Engineering for All

Strategies for helping all students succeed in the design process

By Pamela S. Lottero-Perdue, Sarah Lovelidge, and Erin Bowling

As calls for science, technology, engineering, and mathematics (STEM) education at the elementary level become more vociferous, elementary teachers may be wondering whether engineering is meant for all students. They may question whether engineering is appropriate for their inclusive classrooms, where children with special needs are included in regular instruction.

We—an assistant professor of science education, an enrichment teacher, and a third-grade teacher—assert that engineering can be taught in inclusive environments. It may be especially empowering for those who struggle with traditional subjects. Here we describe how the core practice of engineering, the engineering design process, was taught in a third-grade inclusive classroom in which students used this process to design windmill blades. In this class, 7 of the 20 children received assistance from a reading specialist, and one child had an Individual Education Plan. However, the multiple strategies we feature can help all students succeed in engineering design.

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Engineering Design Process

Engineers use the engineering design process to solve problems (e.g., how to transform wind into useable energy). The nomenclature used to describe the steps of the process varies across engineering education programs. However, the steps take a form similar to those in Figure 1 as articulated by Engineering is Elementary (EiE), a national program that has created elementary-level engineering units that link to national science education standards (see Internet Resource). Although Figure 1 suggests only one improved design, engineers improve their designs many times. Students can repeat the Improve step as time allows.

Windmill Blade Design

The EiE unit *Catching the Wind: Designing Windmills* was situated within a science unit in which students learned about position, force, motion, and energy. This introductory unit uses inquiry-based science instruction to help students understand these basic physics concepts prior to engagement in the engineering design process. For the culminating lesson in the unit, the students designed windmill blades. The blades are tested on a windmill apparatus placed in front of a fan. Ideally, the wind from the fan causes the blades to turn the windmill's axle, which winds a string on the other end of the axle, lifting a cup (like a bucket-type well). The cup is initially empty; pennies or washers can be added to create a greater lifting challenge. Teachers should operate the fan to ensure that students do not put fingers in or get long hair too close to the fan. Students and teachers must wear safety goggles or safety glasses, have long hair tied back to prevent entanglement in the fan blades, and wear only closed-toe shoes or sneakers during windmill operation. OSHA regulations and best practice require fan blades to be protected with a guard having openings no larger than ½ in. (1.27 cm). The teacher should review safety precautions and proper equipment use technique with students prior to starting the activity.

CAUTION

Ask

Students were introduced to the concept of constructing a windmill when the teacher read aloud the EiE storybook "Leif Catches the Wind" (see Internet Resources). In this story, two children, guided by the advice of a mechanical engineer, designed a windmill that turned a paddle to aerate a pond. The teachers noted that the students would design a similar windmill, yet theirs would lift a cup instead of turning a paddle.

To begin the Ask step, the teachers showed the students the windmill apparatus and asked how well-designed blades could make it work. Here and throughout the engineering design process, they encouraged students to use words like *spinning, force,* and *kinetic energy* to describe the windmill's operation and reinforce science learning.

The teachers reminded the students of a sailboat activity the students had completed. In this activity, children designed simple sails affixed to craft stick masts made from a range of simple materials including felt, paper, plastic bags, and coffee stirrers. The masts attached to sailboat hulls on a low-friction slide and were placed in front of a fan. The sailboat's motion was analyzed for its speed and consistency of motion, then children improved sails based on testing results. The engineering design process was at work here only implicitly; the careful work of moving through each step of the process was saved for the windmill design.

The teachers elicited what the students learned from the sail activity: that certain materials worked better than others, and that large, well-supported sails were effective at catching the wind. They also shared with the students that windmill blades could be designed using the same materials as were used for sail design.

The classroom teacher led a whole-class discussion to complete a worksheet summarizing key aspects of this Ask step: the purpose of the windmill, testing procedures, and what was learned about effective sails. Worksheet questions projected on an interactive white board enabled her to guide struggling writers as she carefully recorded and projected essential Ask-step information for all to document. Students wrote, for example, that the purpose of the windmill was "to catch the wind and lift weight."

Imagine

Students worked in pairs during the Imagine and subsequent steps. During the Imagine step, students brain-

Figure 1.

EiE engineering design process steps and descriptions.

Engineering Design Process Step (EiE)	Description of Step
Ask	Identify the problem. Determine design constraints (e.g., limitations on materials that can be used). Consider relevant prior knowledge (e.g., science concepts).
Imagine	Brainstorm design ideas. Draw and label those ideas.
Plan	Pick one idea. Draw and label the idea. Identify needed materials or conditions.
Create	Carry out the plan; create the design. Test the design.
Improve	Reflect on testing results. Plan for, create, and test a new (improved) design.

PHOTOGRAPH COURTESY OF THE AUTHORS

Up-close view of windmill with four blades.

stormed what different windmill blades might look like that could solve the problem. The focus of this step was on blade shape. An Imagine step worksheet provided four blank boxes in which students draw up to four windmill blade ideas. No scoring rubric was used, but teachers circulated the room to ensure that each pair of students drew at least two ideas and that each idea was drawn with clarity. Students drew a range of blade shapes, including squares, triangles, and rectangles, all affixed to skinny upright rectangles representing craft stick base supports.

Plan

During the Plan step, students selected one of their brainstormed ideas, sketched it, determined how many blades to include in their design, and listed needed materials. The teachers asked students about students' plans and why those plans might help solve the engineering problem. They inquired about students' choices in blade shape and material (Were these choices consistent with what was learned from the sails activity?); the number of blades students chose to put on the windmill (Why 3, 4, or 10?); and, blade angle, whether students chose to angle some or all of the blades (What made you decide to put this windmill blade at this angle?). The minimal writing demands of this task (the materials list) were primarily supported by the pairing strategy used, in addition to monitoring and assistance from the teachers. When pairing students, a somewhat stronger reader/writer was matched with one who needed a bit more help. This provided peer support for those with reading and writing difficulties. Children who had difficulty listing the materials they planned to use were able to copy from their partner's list after agreeing on necessary materials.

Create

The students eagerly and swiftly created their blades. To prevent shoddy construction, at least eight minutes had to be spent building.

Two pairs of busy engineers seated at one table were Beth and Caitlin (girls) and Trevor and William (boys). One of these children has significant language challenges. Although we refer to these as the "girls" and "boys," we do not intend to generalize their experiences to all girls or boys.

Beth and Caitlin brought their first design to the apparatus. When the wind blew, nothing happened but a quiver of the four large card stock blades set on craft sticks, rattling in place but not spinning the windmill axle. The girls had learned from the sails activity that the blades needed to be large and stiff. However, the blades were not angled. Blade angle was not important in the sails activity, yet it was important for windmill blade design. Students were to discover this essential design feature themselves or with guidance from teachers.

William and Trevor's first design spun the axle and lifted the empty cup. Adding washers to the cup, however, brought the windmill to a halt. Most of their eight windmill blades made of cardstock were angled, yet some faced opposite one another, negating their potentially helpful angled positions. Unable to come to consensus about blade size and shape, the boys compromised: four of the blades were small and triangular (William's idea), and four were somewhat larger, elongated trapezoids (Trevor's idea).

Many of the students at work building at their desks would routinely pause to watch another pair's test. Once all students had tested their first designs, the teachers led a whole-class discussion so that students could share and reflect on their findings with one another.

Improve

The Improve step began immediately after each pair tested their first design, as the teacher asked each pair to reflect on testing results, and continued with more reflection during the class discussion. The students returned to pair work, this time to focus on design improvement. The enrichment teacher circulated, posing questions about how students could improve their designs. She referenced the concept of "form fits function" from an earlier biology unit to suggest that students consider how the features of their designs (e.g., blade shape, size, and material) should be purposeful.

With Caitlin and Beth, who seemed stuck regarding how to proceed, the teacher shared images of real windmills and wind turbines, noting the angle of the blades. She demonstrated how to place one of the blades at an angle by picking up a blade and angling it, and left the girls to modify the other blades.

The enrichment teacher met with the boys and inquired about their first design, yet the boys were satisfied with their blades and the compromise they had made. The teacher shared the windmill and wind turbine images with the boys, focusing on the blade-to-blade consistency of angle, and used her hands to show the boys how some of their blades opposed one another or were not angled.

After documenting the testing results and improvements they made, both groups were ready to test their improved design. The boys retested and were able to lift 30 washers in the cup, a marked improvement beyond their first design, which lifted only the empty cup. The girls, whose first design did not lift the cup at all, had looks of surprise and joy on their faces as their improved design lifted 50 washers. We suspect that the girls were not only excited by their design success, but felt a rare moment of achievement above others in the classroom.

Assessing the Design Process

During each step of the design process, the teachers formatively assessed students' progress by examining their participation, worksheets, and blade construction and testing. By the end of the design process, all student pairs were successful in lifting at least 20 washers, and many pairs lifted as many as 50.

Summative assessments included the success of students' improved designs and student achievement on a postunit EiE-developed test. It asked questions such as, "Shara is making a windmill, but cannot make it spin. She made the blades bigger, but it still did not spin. Which of the following things could she do to improve her windmill?" (Check all that apply.) Students should correctly identify that Shara could add more blades, change the angle of the blades, or change the materials the blades are made of. Students should leave unchecked "Put holes in the blades to let air through."

Students performed significantly better on the postunit questions that assessed student understanding of wind energy, windmill operation, and engineering than for identical questions on the preunit test. The postunit average was 6.7 of 9 answers correct (standard deviation = 1.3); the preunit average was 4.8 (standard deviation = 1.6).

Helping All Students Succeed

Caitlin, Beth, Trevor, William, and their classmates all met varying degrees of success during the engineering design process. They enthusiastically participated in and documented the steps of the engineering design process. They created a first design using at least some aspects of prior knowledge from the sail activity. All of the pairs were then able to improve their designs, with some having more well-reasoned improvements and ideas than others. Online, we have listed teaching strategies introduced in the vignette that encourage success for all students in engineering design, especially those who have special needs (see NSTA Connections).

Although we want well-reasoned designs, we also want students to try their own ideas. If students are attached to design ideas that fail to incorporate relevant concepts, allow them to test their designs. Testing results will help make the case to students that the most successful designs employ good reasoning.

We end with two warnings: (1) brace yourself for the excitement that students have as they engage in the engineering design process; and (2) be prepared for all students to succeed and for some who normally struggle to shine. ■

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Internet Resource
Engineering Is Elementary (EiE)
www.mos.org/eie

NSTA Connection
Download a list of teaching strategies at *www.nsta.org/SC1003*.

Connecting to the Standards

This article relates to the following *National Science Education Standards* (NRC 1996):

Content Standards:

Grades K–4

Standard B: Physical Science

- Motions and forces

Standard E: Science and Technology

- Abilities of technological design
- Understanding about science and technology

National Research Council (NRC). 1996. *National science education standards*. Washington, DC: National Academies Press.