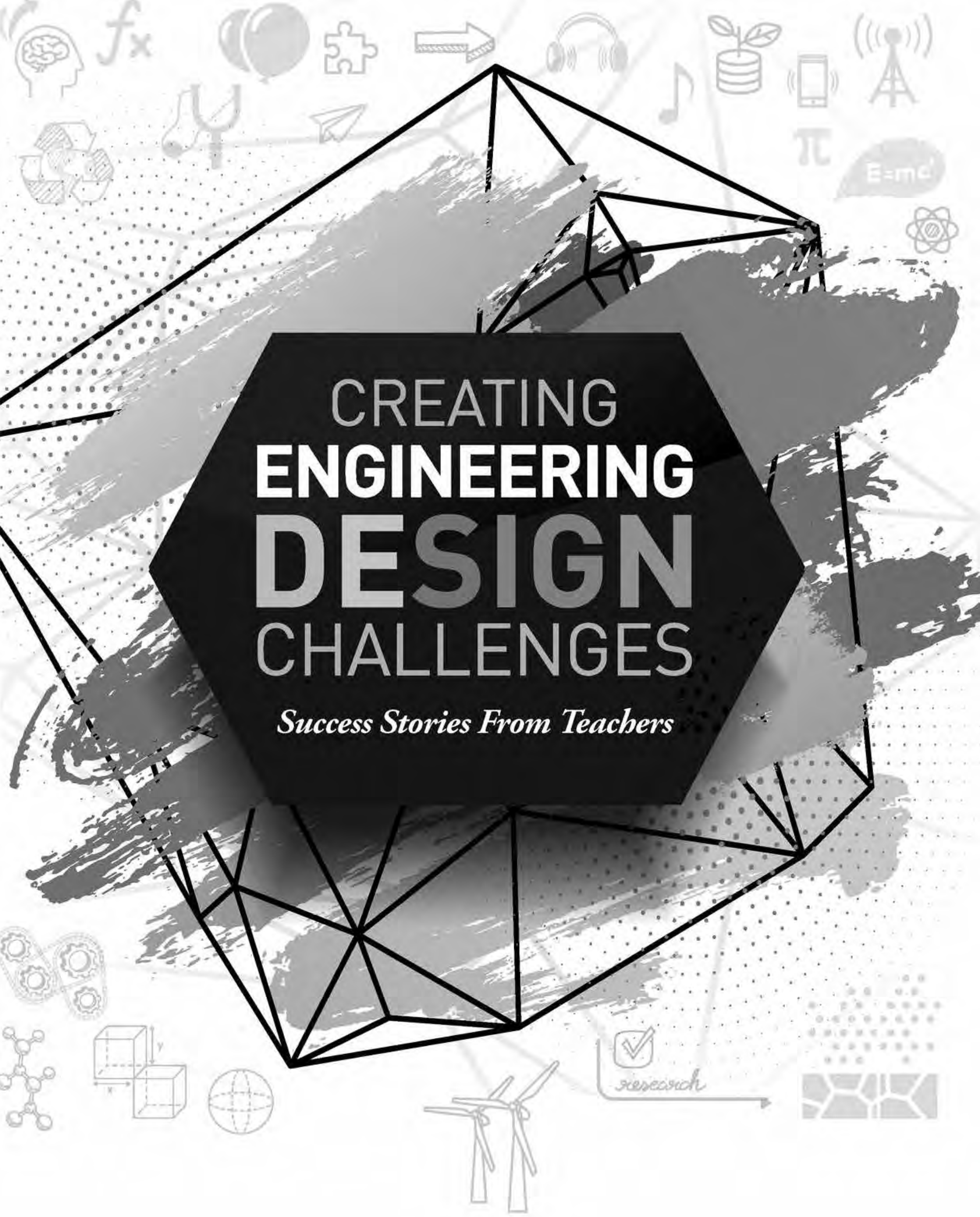
CREATING ENGINEERING DESIGN CHALLENGES

Success Stories From Teachers

Edited by
Helen Meyer, Anant R. Kukreti,
Debora Liberi, and Julie Steimle

NSTA press
National Science Teaching Association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Acknowledgments

First and foremost, we would like to thank NSTA Press for investing in our book and for helping us with revising, editing, designing, and marketing; Breakthrough Cincinnati for help with pictures; and Kayla Kurkowski for her photography work.

This book is based on the teacher professional training program developed and executed through financial support provided by the U.S. National Science Foundation Award, #DUE-1102990, for the Targeted Math and Science Partnership Project on the Cincinnati Engineering Enhanced Mathematics and Science (CEEMS) program. Any opinions, findings, conclusions, and/or recommendations are those of the contributing authors of this book and do not necessarily reflect the views of the Foundation.

CEEMS was led by three colleges at the University of Cincinnati, in Cincinnati, Ohio: the College of Engineering and Applied Science; the McMicken College of Arts and Sciences; and the College of Education, Criminal Justice, and Human Services. These institutions were the higher education Core Partners who worked with 14 Core Partner school districts, including Cincinnati Public Schools, Oak Hills, Princeton, Norwood, Winton Woods, and nine rural school districts within Clermont County, Ohio. The CEEMS project and this book would not have been possible without the support and guidance provided by all these partners collectively.

More specifically, this book is a result of the engineering design challenge curriculum developed and taught by 88 CEEMS teachers from the partner school districts that participated in the program. These teachers were supported by 10 resource team members, who served as coaches and guided the work of the CEEMS participants. The resource team members included Jack Broering, Lori Cargile, Tim Dugan, Dennis Dupps, Meri Johnson, Kimya Moyo, Rob Rapaport, Pamela Truesdell, David Vernot, and Tom Vinciguerra. The impact of the CEEMS curriculum on student learning and on the teaching practices of the participating teachers was evaluated by the University of Cincinnati's Evaluation Services Center and the Discovery Center for Evaluation, Research, and Professional Learning at Miami University in Oxford, Ohio. The contributions of all these participants is acknowledged.

Acknowledgments

Last but not least, we would like to acknowledge the contributions and guidance provided throughout the CEEMS project by team members Eugene Rutz, Howard Jackson, and Stephan Pelikan. We would also like to thank the CEEMS National Advisory Board, which consisted of 10 eminent scholars from engineering education and educational research.

Preface

We created this book with the educator in mind—specifically secondary mathematics and science teachers (grades 6–12) looking for ways to integrate engineering practices into classroom instruction. The writing team consisted of university faculty from both engineering and education departments, as well as practicing science and mathematics teachers. The teacher contributors have shared design challenge units they developed, implemented, and revised over a two-year period as participants in the National Science Foundation–funded (grant #DLR-1102990) Cincinnati Engineering Enhanced Math and Science (CEEMS) program. These teachers worked in a wide range of schools (including in rural, suburban, and urban settings) and in different grade levels and subjects, thus demonstrating the broad relevance and applicability of the pedagogies promoted in this book. Readers will be provided with detailed accounts of the teachers' design challenge units, as well as the lesson plans, handouts, and other teaching materials, which can be used in or adapted for other classrooms. The design challenge units were developed using a hybrid of two pedagogies: challenge-based learning and the engineering design process.

All the contributing authors were part of the CEEMS program. The university faculty who worked on this program provided background information focused on the importance of the engineering practices, the challenge-based learning framework, the learning theory guiding the work, and the structure and implementation of the larger CEEMS project. This uniquely structured program has key components that can change the classroom environment, empower students, and move toward a more student-centered classroom culture in order to produce positive learning results. Our objective is to share the best practices that have resulted from CEEMS and provide strategies for how to incorporate these into your own teaching practices.

The book is divided into two parts and an appendix containing helpful resources:

Part 1 encompasses Chapters 1–3, which provide background information and introduce the particular engineering design process we used. We discuss how the design challenge unit framework connects with current education standards and reforms, including the *Common Core State Standards for Mathematics* and the *Next Generation Science Standards*. This section also details educational research on learning and teaching, which supports the use of design challenges. In Chapter 3, we define the terms you will see in the teachers' stories and provide details and a useful template for developing design challenge units.

Part 2 includes Chapters 4–8. Chapters 4–7 contain sections written by individual secondary math and science teachers (grades 6–12), who focus on different aspects of implementing design challenge units. These aspects include creating an engaging hook, guiding students to provide input on an essential question and suitable challenge, integrating the engineering design process, incorporating formative and summative assessments, and developing 21st-century skills in design challenge units. Chapter 8 demonstrates how to modify another teacher's design challenge for your own classroom and how to reflect on and improve your own units after implementation. Chapter 8 also shares resources for finding design challenge unit ideas and provides suggestions for building a community of likeminded teachers who want to go on this journey with you.

About the Editors and Contributors

Editors

Helen Meyer is an associate professor in science education at the University of Cincinnati. In her role as the director of the Fusion STEM Education Center, she works with STEM teachers and faculty on engineering, information technology, and teacher education projects. Prior to this experience, she taught secondary science in Wisconsin and New York City and with the Peace Corps in Swaziland in southern Africa. In her role as a science teacher educator, Helen wants to ensure that all children have equal access to high-quality science instruction so that they can make sense of the world and participate in our democratic society.

Anant R. Kukreti has been a professor emeritus of engineering at the University of Cincinnati since August 2018. Prior to retirement, he was the director for engineering outreach and a professor at the University of Cincinnati's College of Engineering and Applied Science. Here, he oversaw the K–12 Pathway Programs and undergraduate and graduate enrichment programs. He has extensive experience in managing major National Science Foundation educational grants for in-service and preservice K–12 teacher training programs. Among many others, this has included the Cincinnati Engineering Enhanced Mathematics and Science (CEEMS) program (which resulted in the production of this book) and the Research Experiences for Teachers (RET) site programs. The primary vision of these programs was to establish a cadre of teachers who can implement the authentic articulation of engineering with science and mathematics in K–12 classrooms.

Debora Liberi is the district coordinator for the CEEMS program. In addition, she served from 2013–2018 as the program coordinator for the RET grant. She was an adjunct professor at the University of Cincinnati's College of Education, Criminal Justice, and Human Services. Prior to her university work, she was a middle school science teacher and high school librarian in Cincinnati Public Schools for 35 years.

Julie Steimle formerly served as the director of the CEEMS program. As such, she was in charge of recruiting teachers for the program, coordinating with the partnering school districts, organizing the summer institute, serving as the liaison with the evaluation team, and many other tasks. Prior to directing the CEEMS program, she led another grant-funded program at the University of Cincinnati, which provided free tutoring services to hundreds of low-income students. Before working at the University of Cincinnati, she worked at nonprofit organizations focused on education.

Contributors

Kristin Barnes serves as the program director for the CEEMS program. Prior to this, she served as the assistant director for the MD/PhD program in the University of Cincinnati's College of Medicine. Her experiences span the educational spectrum as she has worked with programs serving everyone from early-childhood educators to graduate students.

Kathryn Blankenship has a master's degree in chemistry and is classified as a Rank I–certified chemistry and physics teacher in Kentucky. Currently teaching at Indian Hill High School in Indian Hill, Ohio, she previously taught at Highland Heights High School in Highland Heights, Kentucky, and at Oaks Hill High School in Cincinnati, Ohio. She participated in the CEEMS program from 2013–2015 as a member of Cohort 2.

Lori Cooper is a middle school science teacher with 15 years of experience working with children who attend some of the most high-needs schools in the Cincinnati Public Schools district. From 2015–2017, she was a member of Cohort 4 in the University of Cincinnati's CEEMS program, receiving a master's degree in curriculum and instruction and a certificate in engineering education.

Kelly DeNu teaches eighth-grade prealgebra at Goshen Middle School in Clermont County, Ohio. She has a master's degree in mathematics education and received a certificate in engineering education from the University of Cincinnati by completing the CEEMS program, where she was a member of Cohort 2 from 2013–2015.

Brandi Foster teaches eighth-grade science at Aiken High School in the Cincinnati Public Schools district. In 2014, she became a member of Cohort 3 in the CEEMS program.

Rashanna Freeman is a veteran biology and chemistry teacher with 16 years of experience. She currently teaches at Princeton High School in a suburb outside of Cincinnati. From 2016–2018, she participated as a member of Cohort 5 in the CEEMS program.

Amy Jameson teaches advanced academic physics, advanced academic chemistry, and anatomy and physiology at Gilbert A. Dater High School, which is part of Cincinnati Public Schools. She has been teaching in public schools for over 30 years and also serves as an adjunct professor at the University of Cincinnati in the College of Education, Criminal Justice, and Human Services. She joined the CEEMS program in 2015 as a member of Cohort 4.

Leslie Lyles has been an educator for 13 years and holds a middle childhood (4–9) and mathematics (4–9) teaching license in Ohio. She currently teaches seventh-grade prealgebra and eighth-grade algebra at Hartwell School, a Title I–funded Cincinnati public school for grades preK–8. As a member of Cohort 4, she joined the CEEMS program in 2015.

Kimya Moyo is a retired math educator who teaches high school mathematics part time for the Title I program in Cincinnati, Ohio. She currently is providing professional development to the math department of the Mount Healthy school district in Ohio. Her primary interests include assisting teachers as they infuse STEM into their mathematics instruction and developing a learning environment in the classroom that creates safe spaces for growth mindsets while highlighting culturally diverse contributions to the field of mathematics. Her research on meaning making in mathematics led to the development of Kuringa paper, which she incorporates into her workshops.

Marie Pollitt is a middle school science teacher at Felicity-Franklin Middle School in Clermont County, Ohio. From 2015–2017, she was member of Cohort 4 in the CEEMS program at the University of Cincinnati, where she also earned a master's degree in curriculum and instruction.

Stephanie Stewart joined the CEEMS program as a second-year teacher. As a member of Cohort 5 from 2016–2018, she earned her master's degree in curriculum and instruction and a graduate certificate in engineering education. She currently is an eighth-grade science teacher at Bridgetown Middle School in suburban Cincinnati.

Kevin Tucker has been teaching mathematics at the high school level for 14 years. He has a bachelor's degree in mathematics and a master's degree in education. His teaching certification is in mathematics (7–12). He was a member of Cohort 1 in the CEEMS program from 2012–2014. He currently teaches precalculus at Princeton High School in a suburb of Cincinnati, Ohio.

Chapter 1

Engineering Design Challenges

The purpose of *Creating Engineering Design Challenges* is to highlight the stories and design challenges of teachers who designed, implemented, revised, and finalized engineering challenges for their sixth- through twelfth-grade students as part of the Cincinnati Engineering Enhanced Math and Science (CEEMS) program. We developed this book after seven years of experience working as a team of engineers, teacher educators, and active and retired secondary science and mathematics teachers. In order to provide models for the greatest number of educators possible, we included stories from teachers who worked in a range of school types, including those in suburban, rural, and urban settings; we also made sure to work with teachers who taught different grade levels and subjects. Chapters 4–7 highlight these stories and document how teachers worked through different stages of their design challenge units. We have used engineering design challenge examples throughout the book to (1) introduce and highlight important ideas, strategies, and points of discussion and (2) keep the book both interesting and embedded in classrooms and teaching.

The first three chapters of this book provide background information and introduce the particular engineering design process (EDP) we used in the CEEMS program. We discuss how the design challenge unit framework connects with current education standards and reforms, including the *Common Core State Standards for Mathematics* (*CCSS Mathematics*) and the *Next Generation Science Standards* (*NGSS*). We also explain how design challenges link to educational research on learning and teaching. In Chapter 3, we define the terms related to engineering design challenges and provide details about putting together a design challenge unit. Chapters 4–7 feature the teachers' stories and include portions of their teaching plans, student work, and classroom handouts. Chapter 8 is a resource toolkit for teachers interested in designing and implementing the provided design challenge units or their own design challenge units. This final chapter includes ways to support teachers' work and learning with resources for ideas and information that are publicly available to access. The chapter also includes templates and documents that CEEMS teachers found useful to organize their challenges.

Engineering Design Challenges

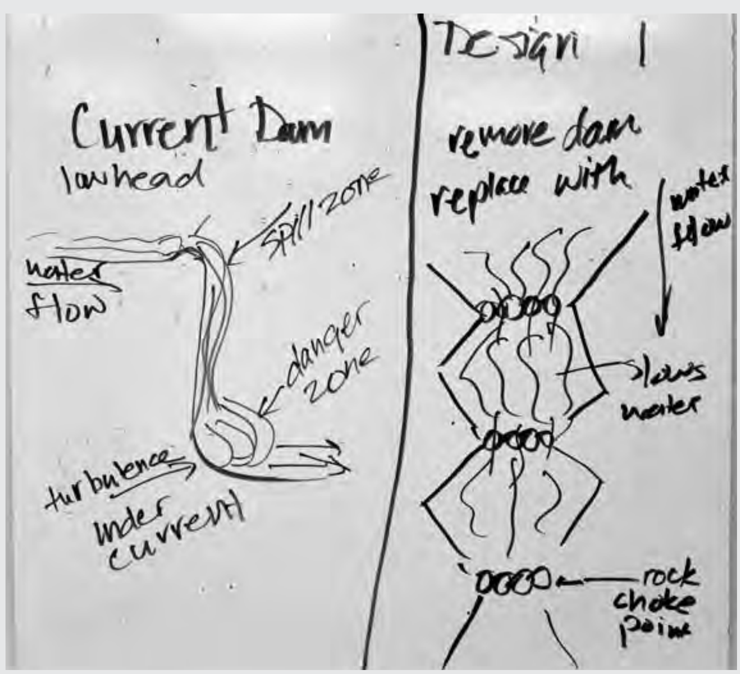
Model-Testing Day

The classroom is abuzz with activity as teams of eighth graders test and evaluate their designs for replacing a low-head dam. Using the engineering design process, they have conducted research, drafted and adjusted plans, and built a model for a dam replacement. Now it's model-testing day, a time for students to assess their replacement designs for the local low-head dam.

The dam replacement challenge is part of the students' Earth science semester, which focuses on the role of water on our planet and human impacts on Earth systems. Their teacher knew this challenge would be perfect because it connected with the larger global issues of infrastructure and water resources. It was a great example of how engineering and technologies need to change over time. Finally, a recent accident at the low-head dam two blocks away meant dams were on everyone's mind.

Most student teams built their designs using stacked clear containers, sand, and wood to replicate water flowing over the dam and demonstrate how to disrupt it. However, one team tested a stream reconstruction (Figure 1.1) using a borrowed stream table to replicate what they had heard from the county's conservation officer, who had accompanied the class on a trip to the dam.

Figure 1.1. Student Drawing of Low-Head Dam and Initial Design Idea



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Each team documented the amount of eroded sand and the degree of splash and speed of the water before and after their design model. The design goal was to reduce the speed of the water falling over the dam, reducing the back current while keeping the degree of erosion to a minimum. In preparation for a class sharing, each team posted their design plan, a picture of the test model, and their measurements.

The students' teacher was delighted with the results of the design challenge. In addition to students learning the disciplinary content required by the standards, the challenge connected their local dam problem with water, energy, and resource issues that are faced all over the world. It had provided an opportunity for the students to connect with the local government, represented by the county conservation officer. It also provided the students with agency to address a local problem, and they used engineering practices in an authentic fashion.

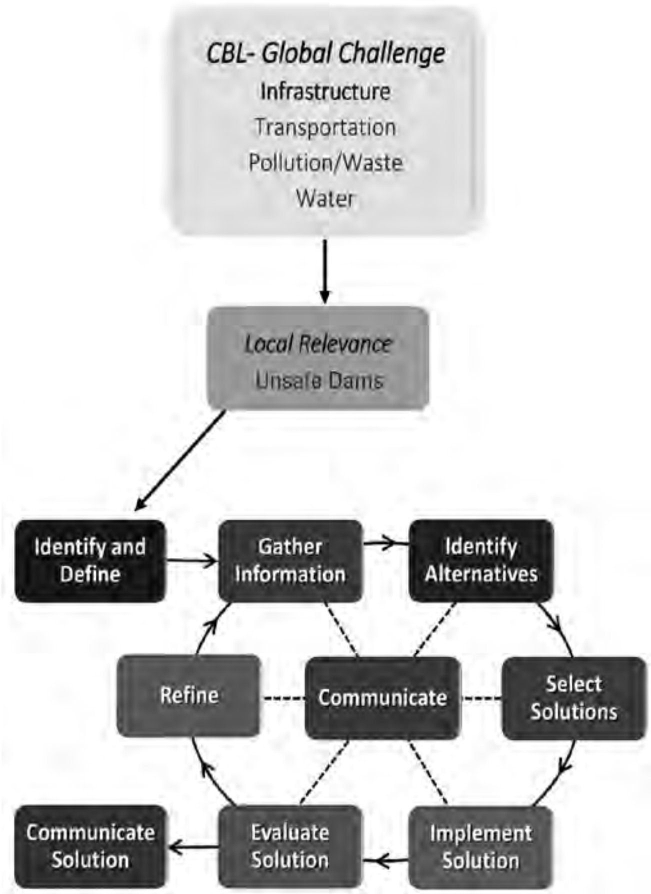
This is what teaching and learning in an integrated STEM (science, technology, engineering, and mathematics) classroom can look like. It incorporates two key pedagogical strategies we used to develop design challenges: challenge-based learning (CBL) and the engineering design process (EDP). Apple, Inc. initially developed CBL and has since extended the strategy to be part of The Challenge Institute. They describe CBL as a flexible and adaptable pedagogy with a primary goal of fostering student ownership of real-world problems contextualized with course content to enhance student motivation and learning (Apple, Inc. 2010). Our addition of the EDP to CBL highlights a particular kind of problem solving—how engineers solve problems. Student teams work to design engineering solutions for problems arising from a larger global challenge. Figure 1.2 (p. 6) demonstrates how we linked these two strategies.

Later in this chapter, we provide more details about how we integrated CBL and the EDP into the unit design model used throughout this book. For clarity, we use the term *design challenges* to describe the engineering design activity or task students undertake and the term *design challenge unit* for the instructional plans and materials teachers develop to establish the instructional environment for their students.

The Paradigm Shift Toward STEM Education

STEM education is often called a metadiscipline. Instead of learning isolated facts and observing only pieces of phenomena, this "new whole" offers students the opportunity to make sense of the world in a more authentic way. The components in an integrated STEM framework often include an inquiry-based approach, the crossing of traditional curriculum lines, usage of authentic learning situations, engineering and design processes, project-based and problem-based learning activities, career exploration, and a collaborative learning environment. The National Academies of Sciences, Engineering, and Medicine

Figure 1.2. Diagram of EDP as Part of the Larger CBL Process



(NASEM) report *Science and Engineering for Grades 6–12* (NASEM 2019) supports a STEM approach as an example of "inclusive pedagogies to improve education so all students in all schools can fully participate in learning sciences and engineering through engaging in high-quality experiences with … engineering design to make sense of the natural and designed world" (p. 13).

The use of a STEM approach emphasizing design pushes students to understand the natural and designed world as a complex place where problems rarely result in solutions with a single right answer; rather, students are engaged in a productive struggle through the development of models leading to explanations and multiple solutions (NASEM 2019). Although there is no single model for engineering and the design process, the engineering design process incorporates a set of core ideas that guide the development of models for use in practice. These core ideas of engineering design include the following (NGSS Lead States 2013, p. 467):

1. Defining and delimiting engineering problems involves stating the problem to be solved as clearly as possible in terms of criteria for success and constraints or limits.
2. Designing solutions to engineering problems begins with generating a number of different possible solutions, then evaluating potential solutions to see which best meet the criteria and constraints of the problem.
3. Optimizing the design solution involves a process in which solutions are systematically tested and refined and the final design is improved by trading off less important features for those that are more important.

Another way to understand engineering is through Rodger Bybee's (2011) comparison of science and engineering practices, shown in Table 1.1.

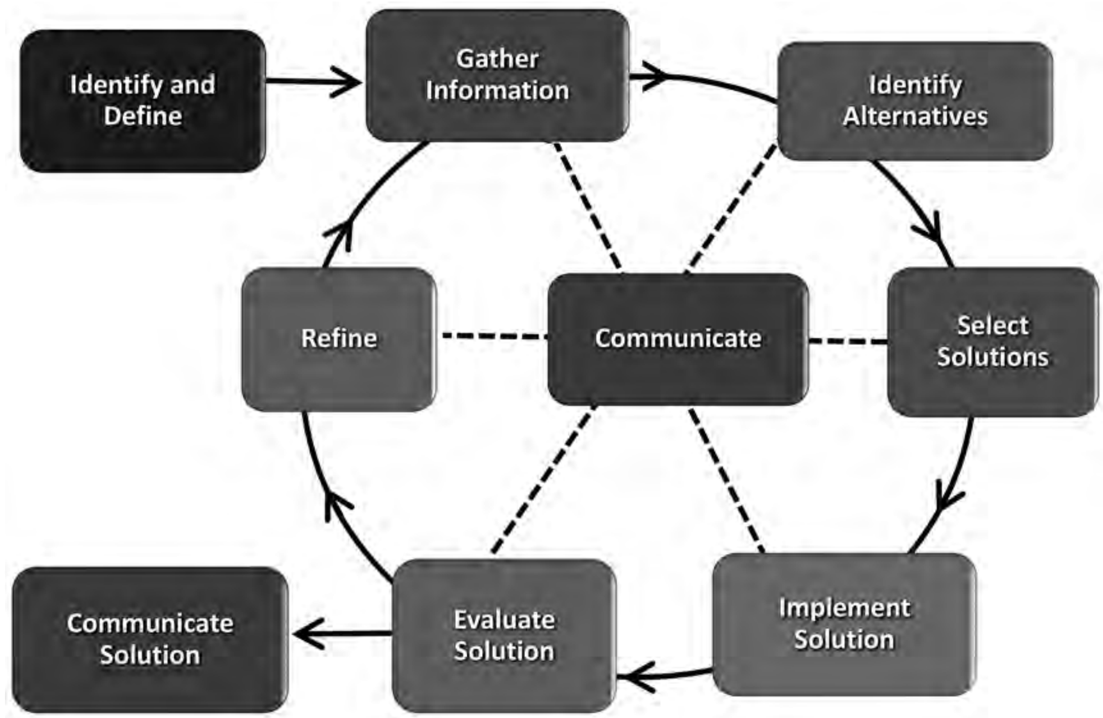
Table 1.1. Bybee's Comparison of Science and Engineering Practices

Science Practices	Engineering Practices
Asking questions	Defining problems
Developing and using models	Developing and using models
Planning and carrying out investigations	Planning and carrying out investigations
Analyzing and interpreting data	Analyzing and interpreting data
Using mathematical and computational thinking	Using mathematical and computational thinking
Constructing explanations	Construction design solutions
Engaging in argument from evidence	Engaging in argument from evidence
Obtaining, evaluating, and communicating information	Obtaining, evaluating, and communicating information

Combining the core ideas discussed above with Bybee's outline, we arrived at a model to focus on how engineers apply science and math to design solutions for human problems; use a systematic approach to their work, including tests and iterations; and work in collaborative teams to propose and defend the solutions they believe to be optimal within given constraints. This resulted in a common diagram of the EDP, which we used with our teachers and for this book. The teachers in this book and in our larger program used this model to create their design challenge units and displayed the model as guideposts for their students as they worked on their design challenges. Figure 1.3 (p. 8) is the model we used for the EDP.

Although inclusion of engineering design is more explicit in science classrooms, mathematics educators are also increasingly recognizing the value of engineering design in math instruction. The National Council of Teachers of Mathematics process standards and *CCSS Mathematics* do not directly refer to engineering; however, both sets of standards recognize that mathematics involves more than learning content knowledge. Teaching students

Figure 1.3. CEEMS Model of the EDP



"habits of mind" is just as important (Hefty 2015). Engineering design is one vehicle for developing these critical habits of mind. In a math classroom, engineering design challenges engage students in problem solving, critical thinking, sense making, reasoning, collaboration, communication, precise measurement, and the collection and analysis of data. Students learn to persist in finding solutions when their designs initially fail (Hefty 2015). The *CCSS Mathematics* (NGAC and CCSSO 2010) list the following eight Standards for Mathematical Practice. Using engineering projects and the resulting habits of mind, teachers can address each of these standards.

1. Make sense of problems and persevere in solving them.
2. Reason abstractly and quantitatively.
3. Construct viable arguments and critique the reasoning of others.
4. Model with mathematics.
5. Use appropriate tools strategically.
6. Attend to precision.
7. Look for and make use of structure.
8. Look for and express regularity in repeated reasoning.

A strategic use of engineering design challenges has the potential to connect mathematics knowledge to real-world problems. Here are two examples of engineering design challenges inspired by actual issues that our teachers developed: (1) How can the Pythagorean theorem create safer, more stable building designs? (2) How can one apply surface area and volume to reduce packaging waste? Math teachers can skillfully integrate engineering design into their classrooms in a fashion that develops students into STEM thinkers.

Table 1.2 shows the alignment of the *NGSS* core engineering ideas, the engineering practices detailed in Table 1.1 (p. 7), the *CCSS Mathematics* practices, and the EDP framework from Figure 1.3. Putting such complex ideas into a table oversimplifies them and reduces the intersecting and iterative nature of the different practices; however, we have included it to show how design challenge units can meet multiple goals simultaneously.

Table 1.2. Alignment of Engineering and Mathematics Practices With the CEEMS EDP Model

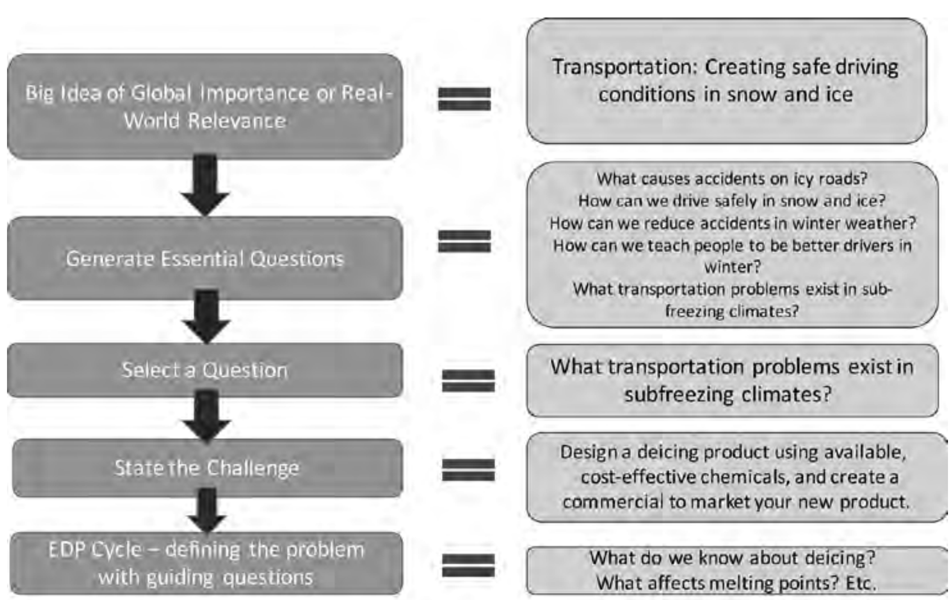
Core Engineering Idea	*NGSS* Practice	*CCSS Mathematics* Practices	CEEMS EDP Model
(1) • Define • Delimit • Criteria constraints	1. Defining problems 7. Argument from evidence 8. Communicating information	1. Sense making and perseverance 2. Reason abstractly and quantitatively 6. Attend to precision 7. Make use of structure	• Identify and design • Gather information • Identify alternatives • Communicate solution
(2) • Generate solutions • Testing • Evaluating	2. Developing models 3. Investigations 4. Analyzing and interpreting data 5. Computational thinking 6. Design solutions 8. Communicating information	1. Persevere in problem solving 2. Reason abstractly and quantitatively 3. Construct and critique arguments 4. Model mathematically 5. Use tools strategically	• Identify alternatives • Communicate • Select solution • Implement solution • Evaluate solution
(3) • Optimize • Refine • Redesign	2. Developing models 5. Computational thinking 7. Argument from evidence 6. Design solutions 8. Communicating information	1. Sense making and perseverance 3. Construct and critique arguments 6. Attend to precision 7. Look for structures 8. Express regularity in repeated reasoning	• Communicate • Identify alternatives • Refine • Evaluate • Communicate solution

Challenge-Based Learning and Engineering Design

CBL is similar to both project-based learning and problem-based learning in many of its instructional practices, and the way we use CBL combines practices from these other two methods. A typical project-based learning activity begins with students working to meet a result, with specifications for the end product presented to the students by the teacher at the start of the activity. For instance, a teacher leading a project-based activity might tell students to design and construct a water filter that removes a dangerous chemical, such as lead. In problem-based learning, the problem—and thus the product—is ill-defined, and students set the parameters themselves (Morrison 2006). Problem-based learning is frequently used in medical education where medical students not only have to identify the treatment for a health issue but also use multiple information sources to define the health issue. CBL brings together both of these strategies by presenting students with an ill-defined "big idea" tied to a global issue that the teacher and students work to narrow into a related, actionable design product.

CBL provides students with the opportunity to define the questions they want to answer and provide input on the challenge to be solved. Student choice has been shown to be highly motivating and increase student learning (NASEM 2018). Pragmatically, however, giving students control over the shape of the problem, the questions to be answered, and the methods to be used can be frightening and impractical. Curt Blimline's design challenge, described in the following story, shows how one teacher worked through the processes of CBL and the EDP while still meeting his chemistry curriculum dictates. Figure 1.4 details Curt's process of combining CBL with the EDP to develop a design challenge for his students.

Figure 1.4. Challenge-Based Learning Leading to Engineering Design



Curt's Story

Curt, a chemistry teacher, wanted a creative way to teach the content of intermolecular bonding and stoichiometry. He also needed to incorporate several key science and engineering practices. Curt knew what his standards required and where he wanted his students to end up, and he had a starting idea in mind; this was how he moved from a big idea to a design challenge.

Curt taught in a rural school where snow days were a frequent occurrence due to icy roads; this could make educational access an issue for his students. Equal access to education, Curt's big idea, is a global problem, although it looks different in different places. Curt introduced the big idea of equitable educational access to his students. He then showed YouTube videos of car accidents resulting from snowy or icy roads. The class discussed how icy conditions affected their access to education.

To get to the next stage, Curt shared ideas about what makes a good essential question to understand and solve problems. An essential question does not have one correct answer; it can't be answered by a simple "yes" or "no." Rather, essential questions are broad in scope, they involve information and actions to resolve, they are not limited to factual answers, and they require students to make judgments and use predictive skills (Global Digital Citizen Foundation 2016). Curt then had the class work in teams to brainstorm essential questions related to their real-world problem of icy roads affecting their educational access. At the end of brainstorming, Curt had each student team share their essential questions, which he listed on a whiteboard. He then skillfully led the class to settle on one essential question, a question that approximated his original idea for a challenge: What transportation problems exist in subfreezing weather?

Once the class had settled on their challenge question, Curt needed to help the students shape it into an engineering design challenge. To do this, he was able to prompt the students to focus on ice and deicing by asking, "How could we use chemistry to solve transportation problems in subfreezing weather? Do you have similar issues at home? Do you have icy walkways at home?"

In one day, Curt led his students from the global issue of equitable educational access and transportation to road safety in freezing temperatures. From here, Curt and the class negotiated a final challenge: to design a deicing product using available, cost-effective chemicals and create a commercial to market the new product.

With the design challenge defined, Curt and the class brainstormed guiding questions, which connected more directly to the required chemistry content and focused the students on what they needed to learn to design the deicer. The guiding questions,

Continued

the starting point of the EDP process, clarified the constraints of the challenge. Some examples of guiding questions for this unit are as follows:

- What is a deicer?
- How do deicers melt ice?
- What chemical compounds are used as deicers?
- What chemicals will we have access to when we design our deicers?
- What environmental risks are associated with the use of deicers?
- What impact will the product have on the surfaces it is placed on?

Curt used these questions to refine his chemistry instruction and establish the resources the students needed to complete their design challenge and his design challenge unit.

After identifying the essential question, students are able to provide input to shape the design challenge in order to address the essential question. It should be the teacher's goal to promote as much student-centered learning and choice as possible; however, teachers must also ensure that required academic content is incorporated. It is critical that teachers take an active role to guide the process of moving from big idea to design challenge in a way that allows for student input and choice but also sets goals and parameters to ensure the challenge can be accomplished in a classroom setting. To do this, teachers need to have a challenge in mind from the start. In other instances, teachers can have students submit ideas in writing, read all the ideas after class, and select or modify a popular, doable option that also satisfies the academic goals of the unit.

After the essential question is transformed into a design challenge, the class can form guiding questions. Guiding questions for the design challenge detail the content students will need in order to learn the necessary science behind the challenge; they also explain the materials and resources students will need to design, test, revise, and redesign their product ideas. Guiding questions start the EDP cycle and focus the content learning goals.

Working With Academic Standards

When asked to incorporate new pedagogical strategies, most teachers worry about how they will still cover the necessary standards and prepare their students for the inevitable high-stakes testing. Design challenge units may elicit the same concern as they appear time consuming when first presented. However, in our experience with evaluating students' content knowledge growth with pre- and post-assessments in the design challenge units, the students performed similarly to those taught with traditional instructional approaches. Our results are supported by robust educational research, which suggests that students learn best in engaging and empowering classrooms where learners are "supported in taking charge of their own learning" (NASEM 2019, p. 148).

An important key to our success was carefully considering and choosing the right standards or blend of standards when developing a design challenge unit. To do this, some teachers chose the standards first and then brainstormed potential design challenges that would illustrate the standards. Because some standards are difficult for students to grasp and due to student misconceptions regarding certain topics, teachers must seek ways to make the phenomena more understandable through a hands-on project. For example, an AP calculus teacher noted that related rates was a hard topic for students to grasp during the first round of teaching. Typically, students did not fully understand related rates until the end-of-semester review, just prior to the AP calculus exam. This teacher devised her design challenge unit to highlight the real-world example of how related rates are used in water flow, leading to the design of a specialized rain barrel.

Other teachers have a big idea or design challenge in mind and then work to incorporate the appropriate standards into that challenge. For example, a seventh-grade math teacher worked in a school building where the lockers were outdated, small, and damaged. The students constantly complained about them. The teacher started with this real-world issue, developing a series of design challenge units based on the sorry state of the lockers. She then worked to connect this to a global challenge and her geometry standards. In the first unit, students applied the geometry standards of surface area, volume, and problem solving with scale models to design replacement lockers for the school. In the next unit, student teams explored the importance of accurate measurements and conversion of measurements to build a scale model of the warehouse where the new lockers would be manufactured. Finally, students applied ratios and proportional relationships to the industry of logistics as they decided on the most efficient and cost-effective way to transport the lockers to schools.

Another approach some teachers took with the design challenges involved "bundling" a wide range of skills and standards into one unit (Heitin 2015). They viewed the units as opportunities for students to apply skills and knowledge across multiple content standards, modeling the real-world work of engineers who apply numerous concepts from a variety of disciplines to solve a problem. As an example, an eighth-grade math teacher needed to include all the eighth-grade math standards and get deeply into high school algebra. Therefore, his design challenge units consisted of design challenges that required knowledge from multiple standards. His "Barbie Bungee" unit utilized eighth-grade standards of statistics and probability, plus linear functions from algebra. During the activity, students designed a safe but thrilling bungee jump for a Barbie doll or other action figure. The challenge was not only engaging but also effective at covering the diverse set of standards.

Establishing an Inclusive and Appropriate Classroom Culture

In order for students to be successful with design challenge units, their teachers must have already established a classroom culture that highlights working in teams, communicating with peers, and feeling safe to share math and science ideas despite possibly lacking confidence in those ideas. A classroom in which information typically flows from a teacher or book directly to students is not ready to leap into a design challenge. Teachers with such classrooms will need to provide opportunities for students to learn and gain confidence in taking the lead of their own learning before utilizing design challenge units.

Furthermore, design challenge units are built for classrooms in which the teacher embraces and prepares for an inclusive learning environment. Teachers need to develop design challenge units that welcome the rich cultural, historical, and developmental diversity students bring to a learning opportunity (NASEM 2018). A classroom in which learning is regimented and the same single outcome is expected for all students should hold off on creating design challenges. First, the teacher will need to build a repertoire of strategies to support all students and offer opportunities for them to select how they want to access information and display their learning.

The ideal learning environment for a design challenge cannot be created with the launch of the design challenge unit; it has to be developed and sustained as an established feature of the classroom. Our suggested strategies draw heavily from the reports *How People Learn II* and *Science and Engineering for Grades 6–12*, which were created in 2018 and 2019, respectively, by the National Academies Press. (Both are available online from National Academies Press.) What these two reports emphasize is that learning is a social activity in which cultural and historical context and socialization establish the habits of mind that students bring to class. Design challenge units can serve as bridges that allow diverse students to use their particular ways of knowing to meet school curricular goals. The CBL framework, with its use of complex global and real-world issues, has been shown to increase equity in STEM classrooms. "Relevant, contextualized experiences connect underrepresented populations in STEM and English learners to the science community" (Tolbert et al. 2014). In this way, well-developed design challenge units completed in classrooms by students prepared to engage in complex, team-based work serve all students, independent of background.

If teachers do not feel their classrooms are ready to jump in with a multiday design challenge, it may be useful to incorporate some basic student-centered learning activities early on during the academic year. Teachers should get to a point where they feel comfortable with students making choices and decisions about how to complete their work. Meanwhile, students should come to feel safe communicating tentative ideas in small- and large-group settings. All students in the class need to be able to work with a team on a shared task. Finally, students need to be comfortable generating multiple solutions and options and then defending their selection of *a best answer* rather than *the only answer*.

To increase everyone's comfort with making decisions and choices about learning, we suggest a Universal Design for Learning (UDL) approach (Buxton et al. 2013; Center for Universal Design 1997; Rose and Meyer 2002). The guiding principle of UDL is to provide students with multiple ways to access, communicate, and represent information and learning. Basic technologies, including calculators, spreadsheets, or text readers provide students with alternatives for how to gather or process needed information.

Increasing students' comfort with sharing tentative ideas and defending their ideas requires practice on the teachers' part. Both teachers and students are used to the question-response-assess structure of classrooms, also known as the Initiation-Response-Evaluate/Follow-Up discourse pattern (Cazden and Beck 2003). This discourse pattern can be boiled down to constant minitesting from the students' point of view. To move beyond this discourse pattern, teachers need to ask deeper initial questions. Then, when an individual responds, teachers need to continue with questions that bring other students into the conversation. For example, a teacher might ask the following:

- What was good about that response?
- Can someone suggest a different way to express the answer?
- Can you give an example that would give a different result?

Questions that explore the reasoning used to get to an answer and invite alternative ways to express ideas shift the focus from *the answer* to *the thinking*. This demonstrates the idea that there is not always a single answer or route to an answer.

Helping students to work in teams or small groups takes practice and ground rules. Whether you call them student groups or teams is not important—the terms are frequently used interchangeably. However, we believe the idea of a team is more appropriate for a design challenge, since it indicates that a collective effort is needed to complete the challenge. Some teachers like to assign roles; others allow for a more free form of teamwork. We suggest starting by giving each team member a role. In advance of assigning the roles, be sure students know what each role means and what the person in the role is expected to accomplish. Then give the students the opportunity to practice each role. Once students are familiar with the roles and activities of each role in a design challenge, they can adapt and distribute tasks as needed.

The goal of preparing your classroom environment for your design challenge unit is to develop practices and processes so students can smoothly and confidently engage their knowledge base and use it for collective success. A design challenge unit needs to push students out of their typical classroom comfort zones but not push so far that success is out of reach. Finding the point of productive struggle is a design challenge for each teacher!

Summary and Takeaways

Design challenge units reflect the needs and demands of STEM education. They align with and meet national science and mathematics standards and practices. They provide new opportunities for students and teachers to connect school science and mathematics to real-world issues. Challenge-based learning draws from several instructional practices that hold student-centered learning as their central component. Integrating a CBL approach to engineering design has the unique potential of making science and mathematics more accessible for all students. Design challenges stimulate student interest and increase learning, and students who might not have considered a STEM career may change their minds.

Teachers play an important role in establishing an effective learning environment for design challenges. Teachers need to draw on their knowledge of the curriculum and its potential to connect to engaging design challenges. Whether teachers start with required standards or bundle them in new ways around a design challenge, they need to take into account their students' ideas, curricular requirements, and available time and resources to create design challenge units. Finally, teachers need to make sure they are ready to engage in an inclusive student-centered classroom environment. Most students are not ready to tackle a complex design challenge without practice in student-driven learning and confidence in their ability to take charge. This chapter highlighted the following five takeaways we believe teachers need to keep in mind as they start their journey into design challenge units:

1. Engineering design activities incorporate science and mathematics practices and habits of mind as laid out in the *CCSS Mathematics* and the *NGSS*.
2. Challenge-based learning draws on aspects of project-based learning and problem-based learning. Using a global challenge to initiate the unit design challenge creates an inclusive learning environment.
3. Teachers must take an active role in the process of narrowing the big idea into a classroom design challenge. To do this, teachers need to come to the unit development process with an idea in mind and work with students to shape and refine the questions and challenge.
4. Science and mathematics standards and practices need to guide the design challenge units, but teachers can use them flexibly depending on the learning needs of the students and curriculum.
5. Design challenge units are an inclusive instructional strategy; however, classrooms must be ready to take on a complex learning environment. Teachers should evaluate

their classroom environments beforehand and use preparatory activities to develop the needed skills and practices to allow for student success.

Table 1.3 features a short dos and don'ts list for developing design challenge units to meet your classroom instructional requirements.

Table 1.3. Dos and Don'ts for Introducing Design Challenge Units

Do	Don't
Present students with a big idea tied to a global issue	Make your big idea too narrow
Have students brainstorm the essential question from the big idea	Tell or define the essential questions without student input
Shape student questions to align with required standards and learning objectives	Allow students to wander from the learning objectives
Consolidate essential questions into one question that can be restated as a design challenge	Leave the question or design challenge too open-ended
Create guiding questions that focus on the content the design challenge requires	Develop guiding questions that stray from the academic content and processes required

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CREATING ENGINEERING DESIGN CHALLENGES

Success Stories From Teachers

"We created this book with the educator in mind—specifically secondary mathematics and science teachers looking for ways to integrate engineering practices into classroom instruction."

—from the preface to *Creating Engineering Design Challenges*

If you've ever wished for advice you can trust on how to make science and math more relevant to your middle or high school students, *Creating Engineering Design Challenges* is the book for you. At its core are 13 units grounded in challenge-based learning and the engineering design process. You can be sure the units are classroom-ready because they were contributed by teachers who developed, used, and revised them during the Cincinnati Engineering Enhanced Math and Science (CEEMS) program, a project funded by the National Science Foundation.

Detailed and practical, the book is divided into three sections:

1. The rationale for making engineering an effective part of math and science instruction.
2. Thirteen engineering-related units, including the teacher-contributors' detailed accounts, lesson plans, and handouts. Content areas include biology, chemistry, physical science, Earth science, and environmental science. Topics range from developing a recipe for cement to implementing geocaching to calculating accurate aim with slingshots and water balloons.
3. Guidance on how to develop, support, and grow your engineering practice. This section offers useful templates and frameworks for you as well as professional development guidance for your school.

The contributors' goal is to help you benefit from their hard-won experience. They write, "During our time with the CEEMS project, we learned a great deal from our mistakes and our successes, and we felt it would be important to share what we learned with the hope that you can build on your own success." Working from their advice, you can develop a more student-centered classroom culture and nurture learners who are engaged in real-life engineering challenges.

Grades 6–12

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