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Innovation and Design

Using books to introduce engineering-based thinking

Engineering design-based learning entered the discourse of science education with the release of the *Next Generation Science Standards* (NGSS Lead States 2013). Since that time there has been a focused effort to embed engineering design and engineering-based thinking in elementary school experiences. As thinking like an engineer is central to design-based learning, both the National Academy of Engineering (NAE) and the International Technology and Engineering Educators Association (ITEEA) recommend that educators use "stories that dramatize the rich legacy of engineering achievements" to "bring the experience of engineering to life" (NAE 2008, p.44). We have found that using books to reverse-engineer the processes by which engineers solve problems can help us implement these recommendations and embed engineering-based thinking as a cross-curricular activity in elementary classrooms.

Like Hill-Cunningham, Mott, and Hunt (2008), we view children's literature as providing a "real life" application for the Engineering Design Process. Furthermore, children's literature provides a comfortable, familiar platform from which both teachers and students can connect with engineering. Most often, we use trade books and picture book biographies of engineers and inventors with younger students and chapter book biographies with older students (Forsythe, Jackson, and Medeiros 2019). Biographies are useful in exploring engineering-based thinking because they present a "chronological sequence of events with a framework that assists readers in developing their understanding about the person-of-study and that individual's achievements" (Werderich, Farris, and McGinty 2014, p. 66). Therefore, we select biographies and trade books that include how inventors or engineers apply elements of the engineering design process to systematically and efficiently solve problems and create new technologies.

The Engineering Design Process

The Engineering Design Process (EDP) is a flexible framework that organizes how inventors and engineers ask questions, build and test prototypes, seek solutions to problems, and communicate results. There are several accepted versions of the EDP, and all reflect an iterative cycle "that enables engineers to continually enhance and improve their design [prototypes] through repeated testing, analysis, and redesign" (Parker et al. 2016, p. 400). Most introductory EDP models include common elements that guide problem solving—a goal statement or a recognizable problem followed by an iterative series of steps that guide the engineering design process: Ask; Imagine; Plan; Create, Test; Redesign/Improve; and Communicate. These elements underpin the book selection checklist that we created to help us select biographies and trade books (see NSTA Connection), and they frame the unit examples included in this article. The test and redesign phases of the process are especially important. This is where engineers and inventors use what they learn when a prototype fails or performs in unexpected ways to make improvements to their design. Engineers also consider key criteria as well as any constraints and limitations when making decisions about materials, timelines, and expenses.

Selecting Books

Choosing appropriate biographies and trade books to support the EDP can be challenging. However, we have found a number of reliable resources useful for building a STEM library. The National Science Teaching Association (NSTA) reviews hundreds of books yearly and publishes their recommendations as the Best STEM Books K–12 list, which can be found at *https://www.nsta.org/best-stem-books-k-12*. In addition, *Science and Children's* "Teaching Through Trade Books" column often recommends STEM-related books, and the *Elementary STEM Journal* (formerly known as *Children's Technology and Engineering*) includes a "Books to Briefs" column that models how to use books to launch engineering design challenges. Finally, many online engineering curricula suggest ways to integrate children's literature with their lesson activities. Purdue University's PictureSTEM Project provides free K–2 instructional units that integrate literacy and engineering (*http://picturestem.org*). Similarly, Engineering is Elementary (*https://www.eie.org*) includes online support materials that highlight children's literature connections for the engineering topics included in their curriculum.

However, many of the books recommended by these resources, while useful for supporting STEM lessons in general, do not always include rich detail about an engineer's or inventor's thinking process. This makes using them to teach or reverse-engineer the EDP problematic. In order to find those books that feature the complexity and creativity of engineering in action, we developed a checklist (see NSTA Connection) to guide our review process. This checklist includes traditional EDP elements as well as features such as criteria and constraints, reasoned choices about materials, opportunities to communicate design choices, and application of the solution in everyday life. Even the more detailed biography will likely not address every item on this checklist. However, we have found books with at least seven or more of these items to be complex enough to provide a rich experience of the work of engineers and inventors. When we review books, we often use sticky notes labeled with the elements of the EDP and/or items from the checklist to mark specific pages of the book. This guides book selection and serves as a useful reminder of things that we might want to highlight during later classroom activities such as read-alouds.

Using Books

Once we've selected a biography or trade book featuring engineering, it's time to make decisions about how to use the book in our classroom instruction. To initially unpack the EDP with students, we typically read aloud either a picture-book biography about an engineer or a trade book that contains an obvious problem. As we read, we pause to connect key elements and actions in the story to the process of engineering. The complexity of how students perceive the EDP builds as they re-encounter each EDP element at different moments throughout the book (Forsythe, Jackson, and Medeiros 2019). For example, Table 1 outlines the progression of EDP stages in the book *Manfish: A story of Jacques Cousteau* (Berne 2008). This book introduces Jacques Cousteau and explains how his love for underwater adventure began. It describes several of the tools he invented or improved in order to study and photograph marine environments. Like many other biographies, this story vividly demonstrates how engineers and inventors do not follow a singular step-by-step process but rather engage in cycles of creative innovation and evaluation.

For younger students or students who are just beginning to learn the EDP, we use response sticks that are labeled with the elements of the EDP or engineering-based thinking (Figure 1) and an image to scaffold nonreaders and English learners. For example, the "Ask" response stick includes a question mark and the "Imagine" response stick includes a thought bubble. Our EDP read-aloud response sticks include: Ask, Imagine, Plan, Create, and Improve.

As we read aloud a trade book or picture-book biography specifically chosen to highlight the EDP, we pause at predetermined passages and ask students to identify how a character in the text is using the EDP by raising the response stick labeled with the element they think best represents the actions and current thinking processes of that character. Then we lead a whole-class discussion to decide which EDP element (response stick) is the most appropriate choice for a particular passage of text. The read-aloud, pause, students select response sticks, class discussion sequence continues until the read-aloud is complete. This activity can be modified by allowing students to work in pairs or small groups using a full set of response sticks; assigning only one EDP

TABLE 1

The progression of EDP stages in *Manfish: A story of Jacques Cousteau*.

EDP Stage	Summary of excerpt from *Manfish: A story of Jacques Cousteau*
Ask	Why do ships float? Why does he float in water? Why do rocks sink?
Imagine	He imagined that someday he would be able to breathe underwater.
Plan	He wrote little books and illustrated them with his own drawings
Create and Test	He spent many days during his childhood, playing, experimenting, and creating.
Create and Test	He built a model of a crane that was as tall as he was and it actually worked.
Ask	How are movies made? How do cameras work? How do chemicals make pictures appear in film?
Imagine	He bought a home-movie camera and took it apart and then put it back together again.
Create and Test	He started making home movies. He was an actor, the director, and the cameraman. He made many movies.
Create and Test	He joined the French Navy and he tried to film everything that he saw.
Ask and Imagine	In China, he filmed men who could hold their breath underwater for many minutes. He wondered what that would be like.
Test and Improve	Jacques and his friends experimented to find out how long they could hold their breath while underwater and how deep they could go.
Create and Test	Jacques created a waterproof case for his camera so he could film what he saw underwater.
Create and Test	Jacques and his friends made rubber suits to keep warm underwater and flippers to help them kick better.
Imagine	Jacques realized that he needed to take air with him when he went underwater so he could explore for longer periods of time.
Create and Test	Jacques invents the aqualung—and he used it to breathe beneath the water.
Communicate	Jacques made many underwater movies that he shared with the entire world.

element (response stick) per student or group of students; allowing students to create their own illustrations; translating EDP elements into a student's home language; or editing the EDP phases included on the sticks. For remote instruction, you could create a Google Jamboard with multiple pages focusing on each element of the EDP. As the selected book is read aloud, the teacher pauses and students can add digital sticky notes to the EDP element they are assigned and their work is automatically saved to their Google Drive, which means students can always go back to it to revise or reference. Alternatively, students could write each step of the EDP on pieces of paper or sticky notes and hold them up so that they are visible during a synchronous learning class video read-aloud or discussion.

Once students gain confidence collectively identifying the elements of the EDP, we have them apply their understanding through independent practice. Students use their read-aloud response sticks as a reference to write the EDP elements on sticky notes (or write them down from memory) and then use the sticky notes to mark sections of text in other trade books and biographies from our classroom library that exemplify the EDP in action.

FIGURE 1

Student using EDP response sticks.

Building Cross-Curricular Connections

As students continue to develop fluency with the EDP, we introduce an integrated language arts, social studies, technology, and science unit on using biographies to study the accomplishments of engineers and inventors. Online, we share a list of the *NGSS* and *Common Core* standards that align this cross-curricular unit across grades 3, 4, and 5 (see NSTA Connection). During the unit, student teams read a biography about an engineer or an inventor, conduct research, and create a presentation that includes a summary of the engineer or inventor's accomplishments, the problem they faced, how they applied elements of the EDP (or engineering-based thinking) to solve the problem, and how the innovation benefited the lives of everyday people as well as the national economy. In addition, the students brainstormed one way to improve on the innovation described in the biography and developed their own prototype sketch of the proposed redesign. This allows students to become more than just analyzers of the EDP…they become engineers themselves!

We use an interactive engineer/inventor biography HyperDoc (available at *https://goo.gl/EYuZvp*) to help students organize the required project elements, connect and collaborate with each other, and think critically about the impact of the engineering design. Converting this activity to a remote or hybrid learning experience is easy because HyperDocs include hyperlinks to scaffold and direct students to

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easy-to-use websites and web tools that provide digital support and quick access to helpful explanations online. Teachers using digital breakout rooms can allow students to work in teams remotely. The teacher shares the Hyperdoc with the team and they can effectively communicate as they are researching and recording their findings. This also provides the opportunity for young scholars to collaborate simultaneously. For our biography engineers/inventor HyperDoc (see Figure 2), we included hyperlinks to the Design Squad Station website (*http://pbs.panda-prod.cdn.s3.amazonaws.com/media/assets/wgbh/adptech12/adptech12_int_idsprocess/index.html*) that connected to written descriptions and video examples of each step of the EDP.

Students used class time during their English Language Arts (ELA) and Social Studies blocks to read select biographies, conduct research, and complete the biography HyperDoc. Before beginning the online research, students were taught digital citizenship skills so that they were equipped to not only find kid-safe informational websites but also determine credibility of online resources. This is a critical precursory step. An easy way to quickly and effectively ensure student safety and efficiency online is to provide students with links to a bank of resources. We typically use Google docs to provide various links for students to click straight into rather than using blanket search engines. When the biography HyperDoc was complete, each team presented their findings about how their engineer/inventor created an innovative solution to a problem and how that innovation benefited the community and the United States economy to the rest of the class.

During science, the student teams created their own improvement on or alternative to their engineer/inventor's solution. This revised solution addressed the engineer/inventor's original problem, and it had to meet additional design criteria (must haves) and constraints (limitations) created for each student team. One student group used the engineering design process to improve upon problems of modern transportation as they studied Henry Ford. In their research, they found that car accidents are a significant transportation issue that they could improve upon. Students used their knowledge of magnetism and friction to create systems to prevent collisions. Another team researched how Alexander Graham Bell solved the problem of communication over long distances. Students designed another solution to this overall problem of communication by creating a device that transmitted messages between classrooms.

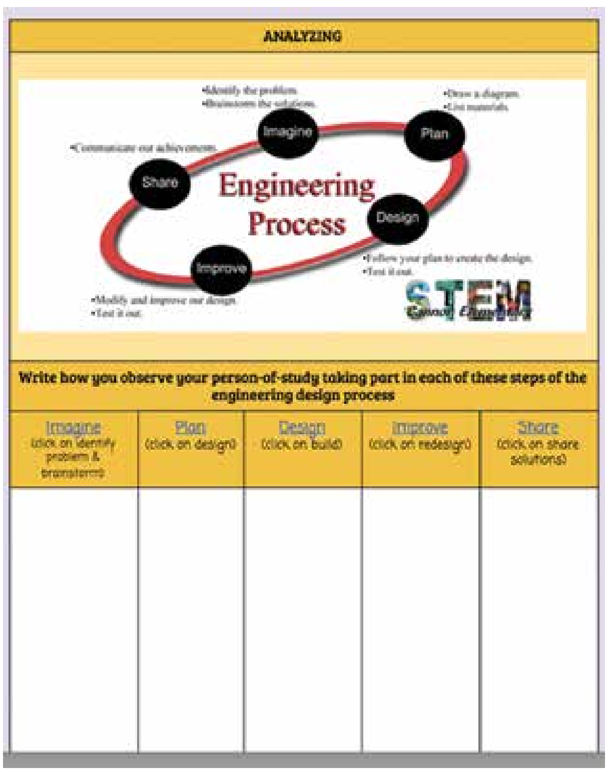
Across the entire unit, the students both identified the way their engineer/inventor applied the engineering design process and put that process into action by envisioning a new solution to a historical problem. New solutions were presented as detailed sketches and both face-to-face and remote students can produce sketches and explanations of how the new solution meets established criteria and constraints.

We assessed students' abilities in research and presentation as outlined in our state ELA and Social Studies standards through this project by using the HyperDoc and presentation rubric. This learning experience became a data point documented on students' report cards. Students' science work was graded using a STEM rubric that includes four categories to position every student—no matter their current level of mastery—as an emergent engineer: Budding Engineer, Sprouting Engineer, Growing Engineer, or Thriving Engineer. This rubric (see NSTA Connection) measures engineering abilities and is used to track growth rather than grades. Students can use this rubric to assess themselves and their group members. Teachers can add to the content mastery portion of the rubric to target specific content standards. At the end of the unit, students reported a stronger understanding of the overall engineering design process and, in particular, developed fluency with both the reasons why and the many methods by which engineers iteratively improve their designs. Students stated that "engineers are good at problem solving" and "need to try a lot of things to discover what works." Students concluded that "engineers really impact our lives and our community" by "making our life easier."

This project involved reading, writing, and research, which may be difficult for some students to accomplish. Students that struggle to access reading material could use lower level texts, recorded books, or digital video resources in order to study their engineer/inventor. Students participating in re-

FIGURE 2

Biography HyperDoc.



mote instruction could use ebooks or digital videos to gather information. A specialized word list that contains vocabulary words specific to their invention (and engineering in general) would help students that are English learners, dyslexic, or in special education. Sentence stems are effective for giving English learners a starting place when presenting their research. For example "One difficulty my inventor had was ______" or "_____ (inventor) solved the problem by________." or "My problem was_____." Sentence stems are also helpful in the context of engineering, such as "If I had more time or materials for my engineering design, one thing I would've done differently is ______ " or "One improvement to my design I made was ____." Students could also complete this project in traditional face-to-face or remote learning groups. Groups whose members have varied strengths typically work best in engineering design challenges. Considerations for group formation include interpersonal communication styles, reading ability, writing ability, and artistic creativity. A strong group typically contains a variety of these abilities without much overlap. This arrangement allows for students with difficulties in traditionally academic areas (such as written expression or vocabulary) to shine as they create hands-on products, and therefore group members find ways to complement each other's strengths in order to create the best possible product.

By encountering the engineering design process through well-chosen trade books and biographies, students can experience how actual inventors and engineers have used the design process and engineering-based thinking to solve important problems and create new technologies. The structure and details of a biography help students reverse-engineer the EDP from the engineer/inventor's own experience and provide a meaningful context for students to begin to think and act as engineers themselves. In addition, the chronological nature of biographies highlights how design-based thinking is an ongoing, iterative process as engineers/inventors continuously look to improve on previous solutions to problems—a search students get to join in on through the creation of their own designs in the interdisciplinary investigation. We hope that by experiencing the real-world contributions of innovative engineers and inventors, students are inspired to become engineers and inventors themselves. Then we can add a whole new generation of biographies to our STEM libraries! ●

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NSTA Connection

Download a checklist for selecting books that support the EDP, project rubrics, and standards alignment for the unit at *https://www.nsta.org/science-and-children*.

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