Disciplinary Literacy in Engineering

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Because the outcomes of engineering have a direct and profound impact on people's quality of life, literacy in engineering, including the rigorous interpretation, evaluation, and production of texts, can be very consequential.

We begin with a common scenario: a team of engineers and corporate managers huddled around a corpus of texts. On the evening of January 27, 1986, such a team gathered for an urgent conference during which they interrogated texts—and one another—to decide whether the space shuttle *Challenger* would be launched the next morning. A NASA engineer recalled how a leader of the meeting

> had his sleeves rolled up and his jaw set hard, and he was examining that data, boy, every line of it, you know. "How do you know this and how do you know that?" And getting the contractor to defend every...argument he had the best he could. And the reason for that is, [if] he tells his boss he's going to stop the launch, then he has to understand why he's stopping the launch. (Moore, 1992, p. 408)

Ultimately, a decision was made to launch the shuttle even though the design of the O-ring for its primary solid rocket booster had not been verified in extreme temperature conditions. As some engineers feared, the O-ring failed during the unseasonably cold launch. At approximately 73 seconds after liftoff, the *Challenger* experienced extreme aerodynamic loading and broke apart in midair.

Although millions of engineered devices and systems work as intended—providing safe building structures, reliable transportation, access to information, potable drinking water, and many other necessities and amenities that improve the quality of people's lives—we offer this example to underscore the criticality of literacy in engineering. Practitioners in this field regularly generate a wide range of texts, such as reports and subcomponent specifications, much as the engineers for the *Challenger* did. They closely interpret these texts, gather evidence, construct and evaluate arguments, recommend courses of actions, and justify decisions to stakeholders (Fosmire & Radcliffe, 2014; Gainsburg, Fox, & Solan, 2016).

Along with designing and evaluating physical products, ranging from O-rings to synthetic vitamins, engineers relatedly design and evaluate systems, such as schedules and instructions that direct public subway cars to prevent accidents and optimize efficiency, and processes or procedures, such as steps for pasteurizing, testing, storing, and transporting cow's milk to ensure that it retains nutrients while remaining safe to drink. Because the outcomes of engineering have a direct and profound impact on people's quality of life, literacy in engineering, including the rigorous interpretation, evaluation, and production of texts, can be very consequential.

In this commentary, we (a former middle school reading teacher with a PhD in literacy education and a registered professional engineer with a PhD in engineering education) illustrate how disciplinary literacy can be applied in engineering. We used two main sources to inform our descriptions of engineering: the Next Generation Science Standards (NGSS; NGSS Lead States, 2013), which have been adopted by many states across the United States and have guided revisions for science standards in many other states, and the National Research Council's (NRC's; 2012) Framework for K–12 Science Education, which formed the basis of the NGSS.

Specifically, we use the NGSS's model of engineering, an expanded version of which appears in Figure 1, to highlight texts and interpretive frameworks that are common across four engineering design processes:

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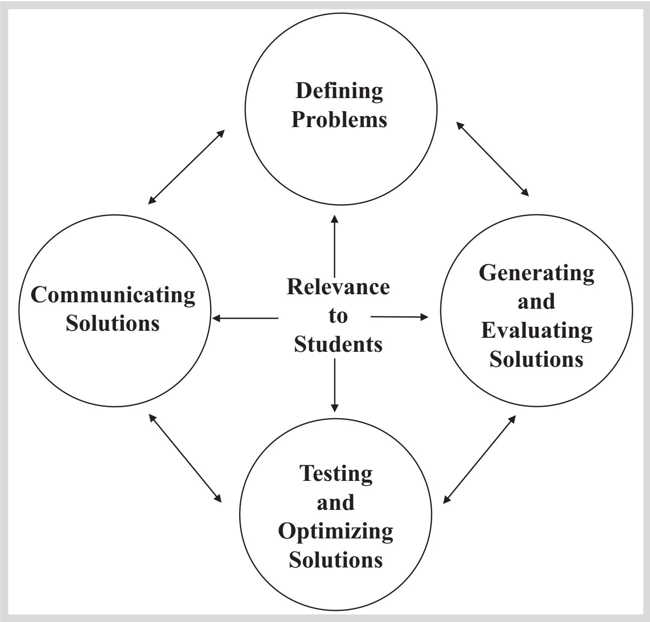
Figure 1
A Model of Engineering Design Processes Based on the Next Generation Science Standards



defining problems, generating and evaluating solutions, testing and optimizing solutions, and communicating solutions. Although practitioners of engineering often engage in multiple processes simultaneously and in a nonlinear way, we present these processes as discrete categories for the sake of clarity. To demonstrate what disciplinary literacy might look like in practice, we describe how seventh graders in a technology and engineering course used literacy practices to redesign their middle school parking lot over the course of one month. The students who addressed this "Parking Lot Challenge" reflected the overall demographics of their middle school: A majority received free or reduced-price lunch, and a large percentage, as compared with the national average for middle schools, was designated as English learners and Hispanic in school records.

Defining Problems

Engineers interpret information across multiple texts to adequately define problems. These texts often include regulations or codes, budgets, scientific or mathematical reference texts, descriptions and visuals of drafts of previous design solutions, and communications from other engineers and from potential clients or users of their products (Tenopir & King, 2004). As engineers read these texts, they identify and prioritize criteria (measurable requirements that their solution must meet) and constraints (limitations and restrictions on possible solutions). Engineers may produce texts, such as spreadsheets or charts, to enable them to track how solutions meet prioritized sets of criteria and constraints (Dym, Little, & Orwin, 2014).

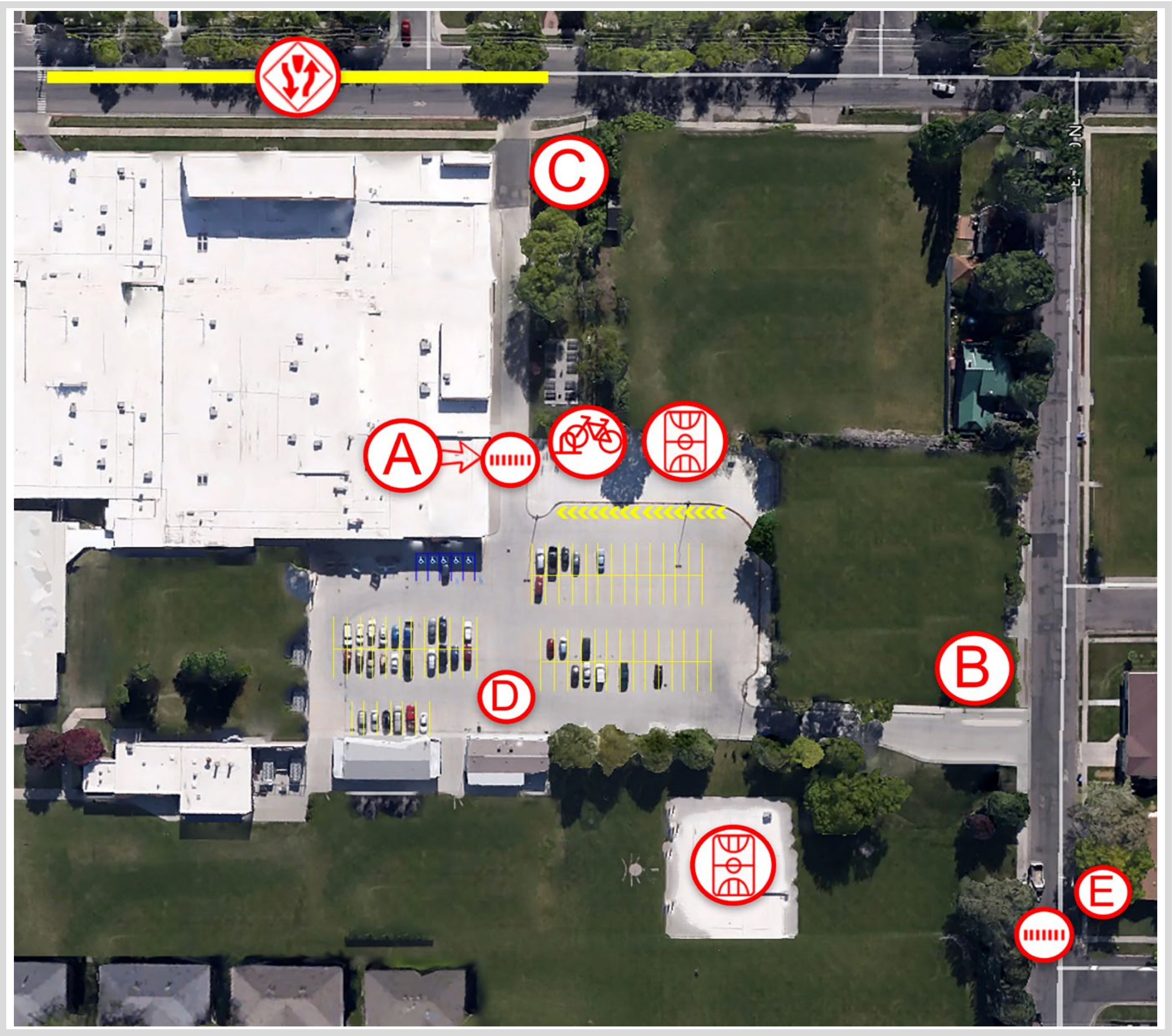
Parking Lot Challenge

To engage students in these practices, we asked one class of seventh graders to identify local problems that could be solved with engineering. Over half of the students stated that they had almost been hit by a car in the parking lot and wanted to redesign it to make it safer. As part of this process, they generated or read several texts, including the following:

- Transcripts from interviews in Spanish or English with parents, middle school students, teachers, and community members regarding what they wanted to see in an improved parking lot: These interviews indicated that the parking lot had other problems as well, such as long waiting times after school.
- A labeled aerial photograph of the parking lot highlighting problem areas, such as points A and D in Figure 2, where pedestrian students were frequently at risk of being hit by cars
- Data displays sharing statistical information related to different points on the aerial photograph, such as the average number of cars that entered and exited different entryways before and after school and the average number of times that a car came within less than 24 inches of hitting a student near points A and D. By this definition, repeated observations indicated that, on average, 33 students were at risk of being hit by a car each day at point A.
- Simplified regulations for parking lots, such as those issued under the Americans with Disabilities Act
- Cost estimates for specific parking lot features, such as the installation of a stop sign

The students compared the visual, mathematical, and written texts to develop understandings of problems with the parking lot. While reading with teacher guidance, they listed criteria and constraints, many of which were established by federal or municipal regulatory agencies or by the school district, such as "the parking lot must include a minimum of three parking spaces, close to a wheelchair-accessible door, for

Figure 2
A Labeled Aerial Photograph of the Middle School Parking Lot



Note. The photograph has been modified to protect the anonymity of the school. The color figure can be viewed in the online version of this article at http://ila.onlinelibrary.wiley.com.

people with disabilities" (a criterion) or "changes to the parking lot must cost less than $100,000" (a constraint). Students later ordered the criteria and constraints in terms of importance by placing some in a "must have" list and others in a rank-ordered "nice to have" list.

Although these texts were specific to this particular parking lot problem, the students engaged literacy practices similar to those used by engineers: gathering information across sources, cross-referencing multiple representations, prioritizing criteria and constraints, and developing texts in the form of lists and tables to enable systematic tracking of whether and how future proposed design solutions meet the design requirements. Table 1 summarizes the types of disciplinary literacy that are common to this stage of the engineering design process.

Generating and Evaluating Solutions

Engineers generate solutions in the form of texts, which often include visual, mathematical, and/or written

Table 1
Disciplinary Literacy During the Defining Problems Stage

Performance expectation in the Next Generation Science Standards	Possible texts	Interpretive frameworks
"Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution" (MS-ETS1-1).	■ Verbal, quantitative, and/or visual description of the context of the problem ■ Regulations, standards, or codes ■ Budgets ■ Relevant scientific or mathematical information ■ Lists of criteria and constraints	■ Identify and prioritize criteria and constraints that are implied or explicitly stated in multiple texts. ■ Determine whether one has enough information to solve the problem and where one should go to collect additional useful and reliable information.

elements produced with the help of computer-aided design tools (Dym et al., 2014). Engineers evaluate potential solutions to determine how well they meet prioritized criteria and constraints. In evaluating potential solutions, engineers engage in systems thinking by predicting how changes to one solution element affect outcomes across multiple systems. Engineers make trade-offs by evaluating whether gains or improvements related to one outcome justify losses to another outcome.

Parking Lot Challenge

To engage students in evaluating possible parking lot designs, we first showed them four exemplar texts: possible parking lot designs produced by a civil engineer specializing in traffic analysis. Each design included a labeled aerial image of the parking lot, a cost estimate, and a brief written justification for each design decision. Students used a checklist to identify the extent to which each design met their prioritized criteria and constraints. The students verbally debated solutions (parking lot designs) and solution elements (e.g., painting a lane to redirect traffic). Later, they used Google Earth to take aerial images of the school and then used photo-editing software to edit these images with their own preliminary ideas for the parking lot. Many of the edited images included solution elements not suggested by the engineer.

While generating and discussing proposed parking lot designs, students justified trade-offs. For example, one student suggested installing a new exit road that directed all cars away from point A. Although he knew his design cost more than many other proposed designs, he justified this high cost in part by stating, "You can't put a price on a student's life." After he had prioritized minimizing student injuries at point A as his most important criterion, he felt that his design's positive outcome, increased student safety, justified its negative aspects, such as high cost. Other students recommended the installation of a stop sign at point A, even though they projected that it would increase waiting times for cars, because they explicitly prioritized safety for child pedestrians above convenience for adult drivers.

In addition to justifying trade-offs, students used systems thinking when they viewed individual points as part of an interrelated system (the parking lot)—itself embedded within a larger system (the residential block). One student argued that the installation of a stop sign at point A, although it would increase student safety, might also lead to long lines of cars and buses that would ultimately back up traffic on the road in front of point C. In brainstorming how to minimize long waiting times at point B, other students argued that the problem was due not to the parking lot itself but to the nearby crosswalk at point E. They suggested moving the crosswalk to an area with less traffic. In these examples and others, students predicted how changes to one element (e.g., crosswalk placement, stop sign installation) might affect multiple outcomes within or across embedded systems.

These examples serve to highlight the complexities involved in reading and producing texts while engaging in systems thinking and trade-off justifications. To complicate this process further, a solution's effects on system outcomes are often unknown early on. Yet, even when faced with profound ambiguities, engineers are charged to abide by the profession's first fundamental canon: "Hold paramount the safety, health, and welfare of the public" (National Society of Professional Engineers, 2007, p. 1) when justifying trade-offs. This canon requires practitioners to foreground ethics as they consider whether and how their solutions might harm or disadvantage people, especially historically underserved populations. Students can use this canon to guide the generation and evaluation of their ideas during early stage design (see Table 2).

Table 2
Disciplinary Literacy During the Generating and Evaluating Solutions Stage

Performance expectation in the Next Generation Science Standards	Possible texts	Interpretive frameworks
"Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem" (MS-ETS1-2).	▪ Preliminary design drafts (visual, mathematical, and/or written) ▪ Charts, tables, or prioritized lists of criteria and constraints	▪ Predict and evaluate how changes to one solution element will affect outcomes across systems. ▪ Use prioritized criteria and constraints and ethical considerations to evaluate and justify trade-offs.

Testing and Optimizing Solutions

After developing promising solutions, engineers conduct fair and ethical tests to determine whether they have adequate evidence to justify their solutions. Fair tests can be defined as tests that enable people to accurately predict outcomes under specified conditions. At times, ethics and fairness are related. For example, medical engineers in the United States historically developed medicines through tests with male subjects, leading to negative outcomes for many females whose doctors prescribed those same medicines (Rabin, 2014). These tests were not fair for female clients, in the sense that they were not designed to accurately predict outcomes for them, and products that disproportionately harm women—or any historically marginalized group—are not in keeping with societally accepted standards of ethics.

Engineers conduct tests in many ways, including through the use of preliminary physical models and prototypes, mathematical models, and computer simulations. Because fair tests are vital to design realization, engineers often develop texts in the form of testing protocols to specify how to conduct tests and record outcomes for critical elements within a design. Testing protocols help engineers ensure safe operation of their designs. Additionally, tests help engineers select designs that lead to the most positive outcomes for specified populations and conditions. The *Challenger* accident highlighted the importance of rigorous testing, because the failed O-ring design had not been tested in a wide range of temperatures.

Parking Lot Challenge

To test students' ideas related to the parking lot, we (the authors) developed simple mathematical models using spreadsheets. One model predicted how much a parking lot would cost if it included different elements, such as the installation of a stop sign. Another model predicted wait times for cars at crosswalks and stop signs, given a projected number of pedestrian students and cars that would pass there. Students entered data that they gathered into the spreadsheets to predict costs and outcomes related to waiting times.

In addition to these mathematical simulations or virtual tests, several students proposed conducting physical tests. Specifically, they recommended redirecting pedestrian traffic away from crosswalk E to see if this would reduce waiting times for cars at point B. Other students wanted to send out a survey to parents and teachers to determine whether they liked (and would adhere to) their new proposed parking lot rules. Due to school policies, the students were not able to distribute their survey or redirect the traffic at the crosswalk. However, their ideas indicated the potential for students of engineering to conduct multiple tests—whether physical tests, consumer tests, or virtual tests—to predict whether a solution will work as intended.

Although these tests were specific to this engineering design challenge, other students can use similar practices to engage with multiple core ideas across the NGSS. Specifically, students can develop, evaluate, and/or modify texts, such as written protocols or procedures for conducting fair and ethical tests. Students can record results from repeated tests, whether they are virtual tests on apps or physical tests using prototypes. They can generate texts, such as graphs or tables, that enable them to compare and contrast results from iterative tests to determine which solution elements maximize positive outcomes or minimize negative ones. Table 3 summarizes types of disciplinary literacy that are common to this stage of the engineering design process.

Communicating Solutions

It is almost a cliché to assert that engineering is a team endeavor. After the *Challenger* tragedy, thousands of

Table 3
Disciplinary Literacy During the Testing and Optimizing Solutions Stage

Performance expectation in the Next Generation Science Standards	Possible texts	Interpretive frameworks
Analyze data from tests to determine differences and similarities among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success (MS-ETS1-3).	▪ Procedures for performing fair and ethical tests ▪ Tables, graphs, or other texts that enable the comparison of results from iterative tests	▪ Determine whether tests are fair, ethical, and adequate. ▪ Use evidence from tests to compare and contrast how solution elements and other variables influence multiple outcomes.

engineers, technicians, manufacturers, contractors, and NASA officials worked collaboratively to improve space shuttle designs by cross-communicating a range of solution elements orally, visually, mathematically, and in writing. Engineering communications take many forms, but for the purpose of adherence to the NGSS, we focus on "engaging in argument from evidence" (NGSS Lead States, 2013, p. 87), specifically by constructing an argument that supports or refutes a design solution.

Proposed design solutions typically meet minimum design requirements—those on the "must have" list—but vary according to the extent to which they incorporate "nice to have" features and meet specific outcomes. For this reason, argumentation in engineering is not only about using tests to support claims about a design's performance; argumentation entails the promotion of particular values and priorities in the process of justifying trade-offs. Why is an inexpensive parking lot better than one with minimal waiting time (or vice versa)? Why is a product made from nonbiodegradable materials, which harms the environment but can be purchased by people with limited incomes, better than a product made from expensive biodegradable materials (or vice versa)?

Questions such as these potentially have many justifiable and ethical answers, some of which may contradict each other. Moreover, stakeholders often hold different priorities. For example, a parent who uses the middle school parking lot might prioritize shorter waiting times, whereas a district school board member might prioritize lower cost. When crafting their arguments in light of these issues, students can revisit their original list of desirable design features and articulate the values, ethical considerations, or other reasons that caused them to rank some features higher than others. Students can also consider the priorities of the audience to whom they are communicating and underscore the features of their proposed solution that might appeal to that particular audience.

Parking Lot Challenge

In the context of the parking lot problem, 10 middle school students collaborated to present their parking lot design at a community council meeting attended by middle school teachers, community members, and school board members. In a PowerPoint presentation, the students displayed the four solutions initially developed by the civil engineer, and then they argued why their proposed design (presented as a labeled aerial image) was better than the engineer's solutions. The students drew from evidence created via mathematical models, as well as appeals to the audience's concern for student safety, to justify their proposed design.

The school's principal, who led the council meeting, praised the students for their work and noted that the council had been talking about the need to improve the parking lot all year. He promised to further deliberate on the students' ideas in future council meetings. This example highlights how students can create evidence-based arguments to justify or refute design solutions to stakeholders. Table 4 indicates how these activities can be applied to other situations.

Relevance to Students' Lives

Although the NGSS emphasize engineering design processes, we do not mean to imply that disciplinary literacy in engineering should focus exclusively on these processes. On the contrary, literacy instruction in engineering can also foreground diverse students' interests, home languages, and communities as they develop solutions to problems that matter to them. In fact, the creators of the NGSS explicitly stated that the standards

Table 4
Disciplinary Literacy During the Communicating Solutions Stage

National Research Council framework cited in the Next Generation Science Standards	Possible texts	Interpretive frameworks
Construct a convincing argument that supports or refutes claims for either explanations or solutions about the natural and designed world (cf. MS-ETS1-2).	▪ Visual, written, and/or mathematical text explaining a design solution ▪ Argument justifying or refuting a design solution	▪ Predict and evaluate overall positive and negative outcomes of the proposed design on people, animals, and/or the environment. ▪ Determine whether the solution is justified in terms of meeting prioritized requirements and ethical frameworks.

foregrounded engineering to establish the relevance of science to historically marginalized groups: "By solving problems through engineering in local contexts, …students gain knowledge of science content, view science as relevant to their lives and future, and engage in science in socially relevant and transformative ways (Rodriguez and Berryman, 2002)" (NGSS Lead States, 2013, p. 29).

In keeping with this principle, the National Academy of Engineering (2008) asserted that engineering should be framed as making a difference, or as harnessing the creative and productive power of design to make tangible improvements in the lives of students and their loved ones. The academy's research with diverse focus groups indicated that this message had the potential to attract more African Americans, American Indians, Latinxs, and women to engineering under the hopes that, together, people can ultimately solve some of the world's most wicked problems, from global warming to the scarcity of available and safe drinking water.

Parking Lot Challenge

Students used engineering to make a difference when they sought to address a pressing local problem that they had experienced. They interviewed their parents and other students in Spanish or English and used information from these interviews as important sources of knowledge that shaped their parking lot designs. During these interviews, many parents shared additional information that they had derived from their workplaces. For instance, one mother who worked in the city's water department challenged the authors' estimate for stop sign installation (based on national averages) after she called her friend from another municipal department who told her how much it cost to install a stop sign in this particular city. Finally, students presented their designs to an audience who had the power to realize their ideas, and their presentations incorporated this more accurate local and experiential knowledge derived from the students' parents.

Another method of establishing relevance, in addition to foregrounding students' communities, is critiquing exclusionary or harmful acts that have been committed or ignored under the umbrella of engineering (cf. Ladson-Billings, 1995). Although we did not use case studies in this particular unit, they can provide a powerful vehicle for discussing how technologies are developed and deployed in ways that harm or unfairly advantage particular groups (Wilson-Lopez, Strong, & Sias, in press). When students read about and discuss the "big picture" implications of technologies on their families and communities, they can become critical designers, consumers, and citizens who are able to more comprehensively evaluate the impact of proposed and current designs. Table 5 outlines texts that teachers might use to achieve this goal.

Conclusion

The National Academy of Engineering (2008) offered the following vision of engineering:

> No profession unleashes the spirit of innovation like engineering….Few professions turn so many ideas into so many realities. Few have such a direct and positive effect on people's everyday lives. We are counting on engineers and their imaginations to help us meet the needs of the 21st century. (p. 5)

We see literacy as a vital component of this vision.

Engineering requires the rigorous interpretation and evaluation of a wide range of texts, including clients' problem statements, results from tests, and communications from other engineers. Engineering also

Table 5
Relevant Engineering

National Research Council (NRC) framework guiding the Next Generation Science Standards	Possible texts	Interpretive frameworks
Guiding principles of the NRC framework include "the linkage of science education to students' interests and experiences, and the promotion of equity" (NRC, 2012, p. 24).	▪ Case studies that highlight consequences of designs on underserved communities ▪ Biographies that feature diverse engineers using different approaches to solve a range of social problems ▪ Texts (e.g., advertisements, newspaper articles, photographs) related to designs in students' lives or in popular media ▪ Texts from people in students' communities, such as transcribed interviews with community members	▪ Project or evaluate how engineering designs result in unequal outcomes for different populations. ▪ Question implicit values and interests promoted by the products of engineering. ▪ Identify how engineering can be used for purposes that matter to students and people in their communities.

requires the creation of an equally robust set of texts, such as arguments for or against particular designs based on a consideration of ethical and societal outcomes. Disciplinary literacy in engineering can provide students with tools needed to evaluate, critique, and design solutions that positively impact the quality of life for all people, especially those who have been historically underserved.

NOTES

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