prepared a 15-minute PowerPoint presentation, which included a brief background summary, the research question, hypothesis, variables and control table, procedure with a diagram, data presentation, conclusion, and evaluation.

FIGURE 5

Students retrieve payloads from the farm fields after touchdown.

SALVADOR GAMINO

Assessment

We used the science writing heuristic (Hand and Keys 1999) as a framework for student investigations throughout the balloon project (see "On the web"). The SWH supports the *Common Core State Standards'* emphasis on literacy practices across content areas (NGAC and CCSSO 2010) by encouraging students to integrate group discussions, writing, and reflection with their lab work. It's also designed to help students take ownership of their lab work by asking them to formulate their own research questions, develop investigations to address those questions, and make claims based on the evidence they collect. The balloon investigations were conducive to the SWH framework because they are inherently open-ended. We used a modified version of the SWH grading rubric for instructors (Burke, Greenbowe, and Hand 2006) to evaluate students' lab reports.

Student experiments

There are many possibilities for balloon-based student research not just in chemistry but in biology, physics, and astronomy as well. Our balloon flight included 12 experiments, and students conducted all of them with standard Vernier probeware (although sensors from other vendors, such as Pasco, could be used instead) and other equipment and supplies readily available to many high school science teachers. Here are examples of other potential research questions students might explore with this project:

- How does altitude affect sky brightness?
- How does temperature affect the speed of sound?
- How do cosmic rays affect mutation rates of yeast?
- How do cosmic rays affect radish seeds?
- How do different liquids cool and freeze when exposed to the low temperature in the upper atmosphere?
- How does the ozone layer affect ultraviolet light intensity?
- Does the ideal gas law hold true in Earth's upper atmosphere?
- How does exposure to the conditions in the upper atmosphere affect cricket chirps and *daphnia* swim patterns?

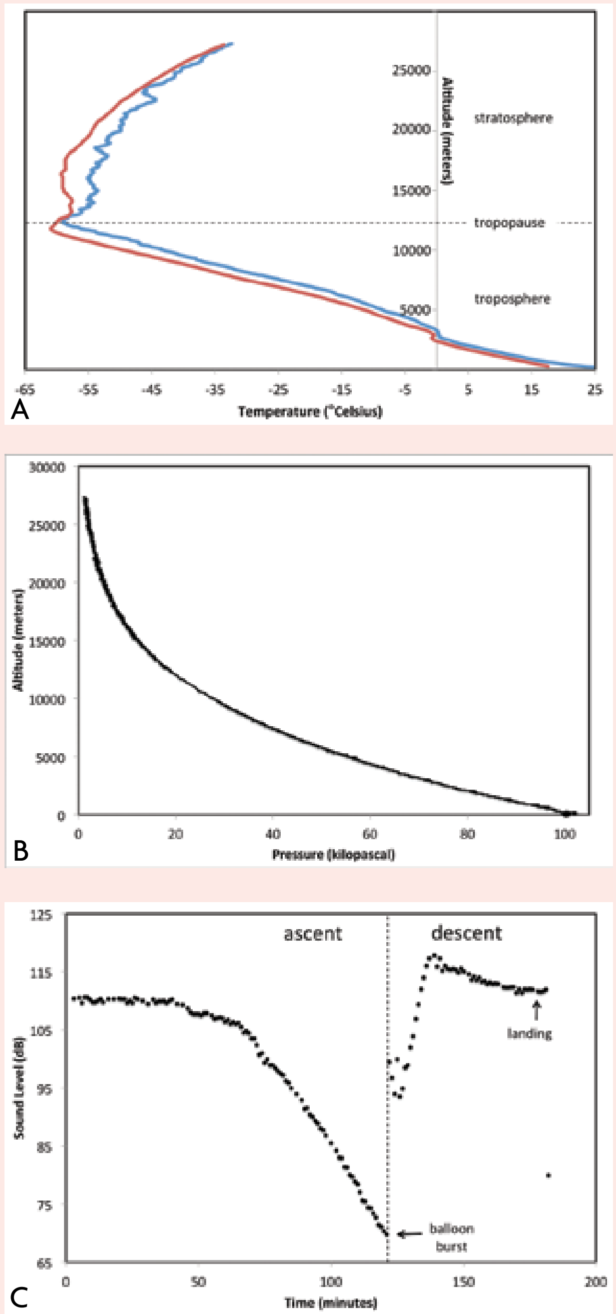
Conclusion

HAB is an exciting way to engage students in a real-world science and engineering project. You may be intrigued by HAB but worry that it might be impractical for your own classroom. Ballooning may seem daunting at first, but

FIGURE 6

Temperature, pressure, and sound level measured during the flight.

The temperature (A) during ascent (blue line) and descent (red line) was measured outside of the payload containers with a temperature sensor. Atmospheric pressure (B) was measured with the sensor built into a GPS tracker. Sound level (C) was measured with a Vernier sound level meter connected to a LabQuest 2 interface.



many high schools have successfully launched and recovered balloons.

As with any new activity, it's helpful to have an experienced partner who can help you get started. Our high school, for example, partnered with a faculty member at DePaul University (Bernhard Beck-Winchatz), who regularly conducts balloon launches with college students. You may be able to coordinate similar partnerships in your city through organizations such as Amateur Radio High Altitude Ballooning, the Stratospheric Ballooning Association, or the Space Grant Consortium of your state (see "On the web"). There are also commercial flight systems and "launch for hire" services available, but these add expense. Of course, you can also learn everything you need to know about ballooning yourself by taking advantage of the many free ballooning resources available online (see "On the web"). Exposing students to space beyond the big screen is certainly worth the effort. ■

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Acknowledgments

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On the web

Free resources for learning how to launch balloons:

Near Space Exploration With the BASIC Stamp Handbook: *www.nearsys.com/pubs/book*

The Montana Space Grant Consortium Ballooning Program Handbook: *www.mrc.uidaho.edu/~atkinson/ENGR_RISE/Borealis.pdf*

Organizations to help you get started:

Amateur Radio High Altitude Ballooning: *www.arhab.org*

NearSys LLC: *http://nearsys.com*

Stratospheric Ballooning Association: *www.stratoballooning.org*

State Space Grant Consortia: *http://spacegrant.org/about/who*

Stratostar Education Company: *www.stratostar.net*

Online flight track and ascent rate prediction software:

UK High Altitude Society Landing Predictor: *http://predict.habhub.org*

University of Southampton High Altitude Balloon Flight Planner: *http://astra-planner.soton.ac.uk*

Near Space Ventures (ascent calculator): *http://nearspaceventures.com/*

Writing and assessment tools:

MEL-Con Writing: *http://melcon.weebly.com/index.html*

Science writing heuristic: *www.nsta.org/highschool/connections.aspx*

Son of a Citation Machine: *www.citationmachine.net*

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POWERED by the Sun

Teaching the science of energy, force, and motion through an engineering design challenge

Christine Schnittka and Larry Richards

Solar energy is clean, free, and abundant worldwide. The challenge, however, is to convert it to useful forms that can reduce our reliance on fossil fuels. This article presents an activity for physical science classes in which students learn firsthand how solar energy can be used to produce electricity specifically for transportation. The activity introduces students to solar-powered mass transit currently in use and then challenges them to create their own vehicle (Figure 1). When students create a successful solar-powered mass transportation vehicle, they use the engineering-design process to create designs that solve problems and carry out relevant scientific investigations (see box, p. 32, for connections to the *Next Generation Science Standards*).

Engaging students

Directly or indirectly, people and products are transported by fossil fuels that are mined or drilled from the Earth, then burned with many environmental consequences; there is a growing need for cleaner sources of energy. After describing this problem, give students a miniature toy solar car, a Matchbox car, and a shop light (Figure 2; see "On the web" for sources for materials and parts). Explain that energy from the light transforms into motion for the solar car. Share images of solar transportation—of say, the *Solar Impulse* or the *Türanor* (see sidebar, p. 29)—or let students browse the internet for images, videos, and news stories related to solar transportation. Plan on one class period for the pretest on energy and motion (included in the complete curriculum; see "On the web"); learning about solar trains, planes, boats, and automobiles; and the investigation with the toy solar and Matchbox cars described above.

FIGURE 1

Testing a solar car.

ALL PHOTOGRAPHS BY CHRISTINE SCHNITTKA

FIGURE 2

Toy car and miniature solar car.

Testing the components

Next, students will prepare to design their own solar vehicles by devoting a few class periods to testing the various design components: the solar cells, motors, gears, and wheels.

Solar cells

Distribute the solar panels for students to examine. Ideally, one panel should be rated for high voltage and low current (5.0 V and 100 mA) and another for low voltage and high current (1.0 V and 415 mA). Have students compare them by measuring surface area, counting the number of cells within the panels, and observing the wires beneath the plastic surface. Challenge them to use a light source and multimeters to determine how much energy the solar cells produce (Figure 3). (See "On the web" for a video on how to use a multimeter.) Have students use the multimeters' direct current (DC) settings to measure voltage and current. Many will be familiar with the former but not the latter. Both are important for understanding how much energy a solar cell can produce. Have students test the solar cells in series and in parallel to see which configuration produces more power over time. The overhead

FIGURE 3

Testing a solar cell that produces .528 volts.

FIGURE 4

Data collected from solar cells.

Solar cell	Voltage (volts)	Current (amperes)	Energy per second (joules/second)	Power (watts)
A				
B				
A+B in series				
A+B in parallel				

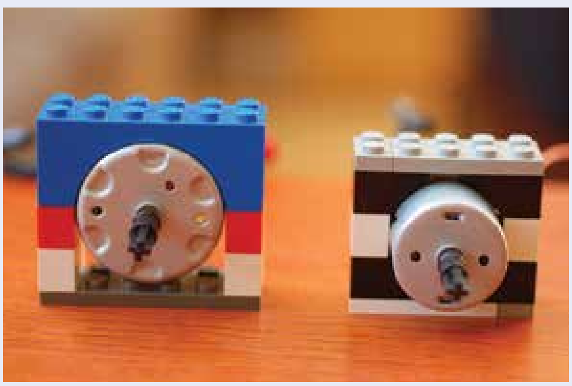
light in the classroom might be sufficient as a power source, but we find it better to conduct this activity outside in the sunshine or with shop lights in the classroom. (**Safety note:** When using shop lights, 150-watt incandescent bulbs are ideal but get very hot. Mount the shop lights so that students do not have to touch them and remind students to keep all hands and solar panels at least 50 cm away.) After testing, students might create a data chart similar to the one in Figure 4.

Electric motors

Distribute inexpensive electric motors typically used for hobbies and robotics. Ideally, one should be rated for high speed and low torque and another for lower speed and higher torque. We mount ours in Lego pieces glued together to make them easier to use (Figure 5) and mount special Lego-type pieces on the shafts as well (Figure 6). These are made especially for the 2 mm- or 3 mm-diameter motor shafts that we purchase from Pololu (see “On the web”).

FIGURE 5

Two different motors in Lego motor mounts.



Torque can be defined as a twisting force. A higher-torque motor can move a heavier load than one with lower torque. When students connect a motor to a solar cell under light, they can compare how much twisting force each motor produces.

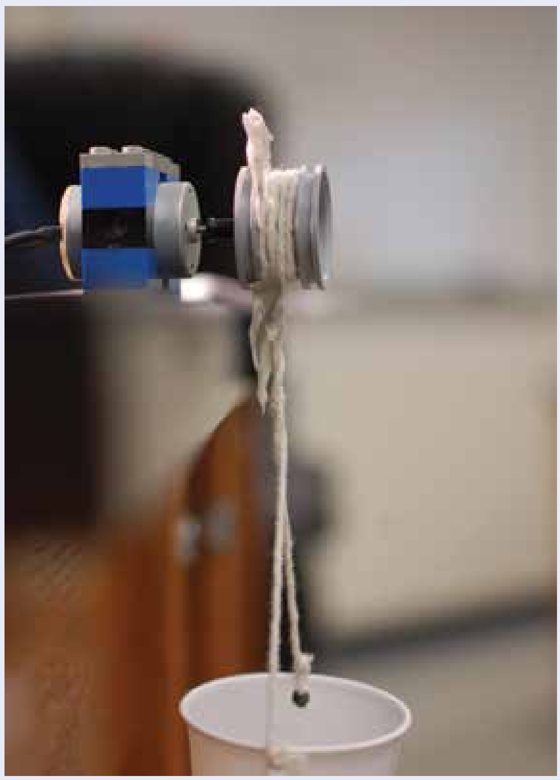
Our students compare motors by seeing how much weight each can lift in a bucket on a string. To do this, place the motor on the edge of a tabletop and attach a Lego wheel to the connector on the motor shaft so it can wind up a string (Figure 6). Secure the string to the wheel with a small piece of tape. Attach a cup to the string so the motor can lift different amounts of weight until students find a load it cannot lift. There should be a marked difference between the output force, or torque, of the two motors, and deciding between them is an important design decision.

Gears

Next, ask students if they can think of a way to enable the motors to pull more weight. If we need solar-powered vehicles that can carry cantaloupes across the country, for

FIGURE 6

Measuring torque: Motor with spool on its shaft lifting a load.



example, then we need electric motors that can exert a lot of torque. Here, someone is bound to suggest gears, which are great for multiplying the output force of a motor (Figure 7).

To test the gears, have students put a small one on the motor shaft and mesh it with a large one on a shaft that will lift a bucket. We use Lego parts and pieces for this, but if you have other parts available, you can make just about anything work. Have students test this configuration and then switch the gears so that the large gear is on the motor shaft and the small one is twisting up the bucket. Which one can lift more weight? Students will find that when speed is sacrificed, force is increased. Both configurations will do the same amount of work, but when the smaller gear is on the motor, the larger gear turns more slowly. Since work = force × distance, and the output distance is decreased, the output force is increased. Students can compute the gear ratio and compare it to the resulting increase in force. We use the GearSketch website to model gear pairs (see "On the web").

Wheels

Students might not think that wheels matter, but they do. Friction is the force that is required between the wheel and the ground for motion to happen; it's the force required between your foot and the ground for you to walk! Different wheel surfaces will produce higher or lower friction forces. Think about a car with wax paper wheels or one driving on an icy road—the car will spin out and not pull much force behind it. Demonstrate this with spring pull-back cars, which can be found at your local toy store (Figure 8). Cover the wheels in different materials, such as sandpaper or wax paper, and show students the effect friction has on motion.

Then, pass out a variety of wheels for testing. Students can use any method to test the wheels' friction, but we find it easiest to connect two wheels to a shaft so that they do not spin, and to hang a string with a cup to see how much weight it takes to overcome static friction and slide the wheels (Figure 9). Discuss how vehicle tires need friction.

FIGURE 7

Multiplying force: Motor with small gear meshed with large gear.

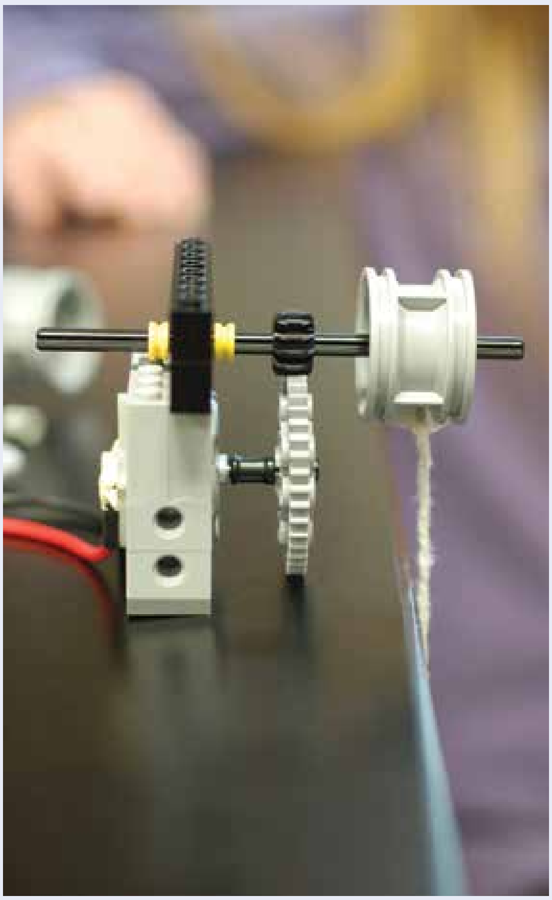


FIGURE 8

Comparing friction: Pull-back cars with different tire surfaces.

FIGURE 9

Testing static friction of wheels.

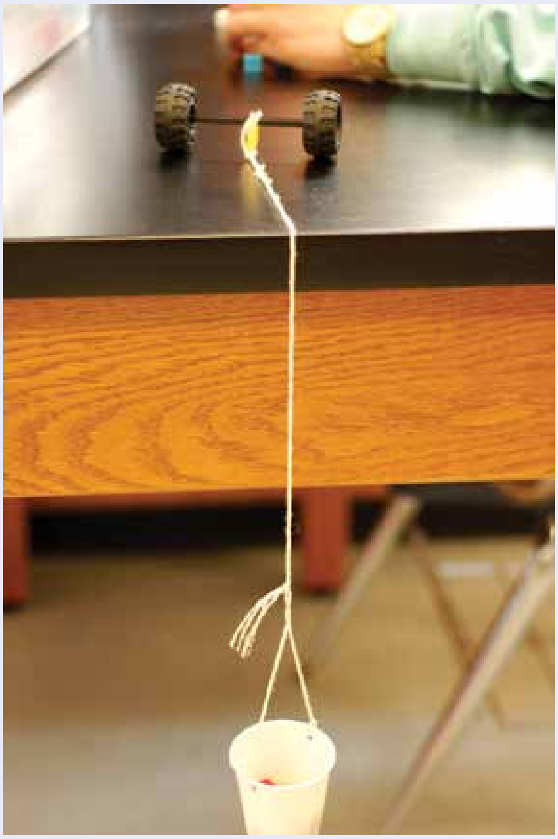
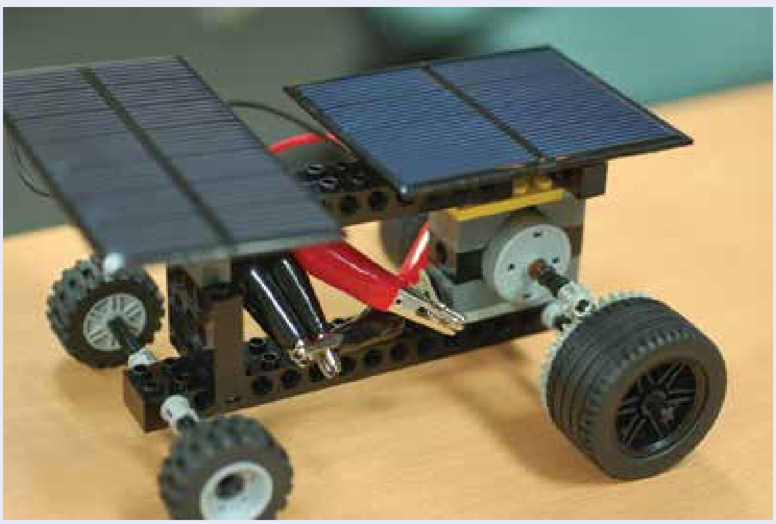


FIGURE 10

A working solar vehicle.



Solar power in transit.

Solar cars, trains, buses, and even airplanes move people and things around the world. In Belgium, for example, 16,000 solar panels form the roof of a train tunnel, helping supply power for that country's train network (Ridden 2011). A comfortable, air-conditioned bus called *Tindo* transports people in the city of Adelaide, South Australia, using only solar energy. The *Solar Impulse* flies across the United States without using a single drop of gasoline and is currently attempting an unprecedented around-the-world flight (see "On the web"). The solar-powered boat, *Türanor*, has circumnavigated the globe. And a solar-powered ferry moves commuters across the Sydney Harbor in Australia. Each of these efforts reduces the world's dependence on fossil fuels for transportation and makes a great example for classroom use.

Truck drivers going up mountains, for example, do better with friction than without (e.g., think of snow and ice and the role of sand on a slippery road, or the role of chains or studs attached to winter tires).

The design challenge

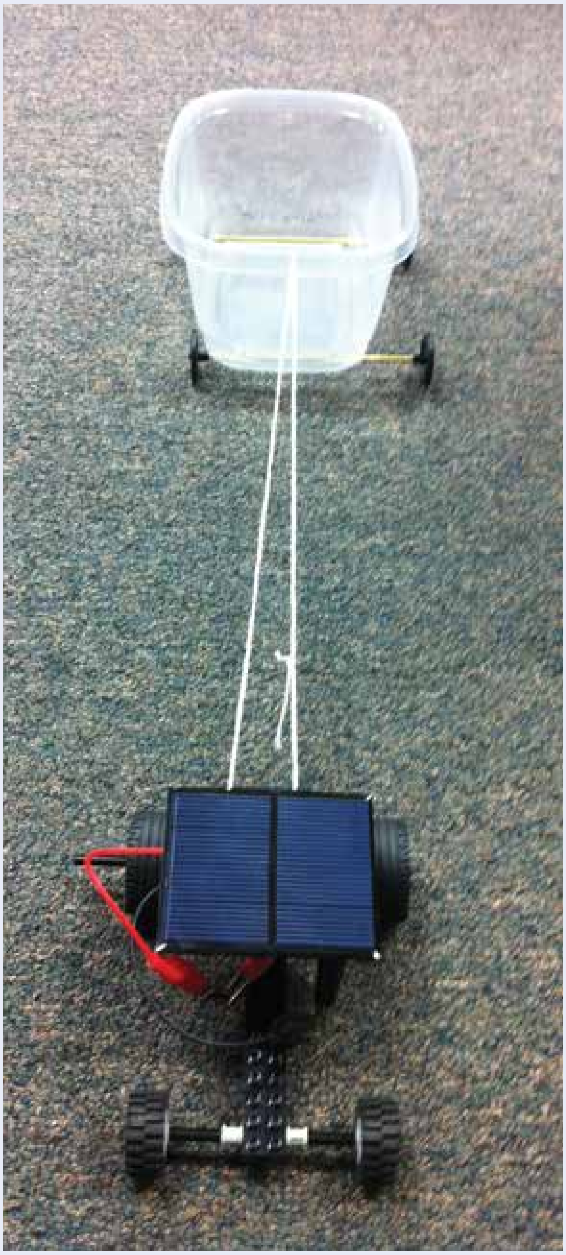
Once your students have interpreted and analyzed data—another important component of the engineering-design process—it's time to put all the pieces together for the next step: model development and use. Encourage students to apply their knowledge of energy, force, and friction to their designs. You can conduct this segment outdoors on a sunny day or indoors with shop lights simulating the Sun. Most students need one or two class periods to design, build, and test their vehicles. Once students have a vehicle that reliably moves (Figure 10), it can be used to start pulling loads. To simulate mass transportation, placing the load in a plastic food storage container with wheels works well (Figure 11, p. 30).

Testing the design

Connect the vehicles to the cart and load it with weights, such as rocks, brass weights, or plastic eggs filled with plaster. When all groups have tested their designs, have them share their design decisions with the class and let everyone go back to the drawing board. The goal is for every group to find a successful solution, which usually means not building a fast car but the one that can pull an adequate load. Depending on your solar cells, motors, and other parts, you can determine a target load weight and encourage each group to meet it. A vehicle made with the parts we typically use can pull up to 1 kg.

FIGURE 11

A solar vehicle pulling an unloaded plastic food container.



Assessment

Assessment of this activity can happen in many different ways. You can administer the pre- and posttest included in the full curriculum (see "On the web"), which assesses understanding of energy transformations, gears, voltage and current, torque, and friction (Schnittka 2009), but you can also have each group create a storyboard on a piece of poster board. Each square of the storyboard tells a part of the story as in a comic strip (Figure 12).

Students can draw their ideas, explain their design decisions, and record their results. Each time students work on the project, have them get out their storyboards. These can serve as a way for you to glance at ideas while walking around a busy room, and you can use the story squares as prompts for informal discussion. Students can use the boards to help explain their reasoning to the class during show and tell "pin-up" sessions. The design challenge itself is a form of authentic performance assessment.

Conclusion

Engineering design is an effective conduit to learning when the science is explicitly taught (Schnittka and Bell 2011; Schnittka et al. 2012). Competitions can actually discourage more students than they encourage, so making the design challenge a cooperative project in which everyone is capable of succeeding helps more students develop an affinity for science and engineering. Engineering comes naturally to youth, who often possess a passionate desire to remake the world around them. Try teaching science through the lens of engineering design and problem solving and watch how it can enrich your classroom. ■

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Acknowledgments

This curriculum was developed in part with the support of the National Science Foundation, grant #1247287. A link to the entire curriculum (in PDF or e-book format) can be found in the "On the web" section and is available at no cost to teachers.

Resources

Home improvement stores sell clamp lamps, multimeters, plaster, string, and other basic parts. We get motors and solar cells for the solar cars from companies such as Pololu; we ordered the mini solar cars from a different source (see "On the web"), Edmund Scientific, and Radio Shack. We purchase Legos directly from Lego's Pick-a-Brick feature online or from BrickLink (see "On the web"). If Lego parts are not affordable, the vehicle can even be built with scavenged wheels and axles.

FIGURE 12

Sample storyboard.

On the web

BrickLink: *www.bricklink.com*
Complete curriculum: *http://bit.ly/1OHkSYS*
GearSketch: *www.gearsket.ch*
Mini solar car source: *http://bit.ly/1RmfZDp*
Multimeter video: *http://bit.ly/1RDfRl6*
Pololu: *www.pololu.com*
Solar cells: *www.futurlec.com/Solar_Cell.shtml.* See parts SZGD6060-PET and SZGD10040-10
Solar Impulse: *http://bit.ly/1QNWvd0*

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Connecting to the *Next Generation Science Standards* (NGSS Lead States 2013).

Standards
HS-PS3 Energy
HS-ETS1 Engineering Design

Performance Expectations
The chart below makes one set of connections between the instruction outlined in this article and the *NGSS.* Other valid connections are likely; however, space restrictions prevent us from listing all possibilities. The materials/lessons/activities outlined in this article are just one step toward reaching the performance expectations listed below.

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.

HS-ETS1-2: Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

Dimension	Name and *NGSS* code/citation	Specific Connections to Classroom Activity
Science and Engineering Practice	**Developing and Using Models** • Develop and use a model based on evidence to illustrate the relationships between systems or between components of a system. (HS-PS3-3, HS-ETS1-2)	Students model the transfer and transformation of energy by designing and testing a solar-powered vehicle.
Disciplinary Core Idea	**PS3.A: Definitions of Energy** • At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, sound, light, and thermal energy. (HS-PS3-3)	Student groups discuss and analyze the voltage and current generated by solar cells under different lighting conditions. Student groups discuss and analyze how gears are used to transfer energy and modify speed and torque.
Crosscutting Concepts	**Systems and System Models** • When investigating or describing a system, the boundaries and initial conditions of the system need to be defined and their inputs and outputs analyzed and described using models. **Energy and Matter** • Changes of energy and matter in a system can be described in terms of energy and matter flows into, out of, and within that system. (HS-PS3-3)	Student groups modify their designs based on performance of the solar vehicle. They may change inputs in the form of solar cells or combinations of solar cells, or they may change the choice of gears or motors or tires to achieve the desired output. Students will use the engineering design process to design and modify technological systems that are key to modern energy transformations in our world.