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Uncovering STUDENT IDEAS About ENGINEERING and TECHNOLOGY

32 NEW Formative Assessment Probes

PAGE KEELEY
CARY SNEIDER
MIHIR RAVEL

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Foreword

Classroom formative assessment is the most powerful form of assessment that teachers have at their disposal to elicit and analyze evidence of student thinking and, consequently, to use this evidence to adjust learning strategies accordingly. When used properly, formative assessment provides the teacher with a constant source of information that can be used during the course of and at the point of instruction. Similar to a GPS device, formative assessment is a means to keep the learner "on the path" by using student feedback as information to guide and adjust instruction. The probes detailed within *Uncovering Student Ideas About Engineering and Technology: 32 New Formative Assessment Probes* provide opportunities for students to engage in self-assessment and feedback from their peers in the areas of engineering and technology.

This book is especially timely, since 43 states and the District of Columbia have now adopted or adapted science standards based on either the *Next Generation Science Standards* (*NGSS*; NGSS Lead States 2013) or *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (the *Framework*; NRC 2012). These new state standards, which provide guidance for the development of curriculum, instruction, and assessment, call for *all students,* "over multiple years of school, [to] actively engage in scientific and engineering practices and apply crosscutting concepts to deepen their understanding of the core ideas," both in the traditional disciplines of science and in the field of engineering (NRC 2012, p. 10).

Uncovering Student Ideas About Engineering and Technology supports the vision of the *NGSS* and the *Framework* by providing educators with a variety of research-based formative assessment probes to uncover their students' prior knowledge and misconceptions in the areas of engineering and technology. This book not only offers tools for teachers to use to uncover their students' thinking, but also provides a foundation to support the importance of engineering and technology in the development of student problem-solving skills and innovative application of science concepts.

The authors of this book represent a "perfect storm" of expertise. Page Keeley is a prolific writer and researcher in the area of science formative assessment. Cary Sneider was a member of the *Framework* and *NGSS* writing teams and has worked extensively with teachers nationwide to bring engineering and design into the classroom. As a distinguished engineer, technologist, and university educator, Mihir Ravel affords his expertise through the creation of authentic, problem-based scenarios and situations addressed through the probes. The product of the collaboration of these talented experts provides the readers of this book with a practitioner-friendly guide to infusing engineering and technology into classrooms through research-based formative assessment prompts and probes.

I am honored to be asked to write the foreword for this book. Supporting educators in the implementation of three-dimensional science and engineering standards is mission critical. Teachers are the key to the positive change we seek in preparing our students to become a STEM literate citizenry. Toward that end, *Understanding Student Ideas About Engineering and Technology* goes far in supporting educators through its teacher-centered approach to engaging students and soliciting evidence of learning within the domains of engineering and technology.

—Peter J. McLaren
Executive Director
Next Gen Education, LLC

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About the Authors

Page Keeley is the primary author of the *Uncovering Student Ideas in Science* series. Her assessment probes and FACTs (formative assessment classroom techniques) are widely used by K–12 teachers, university professors, and professional development and science specialists throughout the United States and internationally. Page is "retired" from the Maine Mathematics and Science Alliance (MMSA) where she had been the senior science program director since 1996, directing projects in the areas of instructional leadership, coaching and mentoring, linking standards and research, and science and literacy. She has been a principal investigator and project director of three National Science Foundation (NSF)–funded projects: The Northern New England Co-Mentoring Network (NNECN), Curriculum Topic Study (CTS), and Phenomena and Representations for Instruction of Science in Middle School (PRISMS). Today she works as an independent consultant, speaker, and author providing professional development to school districts and organizations in the areas of formative assessment, understanding student thinking, teaching science for conceptual understanding, and designing effective instruction.

Page is a prolific author of 22 national bestselling and award-winning books in science and mathematics education. Several of her books have received national distinguished awards in educational publishing. She has authored numerous journal articles and contributed to several book chapters. She also develops formative assessment probes for McGraw-Hill's middle and elementary school science programs.

Prior to joining MMSA in 1996, Page taught middle and high school science for 15 years. At that time she was an active teacher leader at the state and national levels, serving as president of the Maine Science Teachers Association and National Science Teaching Association (NSTA) District II Director. She received the Presidential Award for Excellence in Secondary Science Teaching in 1992, the Milken National Distinguished Educator Award in 1993, and the AT&T Maine Governor's Fellowship in 1994. Since leaving the classroom in 1996, her work in leadership and professional development has been nationally recognized. In 2008, she was elected the 63rd president of NSTA. In 2009, she received the National Staff Development Council's (now Learning Forward) Susan Loucks-Horsley Award for Leadership in Science and Mathematics Professional Development. In 2013, she received the Outstanding Leadership in Science Education award from the National Science Education Leadership Association (NSELA), and she received the NSTA Distinguished Service to Science Education Award in 2018. She has served as an adjunct instructor at the University of Maine, was a Cohort 1 Fellow in the National Academy for Science and Mathematics Education Leadership, was a science literacy leader for the AAAS/Project 2061 Professional Development Program, and has served on several national advisory boards.

She has led science/STEM education delegations to South Africa (2009), China (2010), India (2012), Cuba (2014), Iceland (2017), Panama (2018), and Costa Rica (2019).

Prior to entering the teaching profession, Page was a research assistant for immunogeneticist Dr. Leonard Shultz at the Jackson Laboratory of Mammalian Genetics in Bar Harbor, Maine. She received her BS in life sciences and pre-veterinary studies from the University of New Hampshire and her MEd in science education from the University of Maine. In her spare time she enjoys travel, reading, fiber art, and photography, and also dabbles in modernist cooking and culinary art. A Maine resident for almost 40 years, Page and her husband now divide their time between homes in Fort Myers, Florida, and Wickford, Rhode Island.

You can contact Page through her websites at *www.uncoveringstudentideas.org* and *www.curriculumtopicstudy2.org* or via e-mail at pagekeeley@gmail.com. You can follow her on Twitter at @CTSKeeley or on Facebook through her Uncovering Student Ideas in Science and Mathematics page.

Cary Sneider is a visiting scholar at Portland State University, and a consultant for the STEM Next Opportunity Fund and the Stephen D. Bechtel Jr. Foundation, both charitable foundations that support STEM education. He also continues to be active as a consulting author for Houghton Mifflin Harcourt's Science Dimensions K–8 series, and other writing and curriculum development projects.

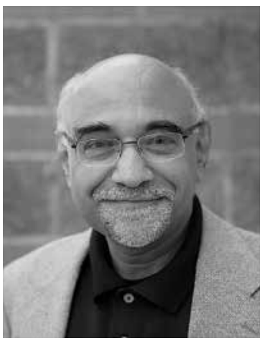
While studying astrophysics at Harvard College in the 1960s, Cary volunteered to teach in an Upward Bound program and discovered his real calling as a science teacher. After teaching middle and high school science in Maine, California, Costa Rica, and Micronesia, he settled for nearly three decades at Lawrence Hall of Science in Berkeley, California, where he developed skills in curriculum development and teacher education.

Starting in 1997, Cary spent 10 years as vice president for programs at the Museum of Science in Boston, where he led development of a high school engineering curriculum, Engineering the Future: Science, Technology, and the Design Process. In 2007, he moved to Portland, Oregon, to take a position as associate research professor at Portland State University, where for the next decade he taught courses in research methodology to more than 80 candidates in a Master of Science Teaching (MST) program. During this period, he led a team in revising science education standards for the state of Washington; served as a consultant to the National Research Council to help create *A Framework for K–12 Science Education: Practices, Core Ideas, and Crosscutting Concepts*; led the engineering team that helped craft the *Next Generation Science Standards: For States, by States*, which were released in 2013; and from 2011 to 2019 served as a member of the National Assessment Governing Board, which sets policy for the National Assessment of Educational Progress (NAEP), also known as The Nation's Report Card.

In 1997, Cary received the Distinguished Informal Science Education award from the National Science Teaching Association (NSTA). In 2003, he was named National Associate of the National Academy of Sciences, and in 2018 he received the Robert H. Carleton Award, NSTA's highest recognition.

Over his career, Cary has directed more than 20 federal, state, and foundation grant projects. He has coauthored two books on STEM education, edited the three-volume

Go-To Guide to Engineering Curricula; authored *Jake and the Quake*, a work of historical fiction for middle school students; and authored several book chapters and numerous articles. He earned a BA in astronomy at Harvard College, and a California Secondary Teaching Credential, MA, and PhD in science education at the University of California, Berkeley.



Mihir Ravel is a noted technology leader in high-performance electronic systems and ultrafast scientific measurements, and a pioneer in design-centric approaches to integrated STEM education.

After a fortunate corporate research and development (R&D) career, Mihir now divides his time between public service in K–12 engineering and science education and advising entrepreneurs and innovators focused on emerging opportunities for social good. He has traveled extensively in developed and developing countries as a speaker and strategic adviser to both public and private institutions. He has been an international advisor to various federal and state agencies on STEM and design education; has served on the advisory boards for EDN magazine, the Austin Technology Council, the Massachusetts Institute of Technology (MIT) Enterprise Forum, and The Indus Entrepreneurs (TiE); and is an adviser to various early stage private ventures and nonprofit educational initiatives and foundations.

Mihir has been an invited faculty collaborating on design-centric learning methods with leading universities in Europe, Asia, and the United States, with a special emphasis on exposing students to the power of engineering design and entrepreneurship for making a better world. A highlight of his university collaborations was helping incubate the Affordable Design and Entrepreneurship (ADE) program at Olin College of Engineering, which was recently recognized alongside MIT as one of the top two global leaders in engineering education. The ADE program is a transformational educational initiative aimed at the problems of global poverty, and immerses student teams in creating social ventures using an engineering design process as a critical tool for improving the daily lives of the world's poor.

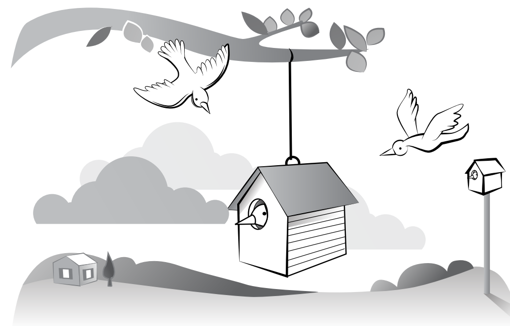
To build on his lessons learned in advancing university education, Mihir has recently been applying those experiences toward design-based approaches to K–12 STEM education. He has partnered with school districts, universities, and foundations in the Pacific Northwest to develop engineering and design–integrated STEM curricula at the high school level. He is a coauthor with Cary Sneider and others of the second edition of *Engineering the Future: Science, Technology, and the Design Process,* developed in collaboration with the Boston Museum of Science and Activate Learning, as an introduction to engineering design for *all* students, not just those interested in engineering careers. He is also an adviser to Houghton Mifflin Harcourt on K–12 science.

Complementing his university experience, Mihir's STEM education work builds on lessons learned from three decades of leading high-tech R&D organizations in a range of technologies spanning ultrafast electronics, optical and wireless communications, digital multimedia, environmental monitoring, and smart sensor networks. He has led research collaborations with leading university and government labs with support from the National Science Foundation, Department of Energy, and Department of Defense. He served as the first vice president of technology for National Instruments, a global pioneer in tools for

About the Authors

measurement, machine automation, and system design. Previously, he was a Technology Fellow and head of Strategic Technologies for Tektronix, a global leader in high performance instrumentation and electronic design. His perspective that STEM education should be a combination of both creative and structured thinking has been shaped by his early training in physics, electrical engineering, and computer science at MIT.

Who Needs It?



Simone recently graduated from college with an engineering degree. She has just been hired by a company to design its new line of birdhouses. She knows that every product has a *client*. The *client* is usually a person or group who has a problem or need that requires a solution. Identifying clients is an important step early in an engineering design process. She asks her friends to help her identify a client for the birdhouses.

Ling: The client is the person who hired you. Just ask your employer to tell you as much as they can about what they want the new birdhouses to be like.

Annapurna: I think the client is the person who is likely to buy a birdhouse. If you meet that person's needs, then your employer will be happy. Go to a garden shop where they sell birdhouses and ask the customers what they are looking for.

Deepali: We need to think of this from the user's point of view. Your client is clearly the bird that will be living in the birdhouse. Go visit some gardens and parks to see which birdhouses attract the most birds!

Melvin: I think all three of you identified a client for the birdhouse.

Katrina: I disagree with all of you. The client is someone else.

Who do you agree with the most? ___________________ Explain your thinking.

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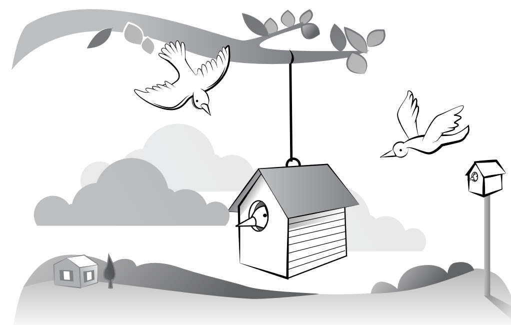
¿Quién lo Necesita?



Simone se graduó recientemente de la universidad con un título de ingeniería. Acaba de ser contratada por una empresa para diseñar su nueva línea de casas para pájaros. Ella sabe que cada producto tiene un *cliente*. El *cliente* es regularmente una persona o grupo que tiene un problema que requiere una solución. Identificar clientes es un paso inicial importante en un proceso de diseño de ingeniería. Ella le pide a sus amigos que la ayuden a identificar un cliente para las casas de pájaros.

Ling: El cliente es la persona que lo contrató. Solo pídale a su empleador que le diga todo lo que pueda sobre cómo quieren que sean las nuevas casas para pájaros.

Annapurna: Creo que el cliente es la persona que probablemente compre una casa para pájaros. Si satisface las necesidades de esa persona, su empleador estará muy contento. Vaya a una tienda donde venden pajareras y pregunte a los clientes qué están buscando.

Deepali: Tenemos que pensar en esto desde la vista del usuario. Su cliente es claramente el pájaro que vivirá en la casa para pájaros. ¡Visite algunos jardines y parques para ver qué pajareras atraen más aves!

Melvin: Creo que los tres identificaron un cliente para la casa para pájaros.

Katrina: No estoy de acuerdo con todos ustedes. El cliente es otra persona.

¿Con quién estás más de acuerdo? ___________________ Explica lo que piensas.

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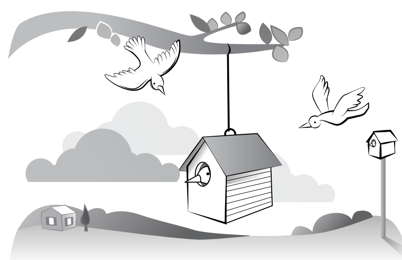
Who Needs It?

Teacher Notes



Purpose

The purpose of this assessment probe is to elicit students' ideas about who needs to be consulted when solving a problem (the client). The probe is designed to reveal the extent to which students recognize that the needs of a number of individuals (in this case an animal as well) have to be understood when defining a problem.

Type of Probe

Friendly talk

Related Key Idea

- Identifying a "client" helps engineers be clear about whose needs the solution must meet.

Explanation

The best answer is Melvin's: "I think all three of you identified a client for the birdhouse." As part of the process of defining a problem, engineers identify the *client*, which is the individual, company, organization, or other entity that has a need or a problem to be solved that uses the expertise of an engineer. It is important to be clear about whose needs will be met by the solution, and who else may be affected when the problem is solved. The birdhouse problem is especially interesting because, in addition to the person who first identified the need (the boss), and the person who will make a decision about whether or not to purchase it (the customer), there is a third client whose needs must also be taken into account (the bird). In engineering, the bird's position is sometimes referred to as "the end user." Melvin is correct that defining this problem will involve learning about the needs of all three "clients."

Administering the Probe

This probe is best used with students in grades 3–12. Be sure students first understand what is meant by the "client" in an engineering situation, and how its meaning differs from the word *customer.* For older students, in addition to *client,* discuss terms like *customer, buyer,* and *end user*—these can all be different people. Have them think about a situation in which their parents are the *buyers* but they are the *users.*

Connections to the Three Dimensions (NRC 2012; NGSS Lead States 2013)

- DCI: ETS1.A. Defining and Delimiting Engineering Problems
- DCI: ETS2.B. Influence of Science, Technology, and Engineering on Society and the Natural World
- SEP: Asking Questions and Defining Problems

Related Research

- Several researchers have investigated the value of using fictional characters in literature to spark discussion about engineering design. Portsmore, Watkins, and McCormick (2012) and Watkins, Spencer, and Hammer (2014) reported on a study of 24 fourth-grade students who identified problems the main characters faced in a fictional story. Pairs of students selected a problem to work on and designed solutions to help the characters by engaging in several types of planning and drawing activities.
- A similar teaching method is described by McCormick and Hammer (2016), who reported on a case study of two students during a fourth-grade engineering activity in which students framed problems based on fictional stories that provided "clients." The outcomes were encouraging but mixed, in part owing to variations in how students framed the task. While in some cases students focused on clients' needs, in other cases they focused on what they thought the teacher wanted.

Suggestions for Instruction and Assessment

- Help students gain insight into the distinction between cases in which the buyer of a technology is different from the end user. For example, ask them to think about situations in which parents are the buyers and the children are the users, or where someone is buying a gift for a friend who will be the end user. How should a person who is designing the technology decide on the qualities of a good solution? What if they please the buyer but not the end user? Or the end user but not the buyer?
- Identify an object that many of your students use every day, such as a backpack, a smartphone, or a common article of clothing. Ask the students who they thought the object was originally designed for, what the users might have said if a design engineer had asked them how they would use the object, and what characteristics they thought it should have and should not have.
- Ask students to imagine they have been hired by a school supplies company and asked to redesign an everyday object typically used in school, such as a cafeteria tray or locker. Who would they talk to in order to find out how the task should be defined? What questions should they ask the person?
- Is the best design always a good choice? What if the best design costs more money than the competition? How might an employer decide if the design that one of its engineers came up with will actually make money for the company?

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INTEGRATING STEM TEACHING AND LEARNING INTO THE K–2 CLASSROOM

Jo Anne Vasquez, Michael Comer,
and Jen Gutierrez

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FOREWORD

Integrating STEM Teaching and Learning Into the K–2 Classroom is a critically important contribution toward advancing STEM (science, technology, engineering, and mathematics) education for two overarching reasons: (1) It blazes a trail for early elementary classroom practitioners to reflect the latest thinking in STEM, and (2) it provides a means by which early elementary educators can meaningfully contribute to America's STEM movement.

The course for STEM education across the United States has been mapped in the report *Charting a Course for Success: America's Strategy for STEM Education*, released by the White House Office of Science and Technology Policy in December 2018. Readers and users of *Integrating STEM Teaching and Learning* by Jo Anne Vasquez, Michael Comer, and Jen Gutierrez can be confident of a close alignment between the broad consensus of the STEM education community as reflected in *Charting a Course* and the research-based insights and practical examples provided throughout this book. Common threads woven through both publications are the integration of STEM concepts and principles, the application of classroom experiences to students' lives, a priority on equal access to high-quality STEM education for all learners, the development of interpersonal skills including communication and perseverance, assessment to continuously improve outcomes, and other hallmarks of STEM education.

Today, STEM education has essentially eclipsed its own acronym to be an educational sea change from disciplinary silos toward solving transdisciplinary big questions and problems that converge multiple disciplines, making the enterprise far more interesting to learners. And it starts early, as Vasquez, Comer, and Gutierrez observe—"there is strong evidence that STEM learning can and does begin in early childhood classrooms" (p. 7). Thus, *Integrating STEM Teaching and Learning Into the K–2 Classroom* provides a superb roadmap.

–Jeff Weld
Executive director, Iowa Governor's STEM Advisory Council;
former senior policy advisor on STEM education,
White House Office of Science and Technology Policy

ABOUT THE AUTHORS

Jo Anne Vasquez is a recognized leader in science education. She is a past president of the National Science Teaching Association (NSTA) and the National Science Education Leadership Association and was a Presidential Appointee to the National Science Board, the governing board of the National Science Foundation, becoming the first and only K–12 educator to hold a seat on this prestigious board. She is currently the senior STEM (science, technology, engineering, and mathematics) consultant for Arizona State University's Office of Knowledge Enterprise Development.

Jo Anne's service and contributions to the advancement of science and STEM education at the local, state, and national levels have won her numerous awards: the 2014 National Science Education Leadership Award for Outstanding Leadership in Science Education, the 2013 National Science Board Public Service Award, and the 2006 Robert H. Carlton Award for Leadership in Science Education. She also received the Distinguished Service to Science Education Award, the Search for Excellence in Elementary Science Education and Supervision Award, and the New York Academy of Science's Willard Jacobson Award for major contributions to the field of science and STEM education. In addition, she was the 2004 National Association of Latino Elected and Appointed Officials honoree for her contributions to improving education.

Jo Anne has been involved with curriculum development for McGraw-Hill K–6 science, and she has facilitated STEM education professional learning sessions throughout the United States and in Thailand, China, Singapore, and the Philippines. A graduate of Northern Arizona University, she holds a bachelor of science degree in biology, a master's degree in early childhood education, and a PhD in curriculum and instruction.

Michael Comer began his educational career teaching middle school science in Dobbs Ferry, New York, and Riverside, Rhode Island, before joining the publisher Silver Burdett and Ginn (SBG) as the regional science/mathematics consultant. At SBG, he developed an expertise for providing rich and meaningful workshops that linked the facets of inquiry teaching with hands-on learning using manipulatives. He was an instructor at the Summer Science Seminar at Bridgewater State College in Bridgewater, Massachusetts, for more than 10 years, where he worked with teachers across the K–12 spectrum.

After the merger of SBG with Pearson in 1999, Michael was promoted to science curriculum specialist for STEM products, where he played a vital role in the development of new educational materials to meet changing market demands. In 2004, he joined Macmillan/McGraw-Hill as the national product manager for science and led the product development team in the creation of a brand-new science series, *Science: A Closer Look*, which quickly became a national bestseller. Michael transitioned from marketing to the editorial side of product development in 2013, when he became the editorial director for science and mathematics at Victory Productions in Worcester, Massachusetts, where he directed a team in content development and *Next Generation Science Standards* (*NGSS*) assessment item writing for major assessment providers and educational service organizations.

Michael, who has a BA in biology from American International College, has led many educational workshops on a range of topics in science and mathematics, helping educators embrace the new standards and infuse more hands-on, problem-based learning experiences into their classroom practices. Internationally, he has provided science professional development to teachers in Puerto Rico, St. Maarten, Bahrain, and the Kingdom of Saudi Arabia. His most recent work was to help produce a two-year professional development series for master science teachers in Thailand for the Institute for the Promotion of Science and Technology.

Jen Gutierrez began her educational career in Arizona in 1988, teaching first through fourth grades as well as K–2 multi-age classes. In 2006 she moved into the role of science curriculum specialist at the district level, and in 2014 she joined the Arizona Department of Education in the K–12 Standards Division as the K–12 STEM education specialist. Today she works as a STEM education consultant developing and delivering professional learning opportunities to support educators. She is a proud member of the *NGSS* writing team, including the Diversity & Equity team. She currently serves on the NSTA Board as division director of professional learning.

Jen is interested in three-dimensional teaching and learning, diversity and equity, and science and literacy, which are additional areas that she focuses on in her professional learning work. She did the keynote presentation, "Introduction to the *NGSS*," at the Shanghai International Forum on Science Literacy for Adolescents.

A graduate of Northern Arizona University, Jen holds a bachelor of science degree in journalism, a post-degree certification in elementary education, and an educational leadership–principal certification. She also has a master's degree in elementary education from Arizona State University.

CHAPTER 6

Developing a STEM Unit With Math as the Driver—Straw Bridges

A square was sitting quietly
Outside his rectangular shack
When a triangle came down—Keerplunk!
"I must go to the hospital,"
Cried the wounded square,
So a passing rolling circle
Picked him up and took him there.

—Shel Silverstein, *A Light in the Attic* (1981)

Bridges, forces, compression, and tension—oh, my! Can this vocabulary be for kindergarten students? You bet! Come along as the "Straw Bridges" STEM (science, technology, engineering, and mathematics) unit unfolds based on the mathematical standards for the geometry concepts of identifying, describing, analyzing, comparing, creating, and composing shapes. Oh, yes. Squares, rectangles, circles, trapezoids, hexagons, cubes, cones, cylinders, and spheres are all found in the kindergarten mathematics standards. Two very creative teachers from Broadmor Elementary School in Tempe, Arizona—kindergarten teacher Lori Schmidt and fifth-grade partnering teacher Joshua (Josh) Porter—have developed and cotaught the following Straw Bridges STEM unit. The fifth-grade students become "learning buddies" to the kindergarteners and help them with their engineering projects.

At the beginning of any new curriculum planning adventure there is always brainstorming and reflection, and as you will read, this was not a canned STEM unit. Yes, Lori and Josh both had ideas about straw-building activities they had studied, but they took those ideas and developed their own integrated straw bridge STEM unit. Was it perfect the first time through? No, of course not. But like all great teachers, they monitored and adjusted their teaching to fit the students' needs. They also took notes about how to change or enhance the lessons to improve them for subsequent years.

Overview of the Straw Bridges STEM Unit

In Lori and Josh's words

We start the unit planning with a big idea or engineering task. We look at what we want students to have as an end product. In this unit, we started with the kindergarten math standards as the "driver." From there we identified the engineering properties as our "copilot," the technology needed to complete the project. We then decided that the science concepts, while necessary to understand the forces at work, would not be the focal point of the learning and therefore were the "back-seat passengers."

The big idea was to design and build a bridge using students' understandings of various shapes. This was the end product. But the necessary steps to complete the bridge design included allowing the students to tinker with their own ideas for design. Each successive lesson reinforced a concept necessary to build an effective bridge. Each lesson ended with examples of successes and failures in the design phase with reflections to help guide decisions for the next steps in the process.

Once the students have their own ideas for design, we introduce vocabulary as we go. Vocabulary is taught with kinesthetic movements so our English language learners and nonreaders can still demonstrate understanding.

DEVELOPING THE STRAW BRIDGE STEM UNIT

Lori and Josh had already decided on their unit's big idea, which was to have the students design and build a bridge using shapes that included circles, triangles, squares, rectangles, rhombuses, trapezoids, hexagons, cubes, cones, cylinders, and spheres. To get to this transdisciplinary task, they began with the first step in the W.H.E.R.E. planning template, which is to decide on the *what* (see Figure 6.1). What standards will be addressed? What content standards and big ideas will the students need to know and be able to do? What are the desired learning goals for this instruction?

Figure 6.1. The *W* section of the W.H.E.R.E. model

W	**What** are the desired results, including the big ideas, content standards, knowledge, and skills? • List the content standards and what the students will know and be able to do.	**Why** would the students care about this knowledge and these skills? • Craft the driving question that will lead to the development of the integrated tasks that provide for the application of the content, knowledge, and skills. • List the essential questions that can be answered as a result of the learning.

Having selected the *what* items in the first step, Lori and Josh began to think about the second part of the *W* guidepost—the *why*. Why would a student care about learning these concepts and skills? This can be hard to articulate beyond the response "Because it's in the standards." Being able to describe the *why* can help more clearly define the learning outcome. The *why* sets the direction of the instruction and helps craft the driving question that ties together the development of the integrated tasks to provide for the application of the content and skills. Without having a *why*, the learning can become directionless, getting mired in activities without having any real purpose or focus for the student. And while these activities may be fun and engaging experiences for children, they do not aid them in developing an understanding of the core ideas listed in the *what*.

In this example unit, the partnering teachers are from different grades. One of the overall goals is for the fifth graders to help the younger students with their constructions and learn how to cooperate with others. For the younger students, working with the older students gives them more in-depth talking time, as they need to describe their ideas and construction plans to their learning buddies. Various research studies support the positive effects that the role of mentor-mentee has on learning. Findings across many subjects have identified learning as an active process that is highly social and is enhanced by the intentional support provided by more knowledgeable individuals, whether they are peers, mentors, teachers, or experts in the field.

For the Straw Bridges STEM unit, the main drivers in its development were the kindergarten geometry standards from the Arizona State Standards (shown in Figure 6.2, p. 50).

Figure 6.2. The geometry standards for the Straw Bridges STEM unit

Geometry		
K.G.A. Identify and describe shapes	K.G.A.1	Describe objects in the environment using names of shapes, and describe the relative positions of these objects using terms such as *above*, *below*, *in front of*, and *next to*.
	K.G.A.2	Correctly name shapes regardless of their orientation or overall size (circle, triangle, square, rectangle, rhombus, trapezoid, hexagon, cube, cone, cylinder, and sphere).
	K.G.A.3	Identify shapes as two-dimensional (lying in a plane, flat) or three-dimensional (solid).
K.G.B. Analyze, compare, create, and compose shapes	K.G.B.4	Analyze and compare two-dimensional and three-dimensional shapes, in different sizes and orientation, using informal language to describe their similarities, differences, parts (e.g., number of sides and vertices/corners), and other attributes (e.g., having sides of equal length).
	K.G.B.5	Model shapes in the world by building shapes from components (e.g., use sticks and clay balls) and drawing shapes.
	K.G.B.6	Use simple shapes to form composite shapes. For example, "Can you join these two triangles with full sides touching to make a rectangle?"

Source: Arizona Department of Education (2016).

In their description of the planning for this unit, Lori and Josh mentioned using the math standards as the "driver." What did they mean? For every STEM unit there may be one discipline—or at the most two disciplines—driving the content standards that are the focus of instruction. In an integrated unit, the central focus for the learning cannot be all the standards covered. Too many different standards being introduced at one time can only serve to create confusion for the learners and interrupt their ability to concentrate on the acquisition of new knowledge and skills. As described in research cited in *STEM Integration in K–12 Education*,

> *Split attention—simultaneously dividing one's attention between competing sources of information—is cognitively demanding and can be a major obstacle to understanding and learning. The split-attention effect is evidenced by difficulties in storing and processing information that is physically separated.* (NRC 2014, p. 84)

Supporting standards can be woven into the learning experiences to provide opportunities for reinforcement and for extended practice of previously learned concepts. To help with this, we use the analogy of a car, first described in Chapter 5. In a four-passenger automobile, there is only one driver—the set of core standards that the instruction will focus on delivering. These cover the primary objectives for the unit and drive the learning forward. In your car, the front-seat passenger represents those standards that may be closely aligned to the driver and are helpful in navigating the instructional route. The front-seat passenger acts as the copilot to the core standards and influences the learning path necessary for greater student understanding. This can help provide context for the learning or make the experiences more rigorous and meaningful.

There may be passengers in the back seat—these are the tangential learning standards that could be tied to individual activities or the culminating product of the unit. For example, in the straw bridge unit, students may use a science text or leveled science readers for content acquisition, which can reflect English language arts (ELA) standards for analyzing informational text. The students will be practicing those ELA skills, but the primary instruction in the unit is not focused on the teaching of reading informational text. Or, students might connect their bridge project to issues that affect their community (whether it is the classroom, the school, or the broader neighborhood), which can tie to social studies standards, but the understanding of "communities" is not the focal point of the learning in the project. These are just tangential standards that help deepen the integrated learning experience beyond the STEM topics. These standards can be opportunities to reinforce previously taught concepts or a way to introduce an idea that will be explored at a future time.

The geometry standards are the driver or primary focus of instruction for the straw bridge unit. But as we all know, it is difficult to separate and focus on only a few standards. Therefore, the beauty of this unit is that it incorporates other standards from both science and ELA. Once you identify the main content driver that you want to stress and really focus the learning around, there also will be other supporting standards (passengers) to consider. This is part of your decision-making process as you begin to think about your STEM unit scenario and start to develop the W.H.E.R.E. template. Integrated STEM units are just that: integrated with more than one standard to help reach the answer to the unit's driving question and to facilitate the completion of the transdisciplinary task.

BRAINSTORMING THE STRAW BRIDGE STEM UNIT

Lori and Josh also realized that they could incorporate standard K-PS2-1, Motion and Stability: Forces and Interactions (see Figure 6.3, p. 52), from the *Next Generation Science Standards* (*NGSS*; NGSS Lead States 2013). This standard was comprehensive enough for them to develop their ideas of having the students begin to understand pushes and pulls as they examined different shapes found in bridges. The students were introduced to local bridge builders who used sophisticated terms such as *compression*, *tension*, *structure*, *support*, and *trusses* in describing the images they shared of how they build bridges. Students' use of this vocabulary evolved naturally as they tried to articulate their understandings of why some shapes were more successful than others. All of this

Figure 6.3. *NGSS* performance expectation for K-PS2-1

<table>
<tr><th colspan="3">K-PS2-1 Motion and Stability: Forces and Interactions</th></tr>
<tr><td colspan="3">Students who demonstrate understanding can:
K-PS2-1. Plan and conduct an investigation to compare the effects of different strengths or different directions of pushes and pulls on the motion of an object.
[Clarification Statement: Examples of pushes or pulls could include a string attached to an object being pulled, a person pushing an object, a person stopping a rolling ball, and two objects colliding and pushing on each other.]
[Assessment Boundary: Assessment is limited to different relative strengths or different directions, but not both at the same time. Assessment does not include non-contact pushes or pulls such as those produced by magnets.]</td></tr>
<tr><td colspan="3">The performance expectation above was developed using the following elements from A Framework for K–12 Science Education (NRC 2012):</td></tr>
<tr><th>SCIENCE AND ENGINEERING PRACTICES</th><th>DISCIPLINARY CORE IDEAS</th><th>CROSSCUTTING CONCEPTS</th></tr>
<tr><td>Planning and Carrying Out Investigations
Planning and carrying out investigations to answer questions or test solutions to problems in K–2 builds on prior experiences and progresses to simple investigations, based on fair tests, which provide data to support explanations or design solutions.
• With guidance, plan and conduct an investigation in collaboration with peers.
- -
Connections to the Nature of Science

Scientific Investigations Use a Variety of Methods
• Scientists use different ways to study the world.</td><td>PS2.A: Forces and Motion
• Pushes and pulls can have different strengths and directions.
• Pushing or pulling on an object can change the speed or direction of its motion and can start or stop it.
PS2.B: Types of Interactions
• When objects touch or collide, they push on one another and can change motion.
PS3.C: Relationship Between Energy and Forces
• A bigger push or pull makes things speed up or slow down more quickly. (secondary)</td><td>Cause and Effect
• Simple tests can be designed to gather evidence to support or refute student ideas about causes.</td></tr>
</table>

Source: NGSS Lead States (2013).

led up to the development of their transdisciplinary engineering design task, which was to have the student groups build a bridge that could hold at least five or more books without collapsing.

In the primary grades, we find it difficult to separate and focus on only one of the engineering design standards. It is not that the individual learning objectives of the standards cannot be isolated, but it is difficult to cut short the learning experience when student excitement is at a peak. What fun is it to talk about a problem or generate a solution without the opportunity to try building it? How do you foster persistence, experimentation, and self-reflection if you don't allow time for solution improvements? For these reasons, in this primary-grade unit the supporting content includes all of the engineering design standards (ETS) in addition to the science. There are of course other content standards, but in this unit, the understandings about geometric shapes will be held at the forefront of the planning and will act as the driver. The engineering design standards will play the role of the front-seat passenger.

Math is the main driver for this STEM unit, but as you can see, the engineering design standards and science are essential secondary or supporting standards (Figure 6.3). These are the passengers in the STEM car. As Lori and Josh were designing this STEM unit, part of their decision-making process was to think about the unit holistically, and looking at the standards that needed to be taught and those that could be used to reinforce previously covered standards helped with the development. As the overall idea for the STEM unit takes shape, it then becomes a process of thinking about what interesting or relevant scenario can be crafted, which will lead to the development of the driving question. In this case, the students were learning about different types of bridges, they were using their straws to construct different geometric shapes, they were learning a rich variety of core ideas and new vocabulary words, and they were building comfort in collaborating and communicating with each other (see Figure 6.4 and Figure 6.5, p. 54).

Figure 6.4. Students creating their shape pieces prior to bridge construction

Figure 6.5. Students beginning construction of the straw bridge

Having decided upon the *what* and the *why*, it was now time to put it all together with an engaging scenario that would draw from the essential questions and bring together all the content for the students. This scenario or storyline helps the students become active participants in the learning, while the driving question communicates the purpose for learning by providing a real-world context that the students can relate to. This scenario gives students the opportunity to apply their key understandings in their transdisciplinary task.

THE SCENARIO

In developing this Straw Bridges STEM unit, the teachers aimed to give students experiences with seeing shapes, creating models, drawing shapes, and composing composite shapes found in the real world (math standards K.G.B.5 and K.G.B.6). The students described the shapes by talking about those found in different types of bridges. From there, Lori and Josh decided to bring this home with the following scenario:

> *There was a very heavy rainstorm, and it washed out the bridge to the town. The families needed to return to their homes. They loaded up trucks with supplies but*

> *they needed a bridge to cross the river in order to get home. You are part of an engineering design team that has been asked to construct a new, strong bridge. But first your design team will need to build and test models to decide on the best and strongest design for this new bridge.*

Now, with a scenario in mind and the content standards in place, it was time to create the driving question that would tie together the development of the integrated tasks: "How can we design and build a bridge out of straws with tension and compression so that the bridge does not collapse when tested?" (see Figure 6.6).

Figure 6.6. Students testing their straw bridge construction

The completed *W* section of the W.H.E.R.E. model (see Figure 6.7, p. 56) provides a description of the planning for the *what* and the *why*. It describes the key drivers for the instruction in the unit.

Figure 6.7. *W* section of the W.H.E.R.E. template for the Straw Bridges unit

W	**What** The students will develop an understanding of different geometric shapes through hands-on experiences where they use these shapes to design and build a bridge. ***Main standard (drivers)*** K.G.A. Identify and describe shapes. 1. Describe objects in the environment using names of shapes, and describe their position using terms such as above, below, besides, in front of, behind, and next to. 2. Correctly name shapes, regardless of their orientation or overall size (e.g., circle, rhombus, trapezoid, hexagon, cube, cone, cylinder, and sphere). ***Secondary standards (passengers)*** *Engineering Design* ETS1.A. Defining and Delimiting Engineering Problems ETS1.B. Developing Possible Solutions ETS1.C. Optimizing the Design Solution *Science* Motion and Stability K-PS2-1. Plan and conduct an investigation to compare the effects of different directions of pushes and pulls on the motion of an object. *English Language Arts* K.RL.1. With prompting and support, ask and answer questions about key details in a text. K.SL.5. Add drawings or other visual displays to descriptions as desired to provide additional detail. K.SL.6. Speak audibly and express thoughts, feelings, and ideas clearly.
W	**Why** Students can better understand the attributes of different shapes when they are used to solve a problem. The bridge problem offers a variety of successful design solutions. ***Driving question*** How can we design and build a bridge out of straws with tension and compression (push and pull) so that the bridge does not collapse when tested? ***Essential questions*** *Mathematics* • What geometric shapes can be used to construct an effective bridge? • What total geometric design used to construct our bridge is most effective? • What are the attributes of the different shapes that were used to construct the bridge?

Continued

Figure 6.7 (*continued*)

W	***Essential questions*** (*continued*) *Engineering Design* • What observations and questions need to be answered before you can solve the problem? • How can the engineering design process be used to find a solution to your design problem? • How will drawing a picture or creating a blueprint of the design help with the construction of the bridge? • Is there more than one design that will provide the best solution for the strongest bridge structure? *Science* • How can we best describe how much force we can place on our bridge? • What simple tests can be used to determine the stability of the bridge? *English Language Arts* • Using the design of the bridge, how can you explain, in your own words, the two types of forces—compression and tension (push and pull)?

Special Thanks

A special thanks to Broadmor Elementary teachers Lori K. Schmidt and Joshua Porter for opening up their classrooms and sharing the Straw Bridges STEM unit. Following is a bit more about these two dynamite teachers and how they became interested in implementing STEM instruction in their classrooms.

In Lori's words

How did I become interested in STEM? My daughter is a senior at Northeastern University and majoring in mechanical engineering. My interest in STEM started with my daughter being in a field dominated by males. It is very important to expose all children to STEM, but getting girls excited about these particular fields has been a focus of mine since I started teaching in the 1980s. If I can give my students opportunities to explore STEM and develop a passion in this area, then hopefully they will seek out jobs in a STEM field.

In kindergarten, the vocabulary learned, the critical thinking processes used, and the development of fine motor skills are enhanced greatly by using STEM. In order to compete in this global world/economy,

Continued

(*continued*)

we need to start teaching STEM when the children are very young, and that is why I started in kindergarten. STEM is fun for me to teach and for my students to learn.

In Josh's words

I have been teaching in the Tempe School District for 10 years and teaching in some capacity for 17 years. I believe in teaching to the head, the hands, and the heart to help develop well-rounded citizens. I focus on integrating English language arts, technology, kinesthetic learning, art, and STEM to create a diverse and innovative classroom. I think that teaching techniques that are a benefit to some will benefit all.

I first began teaching in a STEM-oriented way because conventional math and science classes were not focusing on science and engineering concepts. My goal is to develop STEM units based on real-life scenarios that give children context for the importance of science, technology, engineering, and math. The key to collaboration comes from children of different ages discussing, inquiring, designing, experimenting, and reflecting. I believe that learning by itself isn't fun, but that "fun" is the byproduct of high-quality learning experiences!

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Universal Design for Learning Science

Reframing Elementary Instruction in Physical Science

Deborah Hanuscin and Delinda van Garderen

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Foreword

I was thrilled when Debi and Delinda asked me to write the foreword for this book—almost as thrilled as I was six years ago when they invited me to join their advisory board for the Quality Elementary Science Teaching (QuEST) program, upon which this book is based! I knew of Debi and Delinda's meaningful work in inclusive science education and was piqued by the prospect of a professional development program that used Universal Design for Learning (UDL) and the 5E Learning Cycle as the framework for quality science opportunities for all students. I am happy to share that my experiences on the advisory board only confirmed and strengthened my belief in the power and usefulness of this framework for the entire science education field. I also (fortunately!) came to know Debi and Delinda personally and found them to be incredibly warm, insightful, knowledgeable, and passionate educators who together form a "dynamic duo" in the inclusive STEM education community. This book is the fitting culmination of their brilliant project's work.

Universal Design for Learning Science: Reframing Elementary Instruction in Physical Science is a unique classroom resource, first and foremost, because of its assumption of *ability* rather than *disability*. Through highly readable text describing actual classroom experiences, this book dispels the myth that accessible science means "lowering the bar." Quite the contrary, the authors show how UDL in the context of thoughtfully crafted lessons aligned with the *Next Generation Science Standards* can provide appropriately challenging and dynamic experiences for *all* students, including those with special needs. Nine vignettes provide the reader with a window into lesson implementation in diverse science classrooms, while the accompanying "Teaching Tip" boxes provide easy-to-implement UDL strategies that reduce or eliminate unnecessary barriers to learning. Each of these tips can easily be incorporated across the curriculum!

Another strength of this book lies in its use of teacher-authors' voices. Teacher-participants from the QuEST program wrote most of the vignettes, so the reader is assured of real-world, teacher-tested strategies. Teacher educators will also find a chapter written specifically for them to support their work with methods classes. I personally found the background information on the

5E Learning Cycle and the crystal-clear instructions on developing coherent science storylines in Part I particularly helpful both for my own curriculum development and for instruction of my teacher candidates. Even as a veteran science educator, I experienced many "Aha" moments as I read this wonderful book!

I sincerely hope you share my belief that every child is entitled to quality science learning opportunities; in my mind, it is a practical, legal, and moral necessity. The field of science benefits from many diverse voices while society benefits from a scientifically literate citizenry. But what motivates me in my work (and perhaps you in yours) is the unyielding belief that all children deserve to experience the incredible, incomparable, breathtaking beauty and wonder of science! For that reason, I am most grateful for *Universal Design for Learning Science*, as I know it will inspire elementary school teachers to inspire their students—*all* their amazing students—in science.

—Sami Kahn
Executive Director
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About the Authors and Contributors

Authors

Deborah Hanuscin is an experienced elementary classroom teacher and informal science educator, and since becoming a researcher, she has continued to find ways each year to teach elementary students. She received her PhD in science education from Indiana University and worked at the University of Missouri before moving to her current home in science, math, and technology education and elementary education at Western Washington University. She has led both state and federally funded projects working with teachers as well as students, and she has published more than 60 articles and book chapters for researchers, teachers, and administrators.

Debi's accomplishments include teaching awards at the campus, district, state, and national levels, and most notably she was named Outstanding Science Educator in 2014 by the Association for Science Teacher Education. She is the author of numerous articles in National Science Teaching Association (NSTA) journals and has served on the NSTA Research Committee, the NSTA Alliance of Affiliates, and the advisory boards of *Connected Science Learning* and *NSTA Reports*.

Delinda van Garderen is an experienced elementary and middle school classroom teacher in schools in New Zealand. Motivated by the questions she had about her own students and their diverse needs, she has focused her research in special education on struggling learners in science and mathematics.

Delinda received her PhD in special education from the University of Miami (Florida) and worked at State University of New York at New Paltz before accepting her current position at the University of Missouri in the Department of Special Education. She has led and been involved in both state and federally funded projects working with teachers and students in math and science, and she has published more than 40 articles and book chapters for researchers and teachers.

Contributors

Linda Buchanan is a retired fourth-grade teacher from the Normandy School Collaborative. Her goal as a teacher was to empower students with the desire to become critical thinkers and life-long learners.

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Dante Cisterna was a Postdoctoral Fellow on the Quality Elementary Science Teaching (QuEST) program. He taught science and biology for six years in middle and high school levels. Currently, he conducts research and assessment design in science education.

Tracy Hager is a third-grade teacher in Columbia Public Schools in Columbia, Missouri. She is a Presidential Awardee and National Board Certified Teacher, and she served as the elementary director on the Board of Directors of the Science Teachers of Missouri, an NSTA affiliate. She was also a contributing author to *Seamless Assessment in Science*.

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Brooks Ragar is a fifth-grade teacher in the Hannibal School District in Hannibal, Missouri. Following her participation in QuEST, she helped start a "science cohort" of teacher-leaders at Veterans Elementary School.

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Cathy Newman Thomas was an associate professor at the University of Missouri when she worked with QuEST. She is now an assistant professor at Texas State University. Her interests are professional development and access to the general curriculum for diverse learners.

CHAPTER 3

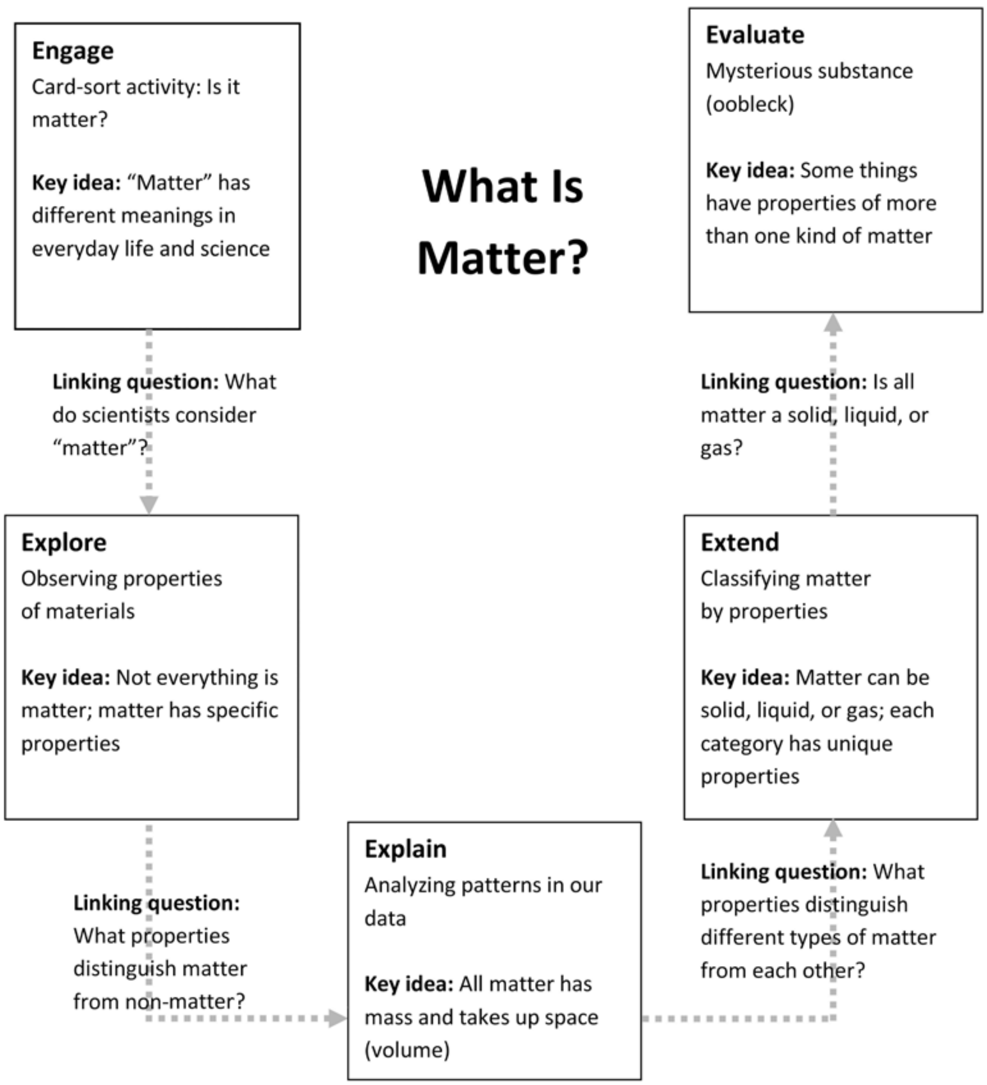
Why Does Matter *Matter*?

Shelli Thelen

This chapter introduces a lesson that engages students in developing an initial understanding of matter by observing and comparing properties, noting patterns for different kinds of materials, and then using that knowledge to identify an unknown substance. This learning cycle represents the first lesson in a fifth-grade unit about matter that engages students in figuring out how a ship might have become stranded in a desert nearly 100 miles from water.[1] The emphasis is on properties that can be used to distinguish matter from non-matter and on differentiating solids, liquids, and gases. See Figure 3.1 (p. 50) for the conceptual storyline of this lesson, "What Is Matter?"

1. See *https://en.wikipedia.org/wiki/Mo'ynoq*.

Figure 3.1. Conceptual Storyline of the Lesson



LESSON VIGNETTE

After many years of teaching kindergarten, I was reassigned to fifth grade. In many ways, I was learning along with my students as I implemented new curricula, addressed new standards, and taught new topics. My first year of teaching fifth grade was a much-needed change from my many beloved years spent teaching kindergarten. I started the beginning of my first year in fifth grade teaching the science units on Earth systems and space systems with gusto, and I felt accomplished. Then November hit and the unit of matter stared at me square in the face. Matter. "What is matter?" It's a big question to think about. Matter has multiple meanings. Matter can be a noun, or it can be a verb.

Admittedly, I was reluctant to teach matter. I was lacking confidence in my own understanding of the content. Simply put, the progression and implementation of teaching matter did not feel cohesive. I gave myself grace that it would be impossible to be an all-star teacher in a new grade level in all content areas.

Talking with my grade-level team, I expressed my lack of enthusiasm for teaching matter and how I found it to be one of my greatest challenges in teaching fifth grade. I shared my urgency for support with planning the matter unit and my longing for a sense of cohesion in the progression of the unit. Mapping out the curriculum's progression is something that usually comes easily for me, and I was feeling frustrated. Fortunately, my team and I had the opportunity that summer to attend the Quality Elementary Science Teaching (QuEST) professional development program, where I learned about planning a coherent conceptual storyline.

Using a conceptual storyline is complementary to backward lesson plan design (Wiggins and McTighe 2005). It requires the teacher to think about the sequence and progression of lessons so that the conceptual knowledge builds with each experience across lessons, units, and topics. This intentional, thoughtful progression is often embedded in a meaningful context or real-life scenario through the 5E Learning Cycle. The matter unit that we developed during QuEST contains eight 5E learning cycles that engage students in developing their conceptual understanding about matter. The first learning cycle of the progression engages them to define matter and to recognize that matter can be identified by certain characteristics.

What I also learned in QuEST about the conceptual storyline was to attend to *the ideas that students would be developing during these activities*. I was used to planning by starting with the activities that the students would be participating in—for example, a card-sort, hands-on exploration, or data analysis. This storyline (shown in Figure 3.1) focuses on the essential question "What is matter?" by

(continued)

(continued)

starting from students' prior knowledge of this term in everyday life and helping them develop understanding of the use of the term in science. Students build this understanding through their own observations of properties and patterns in properties, with specific examples of matter and non-matter, as well as solids, liquids, and gases. While we traditionally teach these as hard and fast categories, the final activity helps students realize that sometimes matter can have properties of both solids and liquids.

Organizing the lesson in this way helped me focus on how students might develop their knowledge in a logical sequence, the questions they would need to answer to move forward in developing their ideas, and the activities that would help them construct their understanding. It also helped me consider how students would be using their knowledge, as described in the *Next Generation Science Standards* (*NGSS*) performance expectation (NGSS Lead States 2013), to identify matter based on its properties (see Table 3.1). That is, knowing the properties of matter *matter* because they are useful in identifying and classifying materials. Additionally, it helped me ensure that students had the necessary knowledge and skills to prepare them to explain phenomena related to matter in later lessons, such as melting, evaporating, and dissolving.

In the sections that follow, I outline the lesson as it unfolded in my classroom, including teaching tips and other information alongside the lesson activities. You can also learn more about this lesson in my blog: *http://thelensthinkers.blogspot.com/search/label/Matter*.

TABLE 3.1. Alignment of the Lesson to the *NGSS*

Connecting to the *NGSS*—Standard 5-PS1-3: Matter and Its Interactions	
www.nextgenscience.org/pe/5-ps1-3-matter-and-its-interactions	
• The chart below makes one set of connections between the instruction outlined in this chapter and the *NGSS*. • The materials, lessons, and activities outlined are just one step toward reaching the performance expectation listed below.	
Performance Expectation 5-PS1-3. Make observations and measurements to identify materials based on their properties. (Examples of materials to be identified could include baking soda and other powders, metals, minerals, and liquids. Examples of properties could include color, hardness, reflectivity, electrical conductivity, thermal conductivity, response to magnetic forces, and solubility; density is not intended as an identifiable property. Assessment does not include density or distinguishing mass and weight.)	
Dimensions	**Classroom Connections**
Science and Engineering Practices	
Analyzing and Interpreting Data Represent data in tables and/or various graphical displays (bar graphs, pictographs, and/or pie charts) to reveal patterns that indicate relationships. Compare and contrast data collected by different groups in order to discuss similarities and differences in their findings.	Students analyze the patterns in their data to identify properties that distinguish solids, liquids, and gases. They use this as a basis to classify oobleck.
Disciplinary Core Ideas	
PS1A: Structure and Properties of Matter Measurements of a variety of properties can be used to identify materials.	Students examine properties including mass, volume, shape, and more to compare different materials. They recognize which properties are most useful for identifying a material and which depend on the amount you have.
Crosscutting Concepts	
Patterns Observed patterns in nature guide organization and classification and prompt questions about relationships and causes underlying them.	Students analyze patterns in their data to identify properties that distinguish matter from non-matter and to classify solids, liquids, and gases. This can be related to patterns important in other units such as phases of the moon and layers in rocks.

Engage Phase (Day 1)

To begin this lesson, I asked my students to take a moment to think individually about the following:

- What the word "matter" means to them
- How they would explain what matter is to another person

> **Teaching Tip:** Providing time for students to think and respond individually is important to learning, and it also can help the teacher document and assess the development of individual students' ideas as they work in groups.

These questions helped activate the students' background knowledge and provided them with the opportunity to consider the many meanings of matter.

After sampling a few students' responses, it became clear to the class that *matter* was a term that could be used in a variety of ways:

- "A *matter* of life and death"
- "It doesn't *matter*."
- "What's the *matter*?"

I explained to the students that scientists also use the word *matter* ("And anti-matter!" as one student called out) and that we were going to try to understand this meaning of matter better in our lesson. It's important to me that I help students recognize differences in the ways they may use words at home and in a scientific context.

UDL Connection
Principle I: Representation
Guideline 3: Comprehension
Checkpoint 3.1: Activate or supply background knowledge

The students were already placed in groups; however, before they worked as a group, I asked students to individually review a checklist and mark the items they believe are examples of matter. At the bottom of the checklist, they responded individually to the following question: "How did you decide whether something could be an example of matter? Explain your thinking."

After each group member had a chance to think and respond on his or her own, I provided the following guiding instructions and questions for the group discussion on the student recording sheet: "Compare your ideas with your group. What similarities and differences do you notice? Try to explain your thinking about why you did or did not check the items above."

As I circulated around the room, I encouraged students to jot down any additional notes or ideas from the group discussion that may have fit with their own thinking, contradicted their thinking, or created a question for further exploration.

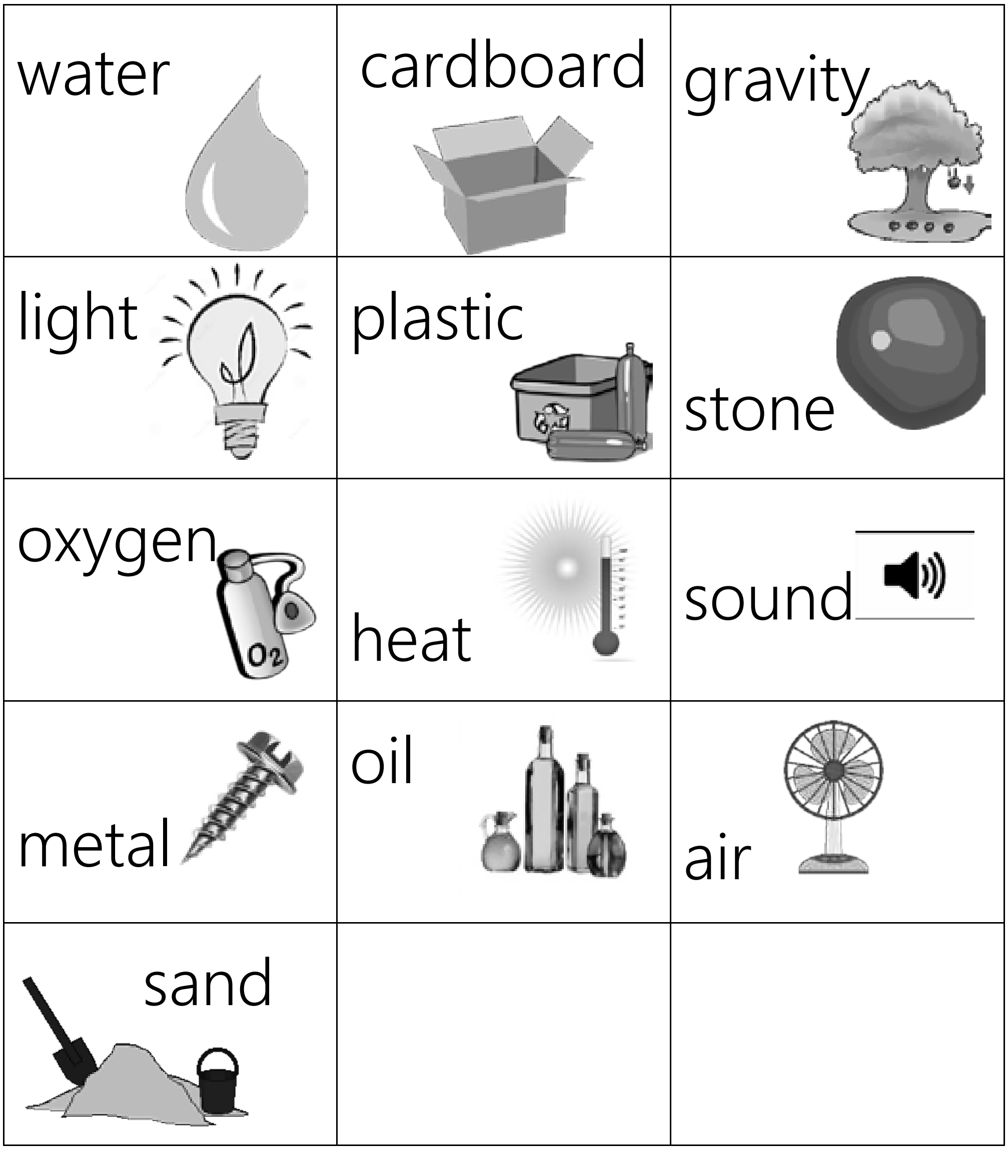
UDL Connection
Principle III: Engagement
Guideline 7: Recruiting Interest
Checkpoint 7.3: Minimize threats and distractions

UDL Connection
Principle II: Action and Expression
Guideline 6: Executive Functions
Checkpoint 6.4: Enhance capacity for monitoring progress

Next, I asked students to work together to complete a card sort (see Figure 3.2, p. 56) that matches the list they just reviewed independently. The cards contained visuals of the words to support understanding across the languages for students who were English language learners (ELLs) and to make text accessible for my struggling readers. Students were to sort the cards collaboratively into two categories: *matter* and *not matter*.

> **Teaching Tip:** Comparing a student's checklist with the group's card sort allows the teacher to ask the student to elaborate on his or her thinking. For example, "I noticed on the checklist that you marked that air is not matter. But when I look at your group's card sort, I noticed that *air* is in the matter category. Can you tell me about that change?"

Figure 3.2. Card Sort for the Engage Phase



UDL Connection

Principle I: Representation
Guideline 2: Language and Symbols
Checkpoint 2.4: Promote understanding across languages

If your students are anything like mine, expect them to disagree on where some of the cards are placed. In this case, I suggested they might make a third pile. Many students in my class were conflicted with the cards labeled *sound*, *energy*, *air*, and *oxygen*. This seems developmentally appropriate as those examples are more abstract. If students cannot see or touch something, they can find it difficult to qualify it as matter.

Teaching Tip: One way to build interest and engage students in this phase of the lesson is to hold a gallery walk in which students can circulate around the room to view how their own ideas line up with those of other groups in terms of sorting the cards. When there are disagreements, this can prompt a desire to find the information—and it can be a great segue to exploration by emphasizing that when scientists disagree, they test their ideas against evidence.

To draw further on students' background knowledge, I asked each group to create a new card (using the blank spaces) with an example of their choice, and then as a class we discussed which group it belongs to. This assessment helped me identify any follow-up discussion that may be needed as I reviewed my plans for the next day.

Explore Phase (Day 2)

During this phase, students had the opportunity to test out ideas. Working in their small groups as a way to keep those with behavior challenges focused and persisting in the lesson, the students rotated through a series of stations to explore the properties or characteristics of five items (light, air, water, stone, and sand) featured in the last activity. (Please see the "Materials and Safety Notes" box, p. 58.) Sand is included purposefully as one of the items because it forces students to clarify their thinking—their answers vary in whether they mean a *grain* of sand or the entire *bag* of sand—and it provides a way to differentiate the degree of complexity for the task to motivate some learners who need more of a challenge. This makes for great discussion in the next lesson phase!

UDL Connection

Principle III: Engagement

Guideline 8: Sustaining Effort and Persistence

Checkpoint 8.2: Vary demands and resources to optimize challenge

Materials and Safety Notes

Materials

Water	Oil	Cups
Stone	Metal	Strainers
Sand	Plastic	Flashlights
Plastic tubs	Balloons	Oobleck in paper cups
Plastic bottles	Containers	Wax paper

Safety Notes

1. Direct supervision is required during all aspects of this activity to ensure that safety behaviors are followed and enforced.
2. Make sure that any items dropped on the floor or ground are picked up immediately after working with them—a trip-and-fall hazard.
3. Immediately wipe up any water or other liquids spilled on the floor—a slip-and-fall hazard.
4. Never taste or drink any materials or substances used in the lab activity.
5. Wear nonlatex aprons when working with oobleck.
6. Use caution when working with glassware or plasticware. It can shatter and cut or scrape skin.
7. Keep all liquids away from electrical outlets to prevent shock.
8. Follow the teacher's instructions for disposing of waste materials.
9. Wash your hands with soap and water after completing this activity.

As students were exploring the materials in the station tubs (see the photos on the next page), they were asked to make sense of and answer each of the following questions on their student recording sheet:

1. Does it take up space?
2. Does it have mass?
3. Does it hold together? Can you pick up the whole thing?
4. Can you easily push another object or your hand through it?
5. Does it have a definite shape? (Does it keep the same shape when transferred to a different container?)
6. Does it have a definite volume? (Does it stay the same if you try to compress it?)
7. Can you pour it?

The students recorded their observations and ideas as they completed each of the seven activities as a tool for sharing and comparing ideas as a class. The stations do not have to be completed in any particular order, so the students are able to work at their own pace. To help those students who struggle with keeping organized and monitoring their progress, I provided data tables for them to record their findings.

Photos of students examining properties of matter in the Explore phase of the lesson. Having materials in tubs or containers that are clearly labeled allows groups to work independently as materials are organized.

UDL Connection
Principle II: Action and Expression
Guideline 6: Executive Functions
Checkpoint 6.3: Facilitate managing information and resources

As the students circulated through the stations, I observed, documented, and anticipated what questions might benefit each group to help them with their understanding: "What are you noticing?" "How is ______ like ______?" I listened to the ways that students exchanged ideas, observed what vocabulary they used, and assessed what misconceptions they might have.

Teaching Tip: Students might point out the expression "light *filled* the room," but that doesn't mean that light can fill a cup or take up space the way that water does.

Explain Phase (Day 3)

The activity in this phase of the lesson was designed to help students clarify and refine their current understanding, first by talking with their group, and then by making sense of their data as a class with teacher support. Using the data collected in the Explore phase, the students completed a data chart to help them look for patterns and use the evidence to explain their thinking. I purposefully structured the data chart (see Figure 3.3) as a scaffold for data analysis, so that when students color-coded their responses, it allowed them to visually recognize patterns with greater ease.

Once each group filled in the chart and discussed their ideas, we compared the results—were there any disagreements? Sand provided a great topic for discussing how granular materials (such as sugar, sand, or salt) can have different properties when you consider questions such as "Can you pour it?" or "Can you pick up the whole thing?" in terms of a single grain or the entire amount you have. Students agreed that sand did not pour the same way that water did, so we marked that "No."

We revisited any other items that prompted ambiguous or inconsistent answers to reach a consensus about the properties of each. For example, students struggled with the idea of air having mass. In the Explore phase, the students tried filling a balloon with air and putting it on a digital scale and comparing the mass to an empty balloon. It often showed no difference. Comparing this to the weight of a single grain of sand as opposed to a bucket of sand can provide a useful analogy to make sense of it. The students realized that air is light enough that a small amount doesn't have much mass, just as a single grain of sand would not register on the digital scale.

Figure 3.3. Data Chart Used in the Explain Phase

Question	Light	Air	Water	Stone	Sand
1. Does it take up space?					
2. Does it have mass?					
3. Does it hold together in one piece when you pick it up?					
4. Can you easily push something through it?					
5. Does it have a definite shape?					
6. Does it have a definite volume?					
7. Can you pour it?					

Note: The students color-code their "Yes"/"No" responses to identify patterns.

Next, I asked students to color-code the different responses in their data chart (e.g., coloring the "No" responses), to help the students who have difficulty identifying important or relevant ideas, as a way to highlight patterns and to help them recall these ideas for later tasks. Once the students reflected on their data chart, they were able to make the generalization that the first two characteristics (mass and volume) were shared by all items they considered to be matter. For light, which they considered *not* to be matter, they noted that they had not been able to demonstrate that light takes up space or has mass. This helped the class construct a formal definition of *matter* as something that both has mass and takes up space. Up until this point we had been using the phrase "taking up space." We clarified what that means (based on their evidence), and I indicated that this is referred to as *volume*. We also differentiated the use of the word to indicate loudness of a sound, and we linked the word to students' learning about area and volume in mathematics.

UDL Connection

Principle I: Representation
Guideline 3: Comprehension
Checkpoint 3.2: Highlight patterns, critical features, big ideas, and relationships

UDL Connection
Principle I: Representation
Guideline 3: Comprehension
Checkpoint 3.4: Maximize transfer and generalization

Extend Phase (Day 4)

In this phase, students extended their understanding by examining how properties of matter that *differed* between objects and materials might help us classify different types of matter further. Using the same core questions from the Explain phase, the students combined their data with new observations for oil, metal, plastic, and oxygen. Checking off the properties of each object listed on the chart, they were again looking for similarities or patterns in their data. Each small group was encouraged to reach an agreement and, if needed, go back to the materials in the previous lesson phase and retest them.

> **Teaching Tip:** Be sure to have enough testing materials for students to test the items on the list. For example, have containers, cups, strainers, a flashlight, and other items available that will help with the investigation.

Using the data from the chart, students devised a way to sort the items into new groups. The order in which I placed the items was intentional, so that similar types of matter were clustered together (see Figure 3.4). The students used color coding to indicate these groups. I asked them the following questions:

- Looking at the sections that are grouped similarly, what do you notice?
- What might you call each group?
- What other items do you think might belong in each group?

In my experience, with color coding, students could begin to see certain patterns emerge. Many quickly recognized that matter could be grouped into a solid, a liquid, or a gas. In some cases, students needed support and encouragement to recall what they observed in the Explore phase of the lesson, or I asked prompting questions such as "What one word could you use that would mean water, oil, or milk?" (*liquids*)

> **Teaching Tip:** As I work with students, I ask myself, "What misconceptions do my students hold, and what experience could I provide for them to further test their ideas?" I often challenge them with new examples or materials "on the fly," so it's helpful to have some extra materials on hand. I suggest salt, rubber, and aluminum foil.

Though students were familiar with the terms *solid*, *liquid*, and *gas*, this was a light-bulb moment for them in terms of how these classifications came about—and how they are defined by common properties. This

Figure 3.4. Data Chart From the Extend Phase of the Lesson

Matter	It holds together in one piece	It is easy to push something through it	It has definite shape	It takes the shape of the container	It has definite volume
Oil					
Water					
Sand					
Stone					
Metal					
Plastic					
Air					
Oxygen					

was also a light-bulb moment for me, as I would have typically introduced the classifications of solids, liquids, and gases first, then introduced students to their properties.

To wrap up the lesson, we constructed a class chart to help organize the information—and make explicit the critical ideas that some students need extra support in drawing out—as a way to solidify (pun intended!) the students' understanding (see Figure 3.5, p. 64).

UDL Connection
Principle I: Representation
Guideline 3: Comprehension
Checkpoint 3.3: Guide information processing and visualization

Evaluate Phase (Day 5)

By this point in the learning cycle, I wanted my students to be able to use the properties of an object to identify it as matter and classify it as solid, liquid, or gas. Providing students with the opportunity to apply what they know to a new experience would give me information to determine if the students have a better conceptual understanding of what matter is as a result of my instruction and whether they can analyze and interpret their data to classify a substance as a solid, liquid, or gas.

Figure 3.5. Summary Chart Identifying Properties of Solids, Liquids, and Gases

Properties shared by the group …		
➢ Holds together in one piece ➢ Has a definite shape	➢ Takes the shape of the container ➢ Easy to push something through	➢ Without a definite volume ➢ The volume fills the whole container
Members of this group …		
➢ Stones, sand, metal, plastic	➢ Oil, water	➢ Oxygen, air
Name for this group …		
➢ Solid	➢ Liquid	➢ Gas

In the final activity, I chose to present students with *oobleck*, a non-Newtonian substance that uniquely behaves as both a liquid and a solid—and it provides a great medium to challenge students' ideas about matter. While the version I use is a combination of cornstarch and water, a quick web search for "oobleck" will provide an assortment of recipes and variations for making your own. I prepared the oobleck ahead of time and distributed a portion of the "mystery substance" in a small paper cup for each student. I also provided each student with a sheet of wax paper as a placemat for easy cleanup. Before handing out these materials, however, I reviewed the exit slip on which students would be asked to individually record and self-assess their thoughts, to gauge and monitor their current understanding about matter. This review helped some of my learners better understand what they were monitoring, as a way to guide their own learning, because some of my students struggled to pose questions while completing tasks.

The exit slip that I used included the following questions:

- Is this substance matter? Provide evidence to support your claim.
- Can you classify this substance as a solid, liquid, or gas? Explain your reasoning.
- Can you think of something else that behaves like a liquid *and* a solid?
- What questions are you still wondering about? What is something that seems confusing or conflicting at this time?

For students who were struggling with a written response, I allowed them to either dictate their thinking to me as I scribed their responses or use voice-to-text on a tablet to support them as they were communicating their ideas.

UDL Connection
Principle II: Action and Expression
Guideline 6: Executive Functions
Checkpoint 6.4: Enhance capacity for monitoring progress

UDL Connection
Principle II: Action and Expression
Guideline 5: Expression and Communication
Checkpoint 5.2: Use multiple tools for construction and composition

As the students received their oobleck, there were many *ooh*s and *ahh*s! Some immediately reached into their cups to touch it, while others attempted to pour it out onto the wax paper. As they explored, students noticed that it pours like a liquid but can be rolled in a ball and picked up in one piece like a solid.

For students who were hesitant to explore, I found action-testing questions (Elstgeest 1985) to be helpful. These "What happens when you … ?" questions can only be answered by students if they try out the action and observe what happens. Examples include the following:

- "What happens when you jab or push on the oobleck slowly? Quickly?"
- "What happens when you squeeze the oobleck in your fist?"
- "What happens when you open your fist?"
- "What happens when you try to stir your oobleck?"

By asking these questions, I could ensure that my students were able to see the full range of properties of the oobleck to prepare them to answer the questions on the exit slip.

All students were able to justify that oobleck is matter, and most accurately identified that it has properties of both solids and liquids (though some were stuck with feeling that it needs to be one or the other). Other examples that students raised include pudding and gelatin—or things like chocolate that are solid at room temperature and behave like a liquid when the temperature increases. Asking students to share their ideas and state something that they were still unsure about, or something that did not make sense, opens the door for me to address their confusion in future lessons and experiences. These examples from students' exit slips can be integrated easily into future lessons about changes in matter!

Unpacking UDL: Barriers and Solutions

I teach in a suburban school district that is located in a university town in the Midwest. I am one of five fifth-grade teachers at the school, which has 724 students—63% are White, 28% qualify for free or reduced lunch, 18% are ELLs, and approximately 7% have an individual education plan (IEP). I firmly believe that all of these students should have access to learning science. Although I had laid out this storyline, I knew that the activities could still pose potential barriers for my students. Using the Universal Design for Learning (UDL) framework and principles (described in Chapter 2), I was able to anticipate challenges that might arise and put specific strategies in place to provide a supportive learning environment for my students. For example, I knew that providing information in text alone would make things difficult for my ELLs. I also knew that for most of the students in my class with behavioral challenges, keeping focused on the task would be difficult.

Although I planned with specific students in mind, I've found that the UDL strategies I implement will benefit most students, regardless of individual learning strengths and challenges. Table 3.2 summarizes the UDL principles, guidelines, and checkpoints that I applied when designing the activities for each phase of the learning cycle lesson to meet the *general* needs of the learners in my classroom—specifically, organizing information, comprehending, staying focused and persisting in a task, and monitoring understanding of learning. Following the table, in the "learner profiles," I provide some examples of how I identified barriers and strategized solutions to meet the *specific* needs of two of the learners in my classroom.

TABLE 3.2. Alignment of the Lesson With Principles of UDL

Connecting to the Principles of Universal Design for Learning	
Principle I: Representation	
Guideline 2: Language and Symbols	
Checkpoint 2.1. Clarify vocabulary and symbols	During the English language arts lesson, students completed a Frayer Model on the word matter to support vocabulary development for ELLs.
Checkpoint 2.4. Promote understanding across languages	Pictures were added to words on the cards used during the card sort to support understanding for ELLs.

(continued)

TABLE 3.2. Alignment of the Lesson With Principles of UDL (*continued*)	
Guideline 3: Comprehension	
Checkpoint 3.1. Activate or supply background knowledge	Students discussed the different meanings for the word matter to activate and provide background knowledge for a shared understanding to complete the learning cycle.
Checkpoint 3.2. Highlight patterns, critical features, big ideas, and relationships	During the Explain phase, students were provided highlighters and a color-code key to highlight findings for identifying patterns.
Checkpoint 3.3. Guide information processing and visualization	During the Extend portion of the learning cycle, a class chart was created to help make ideas explicit and to solidify student understanding.
Checkpoint 3.4. Maximize transfer and generalization	During the Explain phase, the data were color-coded to facilitate the transfer of ideas about matter for the remaining phases of the learning cycle.
Principle II: Action and Expression	
Guideline 5: Expression and Communication	
Checkpoint 5.2. Use multiple tools for construction and composition	For students struggling with writing, they were provided different tools (dictate to a scribe or voice-to-text) to communicate ideas.
Guideline 6: Executive Functions	
Checkpoint 6.3. Facilitate managing information and resources	When collecting data during the Explore phase, students were provided data tables to manage and record findings.
Checkpoint 6.4. Enhance capacity for monitoring progress	In the Engage phase, a checklist with questions asked students to reflect on what they knew and as a way to promote group discussion. Additionally, before completing a task, students reviewed the questions that would be asked on the exit slip, to prompt self-assessment and understanding.
Principle III: Engagement	
Guideline 7: Recruiting Interest	
Checkpoint 7.3. Minimize threats and distractions	Students were provided a checklist to individually complete to ensure that they all had ideas to contribute to a group discussion.
Guideline 8. Sustaining Effort and Persistence	
Checkpoint 8.2. Vary demands and resources to optimize challenge	During the Explore phase, students rotated through stations that were designed to explore the properties of different items, including one item that would challenge thinking and vary the demands of the task.

Learner Profile: Derek

"Derek" was a student who received special education services in the learning disability category. He performed academically on a third-grade level in reading, writing, and math. His IEP included goals for developing executive-functioning skills and comprehension. I anticipated that the Explain phase would be particularly challenging for Derek, as there was a lot of information to make sense of from the Explore phase. Knowing that identifying patterns across the data could be a potential barrier, even though it was organized in a data table (to help students keep information organized and in mind), we planned the activity to include color-coding of the data. I took it one step further and added a "color-code key" to help students interpret the data.

Derek was given a piece of paper that had him use specific colors for "Yes" and "No." As a result, he did the following:

- Recorded all of the Ys for "Yes" first, with a green highlighter (green means *go/yes*), as he went across each row.
- Marked the empty spaces with an *N* for "No." He double-checked his data from the Explore phase to ensure that the empty spaces were really a "No" in his data. He then highlighted the No boxes with a pink marker (red means *stop/no*, but pink allows the student to still see the work and it is easily connected to the color red as they are similar in tone).

After Derek had color-coded his table in this way, he was told to focus on all of the green boxes as a way to identify and see the pattern across the data table. While this was planned with Derek in mind, I noticed that his group members were also struggling with identifying patterns when the table initially contained just "Yes" or "No." Once all students had visually coded their data, they were able to identify a pattern and explain that the properties that were green (mass and volume) were unique to matter.

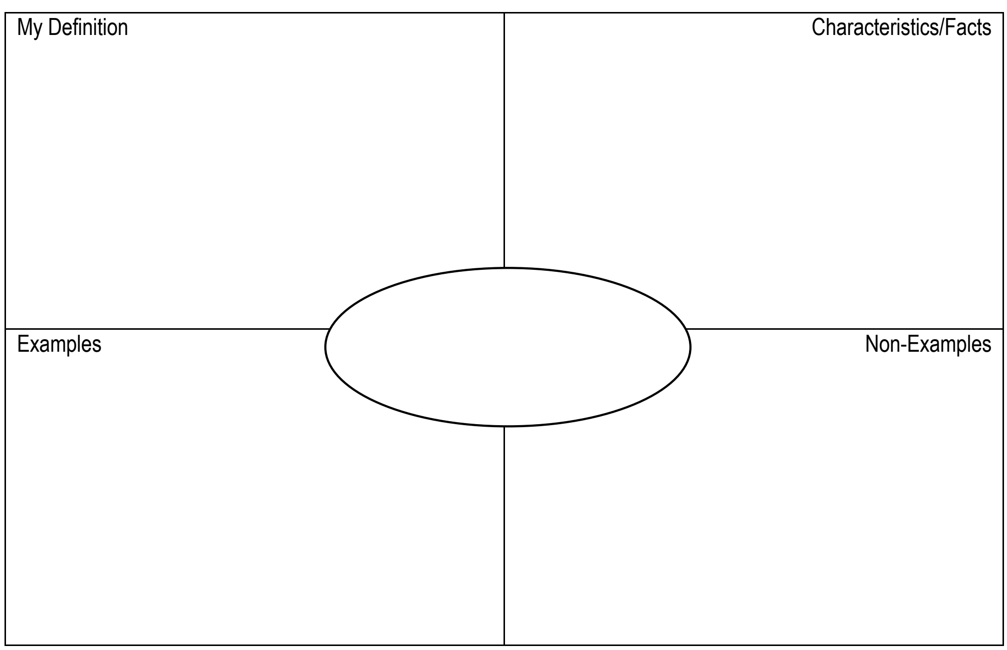
Learner Profile: Thanh

At my school, we commonly encounter students from other countries who are visiting in our city because they have family members doing research at the local university. "Thanh" was proficient in her native language, and she had a working understanding of English. However, she struggled with content-specific academic language.

In the first phase of the learning cycle (Engage), I incorporated pictures along with the words on the cards, so that students could make sense of any unfamiliar objects. For Thanh, I also anticipated that using the term *matter* in a scientific sense could be a barrier—particularly because in English we use the word in many nonscientific ways. I decided to acknowledge this at the beginning of the Engage phase, to signal to students that a familiar word was going to be used in a specific way for a specific purpose.

To further help students define *matter* in a scientific context and support their science learning in other content areas, I introduced the Frayer Model (Frayer, Frederick, and Klausmeier 1969; see Figure 3.6) during English language arts time as we reviewed vocabulary that was being used in the different assigned readings. We constructed this on chart paper and kept it posted in the room as a reference. Adding picture images to the class chart provided another layer of support for ELLs to help them not only make meaning, but also remember these new words in the context that they were learned. This tool was helpful not only in this lesson, but also throughout the unit to define academic vocabulary, including *gas*, *evaporation*, *condensation*, *chemical*, *property*, and other abstract words. Thanh was not the only student who referenced these charts during the lesson—other students also found them helpful when writing in their science notebooks and explaining their ideas to their peers.

Figure 3.6. Frayer Model Chart



Source: Frayer, Frederick, and Klausmeier 1969.

Supporting All Learners: Working in Groups

My students often work in groups. While this can be a source of support for some learners, I also have noticed at times that this can be a barrier as well. Sometimes, certain students will share their ideas immediately—before others have had a chance to think about the question or problem for themselves. As a result, the other students in the group might shut down their own thinking to defer to the authority of the student who is a "quick thinker." These same students, while they mean well, can dominate group discussions, often limiting the contributions of other group members.

In the Engage phase of the lesson, the students were placed in groups to complete a picture card sort activity. Immediately before that activity, I embedded a solution (see Table 3.2, p. 66) that was designed with specific learners in mind. The solution was designed to provide thinking time and facilitate active contribution to the discussion from all students in the group.

Specifically, in the Engage phase of the lesson, I first had the students individually complete a checklist with their own ideas about what is or isn't "matter"—this allowed all students to consider their own prior knowledge and experience before sharing with their group. After the students responded to the checklist, I provided instructions and questions for them to use to guide them in their group discussion. It also helped highlight any areas of disagreement in ideas among the members of the group—which I've found can be a motivator for students to find out what is correct.

While my students sometimes have asked me whether an answer was correct, in this lesson I really tried to empower the students to figure it out for themselves by testing their ideas with evidence. It's important to me that they don't accept answers based on authority, but that they learn to question ideas that aren't supported by evidence.

Questions to Consider

- To what extent did the activities that this teacher chose align with the purpose and intent of each phase of the 5E Learning Cycle?
- Could you envision other activities that would be appropriate for each phase?
- Were you able to follow the sequence of activities and the ideas students developed in the learning cycle that the teacher created?
- How did the storyline of the lesson progress?
- In what ways was the teacher able to assess students during each phase of the lesson? How did this inform her instruction?
- As you read through this lesson, did you come across any activities that might pose a barrier for your own students? What principles of UDL might you apply in those instances?

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Novel Engineering, K–8

An Integrated Approach to Engineering and Literacy

Elissa Milto, Merredith Portsmore, Jessica Watkins,
Mary McCormick, and Morgan Hynes

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Contents

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Elissa's background in teaching and special education led her to purse her second master's in engineering education and to become a core member of Tufts Center for Engineering Education and Outreach. As Director of Outreach, Elissa leads the center's work to provide schools, teachers, and other organizations with engineering design opportunities grounded in research. She leads the Student Teacher Outreach Mentorship Program (STOMP), a community-based outreach program; Design & Engineering Workshops; summer and afterschool programs for students and K–12 teachers; and she consults with local schools and international groups. Elissa is particularly interested in using open-ended, client-centered problems to bring engineering to elementary and middle school students and exploring ways that students with different learning styles and interests can become excited by and access engineering. Elissa has been leading the Novel Engineering project (*www.novelengineering.org*) since it began in 2010.

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Jessica is an assistant professor of science education at Vanderbilt University. She received her PhD from Harvard University, studying the effects of undergraduate reformed physics courses. In her current research, she studies how K–16 students engage in science and engineering as disciplinary pursuits—that is, how they seek deeper understandings of the natural world and solutions to problems within it. She examines both moment-to-moment interactions and long-term dynamics of learners' engagement to understand how their disciplinary pursuits get started and progress over time. Grounding her research is the understanding that learners bring diverse, productive resources for science and that engineering and the role of educators is to help learners build on and refine these resources. Therefore, a second strand of her research is to design and study contexts in which teachers learn to attend to students' thinking in productive and expansive ways.

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Mary started her career in civil engineering working as a geotechnical engineer. When she returned to graduate school, her passion was ignited for engineering education. Mary received her PhD in STEM Education at Tufts, where she was a core member of the Novel Engineering research team. Her research focused on the dynamics of students' framing (sense of the task) during Novel Engineering activities. Mary currently works as a consultant at the Tufts Center for Engineering Education and Outreach, working on research, teaching, and writing projects.

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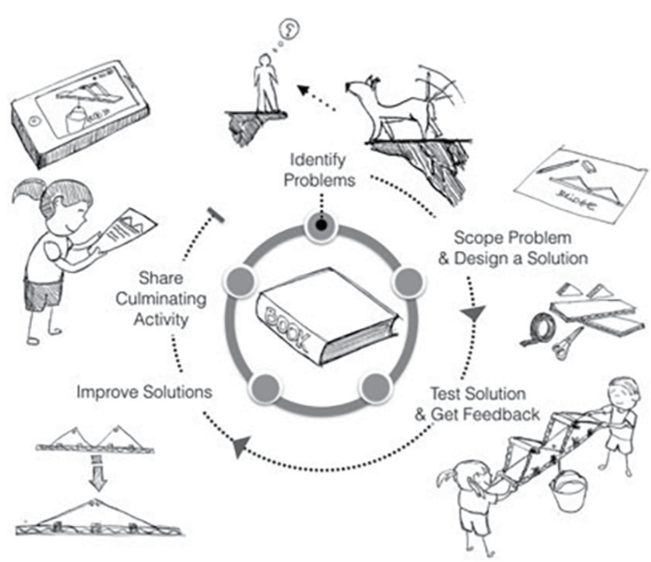
Chapter 1

Introduction to Novel Engineering

A lot of talk in education focuses on integration—combining subjects in meaningful ways to help students learn and see how knowledge and practices cross disciplinary boundaries. Novel Engineering, which follows the trajectory in Figure 1.1, can be taught as part of an English language arts (ELA) curriculum. It has also been implemented in other disciplines. Most of our research took place in ELA classes, so that is where most of the examples in this book take place. At first glance, engineering and ELA may seem like an unlikely pair for integration.

Figure 1.1: Novel Engineering design trajectory



On the one hand, there's engineering, which focuses on solving problems through iterative design. Engineering also pursues solutions to problems through careful identification of needs, requirements, and iterative prototyping, testing, and revision. Literacy, on the other hand, teaches students how to comprehend and interpret text to build understanding and how to engage in discussion, both oral and written, about text.

Novel Engineering gives students the opportunity to enter into engineering design through literature, offering authentic engineering projects that do not have predetermined, "correct" answers. While working on a Novel Engineering unit, students engage in engineering by drawing on their past experiences and understandings of the world and interact with classmates about what's happening in the book and what they have built. As students work on text-based engineering projects, they also engage in productive and self-directed literacy practices, including noting key details in text, making inferences, and writing lists and other notes that support the design process. Novel Engineering projects are therefore interdisciplinary efforts in which students gain experience in both disciplines.

One of the benefits of Novel Engineering is that it allows teachers to use some of their literacy blocks for projects since part of the students' time is used to interact with the text. Novel Engineering is similar to project-based learning in that curricular goals address more than one discipline, but it is different from project-based learning in that it has a specific focus on two disciplines.

This open-ended structure leads to solution diversity among groups within the same classroom. Although there is a basic framework for doing activities, there are not specific lesson plans or scripts. We've found, through our research and interactions with teachers, that by providing a framework for activities, teachers are able to develop their own content based on books that are already part of their curriculum. In fact, teachers with whom we have worked have told us how much they appreciate that Novel Engineering values their expertise and decision-making capabilities by not giving them highly structured lesson plans. It is for this reason that we have not included lesson plans in this book. However, we do include a sample lesson guide on the book's Extras page at *www.nsta.org/novelengineering*.

An Overview of Novel Engineering in the Classroom

The best way to begin this book is to sketch out what Novel Engineering can look like in a classroom. We've seen the book *Wonder* by R. J. Palacio used in several fifth-grade classrooms and are going to present a composite of these classrooms. Although there is variety among the classrooms and students, there are many similarities. *Wonder* is the story of Auggie, a fifth-grade boy who was born with a severe facial difference and is entering school for the first time. The book begins from his perspective and then switches to include the perspectives of the other characters. The teachers have several learning goals for students that include having students think intensely about the characters and the overarching themes of acceptance and friendship. This requires students to think about multiple characters' perspectives and make inferences about their thoughts and feelings. As the teachers read the book, they pause to give students time to discuss the problems that arose and to discuss, as engineers, how they might solve those problems.

As groups are engaged in discussion, the teacher walks around the room and listens to the discussions. One group wants to address the discomfort that the main character, Auggie, feels while eating in the school cafeteria. Due to his facial structure, Auggie is very messy when he eats and feels embarrassed. As two students, Samuel and Mateo, begin to consider solutions to this problem, it becomes evident that they are drawing on details of the story and making spontaneous inferences, all in service of understanding the design context. For example, they describe how they think Auggie feels, cite specific passages in the text, and infer the reason for those feelings—all of which help them empathize with Auggie about how it might feel to be bullied. They also generate a map of the cafeteria based on setting descriptions, consider the social landscape of an elementary school, and come up with a list of foods that may be easier for him to eat in public.

The following is an excerpt of a conversation between the two students. The conversations throughout this book are numbered so that if teachers are discussing them in groups, they can use the numbers to refer to students' statements.

1. **Samuel:** He doesn't like to eat with everyone.
2. **Mateo:** He could just not eat in the cafeteria, maybe in a classroom with a teacher?
3. **Samuel:** No, he is in school to be with the other kids. We need to make something so he can eat in the cafeteria. What can we …
4. **Mateo:** He'll be afraid people will look at him.

5. **Samuel:** We can make something that will let him eat and make it less messy.

6. **Mateo:** Okay. How can it be less messy so the food doesn't fall out? Maybe something that catches food but blocks his mouth?

7. **Samuel:** It can be like a fork but hides his mouth.

The following day, the group begins building a device that will help Auggie eat with less mess. As in most Novel Engineering classrooms, the students are provided with a list of available teacher-supplied materials when they begin to plan, which typically include a variety of cheap and recyclable materials such as tape, paper clips, cardboard, string, and cloth. A suggested list of materials is included in Appendix A (p. 223).

Samuel and Mateo propose to test their device using a range of foods, such as a yogurt, apples, and cheese. As they test their device, they are reminded by the teacher to record their findings in an engineering journal so they can share findings with the class and make changes, if needed, the following day. While sharing their findings with their classmates, the students describe their design choices and rationale, the way they tested their design, and how they intend to improve it. Samuel and Mateo want it to look as much like a traditional fork as possible so Auggie will not feel self-conscious. With that in mind, they include a small guard that helps keep food in his mouth.

In many Novel Engineering units, a writing assignment is included as part of a final culminating activity. In Samuel and Mateo's class, students have been instructed to write a journal entry as Auggie, describing how the engineering solution helped him overcome the problem. The pair of boys write about how Auggie felt less fear during lunchtime and is now able to talk to a friend at the lunch table. The students make projections about how their device would help Auggie gain confidence, which in turn would affect his life. In this example, Samuel and Mateo organically worked through an engineering design process (EDP) without being required to follow the process as a checklist; rather, they were allowed to move naturally through the steps. We will discuss the EDP used in Novel Engineering in the next two chapters.

After their first Novel Engineering experience, teachers often say that their students exceeded their expectations. In the previous example, Samuel and Mateo thought deeply about how Auggie might feel in different situations, such as eating in a school cafeteria or meeting new people. They also made inferences from the text and used their knowledge of the characters to project how different scenarios might play out. The teacher spoke with students as they worked, which provided a strong understanding of what their ideas were around the text, their design choices, and their construction of the final design.

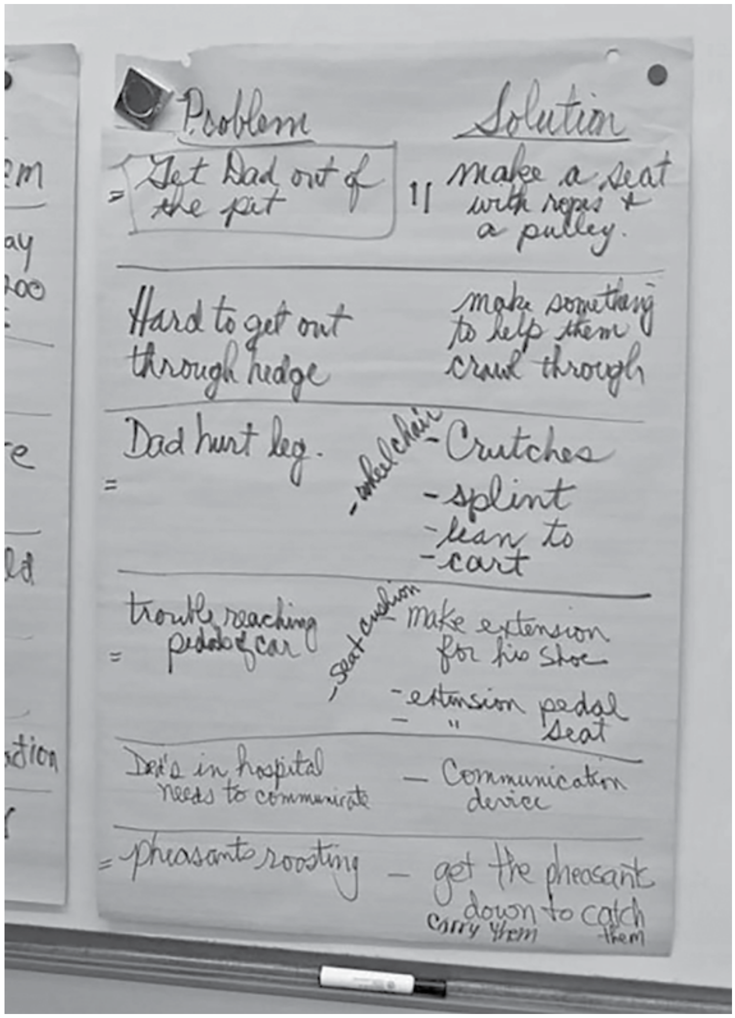
In addition to meeting ELA goals, students worked collaboratively with partners or group members, communicating their ideas and supporting one another in the process. Most surprising to teachers, however, is the way their students act like young engineers. When engaged with the *Wonder* unit, students think critically about their designs, present evidence to support their design decisions, test their ideas, evaluate those ideas, and then iterate to improve their designs.

This example mirrors the experiences of hundreds of teachers with whom we have worked. Teachers consistently indicate that the integration of engineering and literacy is synergistic and powerful. Stories provide complex settings (engineering design contexts) and characters (clients) with real problems and needs, and the students' desire to help those characters by designing functional engineering solutions motivates a deeper reading and understanding of the texts. Most important, students become excited about what they are reading, writing, designing, and building! This excitement in turn helps them make strides in both engineering and literacy, as well as in their abilities to work together, think creatively and analytically, and communicate their ideas.

Novel Engineering provides a structure for students to do engineering while simultaneously working in the content areas. Books, short stories, and nonfiction texts can offer a broad context for engineering design problems that are complete with built-in constraints and criteria. In Novel Engineering, students read and identify engineering problems in the books or other texts, consider characters as clients, and then use details from the story to build functional solutions to address the characters' problems. An example of student-generated problems based on students' work with the book *Danny the Champion of the World* can be seen in Figure 1.2 (p. 8).

Books can range from picture books appropriate for kindergarteners to more complex novels for older students (see Table 1.1, p. 9). Although we will talk about the literacy and engineering portions of Novel Engineering as distinct tasks, students actually see them as part of the same task and bounce back and forth between them minute by minute. Including a hands-on piece is more time consuming, but one of the benefits of Novel Engineering is that it allows teachers to use some of their ELA blocks for these projects and provide time for students to interact with the text.

Figure 1.2: List of student-generated problems from *Danny the Champion of the World* by Roald Dahl



Guiding Principles of Novel Engineering

From our work at Tufts University, we've seen that students are capable of jumping into engineering projects with little guidance and that teachers can use Novel Engineering as an entry point to meet classroom goals. We've also seen that Novel Engineering provides teachers with a concrete way to attend to and respond to student thinking. These observations—along with our belief in the abilities of students and teachers—helped us formulate our guiding principles.

Table 1.1: Sample books used as part of Novel Engineering units

Title and Author	Grade Level	Lexile Level	Problems Identified by Students	Solutions Designed by Students
The Snowy Day by Ezra Jack Keats	K–2	AD500L	Keeping Peter's snowball longer	• Insulated snowball savers • Portable insulated snowball saver
Tales of a Fourth Grade Nothing by Judy Blume	3–5	470L	• Protecting Peter's pet turtle from his brother, Fudge • Preventing Fudge from getting out of his crib	• A turtle cage that prevents Fudge from getting to Peter's pet • An alarm system attached to Fudge's crib that will ring a bell when he tries to escape
A Long Walk to Water by Linda Sue Park	6–8	720L	• Nya must carry large amounts of water far distances every day • Thorns cut Nya's feet as she walks through the desert transporting the water	• A sled that can carry the water and move over rocky terrain • Shoes made of cheap materials

Novel Engineering is motivated by two guiding principles:

1. Students of all ages are capable of engineering, and their ideas can be used to inform their designs.
2. Teachers are capable of making decisions about their classrooms and their students' learning.

Rather than working from a deficit model with students, we value pre-existing student knowledge and feel that students can build on what they already know about the world as they design. Regarding teachers, the core belief that they need to be given flexibility and opportunities to make decisions about their own classrooms and students' learning means we see teachers as capable professionals who do not need "teacher-proof" curricula and should be empowered to design learning environments. Along with this flexibility is the opportunity to listen to and respond to students' ideas. When given this freedom, teachers are able to make judgments about their students' learning and decide how best to support their work.

This flexibility for both students and teachers means Novel Engineering is an open-ended approach in both how it is presented to students and how students engage in solving problems. This open-endedness means the engineering closely mirrors the real-world EDP, which is inherently messy. It also means that student engagement is elevated because students find and solve problems that are interesting to them and match their individual skills and interests. A teacher may use the same book two years in a row, but the discussions and student solutions may be very different from year to year. Although there is a trajectory that all Novel Engineering units follow (see Figure 1.1, p. 3), this serves as a path for students rather than a checklist of steps. We will talk more about the Novel Engineering trajectory in the next chapter.

Building off the first principle, students' ideas play an important role in Novel Engineering, and classroom culture should be crafted so students are comfortable sharing and acting on their ideas. We are not saying that you should let your students do whatever they want. Rather, the insight gained from understanding students' ideas gives you information about how to support students and when you can push back on their ideas. For example, there will be times when students plan to make something that is not functional or mechanically possible, such as a shrink ray, or when they want to build something that is more complicated than they have time to build.

Understanding what students are thinking will help teachers respond in a way that builds on and supports students' ideas. Rather than approaching students' work and immediately trying to improve what they are doing, teachers should take time to understand what students are thinking and why they made certain design decisions. This will help teachers respond appropriately so they can meet students where they are. Being a responsive facilitator means guiding students by asking questions and making observations so they can design realistic solutions given the available materials and time constraints.

As is evident in the dialogue between Samuel and Mateo, students are able to participate in complex discussions while navigating the EDP and thinking about the book they are reading. Teachers are often surprised and impressed with what their students can do, and students are excited to engage in hands-on, engineering design activities that do not have predetermined answers.

How Did Novel Engineering Begin?

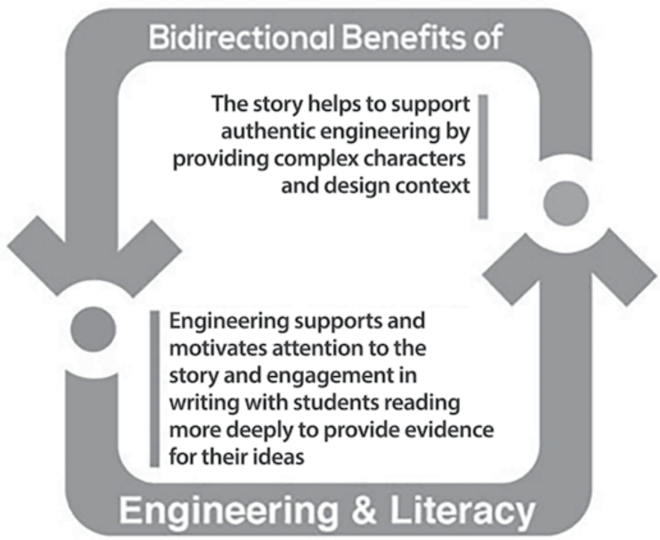
When we started Novel Engineering, we looked at existing research from engineering, literacy, and teacher education to build on an existing concept from a local nonprofit partner, Bill Wolfson, who was using children's books to present engineering to young children. In looking at this research, we found an argument that demonstrated there was potential for design and engineering to facilitate learning in other disciplines (e.g., Kolodner 2002; Wendell and Rogers 2013) and that students' past experiences are rich resources for design projects (e.g., Portsmore 2013). This led us to think about how closely the engineering and literacy in Novel Engineering needed to be linked and how both disciplines needed to have equal value.

The Novel Engineering project began in 2010 with an interdisciplinary team of researchers and educators in engineering, literacy, education, and psychology. Our team spent the first five years of the project working with teachers and conducting research in their classrooms in rural, urban, and suburban schools. Over the course of the research, we worked with more than 500 students and filmed them as they engineered solutions to problems encountered by characters in the books they read. Research revealed what was happening as students engaged in this integrated setting and how teachers interacted with and supported their students. We documented how young students first approached engineering, how novice engineers navigated open-ended engineering design tasks, and how the integrated context influenced students' design methods (McCormick and Hammer 2016; Watkins, Spencer, and Hammer 2014). We also looked at how teachers recognize and respond to students' engineering ideas (Johnson, Wendell, and Watkins 2017; McCormick, Wendell, and O'Connell 2014; Wendell 2014).

Bidirectional Benefits

Constraints on teachers are growing and the freedom to choose what happens in the classroom is shrinking, so it may seem crazy to think of adding yet another initiative into the classroom. New initiatives must fulfill multiple functions. In our research classrooms, we saw that Novel Engineering was able to bridge several disciplines while also meeting educational standards, classroom goals, and individual goals. (In Chapters 2 and 3, we touch on how Novel Engineering aligns with *Next Generation Science Standards* and *Common Core State Standards*.) Figure 1.3 (p. 12) shows some of the benefits we've seen for students in implementing Novel Engineering in classrooms. In practice, we've found that engineering and literacy are mutually beneficial—with the text giving the engineering context and authenticity and the engineering supporting students' attention and engagement.

Figure 1.3: Bidirectional benefits of Novel Engineering



A New Kind of Resource for Teachers in Engineering and Literacy

There are many engineering curricula for young students in which students design solutions for problems rather than clients. For example, students may be tasked with building a tower of marshmallows and uncooked spaghetti. This activity may help students work on collaboration and testing skills, but it does not present students with a client or give them a context to consider as they design. With such structured tasks, there is very little solution diversity since students are working with the same materials and have been given the same constraints and criteria. Additionally, real-world engineering problems are not as neatly packaged as this. Professional engineers must sift through lots of information to figure out design criteria and constraints they need to address as they plan a design. Novel Engineering is unique in that students get to experience the messiness of engineering and have the chance to scope the problem and empathize with their clients as part of the design process.

Our research has shown that students are able to navigate the EDP without explicit directions. As we noted previously in this chapter, most elementary engineering experiences provide students with well-defined problems and a structured path through the EDP. This obviously results in all students arriving at similar solutions. In Novel Engineering, students define the engineering problems themselves as they design functional solutions based on their own ideas. As they work, they make design decisions and refine their ideas based on evidence from the book, feedback from tests, and feedback from peers. In addition to meeting standards and the goals of the classroom, Novel Engineering allows students to take ownership of a project and tackle challenging problems while working collaboratively (see Figure 1.4). This is in line with what has been outlined by the National Academy of Engineering and National Research Council (2009); it's important for all K–12 students—not just those taking engineering courses—to develop engineering habits of mind.

For the literacy aspect of Novel Engineering, we have found that students productively engage with text in a variety of ways that align with *Common Core State Standards*. They take the perspective of characters and note relevant aspects of the physical setting as they plan and evaluate their designs. Spontaneous discussions emerge as students wrestle with unfamiliar concepts and vocabulary in an effort to better inform their designs. These discussions lead to students constructing an informed interpretation of the text.

Figure 1.4: Students working on a communication system for the main character in *The City of Ember* by Jeanne DuPrau

Designed for Educators

Novel Engineering is designed to be a flexible approach for teachers. Though we recommend a semistructured flow of activities, there is no one “correct” way to do Novel Engineering, nor is there a set curriculum for teachers to follow. Novel Engineering works with most trade books and allows students to work on academic objectives identified by each teacher or school. Many teachers have found that Novel Engineering meets their academic objectives in a range of subject areas, from ELA to social studies to mathematics. Teachers have also said the Novel Engineering approach builds on their experiences and expertise rather than having them learn a completely new curriculum that does not necessarily work with the other curricula and structures that are already in place in their classrooms. Novel Engineering works well with existing curricula and plans since teachers get to choose the text and direction of student work; they can use texts students already know and are comfortable with rather than unfamiliar books from an assigned list.

Teachers have also noted that Novel Engineering helps them develop a classroom culture that includes productive class discussions and peer critique. Even though Novel Engineering requires teachers to have a basic understanding of engineering and the EDP, it does not require them to have a formal engineering background. Instead, it builds on their unique disciplinary backgrounds and classroom experiences. When working directly with teachers, we have them do a Novel Engineering unit to get a feel for the process their students will be undertaking. This book, then, is designed to help teachers gain familiarity with key aspects of engineering and help structure the process of presenting engineering to students.

Finally, Novel Engineering helps teachers look at their students in new ways. Many teachers have said that it helped them step back and notice what their students were doing and thinking. This more critical look at student thinking helps teachers understand why students make certain design decisions (related to both the text and the mechanics of the design) and why they have certain interpretations of the text. This more informed view of student thinking enables teachers to respond more appropriately to what students are doing and helps them guide their next moves. Teachers have also said that Novel Engineering helped them notice new things about their students, such as strengths or places for improvement, that did not come out in other classroom activities.

Overview of This Book

We wrote this book to share what we have learned from doing Novel Engineering in more than 100 classes. This book will walk teachers and teacher educators through the Novel Engineering approach, show concrete examples of what students may say and do, and prepare teachers to implement the approach in their classrooms. Although it's a simple concept, Novel Engineering requires teachers to anticipate what their students may do (say, think, and design), listen to their ideas, and set up structures that support students' work while meeting academic objectives.

This book is divided into three sections. Section I describes the Novel Engineering approach in more detail, what engineering looks like in young students, and how literacy and engineering support each other in project-based work. Section II consists of case studies that prepare you to lead a Novel Engineering unit and support your students as they practice being engineers. To this end, you will learn to recognize students' engineering skills and respond to student thinking. Section III includes practical elements that will be helpful in planning and implementing a Novel Engineering unit.

You do not need to read this book straight through; rather, you can jump from chapter to chapter. We definitely recommend starting with Chapters 1, 2, 3, and at least two of the case studies. After that, browse the sections you feel are most relevant to your specific classroom needs. We believe this book will help you respond to your students' work and allow them to have an authentic engineering experience as they play around in the true messiness of engineering. It will also provide students with an opportunity to be creative and follow their own ideas, taking ownership of their learning.

Visit
www.novelengineering.org
for additional Novel Engineering resources!

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National Science Foundation: *www.nsf.org*
Next Generation Science Standards: *www.nextgenscience.org*
Novel Engineering: *www.novelengineering.org*

Book Resources

The City of Ember; DuPrau, J.; Age Range: 5–12; Lexile Level: GN520L
Danny the Champion of the World; Dahl, R.; Age Range: 8–12; Lexile Level: 770L
Wonder; Palacio, R. J.; Age Range: 8–12, Lexile Level: 790L

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9

THE TRIUMPH OF THE PIKA

Understanding Environmental Impacts on Species

A Case Study Using the Discovery Engineering Process

Introduction

Climate change threatens the survival of many species, especially those that overheat in higher temperatures. This is particularly true of the pika (Figure 9.1, p. 180), an animal related to rabbits. This small, herbivorous (plant-eating) mammal lives in the mountains of the American West. Pika are known for being habitat specialists, meaning they can only survive in a narrow range of environmental conditions. (This is opposite from species that are generalists, which can survive in a wide range of environmental conditions.) Pika can easily overheat and are sensitive to changes in the environment. So, when a wildfire destroyed an entire forest, scientists were surprised to find that the pika population had survived. In uncovering the mystery of the pika's survival, the scientists learned valuable information about protecting wildlife in the face of climate change.

FIGURE 9.1

The American Pika

Lesson Objectives

By the end of this case study, you will be able to

- explore how species are impacted by human-influenced changes in the environment;
- examine and then model how change in the environment can alter species populations; and
- create an environmental assessment (EA) to evaluate the ecological impact of (proposed) human activity on a specific species in a specific location.

The Case

Read about research on the pika conducted by Dr. Johanna Varner and her colleagues. Their accidental observation of a wildfire while studying pika populations is helping to construct a better understanding of how wildfires affect species. This is extremely important, because scientists believe that wildfires will grow in both frequency and severity due to climate change. Once you are finished reading, answer the questions that follow.

In August 2011, ecologist Johanna Varner was conducting a field study on a pika population living in an Oregon gorge. Pika typically live in the mountains, not in gorges where the elevation is near sea level. Dr. Varner wanted to understand this unique population. They served as her experimental group. To have a basis of comparison, she also observed a second pika site at Mount Hood. This was her control group. Like most other pika, the Mount Hood population made dens in mountainside rock fields. As part of her observation, Dr. Varner installed temperature-recording devices in the pika's dens. In September, a sudden wildfire broke out at the Mount Hood site, seemingly ruining the experiment.

However, the wildfire led to a novel research opportunity. Natural disasters are on the rise, yet they remain hard to predict and, therefore, study. Science is based on careful and thoughtful design and observation, making investigating natural disasters as they are occurring very rare. But because Dr. Varner and her team already had an experiment set up at the wildfire site, they were in a unique position to study the disaster. And they realized that the wildfire could provide insight into the way such events affect wildlife. The researchers reconsidered their original plan and decided to focus their study on how the pika fared during the wildfire.

It soon became clear that the pika were still abundant at Mount Hood despite the fire. Dr. Varner and her team collected more data on the animals. They looked at the number of dens and the number of pika in each den, both before and after the fire. They also looked at temperature (or thermal) data from the temperature recorders, which had remained intact during the blaze. This gave them an idea of how hot the dens were before, during, and after the fire. They found the temperature in the dens did not rise above 64.4°F (18.5°C), although the fire outside exceeded 932°F (500°C). Varner and her research team found that the rock face provided a way to buffer the temperature, insulating the pika from the extreme heat. Also, the rock face provided a natural barrier to prevent the fire from moving throughout the forest, acting as a fire break. Another factor that allowed for pika survival is that, although these animals are habitat specialists, they are dietary generalists, meaning they can eat a variety of plants to survive. After a fire, the first plants that grow are mosses, which the pika are able to eat.

The results of Dr. Varner's study highlight the importance of maintaining natural features (like rock faces for pika dens) to provide refuges for sensitive species during natural disasters like wildfires. Also, it is important to maintain local, indigenous wildlife, so that after such events animal and plant species may rebound.

Recognize, Recall, and Reflect

1. In Dr. Varner's experiment, which pika population was the experimental group? Why? Which pika population was the control? Why?
2. Pika are described as habitat specialists, yet dietary generalists. What does this mean?
3. What were two recommendations made by the researchers to help sensitive species after natural disasters?

Investigate and Explain

Climate change poses a threat to many species. To better understand how wildlife populations like the pika may be affected by future warming trends, scientists make models that depict various outcomes. Figure 9.2 includes four maps. The first one, labeled Map A, shows current pika populations and the amount of suitable habitats available to them. The pika are shown as black spots; the suitable habitats are shown in light gray. Each consecutive map shows the amount of suitable pika habitats at different levels of warming: Map B shows low warming, Map C shows medium warming, and Map D shows high warming. For these maps, the suitable habitats are shown in dark gray. Current suitable habitat areas still appear on these maps in light gray for comparison. After examining the data, answer the questions that follow.

1. Look at Map A. In which two states do most of the observed pika (black spots) live? Why are there suitable pika habitat areas (light-gray areas) that don't actually have any pika?
2. As temperatures increase from low (Map B), to medium (Map C), to high (Map D), what is the general trend of the American pika's habitat (dark-gray areas)?
3. Look at Map D. In this scenario, what state would have the largest habitat range for the pika? Why do you think that geographic location would be the last refuge for the pika in the highest temperatures?

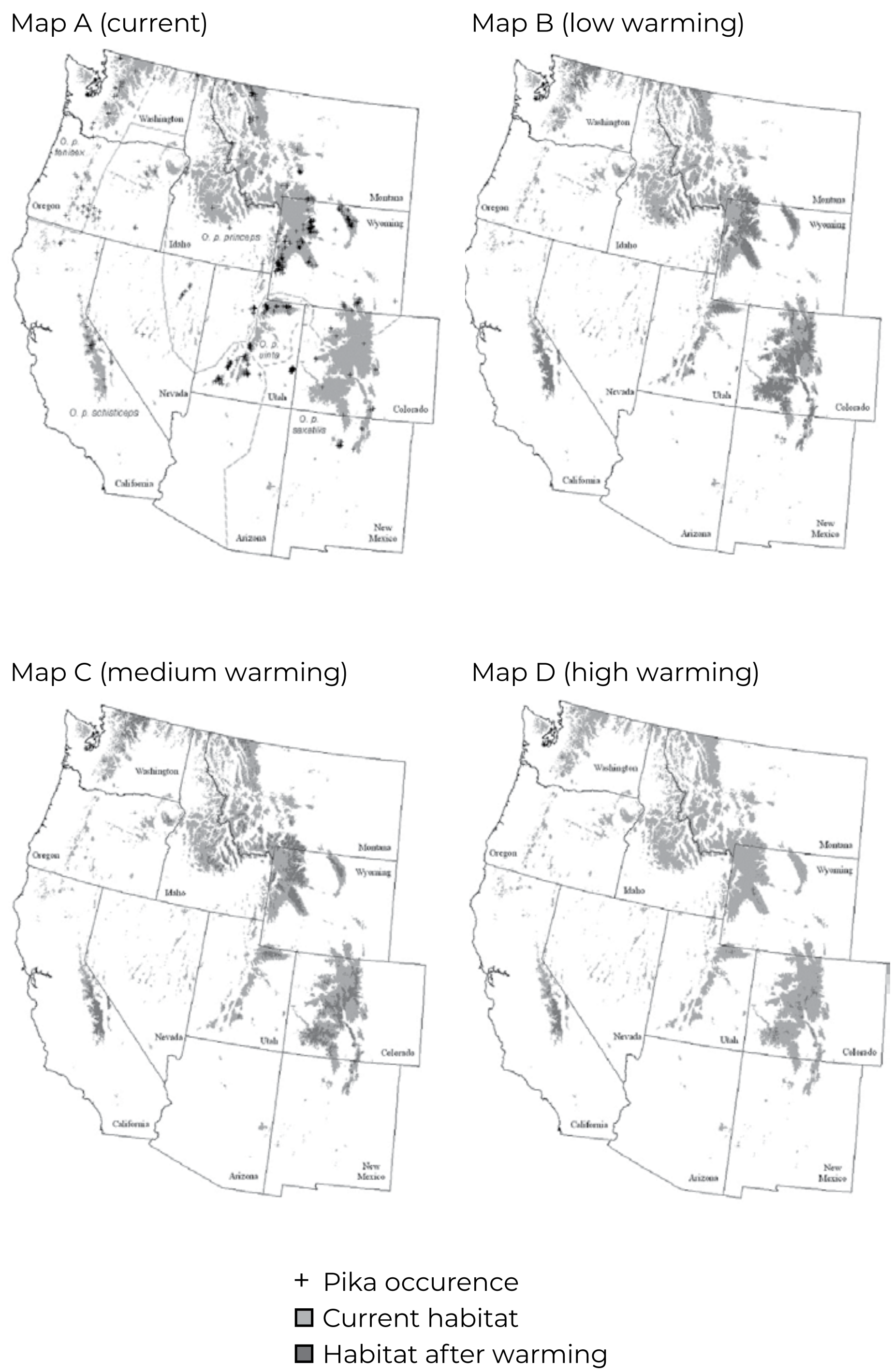
Activity

Imagine you work as a wildlife ecologist, researching how environmental changes can influence the entire population of a single species. You are studying one famous case that illustrates this phenomenon. In the second half of the 18th century, Europe was engaged in the Industrial Revolution, when factories began to dot the countryside. These factories churned out black dust (soot) that blanketed the nearby villages and forests, covering both trees and rocks.

Prior to the Industrial Revolution, the peppered moth population in England was mostly composed of a light-colored variety; a smaller number of the moths

FIGURE 9.2

Pika Habitats in Scenarios of Climate Change



were a darker-colored (melanic) variety (Figure 9.3). The lighter moth's coloration worked as camouflage, allowing it to blend in with surroundings like trees and lichens in order to hide from predators such as birds. In the mid-1800s, several decades after the Industrial Revolution began, people noted that the light-colored moths had become fewer and fewer in number. Instead, people saw more of the darker variety resting on the trees and rocks.

In the 1950s, Bernard Kettlewell conducted experiments to understand what had happened to these moths. He found that the change in the environment caused by the Industrial Revolution had influenced moth predation. During the Industrial Revolution, soot from factories darkened the forests. The darker surroundings caused the light-colored moths to stand out to predators. Because they were easier to hunt, light-colored moths often didn't live long enough to reproduce. Meanwhile, the darker-colored moths were able to camouflage themselves better in the now-dark environment, which allowed them to live longer, mate, and pass on their genes for dark color to their offspring. This, in turn, shifted the peppered moth populations from the lighter phenotype, or appearance, to the darker phenotype.

FIGURE 9.3

Two Types of Peppered Moth

To understand how this occurs, you will explore data on phenotypes of peppered moth populations in 19th-century England. You will conduct a two-part ecological investigation in which you explore the change in the physical appearance of peppered moths, and then create a model to examine how environmental changes can influence populations of species.

Part I

To begin your ecological study, you analyze data from 1860 (several decades after the start of the Industrial Revolution), which was collected during a random sampling of peppered moths from all over England. The summary of that data is in Table 9.1. After completing this part of the activity, answer the questions that follow.

(*Note:* These are mock statistics that reflect the type of frequency differences you might have found in areas of England affected by pollution from the Industrial Revolution. These are not data points that were actually collected.)

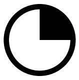
TABLE 9.1

Ecological Survey Data of Light and Dark Peppered Moths in 1860s England

Sampling Location #	Location in England	Distance to Closest Factory	Number of Light-Colored Moths Observed	Number of Dark-Colored Moths Observed	Total Number of Moths Observed
1	Northwest England and Ireland	8 km to 10 km	698	228	926
2	Northeast England and Scotland	More than 20 km	923	22	945
3	Central England	Less than 1 km	18	928	946
4	Southwest England	More than 10 km	840	92	932
5	Southeast England	2 km to 5 km	280	641	921

ACTIVITY QUESTIONS, PART I

1. You will now create a pie chart map of your data. Follow the steps below.
    a. Calculate the percentage of each moth per sampling area in the chart below. (The first one has been done for you.)
    b. Use the calculations to create a pie chart for each sampling area. (The first one has been done for you.)

Sampling Location #	Percent Light-Colored Moths	Percent Dark-Colored Moths	Pie Chart	Geographic Location
1	698/926 = 0.754 0.75 × 100 = 75%	228/926 = 0.246 0.25 × 100 = 25%		Northwest England and Ireland
2				
3				
4				
5				

c. Plot your data to the correct geographic area on this outline map of England.

2. In which regions are light-colored moths most prevalent? In which regions are dark-colored moths most prevalent? How does distance from a factory affect the prevalence of each moth variety?

Part II

Next, you will model how a sudden change in the environment can indirectly influence wildlife populations. Once you're done, answer the questions that follow.

MATERIALS

- ✓ 5 pieces of 8.5 × 11 in. construction paper, one of each color: green, black, yellow, white, and red
- ✓ 2 pieces of 8.5 × 11 in. patterned paper or fabric
- ✓ 1 bag of green, black, yellow, white, and red paper dots (at least 50 in all, 10 of each color)
- ✓ 1 pair of tweezers (to capture dots)

In this modeling activity, you will be a predator that is hunting paper dots for food. The dots are your prey, the sheets of paper are different environments. Follow these steps:

1. First, place down a piece of green construction paper (Trial 1).
2. Then, dump the dots from the bag onto the paper and spread them out.
3. Close your eyes. When you open them, quickly pick up the dot that stands out the most.
4. Once you have picked up your dot, put it back into the bag.
5. Repeat Steps 2 through 4 until about half (25 or so) of the dots are left.
6. Count up the number of dots that you snagged by color, recording the data in the Paper Dot Hunting Chart. Then, add up the data in each row.
7. Put all 50 of the dots back into the bag.
8. Repeat Steps 1 to 7 but with the next "environment," or sheet of paper (Trials 2 through 7).

Paper Dot Hunting Chart

Environment (Paper Color)	Prey A (Green Dots)	Prey B (Black Dots)	Prey C (Yellow Dots)	Prey D (White Dots)	Prey E (Red Dots)	Total Caught
Trial 1: Green						
Trial 2: Black						
Trial 3: Yellow						
Trial 4: White						
Trial 5: Red						
Trial 6: Pattern 1						
Trial 7: Pattern 2						

ACTIVITY QUESTIONS, PART II

1. In this modeling activity, what were the relationships between totals (frequencies) of prey (dot colors) to their environment (paper colors)?
   a. When was the prey the easiest to see?
   b. When was the prey most difficult to see?
   c. How does the environment affect the traits that are common in a population?

Apply and Analyze

Read this short article from Carolina Biological about using a technique called *mark-release-recapture* (MRR) to determine populations of freshwater turtles: *http://classroom.jc-schools.net/coleytech/climate/Carolina%20Tips.pdf*. After reading, answer the questions that follow.

1. Imagine you were conducting an MRR study of the Mexican spider monkey, a critically endangered species. (According to the International Union for Conservation of Nature, a critically endangered species is defined as having an extreme risk of extinction in the wild.) You are able to mark 75 monkeys (categorized as Marked, or M) and release them back into their habitat. When you return, you capture 75 monkeys and note that 45 are recaptures (categorized as Recaptures, or R) and 30 are not marked (categorized as Unmarked, or U). Using this equation ($X = [(U + R)/R]M$),

what is the total number (X) of monkeys you estimate to be in the wild population? Show your work: X = ____________

2. The Mexican spider monkey is one of five subspecies of the Geoffroy's spider monkey species. The other subspecies are the Nicaraguan spider monkey, the hooded spider monkey, the ornate spider monkey, and the Yucatán spider monkey. It is important during MRR studies that the correct species or subspecies is captured, marked, recaptured, and counted. What are three ways you would ensure that you and your research team are marking and recapturing the correct monkeys?

    1. ____
    2. ____
    3. ____

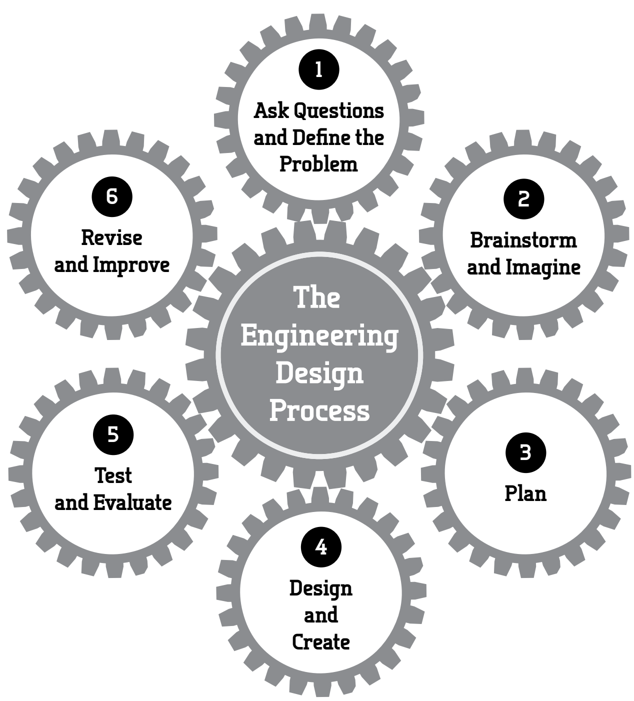
Design Challenge

The case study in this lesson illustrates how scientific observations can lead to potential solutions to problems. Observations and discoveries often spark innovations, especially in the field of engineering. Engineering is the application of scientific understanding through creativity, imagination, and the designing and building of new materials to address and solve problems in the real world. You will be asked to take the science you have learned in this case and design a process or product to address a real-world issue.

Engineers use the engineering design process (Figure 9.4) as steps to address a real-world problem. Environmental engineers provide information for environmental assessments (EAs). Now, you will use the engineering design process to create your own EA. In this case, you are asking questions (Step 1) about species that are threatened or endangered by climate change or other environmental changes. You will then learn about the components of an EA and brainstorm

FIGURE 9.4

The Engineering Design Process



(Step 2) a topic for your own EA—a proposed activity in your community that may affect threatened or endangered local species. After gathering research, you will make a plan (Step 3) for your EA. Then, you will create (Step 4) your EA. Afterward, a peer will evaluate (Step 5) your EA and provide feedback. Finally, you will consider improvements (Step 6) to your EA based on the feedback.

1. Ask Questions

The pika is just one animal species that is threatened by climate change and other environmental issues. What are some other plants and animals that are threatened or endangered? What actions and activities are harming them?

2. Brainstorm and Imagine

An EA outlines the positive and negative environmental effects of a proposed action (usually, an action taken to benefit people). The EA is supposed to (1) demonstrate the need for a human action, (2) consider how that human action would impact the environment, and (3) develop ways to mitigate (or reduce) unintended impacts to endangered or threatened animal or plant species. Examples of proposed actions may include the following:

- <u>Industry</u>: siting and constructing a new factory, farm, business, etc.
- <u>Energy</u>: siting and constructing a new energy source (wind farm, nuclear power plant, etc.)
- <u>Transportation Infrastructure</u>: siting and constructing a new road, bridge, railroad, airport, etc.
- <u>Development</u>: siting and developing land for a subdivision, park, nature refuge, etc.

Think about something your town, city, or county might need to do in order to grow or recover economically or environmentally. Which of the examples listed above are the most relevant in your local context? Conduct some research on your town, city, and county websites to find out what the needs are in your community. Discuss your thoughts and ideas with your classmates.

Choose one action that your city, town, or county might take in order to meet a need. Look at the Environmental Assessment Components section. Think about what information you'll need to create your EA. Keep this in mind (and refer back to the EA description) as you conduct research on your chosen action in Step 3.

Environmental Assessment Components

EAs contain the following five parts: introduction, purpose, need, alternatives, and environmental impacts.

1. **Introduction.** The introduction should include a brief, one-paragraph description of the project background. Include a summary of the need for human action.
2. **Purpose.** The purpose is a statement of the proposed human action and two to three of its objectives. The purpose should be general in nature, whereas objectives are more specific to the actual location of the project. For example, a purpose could be to "put a new park in town." One objective could then be to "find what lots are available for that park."
3. **Need.** Identifying and explaining the need is critical in an EA. The need is the specific problem the project is intended to address. The need should be specific and stated as a problem, not a solution. The need should be described in a manner that allows for multiple ways of addressing the problem. The need should not be defined by the proposed action.
    - Example 1: The need is not "to build a dam" but rather "to control flooding and prevent future flood damages and losses."
    - Example 2: The need is not "to build a 300-foot communications tower" but rather "to improve public safety and interoperable communications among first responders during an emergency event."
4. **Alternatives.** There should be some discussion of various alternatives to justify the EA.
    - No Action Alternative: This is what will happen if no action is taken or this proposed idea does not happen.
    - Action Alternatives: If this course of action is not taken, what are other courses of action? If the proposed project cannot happen, how else could the need be met?
5. **Affected Environment and Potential Impacts on a Single Animal or Plant Species.** In this section, describe the physical setting where the action will take place and give information on the existing environment for a species of concern. Then, discuss how that species may be affected by the proposed action and alternatives.

(Continued)

- Potential effects to the environment (e.g., ecosystem, climate)
- Describe how that environmental change may have potential impacts to your chosen plant and/or animal species (e.g., impacts on threatened or endangered status, habitat, food resources)

Example of an EA Topic

Texas is a very large state. With a land area of 268,597 square miles and almost 30 million people, transporting people from town to town is a serious need. Several times a week, more than 50,000 Texans travel back and forth between Houston and Dallas/Fort Worth. A high-speed rail system could help connect people from the southern part of the state (Houston) to northern parts of the state (Dallas/Fort Worth) in 90 minutes, helping to reduce road traffic and conserving gasoline and productive time lost to commuting.

However, where to locate the rail is important, as the 240-mile route may impact ecosystems and wildlife. Therefore, an ecological study was conducted to determine how wildlife may be affected. One concern is for the whooping crane, an endangered bird that migrates along the proposed high-speed rail route. The rail system may take away needed habitat and resources for the crane, driving it toward extinction. Therefore, the rail will avoid locating near or along major bodies of water (salt marshes and wetlands) where whooping cranes live and travel.

Alternatives are too costly (air travel) or take too long (automobile). High-speed rail also produces less carbon dioxide (CO_2) than airplanes and cars. It will also reduce cars on the road, which could reduce deaths by motor vehicles. If there is no action, Texans will lose jobs and economic gains.

3. Create a Plan

Conduct research on your chosen action in order to gather the information you will need to write your EA. Then create a plan for your EA. In your plan, make sure to (1) identify the community you want to work with, (2) describe one need of that community (either in industry, energy, transportation, or development), (3) identify the action that could be taken to meet that need, and (4) summarize the effects of that action on the environment. Use the Create a Plan graphic organizer (p. 193) for guidance.

4. Design and Create

Write your EA in these five parts: introduction, purpose, need, alternatives, and environmental impacts. Remember to reflect on the following questions:

- How does this action potentially affect the environment?
- What is an endangered or threatened species that would be affected?
- What are alternatives to this action?
- What happens if no action is taken?

5. Test and Evaluate

Share your EA with a peer for feedback. Ask for an evaluation of your work and consider ways your EA could be clearer. Have you made the best case for your EA?

6. Revise and Improve

Revise and make improvements to your EA based on feedback from your classmate. What are some ways you can use the input to refine your plan? You may choose to accept all or only some of the feedback. Be sure to justify your reasoning for using or not taking suggestions.

Create a Plan

What is the community you chose?

____

____

____

Describe one need of this community. Then summarize an action that could be taken to address this need.

Industry Need	Energy Need	Transportation Need	Development Need

Action to Meet Need	Action to Meet Need	Action to Meet Need	Action to Meet Need

Summarize the environmental effects of your chosen action.

____

____

____

TEACHER NOTES

THE TRIUMPH OF THE PIKA

UNDERSTANDING ENVIRONMENTAL IMPACTS ON SPECIES

A Case Study Using the Discovery Engineering Process

Lesson Overview

In this lesson, students explore the impact of environmental change on wildlife. The case study focuses on the pika, a mammal related to the rabbit. Although pika are very sensitive to heat, a group of them were able to survive a wildfire. A team of ecologists who happened to be using the animals as a control group in an experiment were able to figure out that they survived by using available natural resources as a buffer against the fire. Students will use data and maps to understand how environmental changes (including climate change) impact endangered and threatened species. They will also create a model to illustrate the effects of environmental change, using data on peppered moths from 19th-century England. Last, students will create environmental assessments (EAs) to evaluate an action taken in their community to meet a human need. In their EAs, they will evaluate the potential impacts of the action on local endangered or threatened species.

Lesson Objectives

By the end of this case study, students will be able to

- explore how species are impacted by human-influenced changes in the environment;
- examine and then model how change in the environment can alter species populations; and
- create an EA to evaluate the ecological impact of (proposed) human activity on a specific species in a specific location.

Use of the Case

Due to the nature of these case studies, teachers may elect to use any section of each case for their instructional needs. They are sequenced in order (scaffolded) so students think more deeply about the science involved in the case and develop an understanding of engineering in the context of science.

Curriculum Connections

Lesson Integration

This lesson may be taught during a unit on ecology and population dynamics for beginner biology courses. This lesson fits well into topics related to natural selection and human impacts on the environment.

Related Next Generation Science Standards

PERFORMANCE EXPECTATIONS

- MS-LS2-4. Construct an argument supported by empirical evidence that changes to physical or biological components of an ecosystem affect populations.
- MS-LS2-5. Evaluate competing design solutions for maintaining biodiversity and ecosystem services.
- MS-ESS3-3. Apply scientific principles to design a method for monitoring and minimizing a human impact on the environment.
- MS-ETS1-1. Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.
- HS-ESS3-1. Construct an explanation based on evidence for how the availability of natural resources, occurrence of natural hazards, and changes in climate have influenced human activity

SCIENCE AND ENGINEERING PRACTICES

- Asking Questions and Defining Problems
- Developing and Using Models
- Planning and Carrying out Investigations
- Analyzing and Interpreting Data
- Constructing Explanations and Designing Solutions
- Engaging in Argument From Evidence

CROSSCUTTING CONCEPTS

- Cause and Effect
- Systems and System Models
- Stability and Change

Related National Academy of Engineering Grand Challenges

- Restore and Improve Urban Infrastructure
- Develop Carbon Sequestration Methods
- Engineer the Tools of Scientific Discovery

Lesson Preparation

Before starting the lesson, it is helpful for students to have some understanding of human impacts on the environment, climate, and natural selection. Review the concepts of a controlled experiment and ecological succession before beginning the lesson so students can understand how scientists support what they know about climate change. Also review how to interpret data from maps and analyze layered data.

You will need to make copies of the entire student section for the class. Students will need internet access at various points in the lesson. Alternatively, you can project videos or print and distribute copies of online content for the class. Look at the Teaching Organizer (Table 9.2) for suggestions on how to organize the lesson.

For the Activity section, we suggest using green, black, yellow, white, and red construction paper. For the patterned pieces of paper or fabric, choose ones that have many of the same colors as the construction paper. Students can work in pairs. Each group will need five sheets of construction paper (one of each color), two patterned sheets of paper or fabric, and one bag of green, black, yellow, white, and red dots. Use a hole punch to create the dots. Groups will need 10 dots of each color. So for a class of 30 in which you would have 15 groups of two, punch out 150 dots per color. Place 10 dots of each color into a resealable bag for each group.

Materials

Per group

- ✓ 5 pieces of 8.5 × 11 in. construction paper, one of each color: green, black, yellow, white, and red
- ✓ 2 pieces of 8.5 × 11 in. patterned paper or fabric
- ✓ 1 bag of green, black, yellow, white, and red paper dots (at least 50 in all, 10 of each color)
- ✓ 1 pair of tweezers (to capture dots)

Time Needed

Up to 115 minutes

TABLE 9.2

Teaching Organizer

Section	Time Suggested	Materials Needed	Additional Considerations
The Case	10 minutes	Student pages	Activity done individually in class or as homework prior to class
Investigate and Explain	10 minutes	Student pages	Activity done individually or in pairs
Activity	20 minutes	Student pages; 5 pieces of 8.5 × 11 in. construction paper (one of each color: green, black, yellow, white, and red); 2 pieces of 8.5 × 11 in. patterned paper or fabric; 1 bag of green, black, yellow, white, and red paper dots (at least 50 in all, 10 of each color); 1 pair of tweezers (to capture dots)	Activity done individually or in pairs
Apply and Analyze	10–15 minutes	Student pages, internet access	Individual activity
Design Challenge	45–60 minutes	Student pages, internet access	Small-group activity

Vocabulary

- camouflage
- climate change
- control group
- dens
- ecologist
- endangered
- environmental assessment
- experimental group
- extinct
- dietary generalists
- dietary specialists
- habitat specialists
- habitat generalists
- herbivorous
- indigenous
- insulated
- introduced
- invasive
- mammal
- mark-release-recapture
- melanic (melanin)
- phenotype
- pika
- population
- species
- wildlife

Extensions

- The Activity section can be expanded to further explore population dynamics. Tell students that when they "prey" on their dots, the dots that "survive" can go on to "reproduce." After each round in a trial, students can add three more dots of the same colors that have survived to represent the offspring with the same traits as the surviving parent. You can elect to have students time their rounds with a stopwatch to keep up the pace of the activity.
- The Apply and Analyze section can be extended by modeling population size estimation (*www.learner.org/jnorth/tm/monarch/EstimateMRR.html*). This activity requires minimal materials, and students will garner a better understanding of the MRR method.
- The Design Challenge can be extended into an environmental impact assessment, or EIA (*https://link.springer.com/referenceworkentry/10.1007%2F1-4020-4494-1_117*). The EIA expands upon an EA with more information into the mitigation strategies discussed in the EA.

Assessment

Use the Teacher Answer Key to check the answers to section questions. You can evaluate the students' EAs to assess the Design Challenge. Their EAs should be divided into five parts: introduction, purpose, need, alternatives, and environmental impacts. The students should include all the information requested in the Environmental Assessment Components template on page 190. In their EAs, students should identify an action that might be taken in their community to address a human need. They should include research on how that specific action may impact a threatened or endangered species within an environmental context. During the Design Challenge, students should also be able to provide constructive peer reviews on classmates' EAs and incorporate the feedback of others into their own EAs.

Teacher Answer Key

Recognize, Recall, and Reflect

1. **In Dr. Varner's experiment, which pika population was the experimental group? Why? Which pika population was the control? Why?**

   Experimental Group: Pika living in the gorge. Pika normally only live in the mountains, so it is strange to find a pika population at sea level. Control Group: Pika living on Mount Hood. This is because Pika normally only live in the mountains, so it is a "normal" group for comparison.

2. **Pika are described as habitat specialists, yet dietary generalists. What does this mean?**

   Pika can only live in a narrow range of environmental conditions (i.e., only in mountain areas, cool temperatures). This makes them habitat specialists. However, they can eat a wide variety of plants, making them dietary generalists.

3. **What were two recommendations made by the researchers to help sensitive species after natural disasters?**

   First recommendation: Maintain natural features like rock faces to provide refuges for sensitive species during natural disasters like wildfires. Second recommendation: Maintain local, indigenous wildlife so that after a natural disaster, animal and plant species may rebound.

Investigate and Explain

1. **Look at Map A. In which two states do most of the observed pika (black spots) live? Why are there suitable pika habitat areas (light-gray areas) that don't actually have any pika?**

   Utah and Wyoming. The black spots represent locations where pika populations have been observed in the wild. Habitat areas are places that could support the pika, but that does not mean pika actually live there.

2. **What is the general trend of the American pika's habitat (dark-gray areas) as temperature increases from low (Map B), to medium (Map C), to high (Map D)?**

   As temperature increases, the habitats available for the pika decrease.

3. **As temperatures increase from low (Map B), to medium (Map C), to high (Map D), what is the general trend of the American pika's habitat (dark-gray areas)?**

   California. Student answers may vary. They could hypothesize that California has more protected areas or rock faces that provide thermal buffers (mentioned in the case study) to protect the pika. California also has stricter government regulations that may help protect vulnerable species.

Activity Questions, Part I

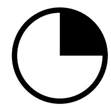
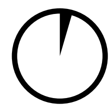
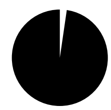
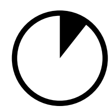
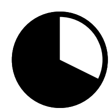
1. **Visualize the data so you can begin to draw conclusions. Create a pie chart using the outline of England. The first location has been done for you.**

   a. **Calculate the percentage of each moth per sampling area.**

   b. **Use the calculations to create a pie chart for each sampling area.**

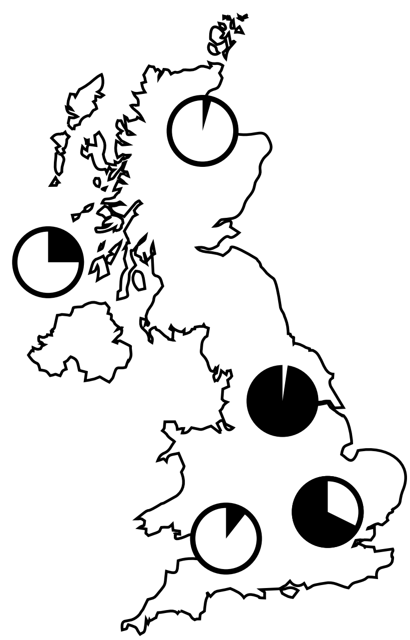
   c. **Plot your data to the correct geographic area on the map of England provided.**

      The key to the chart and map are shown on the following page.

Sampling Location #	Percent Light-Colored moths	Percent Dark-Colored Moths	Pie Chart	Geographic Location
1	*698/926 = 0.754* *0.75 × 100 = 75%*	*228/926 = 0.246* *0.25 × 100 = 25%*		*Northwest England and Ireland*
2	*923/945 = 0.977* *0.98 × 100 = 98%*	*22/945 = 0.023* *0.02 × 100 = 2%*		*Northeast England and Scotland*
3	*18/946 = 0.019* *0.02 × 100 = 2%*	*928/946 = 0.981* *0.98 × 100 = 98%*		*Central England*
4	*840/932 = 0.901* *0.90 × 100 = 90%*	*92/932 = 0.098* *0.10 × 100 = 10%*		*Southwest England*
5	*280/921 = 0.304* *0.30 × 100 = 30%*	*641/921 = 0.695* *0.70 × 100 = 70%*		*Southeast England*

2. In which regions are light-colored moths most prevalent? In which regions are dark-colored moths most prevalent? How does distance from a factory affect the prevalence of each moth variety?

Student answers may vary but should relate these concepts from the data: The melanic moth phenotype is most prevalent in Central and Southeastern England. The prevalence of melanic moths increases with proximity to a factory.



Activity Questions, Part II

1. **In this modeling activity, what were the relationships between totals (frequencies) of prey (dot colors) to their environment (paper colors)?**

   Students' answers may vary but should relate the following concepts from the data.

   a. **When was the prey the easiest to see?**

      When the color of the prey contrasted with the environment, meaning the prey was not camouflaged.

   b. **When was the prey most difficult to see?**

      When the color of the prey was the same as the environment, meaning the prey was camouflaged.

   c. **How does the environment affect the traits that are common in a population?**

      Individuals in the population that are most noticeable to predators (not camouflaged to the environment) are eaten. Those that are eaten do not reproduce and pass on their traits (demonstrated as phenotypes) to the next generation. Therefore, the population's traits will shift to those that can survive predation (and reproduce) by being best to the environment adapted (camouflaged, and therefore able to avoid predators).

Apply and Analyze

1. **Imagine you were conducting an MRR study of the Mexican spider monkey, a critically endangered species. (According to the International Union for Conservation of Nature, a critically endangered species is defined as having an extreme risk of extinction in the wild. You are able to mark 75 monkeys (categorized as Marked, or M) and release them back into their habitat. When you return, you capture 75 monkeys and note that 45 are recaptures (categorized as Recaptures, or R) and 30 are not marked (categorized as Unmarked, or U). Using this equation ($X = [(U + R)/R]M$), what is the total number (X) of monkeys you estimate to be in the wild population? Show your work:**

   $X = 125 = [(30 + 45)/45]75)$

2. **The Mexican spider monkey is one of five subspecies of the Geoffroy's spider monkey species. The other subspecies are the Nicaraguan spider monkey, the hooded spider monkey, the ornate spider monkey, and the Yucatán spider monkey. It is important that during MRR studies that the correct species or subspecies is being captured, marked, recaptured, and counted.**

What are three ways you would ensure that you and your research team are marking and recapturing the correct monkeys?

Students' answers may vary but should be aligned to methods delineated in the article to reduce human sampling error in ecological fieldwork. Here are some examples:

- *Making a close examination of field marks to ensure the animal is the correct subspecies*
- *Ensuring that the MMR occurs in the exact habitat of the subspecies*
- *Using appropriate trapping techniques*
- *Differentiating between adults and juveniles*
- *Accounting for male and female sex differences*

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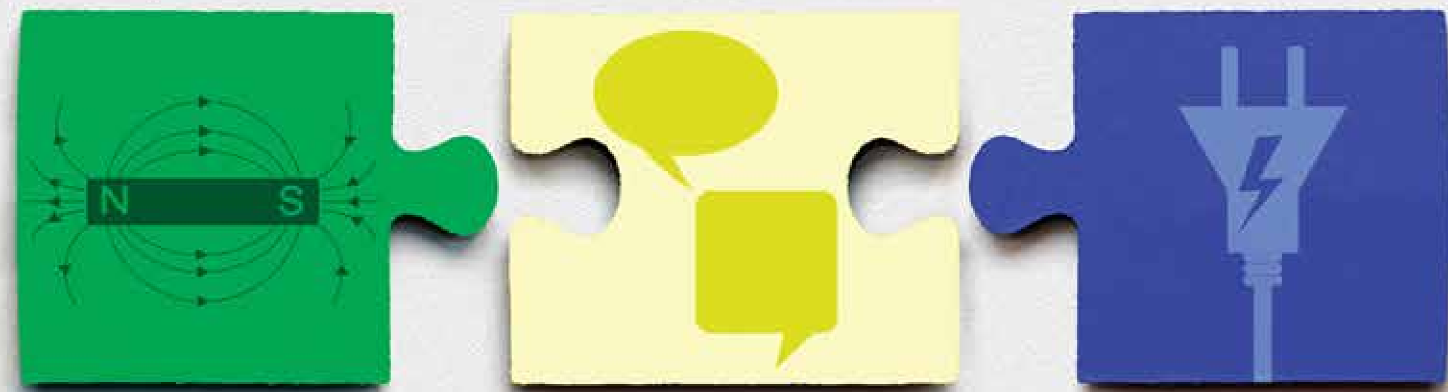
Argument-Driven Inquiry in PHYSICS

VOLUME 2



ELECTRICITY AND MAGNETISM LAB INVESTIGATIONS for GRADES 9–12

Todd L. Hutner, Victor Sampson, Adam LaMee,
Daniel FitzPatrick, Austin Batson, and
Jesus Aguilar-Landaverde

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PREFACE

A Framework for K–12 Science Education (NRC 2012; henceforth referred to as the *Framework*) and the *Next Generation Science Standards* (NGSS Lead States 2013; henceforth referred to as the *NGSS*) call for a different way of thinking about why we teach science and what we expect students to know by the time they graduate high school. As to why we teach science, these documents emphasize that schools need to

> ensure by the end of 12th grade, *all* students have some appreciation of the beauty and wonder of science; possess sufficient knowledge of science and engineering to engage in public discussions on related issues; are careful consumers of scientific and technological information related to their everyday lives; are able to continue to learn about science outside school; and have the skills to enter careers of their choice, including (but not limited to) careers in science, engineering, and technology. (NRC 2012, p. 1)

The *Framework* and the *NGSS* are based on the idea that students need to learn science because it helps them understand how the natural world works, because citizens are required to use scientific ideas to inform both individual choices and collective choices as members of a modern democratic society, and because economic opportunity is increasingly tied to the ability to use scientific ideas, processes, and habits of mind. From this perspective, it is important to learn science because it enables people to figure things out or to solve problems.

These two documents also call for a reappraisal of what students need to know and be able to do by the time they graduate from high school. Instead of teaching with the goal of helping students remember facts, concepts, and terms, the *Framework* and *NGSS* now prioritize helping students to become *proficient* in science. To be considered proficient in science, the *Framework* suggests that students need to understand four disciplinary core ideas (DCIs) in the physical sciences,[1] be able to use seven crosscutting concepts (CCs) that span the various disciplines of science, and learn how to participate in eight fundamental scientific and engineering practices (SEPs; called science and engineering practices in the *NGSS*). The DCIs are key organizing principles that have broad explanatory power within a discipline. Scientists use these ideas to explain the natural world. The CCs are ideas that are used across disciplines. These concepts provide a framework or a lens that people can use to explore natural phenomena. As a result, these concepts often influence what people focus on or pay attention to when they attempt to understand how something works or why something happens. The SEPs are the different activities that scientists and engineers engage in as they attempt to generate new concepts, models, theories, or laws that are both valid and reliable. All three of these dimensions of science are

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1 Throughout this book, we use the term *physical sciences* when referring to the disciplinary core ideas of the *Framework* (in this context the term refers to a broad collection of scientific fields), but we use the term *physics* when referring to courses at the high school level (as in the title of the book).

important. Students not only need to know about the DCIs, CCs, and SEPs but also must be able to use all three dimensions at the same time to figure things out or to solve problems. These important DCIs, CCs, and SEPs are summarized in Figure 1.

FIGURE 1

The three dimensions of science in *A Framework for K–12 Science Education* and the *Next Generation Science Standards*

Science and engineering practices	Crosscutting concepts
1. Asking Questions and Defining Problems 2. Developing and Using Models 3. Planning and Carrying Out Investigations 4. Analyzing and Interpreting Data 5. Using Mathematics and Computational Thinking 6. Constructing Explanations and Designing Solutions 7. Engaging in Argument From Evidence 8. Obtaining, Evaluating, and Communicating Information	1. Patterns 2. Cause and Effect: Mechanism and Explanation 3. Scale, Proportion, and Quantity 4. Systems and System Models 5. Energy and Matter: Flows, Cycles, and Conservation 6. Structure and Function 7. Stability and Change
Disciplinary core ideas for the physical sciences*	
• PS1: Matter and Its Interactions • PS2: Motion and Stability: Forces and Interactions • PS3: Energy • PS4: Waves and Their Applications in Technologies for Information Transfer	

* These disciplinary core ideas represent one of the four subject areas in the *Framework* and the *NGSS;* the other subject areas are life sciences, earth and space sciences, and engineering, technology, and applications of science.

Source: Adapted from NRC 2012 and NGSS Lead States 2013.

To help students become proficient in science in ways described by the National Research Council in the *Framework,* teachers will need to use new instructional approaches that give students an opportunity to use the three dimensions of science to explain natural phenomena or develop novel solutions to problems. This is important because traditional instructional approaches, which were designed to help students "learn about" the concepts, theories, and laws of science rather than help them learn how to "figure out" how or why things work, were not created to foster the development of science proficiency inside the classroom. To help teachers make this instructional shift, this book provides 17 laboratory investigations designed using an innovative approach to lab instruction called argument-driven inquiry (ADI). This approach is designed to promote and support three-dimensional instruction inside classrooms by giving students an opportunity to use DCIs, CCs, and SEPs to construct and critique claims about how things work or why things happen. The lab activities described in this book will also enable students to develop the disciplinary-based literacy skills outlined in the *Common Core State Standards* for English language arts (NGAC and CCSSO 2010) because ADI gives students an opportunity to give presentations to their peers, respond to audience questions and critiques, and then write, evaluate, and revise reports as part of each lab. In addition, these investigations will help students learn many of the mathematical ideas and practices outlined in the *Common Core State Standards* for mathematics (NGAC and CCSSO 2010). Use of these labs, as a result, can help teachers align their teaching with current recommendations for improving classroom instruction in science and for making physics more meaningful for students.

The labs included in this book all focus on the topics of electricity and magnetism. Thus, these labs primarily focus on two of the four physical sciences DCIs from the *NGSS* that are outlined in Figure 1 (although some labs do align with other DCIs as well). These two DCIs are Motion and Stability: Forces and Interactions (PS2) and Energy (PS3). The other two DCIs for physical sciences from the *NGSS* are the focus of other books in the ADI series. All the labs, however, are well aligned with at least two of the seven CCs and seven of the eight SEPs. In addition, the labs in this book are well aligned with the big ideas and science practices for Advanced Placement (AP) Physics 1, 2, and C: Electricity and Magnetism (see Figure 2, p. xii). These labs, as a result, can be used in a wide range of physics courses, including, but not limited to, a conceptual physics course for 9th or 10th graders that is aligned with the *NGSS,* an introductory physics course for juniors or seniors, or even an AP Physics 1, 2, or C: Electricity and Magnetism course.

Finally, this book is the second volume in the ADI Physics series. The first volume has 23 labs focused on mechanics. The structure of the lab handouts is the same in both volumes, making the classroom use of both lab manuals seamless from a structural point of view.

FIGURE 2

Selected big ideas and science practices for AP Physics 1 and 2 and the content areas and science practices for AP Physics C: Electricity and Magnetism

AP Physics 1 and 2 big ideas	AP Physics 1 and 2 science practices
1. Systems: Objects and systems have properties such as mass and charge. Systems may have internal structure. 2. Fields: Fields existing in space can be used to explain interactions. 3. Force Interactions: The interactions of an object with other objects can be described by forces. 4. Change: Interactions between systems can result in changes in those systems. 5. Conservation: Changes that occur as a result of interactions are constrained by conservation laws.	1. Modeling: Use representations and models to communicate scientific phenomena and solve scientific problems. 2. Mathematical Routines: Use mathematics appropriately. 3. Scientific Questioning: Engage in scientific questioning to extend thinking or to guide investigations. 4. Experimental Methods: Plan and implement data collection strategies in relation to a particular scientific question. 5. Data Analysis: Perform data analysis and evaluation of evidence. 6. Argumentation: Work with scientific explanations and theories. 7. Making Connections: Connect and relate knowledge across various scales, concepts, and representations in and across domains.

AP Physics C: Electricity and Magnetism content areas

- Electrostatics
- Conductors, capacitors, dielectrics
- Electric circuits
- Magnetic fields
- Electromagnetism

AP Physics C: Electricity and Magnetism laboratory objectives

1. Visual representations
2. Question and method
3. Representing data and phenomena
4. Data analysis
5. Theoretical relationships
6. Mathematical routines
7. Argumentation

Source: Adapted from *https://apcentral.collegeboard.org/pdf/ap-physics-1-course-and-exam-description.pdf?course=ap-physics-1-algebra-based* (for AP Physics 1); *https://apcentral.collegeboard.org/pdf/ap-physics-2-course-and-exam-description.pdf?course=ap-physics-2-algebra-based* (for AP Physics 2); *https://apcentral.collegeboard.org/pdf/ap-physics-c-electricity-and-magnetism-course-and-exam-description.pdf?course=ap-physics-c-electricity-and-magnetism* (for AP Physics C: Electricity and Magnetism).

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Adam LaMee started teaching high school physics in Florida in 2003 and is currently the PhysTEC Teacher-in-Residence at the University of Central Florida (*http://sciences.ucf.edu/physics/phystec*). He received bachelor's degrees in physics and anthropology from FSU. Adam is a Quarknet Teaching and Learning Fellow, helped design Florida's 6–12 science courses and teacher certification exams, contributed to the Higgs boson discovery with CERN's CMS (Compact Muon Solenoid) experiment, and has researched game-based assessment and performance assessment alternatives to large-scale testing. Learn more about Adam's work at *adamlamee.com*.

Daniel FitzPatrick is a teacher, researcher, and developer of instructional methods and materials. He received a BS and MA in mathematics from UT-Austin and has taught both middle and high school mathematics in public and charter schools. Daniel previously served as a clinical assistant professor and master teacher in the UTeach program at UT-Austin before working full time on research in argumentation in mathematics.

Austin Batson is a physics teacher and assistant coach at Tom Glenn High School in Leander Independent School District, located in the Austin, Texas, area. He received a BS in biomedical engineering and a BA in the Plan II Honors Program from UT-Austin. After graduating, he spent a year in Poland teaching at the University of Bialystok through a Fulbright English Teaching Fellowship. Back in the United States, Austin helped open a new public high school, established the physics program, and helped lead a revamp of the district physics curriculum. His current instructional goals include implementing a blended learning classroom and increasing the amount of argument-driven inquiry practiced in his school.

Jesus Aguilar-Landaverde has been a physics, engineering, and astronomy teacher at all levels in high school for five years. During the same time, he has been a professional tutor in all secondary STEM subjects as well as three languages. During this time, he has designed dozens of inquiries, investigations, labs, and practicums to engage students at various stages in their development.

Teacher Notes

Lab 17. Electromagnetism: Why Does the Battery-and-Magnet "Car" Roll When It Is Placed on a Sheet of Aluminum Foil?

Purpose

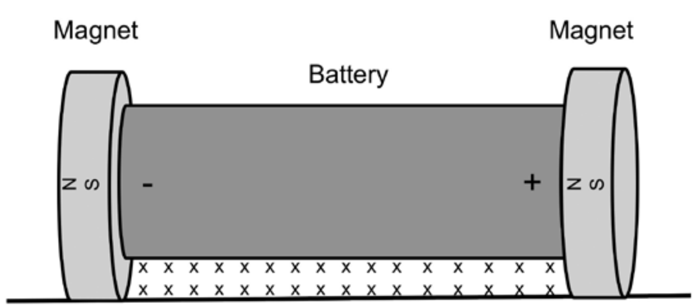
The purpose of this lab is for students to *apply* what they know about the disciplinary core idea (DCI) of Types of Interactions (PS2.B) from the *NGSS* and about electromagnetism by having them develop a model to explain the movement of the battery-and-magnet "car." In addition, this lab can be used to help students understand two big ideas from AP Physics: (a) fields existing in space can be used to explain interactions and (b) the interactions of an object with other objects can be described by forces. This lab also gives students an opportunity to learn about the crosscutting concepts (CCs) of (a) Systems and System Models and (b) Stability and Change from the *NGSS*. As part of the explicit and reflective discussion, students will also learn about (a) how scientific knowledge changes over time and (b) how scientists use different methods to answer different types of questions.

Underlying Physics Concepts

To understand the physics underlying this lab, we start by recognizing that the magnets and the aluminum foil are electric conductors. Thus, when the battery-and-magnet car (henceforth referred to as just "the car") is placed on the aluminum foil, a closed circuit is formed. This leads to a current moving through the magnets and the foil. According to the Biot-Savart Law, the flow of current will create a magnetic field around the current. The Biot-Savart law also states that for a conducting loop carrying current, a magnetic field will be established inside the loop. Figure 17.1 shows the creation of the magnetic field created by the electric current flowing through the loop composed of the battery, magnets, and aluminum foil.

FIGURE 17.1

The magnetic field created by an electric current from the closed circuit formed when the battery-and-magnet car is placed on the aluminum foil



To determine the direction of the magnetic field, we can use a right-hand rule for the magnetic field created by a current-carrying wire to determine that the magnetic field created by the current will be pointing into the page. Notice that the magnetic field will only be established inside the loop of current. This is important for understanding the motion of the car.

Before placing the car on the aluminum foil, a magnetic field also existed around the car due to the presence of the two magnets on either end of the car. Figure 17.2 shows the magnetic field running from right to left, because the north pole of both magnets is pointing toward the left. We use dashed lines for the magnetic field due to the two permanent magnets in Figures 17.2 and 17.3 to avoid confusion with other lines in the figure. Because both magnets point in the same direction, a relatively uniform magnetic field is established around the battery.

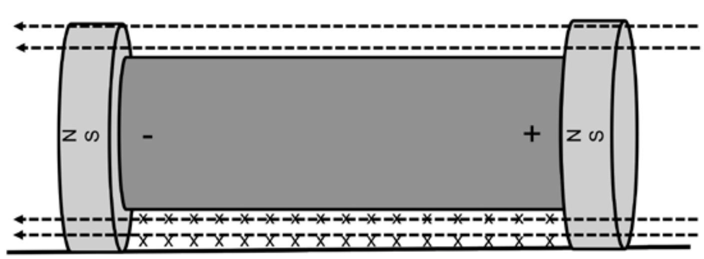
FIGURE 17.2

The magnetic field around the battery due to the magnets on the ends of the battery. The north pole of both magnets faces to the left.

Thus, when we place the car down on the aluminum foil, we have two magnetic fields—one established by the magnets themselves (Figure 17.2) and one from the magnetic field created by the flow of the current (Figure 17.1). Figure 17.3 shows the combination of magnetic fields surrounding the battery when we place the car on the aluminum foil.

FIGURE 17.3

The magnetic fields when the car is placed on the aluminum foil



Notice how there is an additional magnetic field below the battery due to the flow of current but not above the battery. This field will interact with the field established by magnets themselves and create an unbalanced force. This is the force that causes the car to move.

It is important to note that the force exerted on the car exists only below the battery, not above the battery. This force then creates a torque on the magnets, as the force is exerted some radial distance away from their center. It is the torque on the lower half of the magnets that causes the car to move rotationally. It is also important to note that the direction the magnets face is the same. In Figure 17.3, the north pole of both magnets is to the left. This is important because it creates a uniform magnetic field from the magnets. If the magnets face in opposite directions, the magnetic field underneath the battery due to the magnets will not be uniform. This will result in different torques on each wheel. When students conduct the lab, it is OK to let them place the magnets in opposite directions, because this will lead to the car not moving and then they will need to establish why the car does not move under these circumstances.

Once the car starts moving, the physics becomes increasingly complex because the current will also be moving down the aluminum foil as the car moves and the wheels of the car will be rotating. Both magnetic fields will be moving, so students will need to account for additional factors. To mathematically represent this situation, complex sets of differential equations are necessary—mathematics that are beyond the scope of an introductory high school physics course and the AP physics courses. For this reason, we have chosen to present only a conceptual description of the underlying physics for this lab.

Students may establish quantitative relationships between the rotational acceleration of the car and the voltage of the battery and strength of the magnet. As the voltage of the battery increases, the angular acceleration of the car will also increase. This is because a higher voltage will create a larger current, leading to a greater magnetic field inside the loop. Similarly, strong magnets will create a larger magnetic field surrounding the battery. An increase in either magnetic field will lead to an increase in the torque acting on the wheels.

Timeline

The instructional time needed to complete this lab investigation is 170–230 minutes. Appendix 3 (p. 421) provides options for implementing this lab investigation over several class periods. Option C (230 minutes) should be used if students are unfamiliar with scientific writing, because this option provides extra instructional time for scaffolding the writing process. You can scaffold the writing process by modeling, providing examples, and providing hints as students write each section of the report. Option C should also be used if you are introducing students to digital sensors, the data analysis software, and/or the video analysis software. Option D (170 minutes) should be used if students are familiar with scientific writing and have developed the skills needed to write an investigation report on their own. In option D, students complete stage 6 (writing the investigation report) and stage 8 (revising the investigation report) as homework.

Materials and Preparation

The materials needed to implement this investigation are listed in Table 17.1. The equipment can be purchased from a science supply company such as Flinn Scientific, PASCO, Vernier, or Ward's Science. We also suggest companies that specialize in magnets, such as K&J Magnetics, as a source for the magnets for this lab. Video analysis software can be purchased from Vernier (Logger *Pro*) or PASCO (SPARKvue or Capstone). These companies also have apps that can be used on Apple- or Android-based tablets and cell phones. We recommend consulting with your school's information technology coordinator to determine the best option for your students.

TABLE 17.1

Materials list for Lab 17

Item	Quantity
Consumables	
AA batteries	2 per group
C batteries	2 per group
D batteries	2 per group
Duct tape	As needed
Aluminum foil	As needed
Wax paper	As needed
Butcher paper	As needed
Equipment and other materials	
Safety glasses with side shields or safety goggles	1 per student
Disc-shaped neodymium magnets	2 per group
Disc-shaped ceramic magnets (ideally, the same size as the neodymium magnets)	2 per group
Voltmeter	1 per group
Ammeter	1 per group
Multimeter	1 per group
Meterstick	1 per group

Continued

Table 17.1 (*continued*)

Item	Quantity
Stopwatch	1 per group
Electronic or triple beam balance	1 per group
Electronic pole identifier	1 per group
Investigation Proposal A (optional)	1 per group
Whiteboard, 2'× 3'*	1 per group
Lab Handout	1 per student
Peer-review guide and teacher scoring rubric	1 per student
Checkout Questions	1 per student
Equipment for digital interface measurements and video analysis (optional)	
Digital interface with USB or wireless connections	1 per group
Magnetic field sensor	1 per group
Current measurement sensor	1 per group
Voltage measurement sensor	1 per group
Video camera	1 per group
Computer or tablet with appropriate data analysis and video analysis software installed	1 per group

* As an alternative, students can use computer and presentation software such as Microsoft PowerPoint or Apple Keynote to create their arguments.

Use of video analysis software is optional, but using this software will allow students to more precisely measure the movement of the car.

You should conduct a demonstration with two magnets connected to a battery and then placed on a sheet of aluminum foil before students begin their investigation. Learn how to conduct the demonstration before the lab begins; the demonstration provides the context for this lab investigation, so you want to make sure it works correctly.

Be sure to use a set routine for distributing and collecting the materials during the lab investigation. One option is to set up the materials for each group at each group's lab station before class begins. This option works well when there is a dedicated section of the classroom for lab work and the materials are large and difficult to move. A second option is to have all the materials on a table or cart at a central location. You can then assign a member of each group to be the "materials manager." This individual is responsible for collecting all the materials his or her group needs from the table or cart during class and for returning all the materials at the end of the class. This option works well when the materials are small and easy to move (such as magnets, wire, and bulbs). It also makes it easy to inventory the materials at the end of the class before students leave for the day.

Safety Precautions and Laboratory Waste Disposal

Remind students to follow all normal lab safety rules. In addition, tell students to take the following safety precautions:

1. Wear sanitized safety glasses with side shields or safety goggles during lab setup, hands-on activity, and takedown.
2. Never put consumables in their mouth.
3. Wire and other metals with electric current flowing through them may get hot. Use caution when handling components of a closed circuit.
4. Us caution in working with sharp objects (e.g., wires) because they can cut or puncture skin.
5. Neodymium magnets should be at least 30 cm away from sensitive electronic and storage devices. These strong magnets could affect the functioning of pacemakers and implanted heart defibrillators.
6. Big magnets have a very strong attractive force. Unsafe handling could cause jamming of fingers or skin in between magnets. This may lead to contusions and bruises.
7. Neodymium magnets are brittle. Colliding magnets could crack, and sharp splinters could be catapulted away for several meters and injure eyes.
8. Wash their hands with soap and water when they are done collecting the data.

Batteries may be stored for future use. When batteries need replacing, dispose of old batteries according to manufacturer's recommendations.

Topics for the Explicit and Reflective Discussion

Reflecting on the Use of Core Ideas and Crosscutting Concepts During the Investigation

Teachers should begin the explicit and reflective discussion by asking students to discuss what they know about the core ideas they used during the investigation. The following are some important concepts related to the core ideas of types of interactions and electromagnetism that students need to use to explain the motion of the car:

- A field associates a value of some physical quantity with every point in space. Fields are a model that physicists use to describe interactions that occur over a distance. Fields permeate space, and objects experience forces due to their interaction with a field.

- Objects can interact with multiple fields at once, and the vector sum of the fields will determine the motion of the object.
- A current flowing through a conducting material will create a magnetic field around the material. If the current is flowing through a loop, a magnetic field is established inside the loop. The magnitude of the field is proportional to the magnitude of the current in the conducting material/loop. The direction of the magnetic field can be established using a right-hand rule.
- Torque is a measure of force applied perpendicular to a lever arm multiplied by the distance from the point of rotation. Torque is directly proportional to angular acceleration.

To help students reflect on what they know about electromagnetism, fields, and forces, we recommend showing them two or three images using presentation software that help illustrate these important ideas. You can then ask the students the following questions to encourage them to share how they are thinking about these important concepts:

1. What do we see going on in this image?
2. Does anyone have anything else to add?
3. What might be going on that we can't see?
4. What are some things that we are not sure about here?

You can then encourage students to think about how CCs played a role in their investigation. There are at least two CCs that students need to use to determine why the car moves: (a) Systems and System Models and (b) Stability and Change (see Appendix 2 [p. 417] for a brief description of these CCs). To help students reflect on what they know about these CCs, we recommend asking them the following questions:

1. In this investigation, you had to define your system under study. What assumptions did you have to make about the system in order to conduct your investigation?
2. You made models of your system in order to explain how it works. What types of models did you use during this investigation?
3. Your models allowed you to identify factors that affect the rates of change in your system. Why is it important to identify the factors that affect rates of change in systems?
4. What rates of change did you model during this investigation? What additional information would you have needed to model your system using a function?

You can then encourage the students to think about how they used all these different concepts to help answer the guiding question and why it is important to use these ideas to help justify their evidence for their final arguments. Be sure to remind your students to explain why they included the evidence in their arguments and make the assumptions underlying their analysis and interpretation of the data explicit in order to provide an adequate justification of their evidence.

Reflecting on Ways to Design Better Investigations

It is important for students to reflect on the strengths and weaknesses of the investigation they designed during the explicit and reflective discussion. Students should therefore be encouraged to discuss ways to eliminate potential flaws, measurement errors, or sources of uncertainty in their investigations. To help students be more reflective about the design of their investigation and what they can do to make their investigations more rigorous in the future, you can ask them the following questions:

1. What were some of the strengths of the way you planned and carried out your investigation? In other words, what made it scientific?
2. What were some of the weaknesses of the way you planned and carried out your investigation? In other words, what made it less scientific?
3. What rules can we make, as a class, to ensure that our next investigation is more scientific?

Reflecting on the Nature of Scientific Knowledge and Scientific Inquiry

This investigation can be used to illustrate two important concepts related to the nature of scientific knowledge and the nature of scientific inquiry: (a) how scientific knowledge changes over time and (b) how scientists use different methods to answer different types of questions (see Appendix 2 [p. 417] for a brief description of these concepts). Be sure to review these concepts during and at the end of the explicit and reflective discussion. To help students think about these concepts in relation to what they did during the lab, you can ask them the following questions:

1. Scientific knowledge can and does change over time. Can you tell me why it changes?
2. Can you work with your group to come up with some examples of how scientific knowledge related to electricity and magnetism has changed over time? Be ready to share in a few minutes.
3. There is no universal step-by-step scientific method that all scientists follow. Why do you think there is no universal scientific method?
4. Think about what you did during this investigation. How would you describe the method you used to understand why the battery-and-magnet car starts rolling? Why would you call it that?

You can also use presentation software or other techniques to encourage your students to think about these concepts. You can show examples of how our thinking about electricity and magnetism has changed over time (and continues to change as scientists search for a grand unified theory) and ask students to discuss what they think led to those changes. You can show one or more images of a "universal scientific method" that misrepresent the nature of scientific inquiry (see, e.g., *https://commons.wikimedia.org/wiki/File:The_Scientific_Method_as_an_Ongoing_Process.svg*) and ask students why each image is *not* a good representation of what scientists do to develop scientific knowledge. You can also ask students to suggest revisions to the image that would make it more consistent with the way scientists develop scientific knowledge. Be sure to remind your students that it is important for them to understand what counts as scientific knowledge and how that knowledge develops over time in order to be proficient in science.

Hints for Implementing the Lab

- Allowing students to design their own procedures for collecting data gives students an opportunity to try, to fail, and to learn from their mistakes. However, you can scaffold students as they develop their own procedure by having them fill out an investigation proposal. The proposals provide a way for you to offer students hints and suggestions without telling them how to do it. You can also check the proposals quickly during a class period. For this lab we suggest using Investigation Proposal A.
- Learn how to set up the battery-and-magnet car and how to use the equipment before the lab begins. If you set up the magnets improperly, the car will not move. It is also important for you to know how to use the equipment so you can help students when technical issues arise.
- When setting up the demonstration to introduce the lab, make sure that the north poles of the magnets face in the same direction. This establishes a uniform magnetic field around the battery and will result in the car moving. If the magnets' north poles face in opposite directions, the car will not move.
- Allow the students to become familiar with the equipment as part of the tool talk before they begin to design their investigation. Give them 5–10 minutes to examine the equipment and materials before they begin designing their investigations. This gives students a chance to see what they can and cannot do with the equipment.
- The resistance in the circuit comprised of the battery, magnets, and aluminum foil is minimal, so the battery will deplete rather quickly. We suggest providing fresh batteries to each group as they begin to collect data. Because of this, we also suggest using the investigation proposal guide before providing groups with batteries as a way to minimize students' undirected use of the batteries.

- The performance of the magnet car will be improved by using flat aluminum foil. If the foil is wrinkled, this will cause the current to flow in random directions and not directly underneath the battery.
- If you do not have an electronic pole identifier for each group, you can identify the north pole on the magnets prior to class and then place a small sticker on the north pole of each magnet.
- In the lab materials, we have included butcher paper and wax paper, because students must show that the car is not just interacting with Earth's magnetic field to produce the motion. We anticipate that most groups will not initially think of this possibility. This is a good opportunity to discuss initial assumptions and how we often need to run experiments to rule out other possible explanations.
- If students want to test the relationship between the voltage of the battery and the angular acceleration, you can either give them batteries with higher voltage (e.g., 3V batteries, which are sold by Duracell and Energizer) or have them tape two 1.5V batteries together in series.
- Be sure to allow students to go back and re-collect data at the end of the argumentation session. Students often realize that they made numerous mistakes when they were collecting data as a result of their discussions during the argumentation session. The students, as a result, will want a chance to re-collect data, and the re-collection of data should be encouraged when time allows. This also offers an opportunity to discuss what scientists do when they realize a mistake is made inside the lab.

If students use digital interface measurement equipment and video analysis

- We suggest allowing students to familiarize themselves with the sensors, data analysis software, and video analysis software before they finalize the procedure for the investigation, especially if they have not used such software previously. This gives students an opportunity to learn how to work with the software and to improve the quality of the data they collect and the video they take.
- Remind students to follow the user's guide to correctly connect any sensors to avoid damage to lab equipment.
- Remind students to hold the video camera as still as possible. Any movement of the camera will introduce error into their analysis. If using actual camcorders, we recommend using a tripod to hold the camera steady. If students are using a camera on a cell phone or tablet, we recommend using a table to help steady the camera.
- Remind students to place a meterstick in the same field of view as the motion they are capturing with the video camera. Also, the meterstick should be approximately the same distance from the camera as the motion. Most video analysis software requires the user to define a scale in the video (this allows the software to establish distances and, subsequently, other variables dependent on distance and displacement).

Connections to Standards

Table 17.2 highlights how the investigation can be used to address specific performance expectations from the *NGSS;* learning objectives from AP Physics 1 and 2; learning objectives from AP Physics C: Electricity and Magnetism; *Common Core State Standards for English Language Arts* (*CCSS ELA*); and *Common Core State Standards for Mathematics* (*CCSS Mathematics*).

TABLE 17.2

Lab 17 alignment with standards

***NGSS* performance expectation**	• HS-PS2-5: Plan and conduct an investigation to provide evidence that an electric current can produce a magnetic field and that a changing magnetic field can produce an electric current.
AP Physics 1 and AP Physics 2 learning objectives	• 1.A.5.2: Construct representations of how the properties of a system are determined by the interactions of its constituent substructures. • 2.D.1.1: Apply mathematical routines to express the force exerted on a moving charged object by a magnetic field. • 3.C.3.2: Plan a data collection strategy appropriate to an investigation of the direction of the force on a moving electrically charged object caused by a current in a wire in the context of a specific set of equipment and instruments, and analyze the resulting data to arrive at a conclusion. • 4.E.1.1: Use representations and models to qualitatively describe the magnetic properties of some materials that can be affected by magnetic properties of other objects in the system.
AP Physics C: Electricity and Magnetism learning objectives	• CNV-8.B.a: Derive the expression for the magnitude of magnetic field on the axis of a circular loop of current or a segment of a circular loop. • CNV-8.C.a: Explain Ampère's Law and justify the use of the appropriate Amperian loop for current-carrying conductors of different shapes such as straight wires, closed circular loops, conductive slabs, or solenoids. • ACT-4.A.a: Determine if a net force or net torque exists on a conductive loop in a region of changing magnetic field.
Literacy connections (*CCSS ELA*)	• *Reading*: Key ideas and details, craft and structure, integration of knowledge and ideas • *Writing*: Text types and purposes, production and distribution of writing, research to build and present knowledge, range of writing • *Speaking and listening:* Comprehension and collaboration, presentation of knowledge and ideas

Continued

Table 17.2 (*continued*)

Mathematics connections (*CCSS Mathematics*)	• *Mathematical practices*: Make sense of problems and persevere in solving them, reason abstractly and quantitatively, construct viable arguments and critique the reasoning of others, model with mathematics, use appropriate tools strategically, attend to precision • *Number and quantity*: Reason quantitatively and use units to solve problems, represent and model with vector quantities, perform operations on vectors • *Algebra*: Interpret the structure of expressions, understand solving equations as a process of reasoning and explain the reasoning, solve equations and inequalities in one variable, represent and solve equations and inequalities graphically • *Functions*: Understand the concept of a function and use function notation; interpret functions that arise in applications in terms of the context; analyze functions using different representations; construct and compare linear, quadratic, and exponential models and solve problems; interpret expressions for functions in terms of the situation they model • *Statistics and probability*: Summarize, represent, and interpret data on two categorical and quantitative variables; interpret linear models; make inferences and justify conclusions from sample surveys, experiments, and observational studies

Lab Handout

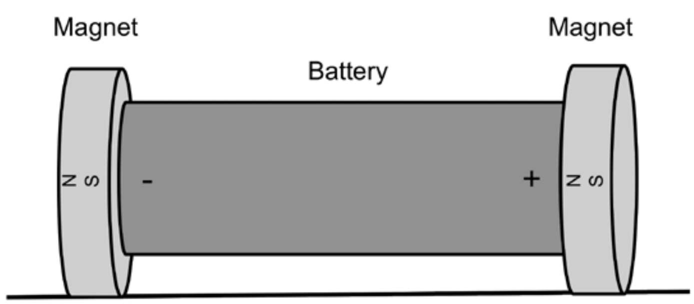
Lab 17. Electromagnetism: Why Does the Battery-and-Magnet "Car" Roll When It Is Placed on a Sheet of Aluminum Foil?

Introduction

Children of all ages often like to play with magnets. Simple combinations of magnets can lead to complex behavior—for example, pushing the north poles of two magnets together and letting go causes the two magnets to move away from each other. Your teacher is going to demonstrate another complex phenomenon where two magnets are connected to a battery and then placed on a sheet of aluminum foil. Figure L17.1 shows the setup of the magnets and battery.

FIGURE L17.1

A battery-and-magnet "car"



Electricity and magnetism were viewed as two different things prior to the 19th century. The work of scientists including André-Marie Ampère (1775–1836), Hans Christian Ørsted (1777–1851), and Michael Faraday (1791–1867), among others, led to the eventual development of a *unified theory of electromagnetism* (Giancoli 2005). One of the fundamental postulates of the unified theory of electromagnetism is that an electric current will produce a magnetic field surrounding the current-carrying object (often a wire, but not always). Another important idea of the unified theory of electromagnetism is that a change in the magnetic field near an electrical conductor will cause a current to flow through the conductor. Other findings related to the unified theory of electromagnetism have shown that a moving point charge (such as an electron) produces a magnetic field and that a magnetic field exerts a force on a charged object moving through the magnetic field. These findings are important for the working of electrical infrastructure and many modern electronic devices, such as magnetic resonance imaging (MRI) machines.

Besides underlying the working of many of our modern technologies, knowledge of electromagnetism can also help us explain many other observed phenomena and inform the way we design tools. Our understanding of magnetic fields helps explain why two north poles will push each other apart. And our understanding of electric currents informs the design of power strips, leading to power strips being wired in parallel and not in series.

Your Task

Use what you know about electromagnetism, forces, rotational motion, systems and system models, and stability and change to design and carry out an investigation to develop a model that explains the movement of the battery-and-magnets "car." Your model should allow you to make predictions about variables such as the total mass of the car, the voltage of the battery, and the strength of the magnets. There may be other variables that influence the movement of the car that your model will want to account for as well.

The guiding question of this investigation is, ***Why does the battery-and-magnet "car" roll when it is placed on a sheet of aluminum foil?***

Materials

You may use any of the following materials during your investigation:

Consumables
- AA batteries
- C batteries
- D batteries
- Duct tape
- Aluminum foil
- Wax paper
- Butcher paper

Equipment
- Safety glasses with side shields or goggles (required)
- Neodymium magnets
- Ceramic magnets
- Voltmeter
- Ammeter
- Multimeter
- Meterstick
- Stopwatch
- Electronic or triple beam balance

If you have access to the following equipment, you may also consider using a video camera, a digital magnetic field sensor, and a digital current sensor and/or digital voltage sensor with an accompanying interface and a computer or tablet. Also, your teacher may give you an electronic pole identifier, which will allow you to determine the north and south poles of your magnets if they are not already labeled.

Safety Precautions

Follow all normal lab safety rules. In addition, take the following safety precautions:

1. Wear sanitized safety glasses with side shields or safety goggles during lab setup, hands-on activity, and takedown.
2. Never put consumables in your mouth.

3. Wire and other metals with electric current flowing through them may get hot. Use caution when handling components of a closed circuit.
4. Us caution in working with sharp objects (e.g., wires) because they can cut or puncture skin.
5. Neodymium magnets should be at least 30 cm away from sensitive electronic and storage devices. These strong magnets could affect the functioning of pacemakers and implanted heart defibrillators.
6. Big magnets have a very strong attractive force. Unsafe handling could cause jamming of fingers or skin in between magnets. This may lead to contusions and bruises.
7. Neodymium magnets are brittle. Colliding magnets could crack, and sharp splinters could be catapulted away for several meters and injure eyes.
8. Sharp splinters could be catapulted away for several meters and injure eyes.
9. Wash your hands with soap and water when you are done collecting the data.

Investigation Proposal Required? ☐ Yes ☐ No

Getting Started

To answer the guiding question, you will need to design and carry out an investigation to determine the mechanisms underlying the movement of the car. You will need to develop a conceptual model that allows you to describe the motion of the car and to predict if a particular arrangement of the battery and magnets will result in the car moving when placed on a certain surface. Furthermore, your model should also allow you to predict how a change in the arrangement of the battery and magnets will result in a change to the motion of the car. Before you can design your investigation, however, you must determine what type of data you need to collect, how you will collect it, and how you will analyze it.

To determine *what type of data you need to collect*, think about the following questions:

- What are the boundaries and components of the system?
- How do the components of the system interact with each other?
- When is this system stable and under which conditions does it change?
- How could you keep track of changes in this system quantitatively?
- What forces, if any, are acting on the objects in the system?
- Which factor(s) might control rates of change in this system?

To determine *how you will collect the data*, think about the following questions:

- What scale or scales should you use when you take your measurements?

- How will you make sure that your data are of high quality (i.e., how will you reduce error)?
- How will you keep track of and organize the data you collect?
- What are the boundaries of this phenomenon or system?
- What are the components of this phenomenon or system and how do they interact?
- How will you measure change over time during your investigation?

To determine *how you will analyze the data*, think about the following questions:

- What type of calculations, if any, will you need to make?
- What types of patterns might you look for as you analyze your data?
- What type of table or graph could you create to help make sense of your data?
- How could you use mathematics to describe a change over time?

Connections to the Nature of Scientific Knowledge and Scientific Inquiry

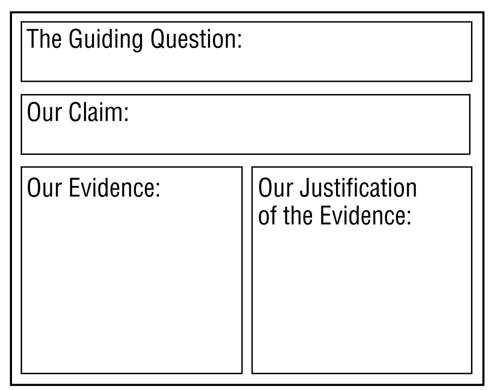
As you work through your investigation, you may want to consider

- how scientific knowledge changes over time, and
- how scientists use different methods to answer different types of questions.

Initial Argument

Once your group has finished collecting and analyzing your data, your group will need to develop an initial argument. Your initial argument needs to include a claim, evidence to support your claim, and a justification of the evidence. The *claim* is your group's answer to the guiding question. The *evidence* is an analysis and interpretation of your data. Finally, the *justification* of the evidence is why your group thinks the evidence matters. The justification of the evidence is important because scientists can use different kinds of evidence to support their claims. Your group will create your initial argument on a whiteboard. Your whiteboard should include all the information shown in Figure L17.2.

FIGURE L17.2
Argument presentation on a whiteboard



Argumentation Session

The argumentation session allows all of the groups to share their arguments. One or two members of each group will stay at the lab station to share that group's argument, while the other members of the group go to the other lab stations to listen to and critique the other arguments. This is similar to what scientists do when they propose, support, evaluate, and refine new ideas during a poster session at a conference. If you are presenting your group's argument, your goal is to share your ideas and answer questions. You should also keep a record of the critiques and suggestions made by your classmates so you can use this feedback to make your initial argument stronger. You can keep track of specific critiques and suggestions for improvement that your classmates mention in the space below.

Critiques about our initial argument and suggestions for improvement:

If you are critiquing your classmates' arguments, your goal is to look for mistakes in their arguments and offer suggestions for improvement so these mistakes can be fixed. You should look for ways to make your initial argument stronger by looking for things that the other groups did well. You can keep track of interesting ideas that you see and hear during the argumentation in the space below. You can also use this space to keep track of any questions that you will need to discuss with your team.

Interesting ideas from other groups or questions to take back to my group:

Once the argumentation session is complete, you will have a chance to meet with your group and revise your initial argument. Your group might need to gather more data or design a way to test one or more alternative claims as part of this process. Remember, your goal at this stage of the investigation is to develop the best argument possible.

Report

Once you have completed your research, you will need to prepare an investigation report that consists of three sections. Each section should provide an answer to the following questions:

1. What question were you trying to answer and why?
2. What did you do to answer your question and why?
3. What is your argument?

Your report should answer these questions in two pages or less. This report must be typed, and any diagrams, figures, or tables should be embedded into the document. Be sure to write in a persuasive style; you are trying to convince others that your claim is acceptable or valid!

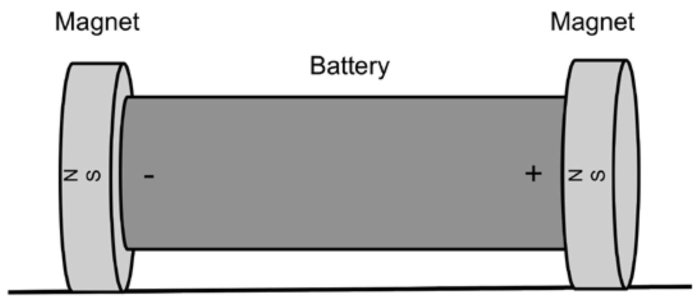
Reference

Giancoli, D. G. 2005. *Physics: Principles with applications.* 6th ed. Upper Saddle River, NJ: Pearson.

Checkout Questions

Lab 17. Electromagnetism: Why Does the Battery-and-Magnet "Car" Roll When It Is Placed on a Sheet of Aluminum Foil?

Use the picture below to answer questions 1–3.



1. The magnet car is set up so that two magnets of equal strength **B** have the north pole facing to the left. When placed on a piece of aluminum foil, they begin rolling. If the two magnets were replaced with magnets of equal mass but with a magnet field strength of 3**B** with both north poles facing to the left, how would this affect the motion of the car?

   a. The car would roll slower.
   b. The car would roll faster.
   c. The car would not roll at all.
   d. The car would roll the same.

   How do you know?

2. Assume now that the magnet on the right is flipped, so that its north pole faces to the right. How would this affect the motion of the car?

   a. The car would roll slower.
   b. The car would roll faster.
   c. The car would not roll at all.
   d. The car would roll the same.

   How do you know?

3. Assume now that the magnets both have the north poles facing to the left. However, the magnet on the left has a strength of **B** while the magnet on the right has a strength of 3**B**. How would this affect the movement of the car?

   How do you know?

4. Scientific knowledge does not change—that is why we still learn about Newton's laws over 300 years after he published them.
   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using examples from this investigation and at least one other investigation you have conducted.

5. Scientists have always used the same method for investigating questions regarding the interaction between electricity and magnetism.
   a. I agree with this statement.
   b. I disagree with this statement.

   Explain your answer, using examples from this investigation and at least one other investigation you have conducted.

6. Why is it useful to understand factors that influence rates of change in systems? In your answer, be sure to use examples from this investigation and at least one other investigation you have conducted.

7. Why is it useful to assume that you are studying a closed system during an investigation? In your answer, be sure to include examples from your investigation about the battery-and-magnet car and one other investigation you have carried out.