A Model for Equity-Oriented PreK-12 Engineering

The increasing diversity in student populations, the complex challenges facing the world, and the disproportionate consequences of engineered technologies, require attention to the ways that youth experience and learn engineering. This is especially important for students who have been historically marginalized in education systems. Educational environments in which all youth flourish are designed intentionally. Critical components of such environments include the designed and enacted curriculum. Engineering curricula need to be designed to engage all youth, to draw upon on students' strengths, and to provide opportunities for learning disciplinary knowledge, practices, and ethics. This can be achieved by attending to the ways youth are situated in cultural, linguistic, social, and institutional contexts. Educational research focused on equity and disparities in STEM fields across races and ethnicities, genders, socioeconomic backgrounds, and language backgrounds offers insights into approaches and strategies that provide opportunities for participation by all students. Empirical studies of professional engineering highlight core practices of the discipline. In additional to this theoretical framing, we consider the value of design-based research for curriculum innovation and draw from educational research on the enactment of K-12 engineering. From this literature and our experience in curriculum design, we propose design principles for equity for K-12 engineering education. Our principles encompass four dimensions—socially engaged engineering, authentic engineering practices, asset-oriented pedagogies, and student engineering identity. We generated the principles to guide development of our preK-8 engineering curricula and resources and offer examples of how these are manifested in lessons and curricula.

Theoretical Framework

Sociocultural learning theory informs how we understand youth to be situated in cultural, linguistic, social, and institutional contexts (Kelly 2008; Kelly & Green 2019). Students develop proficiency with disciplinary knowledge and practices through meaningful engagement and authentic activity (Engle & Conant, 2002; Kelly, 2014a). Such engagement provides opportunities for learning engineering design, engaging in practices of engineering, using epistemic tools for learning, and fostering identity development as related to the subject matter (Cunningham & Kelly, 2017a; Cunningham & Kelly, 2017b; Kelly & Cunningham, 2019; Kelly, Cunningham, & Ricketts, 2017). This sociocultural view of learning emphasizes the importance of engaging in the social practices of a discourse community, such as those of various engineering disciplines or classroom communities (Farrell, Godwin, & Riley, 2021; Kelly, 2014b; Kelly, 2016). In this way, learning occurs in social settings with the artifacts and cultural tools created by more-knowing others (Vygotsky, 1978). Through engagement in engineering design and analysis, students come to internalize the ways of talking, knowing, and being that constitute engineering, and subsequently external their knowledge to contribute to the emergent epistemic culture (Kelly & Licona, 2018; Moje, 2015).

To effectively engage students in disciplinary knowledge and practices, engineering curricula need to be designed to provide students with opportunities to recognize and address client and stakeholder needs, balance criteria and constraints, optimize solutions, use evidence to make decisions, and persist and learn from failure (Cunningham & Kelly, 2017b; Purzer, Quintana-Cifuentes, & Menekse, 2022; Wendell, Wright, & Paugh; 2017). Much of this work entails using specialized discourse processes, derived from the work of engineering. This discourse can be a resource for learning and solving problems. Disciplinary discourses challenge students to learn specific norms for supporting proposed solutions with evidence and communicate such solutions to a larger audience (Kelly, 2014b). For such discourses to be effective epistemic tools for learning, educative events need to be carefully constructed with this in mind.

Discourse is defined as language-in-use that includes verbal exchanges, gesture, proxemics, written texts, sign and symbols, and other semiotic resources (Kelly, 2014a; Bloome, Carter, Christian, Otto, & Shuart-Faris, 2005). In engineering, consideration of discourse processes is particularly important given the need to interact with clients, work on teams, and use multiple semiotic fields to solve complex problems (Cunningham & Kelly, 2017b; Kelly & Cunningham, 2019; Guzey & Aranda, 2017; McFadden & Roehrig, 2019). Engineering design challenges situate students in rich semiotic fields where the materiality of the designed devices and embedded knowledge are interpreted through meaning-making discussions. In this way, discourse serves multiple functions in social situations beyond just communicating information. Social order, relationships, and identity are constructed in and through discourse (Castanheira, Crawford, Dixon, & Green, 2001; Cazden, 2001; Fairclough, 1995).

From a sociocultural point of view, engineering as a discipline offers unique affordances but also poses serious challenges for students. Curricula need to recognize how the affordances of engineering can support student learning (Cunningham, Kelly, & Meyer, 2021; Paugh, Wendell, & Wright, 2018; Purzer, Quintana-Cifuentes, & Menekse, 2022). Our approach to curricular design is centered on providing opportunities for all students to learn engineering. In this way, we seek to engineer engineering curricula through a commitment to design principles for equity (Cunningham, 2018).

Analyses

Our curriculum design principles for equity engineering are derived from the careful analyses of the study of professional engineering across settings; review of research focused on equity, especially in STEM; iterative design cycles of curriculum development based in design-based research; and educational research that examines the enactment of engineering in school and out-of-school contexts. Over the past two decades, we have worked collaboratively with educators and engineers to design curricula for preK-12 classrooms and out-of-school settings. These co-designed curricula have been extensively tested and informed by discussions with practitioners and subject-matter experts. Such pressure-testing in classrooms has honed the principles to a set that can inform preK-12 education nationwide. Our empirical research program builds on work in engineering education and examines ways students can actively participate in engineering design and analysis in varied educational contexts. Attention to underrepresented groups and those historically marginalized in STEM fields has demonstrated ways that engineering education can be structured to tap the rich ideas and talents of all youth and open up new educational opportunities (Calabrese Barton & Tan, 2019; Sneider & Ravel, 2021; Wilson-Lopez & Acosta-Feliz, 2021). Our analyses seek to identify and coalesce principles supporting effective engineering education to bring about change in curricula, programs, pedagogy, and assessment.

Theoretical Study of Professional Engineering Across Settings

Our first analysis includes extensive consideration of the research on professional engineering practice across settings (summarized in Cunningham & Kelly 2017a &b; Hertel, Cunningham, & Jelly, 2017; Kelly & Licona, 2018). The empirical study of engineering by scholars in science and technology studies has provided insights into the inner workings of engineering as it is practiced (Bucciarelli, 1994; Johnson, 2009; Petroksi, 2006; Vincenti, 1990).

For example, *Hitting the Brakes* (Johnson, 2009) detailed the ways that engineers worked together, under technical, financial, and societal constraints, to design and make operational antilock braking systems for automobiles. Drawing from an extensive review of literature about engineering using a snowballing technique (Wholin, 2014), we distilled a set of 16 epistemic practices of engineering (Cunningham & Kelly, 2017b). These practices include developing processes to solve problems; envisioning multiple solutions; making trade-offs between criteria and constraints; investigating properties and uses of materials; and persisting and learning from failure. The complete list of epistemic practices of engineering for preK-12 education can be found in Table 1.

Table 1

Epistemic Practices of Engineering for preK-12 Education Engineering (adapted from (Cunningham & Kelly, 2017b)

Engineering Practices	
Consider problems in context	Use systems thinking
Use processes to solve problems	Construct models and prototypes
Investigate properties and uses of materials	Make evidence-based decisions
Balance tradeoffs between criteria and constraints	Persist and learn from failure
Innovate processes, methods, and designs	Assess implications of solutions
Apply science knowledge to problem-solving	Work effectively in teams
Apply math knowledge to problem-solving	Communicate effectively
Envision multiple solutions	Identify themselves as engineers

During our review, we considered what age-appropriate manifestations of practices might be, working closely with preK-8 classroom teachers to understand the capabilities of students in their classes. In each instance, we first articulated how the engineering practice may be manifest in professional settings. Then we derived the epistemic practices for preK-12 education by considering the potential for learning about engineering design and problem solving.

Review of Research Focused on Equity in STEM

The second analysis informing the development of the design principles for equity for K-12 engineering education was an extensive, ongoing literature review of published research regarding equity in science, technology, engineering, and mathematics education, with an emphasis on strategies for supporting underrepresented and underserved students in these areas (Brown, 2019; Farrell, Godwin, & Riley, 2021; Muhammad, 2020). We focused on equity issues along intersectional dimensions of identity such as race, ethnicity, language background and proficiency, gender identification, special education, and disability status. Through review of these literatures, we identified characteristics of educational programs that support equity in STEM. For example, students build connections to their lives and develop increased interest through narrative and real-world contexts (Cunningham & Higgins; 2016; Gunckel & Tolbert, 2108; Lee, Llosa, Grapin, Haas, & Goggins, 2019; McGowan & Bell, 2020; Wilson-Lopez, Meija, Hasbún, & Kasun, 2016). Diverse learners benefit from lessons designed to support sense making, where multiple solutions are encouraged (Augirre-Muñoz & Pantoya; 2016; Bang et al., 2017; Blanchard et al., 2010; Brotman & Moore, 2008; Cuevas, Lee, Hart, & Deaktor, 2005; Cunningham & Lachapelle, 2014; Ernst-Slavit & Pratt, 2017). In addition, use of small group work supports alternative ways of knowing, often valued by girls and underserved minorities (Carlone, Haun-Frank, & Webb, 2011; González-Howard, & McNeill, 2016; Lee, 2003; Olitsky, Flohr, Gardner, & Billups, 2010; Wendell, Andrews, & Paugh, 2019). Through the design of engaging, meaningful engineering experiences, the intersectional identities of students otherwise marginalized across racial, gender, ethnicity, and language preference can thrive. Learning substantive knowledge and practices can foster changes in students' perceptions of themselves and their peers as successful problem solvers and disrupt classroom hierarchies (Hegedus, Carlone, & Carter, 2014).

Iterative Design Cycles of Curriculum Development Based in Design-Based Research

Our third analysis is a re-assessment of the lessons learned from over 20 years of design-based research (DBR) on curriculum development (Boda & Brown, 2020; Design-Based Research Collaborative, 2003; Lyon & Magana, 2021; Tan, Calabrese Barton, & Benavides, 2019). We have used design-based research (DBR) as a central methodology and framework to systematically design over 80 engineering units from pre-school through middle grades for school and out-of-school settings, while simultaneously researching the efficacy of the design through educators' interpretation and implementation (Barab, 2014; Collins, Joseph, & Bielaczyc, 2004). DBR incorporates progressive iterations of design and matching research approaches, to test research questions about the design of the curriculum using a mixture of quantitative and qualitative research methods (Puntambekar, 2018, Sandoval & Bell, 2004). Throughout our studies, we have prioritized research and analysis focused on whether and how *all* children were engaging in engineering design and practices. Cycles of research, design, testing, data collection, analysis, and redesign have probed how curricular principles, manifest in particular curricular approaches and features, impact opportunities for youth to engage in engineering practices, produce discourse and artifacts, participate in learning communities, and develop engineering interest and identities. Our iterative development process involves four major design cycles—foundational research and conceptual development, review by subject-matter and educational experts, pilot testing and revision, and field testing and revision. In this way, multiple forms of expertise are brought to the curriculum design from curriculum designers, engineers, and educators.

DBR aims not only to identify whether something works but how the learning environment functions by considering interactions and processes (Design Based Research Collaborative, 2003). Following Sandoval (2014), we have conceptualized our design research with conjecture maps. Conjecture mapping is "a means of specifying theoretically salient features of a learning environment design and mapping out how they are predicted to work together to produce desired outcomes" (p. 19). It illustrates the aim of the design, distills particular features of the design and what they are expected to do, and specifies what they should produce. As we have engaged in research over the past two decades, we have modified and revised our conjecture maps to reflect our learning. By adhering to the principles of DBR, with ongoing data collection, testing, and examination of research questions during iterative development of curricula, we have distilled design principles for equity-oriented engineering curricula that meet the needs of diverse stakeholders and can be used at scale (Cunningham et al., 2020).

Educational Research on the Enactment of Engineering Across preK-12 School and Out-of-School Contexts

In addition to the design-based research directly informing the curriculum design, we have conducted a series of research studies drawing from multiple research methods, including educational ethnography, sociolinguistics, research interviewing, quantitative testing of student knowledge (including performance assessments), and random-control trials. Through these studies, we have distilled a set of implications that examine and contribute to the extant knowledge regarding engineering education. We provide two examples for illustrative purposes. Kelly, Cunningham, & Ricketts (2017) examined ways that engaging in engineering practices transforms students' views of engineering and themselves. Through detailed discourse analysis, grounded in sociolinguistics, the study demonstrated how two elementary teachers and their students came to understanding engineering differently as their identities as engineers evolved through learning. Students were able to transform their identity by engaging in epistemic practices of engineering and through ways of talking about their experiences. In this way, disciplinary affinity was developed both through purposeful activity in engineering and metadiscourse about participation. Another study sought to provide an assessment of curricular design principles through a cluster randomized controlled trial in 604 classrooms in 152 schools in three states (Cunningham et al., 2020). By comparing two elementary engineering curricula, the study was able to identify that equity-oriented critical curriculum components had consequences for student learning. Students in the treatment curriculum outperformed students in the comparison group on outcome measures of both engineering and science content learning regardless of demographic characteristics. Therefore, in addition to the use of extant literature, the findings of this theoretical paper are derived from extensive empirical research based in video analysis of classrooms, interviews with students and teachers, and assessments of student learning and interests.

The model presented in this paper has evolved over more than two decades. When we began our work 25 years ago, we drew from studies of engineering in practice as well as studies of equity in K-12 science and college-level engineering (research about K-12 engineering did not exist) to posit principles that reflected the nature of engineering knowledge and practices and/or featured approaches that would be inviting, accessible, and inclusive. From long lists of possibilities, the team distilled principles and grouped them into categories. We wanted to generate something that was comprehensive, yet manageable. The principles also needed to be useful. We tested our early principles by applying them to the design of K-12 engineering curricula. The development team and researchers spent thousands of hours conducting classrooms observations of engineering lessons written to align with the principles. Educators also provided copious feedback about what was working and for whom. For over 20 years, we have engaged in an iterative process of refining the design principles we first created, applying them to curricula, and testing them.

As a set of stable curricular principles emerged, we began to conduct empirical educational research studies. The prevalence of K-12 engineering education research also allowed us to draw from others' studies—how did our set of principles align with their work and findings? Were there other principles or modifications that we should consider? We continue to revisit and revise the model as new research emerges related to engineering education or equity. For example, a review of recent research related to social justice, English learners, and identity work prompted us to generate additional principles and incorporate these into the model. Revisions in the model then prompt us to rework curricula. We are committed to ensuring that the principles move beyond the theoretical to the practical realm. Data and feedback from teachers implementing materials rooted in the model help us determine whether or not the model helps to create more equitable learning environments for all students. Our cyclical process of identifying principles, applying them to resource development, and testing and refining them is ongoing; the model continually evolves.

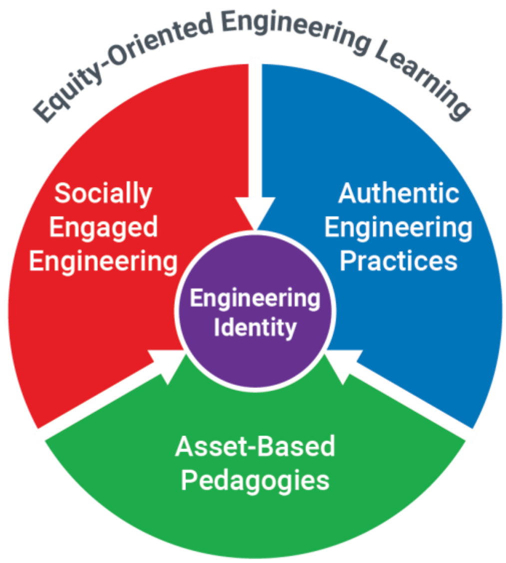
Findings

Overall, we have identified 13 design principles for equity for K-12 engineering education. These fall into four major dimensions—socially engaged engineering, authentic engineering work, asset-oriented pedagogies, and student engineering identity. Each of these dimensions encompasses design principles that foster equitable instruction and environments. For example, engineering activities should introduce multiple perspectives about technology and have students reflect upon the possible impacts of engineered solutions. Our approach foregrounds students' experiences, ideas, and identities. These equity principles are designed to inform design, evaluation, and selection of engineering curriculum and guide classroom pedagogy and instructional and assessment decisions.

We propose a model, composed of three dimensions leading to student engineering proficiency and enhanced engineering identity. This model is depicted in Figure 1. To test the model, our team has applied the model to curriculum design, leading to refinements in the model. We will continue to conduct research about the model and the impact of curricula designed in this way as we implement our curriculum materials with educators. Educators and researchers have communicated the value to this model for thinking about their own work and curricular resources. The primary purpose of this paper is to share the model so it might inform curricular K-12 engineering development, evaluation of curricular resources, or classroom instruction.

Figure 1

Model for Equity-Oriented Engineering Learning (from Youth Engineering Solutions [YES], 2021)



The model communicates how engineering learning—knowledge and facility with engineering concepts, practices, and skills—can be developed through more equitable approaches. As students address engineering problems that are relevant to their lives, communities, and world, they learn and use engineering knowledge and engage in engineering practices. Instruction should be rooted in models that draw on students' assets. The model depicts our belief that students construct an engineering identity by connecting engineering to their lives, developing engineering knowledge and practices, and participating in meta-discourse about their engagement (Brown, 2006; Carlone, Scott, & Lowder, 2014; Chiu, Fink, McElhaney, Alozie, & Fujii, 2021). The doing and learning of engineering knowledge produces changes in student identity.

Socially Engaged Engineering

Drawing heavily from studies of social justice and engineering, socially engaged engineering situates engineering in its larger societal context and helps students recognize how engineering can reproduce societal bias or seek to correct it (Gunckel & Tolbert, 2018; Leydens & Lucena 2017; Lucena, 2013; McGowan & Bell, 2020; Riley, 2008; Riley, Slaton, & Pawley,

2014) Socially engaged engineering fosters students' ability to consider perspectives of diverse stakeholders throughout the design process, from problem scoping to product evaluation, and to build awareness of their own values in relation to the engineering problem at hand. Connections derived from students' families, communities, and cultures provide a framework for understanding the engineering problem on a personal level and serve as points of departure for expanding students' knowledge of, interest in, and ability to address engineering problems on a larger scale. Socially engaged engineering also helps youth understand how political, economic, environmental, and social forces can shape engineering designs and decisions.

Allowing room for students' diverse viewpoints and experiences prompts students to recognize that there are multiple stakeholders impacted by an engineering problem and/or solution and that some stakeholders may be disproportionately impacted. Who most benefits? Who is most harmed? In this way, topics for engineering are chosen to develop engagement among students and help them to understand how engineers shape the world they inhabit. For example, a curriculum highlighting engineering solutions to the problem of pollution might have students reflect on their own experiences with and thoughts on pollution (for example, at their school grounds) before engaging in larger conversations about sources of pollution, inequitable distribution of pollutants and pollution mitigation strategies, and systemic solutions. It anchors issues in real-world solutions and students' interests, as it seeks to build youth's empathy and abilities to take different perspectives and consider multiple possible ways a problem might be addressed. Table 2 presents design principles for equity related to socially engaged engineering.

Table 2

Design Principle for Equity: Socially Engaged Engineering (from YES, 2021)

Design Principle	Student Activity

Situate engineering in real-world contexts	Students engage in real-world engineering challenges that expand their horizons while connecting to their home, communities, and cultures. Activities begin with narratives that engage students' imagination and demonstrate how engineers design and shape our world by solving problems.
Introduce multiple perspectives and possible impacts of technology	Students consider stakeholders and possible impacts of the technologies they design. Each unit situates engineering in local, community, and global contexts.
Connect engineering to students' family, community, and cultures	Students explore cultural and family connections to design solutions that are relevant to their everyday lives.

Situate Engineering in Real-World Contexts. Students engage more readily and develop interest in engineering when the engineering challenges are set in a real-world context. One way to do this focus on problems that are relevant to students' lives, families, cultures, and communities. Because children are motivated by stories and role models, we suggest that engineering activities begin with developmentally appropriate narratives that engage students' imagination and demonstrate how engineers, from a diverse array of cultures and communities, shape our world by designing solutions to problems.

For example, each of our Youth Engineering Solutions (YES) units uses an age-appropriate narrative element to connect the engineering work students do in their classroom with the real world. Students in upper elementary classes (grade 3–5) are introduced to the engineering problem through a narrative presented in the form of a comic story. In the narrative, two children encounter a problem in their community, for example, an abundance of plastic pollution in a local bay or an intersection that is dangerous for bikers and walkers. Curricular materials prompt students to think about similar problems in their lives or communities. For instance, in the Engineering Plastic Filters units, students are asked to consider whether plastic pollution is a problem in their community, where they see plastic pollution in their community, where the plastic pollution in their community comes from and how it is disposed of, and whether their design solution would solve the plastic pollution problem in their community.

Introduce Multiple Perspectives and Possible Impacts of Technology. Engineering and technology are not value-neutral; there are many ways in which the values of society, industries, the values of individual engineers impact technological solutions. To help students build this awareness, an engineering curriculum can have students consider the diverse stakeholders affected by the problem as well as the possible impacts of the technologies they design. Older students can think about who is disproportionately impacted by the problem and the solution and can incorporate this knowledge into problem scoping and design evaluation. Such perspective taking can help students develop empathy and gives students the opportunity to practice integrating empathic thinking with STEM disciplines. Engineering design challenges are thus set in a social context and the consequences of the design, with implications for local or the global community, also examined.

For example, in the first lesson in the Plastic Filters unit, the comic story highlights how various community members are impacted by the problem of plastic pollution in their bay. Students are then asked to consider seven different community groups including: swimmers, grocery store owners, office workers, animals in the bay, shoppers, boaters, and fishers; identify which are most and least harmed by the problem; and array them on a Plastic Pollution Harm

Scale. As they discuss why they think one group is harmed more than another, they also consider how the information might help them solve the town's problem. They learn that it is important to design a solution that will balance everyone's needs, paying particular attention to the groups most impacted by the problem, such as the animals who are dying or the fishers who are losing their livelihood.

Connect Engineering to Students' Family, Community, and Cultures. The third socially engaged design principal centers on the students' own cultural and family connections. Anchoring students' school or engineering work in their everyday lives and communities makes it relevant and demonstrates why such work is important and how it affects them. Situating engineering challenges in lived experiences and problems can also spur students to think differently about what knowledge they, their families, or their communities, possess related to a particular problem, domain, or skill set. Students can be invited to draw upon those voices as they consider design solutions. Families play an important role in students' lives and futures; honoring their knowledge and experiences and soliciting such knowledge strengthens designs and highlights the embeddedness of engineering in communities.

Curricular design can facilitate such connections and encourage students to tap their families' funds of knowledge. For example, the YES Engineering Assistive Sock Devices unit, designed for upper elementary grade youth in out-of-school settings, youth design an assistive device that helps users with limited physical mobility put on a sock. After youth are introduced to this problem, they are asked to talk with family or community members to identify who they know who use assistive devices (such as eyeglasses, canes, or wheelchairs). This invites personally relevant, meaningful discussions that connect family or cultural knowledge or experiences with engineering work. Youth can then draw on these conversations and this knowledge as they share ideas during class or small group discussions. Later in the unit, as youth determine their design criteria, they are asked to reflect on the people they know who use assistive devices and to consider this knowledge to propose an additional criterion for their design tailored for this person or broader population. For example, a youth whose family member experiences low vision might propose the criterion that the sock aid's controls need to be brightly colored to make it more accessible. The YES units designed for out-of-school programs all suggest a showcase event where youth share their engineering designs with invited guests through presentations, displays, demonstrations, and conversations. This is an opportunity for families and community members to learn from, encourage, support, and share with their youth.

Authentic Engineering Practices

Authentic engineering practices are derived from the professional work of engineers. For educators, these practices need to be re-interpreted for educational purposes, while staying true to the disciplinary significance of engineering design and problem solving. Cunningham and Kelly (2017b) proposed 16 epistemic practices of engineering *for* education (Table 1). Active engagement in such disciplinary practices builds students' knowledge of engineering and science, provides them with opportunities to learn from doing, cultivates teamwork, and fosters a sense of accomplishment. Students also benefit from work that is "real." Students should not only engage in such practices themselves but should also come to understand that professional engineers employ these same approaches and skills. Table 3 provides a synopsis of these authentic engineering practices.

Table 3

Design Principle for Equity: Authentic Engineering Practices (from YES, 2021)

Design Principle	Student Activity
Engage students in engineering practices	Students engage in ways of doing engineering, including designing, building, analyzing, testing, and sharing new technologies. Active engagement builds students' knowledge of engineering and science, provides them opportunities to learn from doing and working with other students, and fosters a sense of accomplishment.
Ensure that design challenges have multiple solutions	Students draw on their experiences and strengths and celebrate creative, innovative thinking. Recognizing that an array of possible solutions exist encourages students to consider diverse approaches and evaluate how and for whom specific solutions work best. Challenges are carefully designed so many solutions are possible.
Scaffold persistence, risk-taking, and productive failure	Students embrace the important role of failure and iteration in engineering. Activities model how to persist through and learn from unsuccessful attempts—a mindset that needs to be taught and cultivated in all students.
Cultivate collaboration and teamwork	Students engineer in teams. By sharing ideas, data, and designs in small groups and class discussions, students benefit and learn from each other. Students also learn vital collaboration and negotiation skills. Interactive, collaborative environments can be more inviting for many students than those rooted in competition.

Engage Students in Engineering Practices. To learn engineering, students need to *do* engineering—that is they need to actively engage in engineering practices such as designing, building, analyzing, testing, and sharing new technologies through hands-on activities and sensemaking. The active engagement and associated discussions about engineering provide opportunities to construct knowledge of and about engineering and science. Through experience, students learn new skills, struggle through challenging moments or complicated ideas, and develop facility manipulating concepts and working through processes. Active, project-based, inquiry and sensemaking activities also provide students opportunities for teamwork and help create a sense of accomplishment and interest.

There are many engineering practices, and many ways to engage students in such practices. These need to vary with age and experience. For example, to engage in the practice of balancing tradeoffs between criteria and constraints, early elementary school students might focus on identifying one or two criteria that a design solution needs to meet; for example, a sun hat needs to shade the user’s face and neck. Tradeoffs at this young age might be more related to individual desires—I want to make a crown, not a hat; or I want my hat to be purple even though the purple material doesn’t work well to make shade—than to conflicting criteria and/or constraints. Older students can identify and balance more complicated criteria and constraints as they design; for example, our magnetic door needs to open and close using magnetic forces, be sized appropriately for its user, and meet given cost and materials constraints.

Ensure that Design Challenges Have Multiple Solutions. Engineering is a discipline that seeks solutions by optimizing under the conditions and constraints imposed in a given context. In this way, there are often situations where there is no one correct answer, but rather multiple solutions emphasizing different dimensions of the respective goals of the project. The open-ended nature of engineering solutions often contrasts with exercises in which students must derive a “correct” answer. Many students are energized by the opportunity to generate original, unique solutions. Engineering curricula can be designed so that students draw on their experiences and strengths and celebrate creative, innovative thinking. Recognizing that an array of possible solutions exist encourages students to consider diverse approaches and evaluate how and for whom specific solutions work best. This approach provides insights into the nature of engineering reasoning (Cunningham & Kelly, 2020).

For example, in the YES Engineering Safety Vest unit students tackle the problem of intersections that are dangerous for pedestrians, bikers, or skateboarders. Students are challenged to design a vest that will increase users’ safety by using electrical signals to display information users wish to communicate to others in the intersection. Each student group determines three messages it thinks are important to communicate (e.g., turning left, slowing down, stopping). They then design a system of symbols and signals to communicate this information to others. Testing their design system with others helps them to understand what is working and what needs to be changed. By allowing students choice about what is communicated, how it is signaled, and which type of user they are designing for, students generate original solutions that rely on knowledge of similar electrical technologies.

Scaffold Persistence, Risk-Taking, and Productive Failure. Failure is inherent to engineering design—persistence through and learning from failed attempts can inform successful designs (Madhavan, 2015; Petroski, 2006). In classrooms, failure is often a loaded term with negative connotations (Johnson, Kelly, & Cunningham, 2020; Lottero-Perdue, & Parry, 2017). Engineering can help students re-think their reactions to failure (Marks & Chase, 2019; Stretch & Roehrig, 2021). Curricula need to recognize and support risk-taking and learning from failure.

Students can learn the importance of persistence and how designs can improve through iteration. In this way, knowledge about engineering is instantiated in the activities and students can develop a productive mindset for successful engineering.

For example, the YES engineering design cycle clearly communicates that students will be expected to redesign during the unit—an “Improve” or “Iterate” phase is built in. To guide iteration, a “Flip the Failure” routine is embedded in all units. Narrative characters introduce the term and model how engineering entails keeping parts of the design that worked and improving parts that did not perform as expected or that failed. Students then consider for their own designs how they can use results from testing to inform improvements to their designs.

Cultivate Collaboration and Teamwork. Our review of professional engineering practice, and experience teaching engineering in schools, evinces the importance of working in teams for the success of engineering projects. By sharing ideas, data, and designs in small groups and class discussions, students benefit and learn from each other. Collaborative environments also develop students’ identities as valued contributors. While the knowledge and epistemic practices of engineering are made available through the collective actions of the group, such collaboration also provides opportunities to learn how to negotiate and work together as a team. This cooperation stance has been shown to be more inviting for many students than approaches rooted in competition.

Curricular design can foster collaboration and teamwork within and among groups. For example, in YES activities and challenges, students work in pairs or small groups. Students also share their ideas or initial designs with the larger class as such interactions can spur new ideas. Students score the performance of their solutions against a set of fixed design criteria—groups are not assessed relative to one another. In some activities, testing data are gathered and posted for the whole class and trends analyzed across the larger sample. For example, the YES Engineering Rescue Shuttles unit challenges youth to develop a rescue shuttle that can transport a rope to someone who needs a water rescue. Youth investigate parameters that affect the flight of the shuttle—materials, weight, height, and whether to use fins. Each group investigates a subset of the variables. Then, the class gathers to pool their observations and results and create a chart to summarize their findings. This communal exchange of information encourages youth to discuss ideas and learn from each other. Students can refer to the chart as they engineer their own solutions. They also share their designs with their peers. The goal is to encourage youth to learn with and from each other and celebrate successes, not to compete. Good ideas from a different group may be taken up in a subsequent design attempt.

Asset-Based Pedagogies

Asset-based pedagogies are designed to build on the strengths students bring to the learning context to extend their opportunities to learn (Carlone, Mercier, & Metzger, 2021). For example, students may have developed knowledge and experience with wind power (from observation of blowing leaves, running against the wind, flying a kite), yet this knowledge is likely idiosyncratic, partial, and not yet fully formed. Through engineering design challenges, systemic testing, data analyses, and discussions with others related to the power of wind to move objects, students may refine their understandings of the principles of fluid dynamics. Asset-based approaches start with what students know and draw on these strengths as students engage with new material. Because asset-based pedagogies draw upon students' unique experiences and skillsets, they are necessarily personal, responsive, and multimodal since no student group is identical and individuals change over time. Table 4 shows the three design principles for equity in the asset-based pedagogies category.

Table 4

Design Principle for Equity: Asset-Based Pedagogies (from YES, 2021)

Design Principle	Student Activity
Leverage students' prior knowledge and experiences	Students draw upon their prior knowledge and leverage their personal experiences to improve their engineering solutions.
Develop familiarity with materials, tasks, and terminology	Students of all ages and ability levels are provided with opportunities to meaningfully participate in activities. Previous familiarity with materials, tasks, or terminology is not assumed. Instead, embedded scaffolding activities develop necessary knowledge, skills, and tools.
Create multimodal, flexible activities for different kinds of students	Students interpret content and express their understandings/knowledge in a variety of ways. These span listening, speaking, demonstrating, writing, and drawing.

Leverage Students' Prior Knowledge and Experiences. As children interact with and make sense of their world, they develop ideas that inform engineering. Everyday experiences, such as playing in puddles, can help children learn about properties of materials—in this case, which materials are waterproof, or absorbent. Similarly, youth recognize problems and may already have ideas for how to address them—for example, wrapping their shoes with plastic bags before trudging across a flooded field or sidewalk. This mindset extends beyond engineering-specific experiences to other forms of student knowledge, such as language. Engineering curricula can welcome students' home languages and communication styles by incorporating them into class strategies for learning and sharing. For example, when exploring which materials absorb water, students can discuss their observations using whichever terms that best describe their observations and these terms can be reinforced with academic language and scientific terminology such as “absorbent” and “non-absorbent,” thus making room in the classroom for multiple expressions of the same phenomenon.

In the early lessons of a YES unit, students are asked to reflect on and discuss where they have encountered a similar problem in their home or community and are invited to discuss and share their ideas using whichever language(s) are most useful to them. For example, students might discuss: Where do they see plastic polluting the environment? Have they had challenges crossing an intersection as a walker, biker, or skateboarder? How much light do they like in their room as they go to sleep? By inviting students to reflect on related experiences, students can approach a problem, even a new problem, with a focus on what knowledge and skills they bring that can inform their investigations and solutions.

Develop Familiarity with Materials, Tasks, and Terminology. Students’ background knowledge and experiences differ. Drawing from students’ existing knowledge to inform engineering helps students connect engineering to their learning and lives. However, it is also important to ensure that students are not asked to engage in activities for which they do not have adequate prior experience. Thus, curricula should provide students with opportunities to develop familiarity with materials, tasks, or terminology that they will use in the activities. Embedding scaffolds into the engineering activities can help students develop necessary knowledge, skills, and tools as they use them in purposeful ways. Thus, students with certain types of relevant knowledge, related specialized vocabulary, equipment, or skills from previous education or experience are not privileged.

In designing engineering activities and curricula, it is important to consider what types of scaffolding resources and activities might help all students build familiarity with the building blocks for the activities. For example, YES curricula include lessons in which all students become familiar with the materials they might use. Illustrated vocabulary cards, which are introduced after concepts have been explored or discussed, provide reference points for potentially new terminology (e.g., dowel, pompom, absorbent). All students in the class have opportunities to manipulate the materials and explore how they behave relevant to design criteria. Just-in-time skill-building lessons also help students develop skills such as measuring, calculating costs, or wiring a circuit when they need them. Intentionally incorporating such scaffolds enables all students to bring these resources to their classroom engineering experiences.

Create Multimodal, Flexible Activities for Different Kinds of Students. Students' experiences, abilities, and associated ways of knowing and communicating differ. Curricula should provide multiple avenues for students to receive and interpret content as well as express their understandings. Activities need to feature multiple modes of communication, such as speaking, listening, demonstrating, building, writing, and drawing. Multimodal communication is not only good pedagogy, but it is also true to the communicative competence needed in many engineering teams and projects. Engineering activities should also be flexible to allow for differentiated experiences that meet learners' needs and draw upon their strengths. Modifying the number of criteria and constraints can make a challenge more simple or complex, to account for the developmental needs of different aged students. The hands-on, creative nature of engineering challenges often invites increased participation by students each of whom brings unique abilities, experiences, and dispositions. Furthermore, multimodal communication provides avenues for students with varied language and communication preferences (Cunningham, Kelly, & Meyer, 2021). The physical nature of engineering and the focus on creating a viable design solution helps focus students and remind them of why language, writing, or mathematics might be important.

For example, in the YES Engineering Sun Hats unit, kindergarteners work in pairs to design a sun hat that will meet both of their needs. As they imagine ideas and make a plan, they are invited to manipulate materials swatches, gesture, draw, and talk with their partner to share their ideas and decide on a plan. YES curricula are also designed to promote language development. Drawing from best practices for language learners, all units provide visual scaffolds, have students generate language in small group discussions, and provide tips for educators about strategies that can enhance students' communicative abilities.

Engineering Identity

Taken together, socially engaged engineering, authentic engineering practices, and asset-based pedagogies, foster educational experiences that can lead to improved learning of disciplinary knowledge, a better understanding of engineering in the world, and an engineering identity and mindset. Figure 1 shows how these three dimensions of curricular design work together to lead to engineering identity. Our view of identity, and the identity work produced in a local context, focus on students' competence, performance, and recognition, as constructed in the social and cultural practices of the relevant, local community (Carlone et al., 2015). Thus, the meanings about themselves, engineering, and academic status are produced in the local culture through actions taken by individuals within a group (Green, Skukauskaite, & Castanheira, 2013). Importantly, engineering identity is composed of students' enhanced capacity to engineer, learn new material, and view themselves as capable of engaging effectively in engineering (Capobianco, French, & Diefes-Dux, 2021; Kelly, Cunningham, & Ricketts, 2017). Although student engineering identity is one outcome of engaging with the other three domains, it also includes specific ways that learning knowledge, practices, and values themselves can be interpreted and instantiated in ways that support equity (Brown, 2006; Carlone, Scott, & Lowder, 2014). The design principles fostering engineering identity are presented in Table 5.

Table 5

Design Principle for Equity: Engineering Identity (from YES, 2021)

Design Principle	Student Activity
Use low-cost, readily available materials	Students use inexpensive, common materials to build the technologies. Because they are affordable and available, learners can continue their engineering explorations at home.
Provide role models with diverse demographic characteristics	Students learn from diverse role models in context-setting narratives, videos, and their community. Each unit introduces engineering role models who reflect the diversity of individuals involved in engineering.
Foster students' engineering identities and mindset	Students develop interest, knowledge, abilities, and identities by engaging in authentic engineering practices from a young age. These early, successful experiences build students' confidence in and affiliation with engineering and encourage a problem-solving mindset.

Use Low-Cost, Readily Available Materials. Stereotypes of engineering rest on descriptions of super-intelligent, technologically savvy but socially awkward others (usually white men) that operate in elite settings (Knight & Cunningham, 2004). Debunking this harmful image is important. Anchoring engineering challenges in common, readily accessible, low-tech materials, and everyday products upends this notion of engineering. It focuses engineering on the kind of work that is being done and not the tools or device. And it allows more space for a wider range of students to see themselves as capable engineers. Additionally, challenges rooted in available, inexpensive materials invite learners to continue their engineering explorations outside of school—at home, with their families, etc. This provides a way for students to define themselves as engineers outside of school and to others, such as family members and friends. Students who are successful at developing an engineering identity, come to see themselves as engineers in multiple settings. YES curricula are designed specifically to use readily available materials, such as paper, aluminum foil, craft sticks, fabric, straws, boxes, tape, and tissue paper.

Provide Role Models with Diverse Demographic Characteristics. To work against the pervasive stereotypes of engineers, students need to see role models like themselves—that share their age, gender, race, ethnicity, abilities/disabilities, and/or interests. Engineering curricula can feature role models in context-setting depictions, narratives, or videos. They can also encourage educators to connect their students to people from their community who can support a positive engineering identity among students. To support this work, the YES context-setting narratives features diverse role models. These characters and people model engineering practices, allowing students to see engineering and related STEM work as possible futures for themselves.

Foster Students' Engineering Identities and Mindset. Students' identity formation begins early and is influenced by their experiences. Research on student identities related to science and engineering has demonstrated the importance of developing active, collaborative learning experiences grounded in disciplinary knowledge, while also providing a metadiscourse about the learning processes (Kelly, Cunningham, & Ricketts, 2017; Reveles, Cordova, & Kelly, 2004). In this way, students develop interest, agency, knowledge, abilities, and identities by engaging in authentic engineering practices, and talking about these experiences. Fostering positive identity development related to engineering itself becomes a goal of the experiences. This begins at a young age. Such early, successful experiences have the potential to build students' confidence in, and affiliation with engineering and encourage a problem-solving mindset. Through its materials, YES encourages the development of engineering identity by deliberately casting students as engineers and asking them to engage in authentic activities. Materials also have students reflect on their engineering skills—at the beginning of units, students are asked to reflect on their facility with engineering skills such considering others, working with others, using creativity, and learning from failure and indicate which they would like to develop. At the conclusion of a unit, students return to that exercise to reflect on their growth. This encourages students' metacognition about the work they have done and their abilities to do engineering work while developing important engineering skills.

Discussion

The proposed design principles for equity in engineering presented in this paper were derived from theoretical and empirical work of ourselves and others. We generated this framework to guide our own work as curriculum and program developers. We continue to update it to reflect new research and experiences. We have provided reasons and evidence for the design principles presented here, but we also recognize that principles to guide curricula are optimized through experience, analyses, and critique. In this discussion, we provide some key challenges for the field and invite suggestions and improvements to these design principles for equity-oriented engineering. Design principles need to be thoroughly tested and refined. We propose at least three areas for examining these principles: across educational contexts, with varied student groups, and for changes over time in education. Our hope is that developments in curricular design, implementation, and research can improve the educational experiences of all students, especially those currently underrepresented in engineering.

First, design principles for equity in engineering need to be tested across difference contexts. While we drew from research and experience from school and out-of-school settings, we recognize that different educational contexts pose unique affordances and constraints. Importantly, improving educational equity for engineering should not be confined to schooling. Rather, there are many venues for learning about engineering including in after-school and summer programs, through museums and science and technology centers, in family activity, and in clubs. The design principles for equity need to be examined in these different situations, and adapted, improved, changed, or augmented to be optimized for the local settings.

Second, design principles for equity in engineering need to be examined with the variation in learners in mind. Although our principles were derived from extant research, it would be mistaken to assume that underserved and underrepresented students each bring the same affordances or face the same challenges, given the cultural, linguistic, gender, and ethnic diversity in the nation's and world's youth. These principles should be examined with careful attention to the needs of all students.

Third, design principles for equity in engineering need to evolve given the changing situation in education. Across the many contexts for education, the policies, practices, and procedures change over time. The temporal elements to education need to be taken into consideration to fully examine the efficaciousness of these principles. For example, the recent COVID pandemic brought unforeseen changes in schooling, including remote learning, and social distancing when in classrooms, that pose constraints on pedagogy using of hands-on, small group engineering design challenges.

Finally, we invite comment and critique. We constructed these proposed design principles for equity in engineering from our own experiences and research and the research in the field. Suggestions and ideas for improvement will help refine these principles to improve engineering education for all students.

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