

Engineering for sustainable communities: Epistemic tools in support of equitable and consequential middle school engineering

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Abstract

This study is focused on engineering for sustainable communities (EfSC) in three middle school classrooms. Three in-depth case studies are presented that explore how two related EfSC epistemic toolsets—(a) community engineering and ethnography tools for defining problems, and (b) integrating perspectives in design specification and optimization through iterative design sketch-up and prototyping—work to support the following: (a) Students' recruitment of multiple epistemologies; (b) Navigation of multiple epistemologies; and (c) students' onto-epistemological developments in engineering. Using a theoretical framework grounded in justice-oriented notions of equity intersecting with multiple epistemologies, we investigated the impact of the related epistemic toolsets on students' engineering engagement. Specifically, the study focused on how the tools worked when they were taken up in particular ways by teacher and students, and how the nature of their iterative engagement with the tools led to outcomes in ways that were equitable and consequential, both to students' engineering experiences and their engineering onto-epistemological developments, and also in responding to the community injustices prototypes were designed to address. Tensions that emerged are discussed with further reflection on what the EfSC epistemic toolsets suggest about the affordances of a productive epistemic space and the concomitant risks related to larger institutional norms,

which constrain the extent of students' justice-oriented engineering goals.

KEYWORDS

engineering, epistemic tools, equity, multiple epistemologies

It has been argued that the inclusion of engineering in the current reform initiatives in science education (*Next Generation Science Standards, NGSS Lead States, 2013*) has the potential to promote equity in skilled science, technology, engineering, and mathematics (STEM) by encouraging new forms of learning through the mobilization of students' everyday interests and practices in the context of authentic and project-based experiences (Cunningham & Kelly, 2017). Indeed, many students choose to turn away from engineering learning opportunities because they view it as disconnected from their lives and pursuits, even when they are academically successful (Tonso, 2007). Considering how to promote equity in engineering in K-12 education is critical, especially when considering the fact that society has actively foreclosed pathways to engineering for African Americans, as evidenced by the fact that African Americans make up only 4% of the engineering workforce in the US (National Center for Science and Engineering Statistics, 2017). This statistic has not budged in decades.

One important equity-oriented challenge in designing for engineering learning is how to account for the ways, in which “engineering problems, and respective relevant knowledge, emerge out of social needs and are typically resolved and completed through social processes” (Cunningham & Kelly, 2017, p. 492). Inclusion of authentic social needs and social processes ask designers and educators to be mindful of the cultural contexts, assets, and experiences that students bring to engaging engineering design (Secules, Gupta, Elby, & Tanu, 2018). However, many educators are ill-equipped to make sense of—let alone work with students to navigate—a wider range of experiences and ways of knowing that engineering practices entail. Further, whose experiences and ways of knowing matter, and how, in engineering and science education more broadly is highly contested, yet deeply significant in organizing for equity (Bang, Warren, Rosebery, & Medin, 2012). How the field conceptualizes and designs for learning engineering as a part of integrated science is important. If K-12 engineering is to have equitable and consequential impacts, especially for youth growing up in nondominant communities, it is essential to legitimize and support students' navigation of multiple epistemologies as core to learning engineering. This concern is the focus of our investigation.

In this article, we present an approach to designing for engineering learning experiences that support students in navigating multiple epistemologies, along with the tensions that emerge as they do so, as an integral part of engineering design. We focus, in particular, on a related set of epistemic tools, grounded in a framework of engineering for sustainable communities (EfSC). Specific attention is paid to the roles these tools play in recruiting and facilitating the integration of diverse community epistemologies students possess with canonical middle school engineering knowledge and practices. We are particularly concerned with when and how these tools might cultivate new forms of learning toward equitable and consequential outcomes, which could transform what it means to learn in engineering. As we elaborate later, by equitable and consequential outcomes we suggest that opportunities for meaningful learning attend equally to students' development of robust epistemic knowledge while working to disrupt and restructure power dynamics in classrooms, science, and society (Calabrese Barton, Tan, & Greenberg, 2017).

Our overarching research question is how do epistemic tools focused on supporting students in recruiting and navigating multiple epistemologies (and their resultant tensions) impact youths' engineering processes and prototypes in equitable and consequential ways? What kinds of multiple epistemologies (if any) are solicited, legitimized, and/or navigated? And what are the equitable and consequential learning outcomes that resulted (if any)?

1 | EPISTEMOLOGIES, EPISTEMIC TOOLS, AND EQUITY

1.1 | Equity and epistemology in science education

Equity and epistemologies in science education are critically entangled. Whose knowledge counts? Why? How? And what are the implications for learning? These questions center who has the power to know in science and what forms of knowledge matter. We take the stance, as have others, that the field of science education, broadly speaking, has treated epistemologies as established, agreed upon, and/or “settled” (Bang et al., 2012, p. 302). However, such a stance “privileges epistemologies that reproduce hierarchies such as race, class, gender, sexuality, and nationality and limit other ways of seeing or imagining possibilities for equity” (Philip & Azevedo, 2017, p. 527). The perspective that the epistemologies, that students come to classrooms with, are inferior to that of Western science has been normalized in practice, and it is widely accepted that the process of learning science involves “replacing” such personal epistemologies “with an epistemology aligned with a western scientific epistemology” (Bang & Medin, 2010, p. 9).

1.2 | Social processes of knowledge construction

From an equity standpoint, we seek to challenge these normalized views. One's own locations in the world allows one to consider the questions, “*how* do I know what I know? *Why* does that matter? And to *whom*?” Such questions are important if learning experiences and environments are to be designed in ways “that sustainably disrupt historically shaped inequities and cultivate transformative agency from within communities” (Bang, Faber, Gurneau, Marin, & Soto, 2016, p. 2). We thus view the questions that undergird the construct of epistemology—whose knowledge counts, why and how?—as addressing *both* the nature of knowledge itself, as well as the social processes for achieving possible epistemic aims (Elby, Macrander, & Hammer, 2016).

We are interested in those studies that directly take up how the production of scientific and engineering knowledge in classrooms reflects not only the cultural contexts, in which learning occurs, but also the power dynamics, which operate within such contexts (e.g., Bang & Medin, 2010; Calabrese Barton & Tan, 2009; Nasir & Vakil, 2017; Tan & Calabrese Barton, 2009). For example, Nasir and Vakil (2017) describe how students are racialized and gendered through school practices in science, and other subject areas, through the “framing, construction, and design of environments” that “carry explicit and implicit racialized and gendered notions of who does and does not belong in these classrooms” (p. 378). Other studies suggest how discourses about and enactments of what constitutes meaningful disciplinary learning, for whom and why, differentially position students with or without epistemic authority and/or agency (Rosebery, Ogonowski, Di Schino, & Warren, 2010).

Furthermore, as studies in this area of work intimate, acknowledging the role that community-based epistemologies play in learning science help to mediate these powered dynamics in productive ways (e.g., Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt-Barnes, 2001). For example, in their work with Indigenous youth and community members, Bang and Medin (2010) assert that legitimizing multiple epistemologies, including indigenous communities' values and value-grounded practices with Nature, supports indigenous youths' robust engagement with STEM disciplines sustainably over time. These cultural practices offer different ways of sense-making, grounded in different epistemologies. Thus framed, epistemologies consist of, and reflect the daily, culturally-informed mechanics, by which one leverages particular pieces of knowledge to engage in particular practices.

Yet, science education research on youths' epistemologies have largely ignored the power and importance of such social processes in relation to equity concerns (Sandoval, 2014). Such studies have primarily focused on youths' understanding about the nature of the scientific professions, including the undergirding principles of what renders someone scientific or qualifies something as a scientific phenomenon (nature of science; e.g., Lederman, 1992), or on youths' sense-making through the processes of scientific inquiry (Sandoval & Reiser, 2003). Sandoval asserts that such siloed investigations of youths' science epistemologies “is a major obstacle to producing a

coherent theory of epistemological development” (p. 383). Moreover, such a siloed framing of youths' science epistemologies ignores the situated-nature and the culturally and power-mediated ways, in which youth develop their epistemologies in school science settings (Warren et al., 2001). For example, as Rosebery et al. (2010) point out classrooms as “spaces, in which whole systems of meaning or ways of seeing the world come into contact with one another in both planned and unplanned ways” (p. 351). Such contact is important from an equity standpoint in how it elevates the importance of the “heterogeneity of human cultural practices and experience” as central to everyday life and learning (p. 351).

By extension, these same arguments apply to youths' engineering epistemologies, now that engineering is a core component of K-12 school science with the *Next Generation Science Standards*. How one develops knowledge *in*, knowledge *about*, or knowledge *for*, and how one gains insight into the values foundational to the legitimized suite of knowledge in engineering (or the “nature of engineering”) is integrally intertwined. Studies have revealed the ways, in which the contextual and interactional dimensions to knowledge production shape epistemologies of engineering (e.g., Cunningham & Kelly, 2017), highlighting the importance of social practice and cultural norms.

1.3 | The ontological connection

Being further concerned with equity, we also suggest that questions undergirding the construct of epistemology in science education are ineluctably linked to one's ontological leanings toward science and engineering (i.e., how one identifies with science and engineering, how one answers questions such as, “who makes the decisions as to what counts as science or engineering? Do the values and practices of engineering connect with what I care about and can do? Am I someone who can see myself in engineering now? Or in the future?”). Siegler (1996) reminds us that young people consider issues in multiple ways and that educators need to acknowledge “the omnipresence of variability and choice in children's thinking” (p. 61).

Thus framed, what is deemed “personal epistemologies” is informed by context-dependent variables, oftentimes tied to significant others (Louca, Elby, Hammer & Kagey, 2004). The process whereby youth, in collaboration with community, debate and decide what kinds of knowledge “count,” to whom, and in which contexts, is epistemological in nature. Such epistemological decision-making is vested in one's ontology, and thus also political in nature. Who one is, who one is considered to be, whether and how one has authority to decide, directly influence the pieces of knowledge that get distilled as significant. The question of who gets to decide what counts as knowledge is especially salient in a hierarchically ranked community such as a science classroom where the teacher is often positioned as the primary figure with epistemic authority.

Barajas-López and Bang (2018) posit that “onto-epistemic heterogeneity is fundamental to science learning” (p. 8). Indeed, science education tends to reinscribe white, patriarchal systems of power, and privilege into the ways of, and resources for knowing, normalized within policy and practice, thereby delegitimizing those of nondominant students and communities (Rosebery et al., 2010). Moreover, such systems of power are embedded in the knowledge systems of science education in ways that make them seem objective and even natural, rather than socially and ideologically constructed (Harding, 1991/1991).

Therefore, rather than viewing emerging contradictions and tensions within and across epistemologies as productive places of knowledge production and introspection (where youth can critically use multiple epistemologies toward a range of knowledge production goals instead of being dominated by them), such tensions are viewed hierarchically, requiring nonnegotiable movement toward normativity (Bhattacharya & Kim, 2018). As Barajas-López and Bang (2018) state, equitable learning environments must refuse “epistemic and ontological violence” and resist the “erasure that normative STEM educative spaces deliberately or heedlessly inflict” (p. 10). In short, youths' epistemic and ontological development in science or engineering cannot and should not be divorced from each other. One way of attending to youths' ontological leanings more explicitly is through valuing multiple epistemologies.

2 | EQUITY AND EPISTEMIC TOOLS

STEM learning environments, which support equitable and consequential learning, need to be designed to welcome an expanded suite of epistemologies, in addition to canonical STEM epistemologies. In addition, beyond welcoming multiple epistemologies, equitable and consequential STEM learning environments need to provide a conducive and productive epistemic space, for youth to engage in epistemic sense-making, to parse between the different threads of knowledge grounded in multiple epistemologies, toward particular goals. In our own work, we have seen the transformative power of recruiting and integrating students' diverse funds of knowledge into disciplinary science content pursuits (e.g., Calabrese Barton & Tan, 2009). Here, the goal of such recruitment and integration is toward transforming the pedagogical, physical, and political spaces of science learning toward new forms of knowledge production and organizing for just social futures. We view funds of knowledge—the everyday wisdom inherent in youths' practices in their day-to-day living—as part and parcel of the culturally-informed epistemologies youth possess. Youths' funds of knowledge, in this study, could be construed as “epistemological resources” (Louca et al, 2004), that were “activated” through “a local change in the context of the classroom, which engender(ed) in children a more productive epistemological mode” (Hammer & Elby, 2002, p. 175)

The role of an expanded suite of epistemologies is not simply to value, in theory, what young people bring to learning, but rather to fundamentally transform what counts as valued knowledge, learning, and becoming in the disciplines toward generating “new forms of knowledge, new modes of engagement, and new networks of responsibility” (Bang et al., 2012, p. 315). Learning to consider and navigate between multiple epistemologies require youth to wrestle with the legitimacy of sources of knowledge, the communicative modes of knowledge (and what may be elided or mutated in translation), and the contingency of knowledge. These considerations, again, point to onto-epistemological connections. These studies suggest that research should focus on how youth can be supported in navigating between multiple epistemologies in support of disciplinary learning in noncolonizing ways.

We view the importance of epistemic tools as one approach to this support. In drawing from this critical orientation, we operationalize epistemic tools as designed tools with a high degree of “symbolic pertinence that it becomes an intrinsic system of knowledge and thinking” (Magnusson, 2009, p. 168), as well as “knowledge-generating” in nature (Markauskaite & Goodyear, 2014, p. 237). Given our focus on navigating multiple epistemologies, we consider the importance of tools as also being multidirectional, spatially and temporally, as individuals negotiate knowledge production across social and cultural boundaries (Knuuttila & Boon, 2011). Thus, our study seeks to generate new approaches and epistemic tools that support teachers and students in articulating and critiquing the entrenched norms and practices that frame acceptable forms of knowledge and knowledge production.

3 | EQUITABLE AND CONSEQUENTIAL ENGINEERING

We underpin our study with a stance of learning focused on consequentiality—a stance that values forms of participation, which expand upon who and what areas of expertise are recognized and valued to disrupt normative participation boundaries and knowledge hierarchies among students, teachers, and the discipline (Jurow & Shea, 2015). Focused on more than developing from novice to expert, consequential learning calls attention to new forms of hybrid knowledge and practice that emerge as people move from place to place, widening what counts as expertise, for whom, and why (Gutiérrez, 2012). Such practice challenges and changes sanctioned modes of participation for individuals and collectives across settings and over time.

Specifically, consequential learning provides a framework to examine the ways, in which individuals' experiences, expertise, and commitments to community are legitimized (or not) in pursuit of science learning and action (and how that impacts patterns of participation). Consequentiality in learning is facilitated or constrained by opportunities youth have to navigate the different worlds they encounter. Thus, to understand

consequential learning in practice requires one to pay attention to the power dynamics that shape how youth are recognized for what they know and can do. Young people's experiences in science take place in what Collins (2000) calls a "matrix of oppression," the structure that operates with race, class, gender, and other forms of oppression. They are often positioned as "outsiders" to science based on where they live, what they look like, or a perceived lack of capabilities (or interest) in making contributions to science investigations. Normative discourses and practices position youth from nondominant communities in real and symbolic hierarchies, leaving actors to confront contrary narratives in their experiences. These intersections impact conceptions of what it means to be scientific, who can participate in science and how, or if, science is consequential to their lives and/or communities.

A stance on consequentiality in learning is important from both an equity and an epistemological standpoint. Built into our research foci is the assumption that mobilities (of ideas and resources) should not be assumed. Lending our work with equity necessitates an explicit focus on how entrenched systems of injustice might manifest locally as normed practices that operate to curtail the mobilities of particular bodies (and their associated ideas and resources) between particular spaces. Especially in the fields of science and engineering, long-held gate-keeping norms result in differential access to different bodies. This framework speaks directly to our study in that we are interested in investigating if and how, through navigating between multiple epistemologies during the process of EfSC in science class, middle-grade students were able to move which pieces of knowledge, experience, and practice from their lives as students in the school that were not previously sanctioned in the science classroom, into their engineering design process. We are also interested in how such navigation impacted the engineering process and the prototypes created, possibly toward transformative outcomes.

4 | DESIGNING FOR EQUITABLE AND CONSEQUENTIAL ENGINEERING: EFSC EPISTEMIC TOOLS AND UNDERLYING PRINCIPLES

In this study, we are concerned with how an EfSC framework and the two sets of epistemic tools support students in navigating multiple epistemologies and their ensuing tensions part and parcel of learning and engaging in engineering design toward addressing community-identified issues. We designed for equitable and consequential engineering through anchoring both the processes and goal of engineering (*viz.*, the why, what, how, and for whom of engineering) in the framework "EfSC."

Our designed EfSC framework for middle school engineering sought to address equity and consequentiality in three ways: (a) We operationalized "sustainable communities" to mean, (i) the sustainability of the required engineering expertise is localized and distributed within community, by which we mean the necessarily know-how to engineer is already present within community; and (ii) the engineered artifacts work to restore or maintain the welfare (broadly defined) of the community; (b) the engineering process is iterative in nature, informed by dialogic considerations of the interplay between technical and social elements, gleaned through navigating multiple epistemologies including ones both discipline-based and community-grounded; (c) the engineering process is open-ended and supportive of a range of engineering artifacts that youth, in collaboration with community, deem worthy of pursuit so as to increase the welfare of their community. These three approaches also work in concert to encourage and facilitate increased mobilities of ideas, resources, and expertise as envisioned by the ideal encapsulated in the mobilities of learning perspective, toward meaningful consequentiality.

The associated EfSC epistemic toolsets—community engineering and ethnography toolset #1 and integrating perspectives iterative engineering design toolset #2—when taken up by students, work collaboratively to create what we hope is an "idealized epistemic space" (Green, 2013, p. 178) that is both equitable and consequential to students' engineering learning. Both EfSC epistemic tools work to support students in leveraging their insider community positioning (denoted as social specifications in the EfSC framework) toward engaging meaningfully in engineering design, in tandem with science and engineering knowledge and practices (denoted by technical specifications).

EfSC is an approach to engineering that makes sense of the interplay between the technology of design and the particular vulnerabilities of communities. Not only does this approach situate engineering design within local contexts, it also espouses the importance of participatory practices and humanitarian action-taking. EfSC deals with problems and design solutions for the real world. Engineers often tackle difficult, interdisciplinary problems that are grounded in conflict, crisis, and disaster. Such design problems are often tied to human rights, economics, and oppression, and they have clear technological and social dimensions. Examples range from local problems of building architecture to global concerns such as water quality and access.

EfSC challenges and expands what it means to be an engineer in the ways that connects engineering practice to communities. In addition to focusing on the technical problem-solving dimensions of engineering, EfSC focuses on the needs and rights of communities. EfSC requires the inclusion of community-based forms of research as part of the design process. It requires engineers to ask, "who is the project for? Whose knowledge counts? And who takes part in problem definition, data collection, and analysis?" (National Research Council, 2010, p. 8).

Teaching EfSC requires teachers and students to consider the technical challenge of design as well as how problems and solutions are defined, adapted, and optimized in response to community needs. This necessitates an approach to engineering that moves beyond traditional content and practice to incorporate the social dimensions of problems and solutions. To operationalize this in our EfSC framework, we invited teachers and students to pay attention to both technical and social specifications and the interactions between them.

As a heuristic, we outline four core underlying principles for teaching EfSC intended to support teachers as they facilitate students' engagement with the EfSC learning process. The core underlying principles help teachers navigate from a topic (e.g., alternative energy) to a problem space, where students can develop realistic and testable tools based upon current knowledge, empirical investigation of technical and social dimensions, and operational constraints and specifications (e.g., what devices, powered by alternative energy, can I build to get me safely to my friend's house when my parents cannot take me?).

The principles of EfSC undergird a reform-oriented curriculum designed to foster critical agency (Schenkel, Calabrese Barton, and Tan (In press)) as well as to include community knowledge and wisdom (Tuck, 2009) in engineering design and practices, allowing students to redress systems of injustice within accepted norms of engagement in STEM education. The EfSC principles are:

1. Uses community ideas in engineering: EfSC focuses on defining problems collaboratively with community members with specific attention to improving the daily lives of people with special attention to issues of injustice. Teaching EfSC supports students in learning to engage community members in codefining problems of community concern. The problems identified by student engineers and community members are those that improve the daily lives of people with special attention to those individuals within a community at most risk of injustice. The myriad of problems might include small-scale projects (e.g., youth do not have wide access to a wider range of safe commutes to school) and large-scale projects (e.g., the need for sustainable powering of a school building). Some questions that help to identify the problem for EfSC projects are as follows: (a) What problems affect this community and how do you know? (b) What approaches could we use to help identify those problems of the greatest urgency or the greatest injustice? (c) What roles might community members play in codefining a problem?
2. Helps the community solve their problems in engineering: EfSC requires teachers and students to leverage multiple—and often divergent—perspectives, as they design solutions that positively affect sustainable communities. Learning to design solutions that positively affect sustainable communities requires attention to multiple and often times divergent perspectives. Communities are not homogenous environments, they cannot be treated as if they have only one voice. Most communities have different and often conflicting perspectives within them. Some of these voices are more often prioritized because they hold more power in society, often because of economic, racial, or gendered reasons. Active participation from community members from a range of background and experiences is imperative. Here, the expertise to solve problems is not limited to those with traditional authority (e.g., engineers and teachers). Rather expertise is distributed across a range of perspectives and experiences. Community members



and students bring insider knowledge to community problems that can substantially impact design decisions. In teaching EfSC, teachers support students in deciding on, building, evaluating, and optimizing designs over several design cycles with each iteration paying attention to the needs and considerations of multiple stakeholders. Most educational materials intended to support “designing solutions” focuses broadly on the build–test–refine process, without attention to when or how multiple cycles take place, or what it means to work with data from different epistemological origins, such as technical and social data, and that may include conflicts. The challenge here is in opening up the practice of designing solutions—how can teachers make visible for students the iterative nature of this practice and the importance of multiple perspectives in these iterations? For example, students may not initially realize that a solar-powered light-up scooter has specific energy requirements based on the type/quantity of light desired, hours of power needed, or how energy might be stored until they try a design with particular lights, solar panels, and power pack. They may not initially consider what kinds of light switches are easiest for small hands to use on-the-go, how sleek of a design peers may want, or what city ordinances might require of moving vehicles in the dark, until they engage with various community members. In moving through design iterations, these factors become more salient, but as they do, students also need strategies for considering trade-offs as they further consider what design features are most affordable, important, and salient to their target audience. The goal is for their solutions to actually work for the people of their community.

3. Cares about the environment: EfSC focuses on how the impacts of design solutions on communities are complex; they involve both short and long-term approaches and mutual colearning over time. A “one size fits all” approach to solving community problems does not promote equitable impacts. Local cultures, geographies, and histories all shape how design solutions are taken up and affect members of community differently in both the short and long term. For example, in designing solutions, whose needs are met, and how in terms of current participants and future generations, as well as the environment, are all key considerations. Engineering design solutions are viewed as a part of a “larger complex ecosystem,” rather than in isolation, where impacts are spread across the system. In addition, a process of mutual engagement in the problems of engineering can yield colearning. Not only do engineers learn more about the needs of a community and how those are framed through local knowledge and history, community members can also develop knowledge and practice in the area of engineering and science. This way, the adoption of new technology, and the success of engineering projects can be sustained over time. Furthermore, the development of new knowledge and practice in engineering help to strengthen the process of empowerment within the community members.
4. Designs solutions for now and in the future: In teaching EfSC, students learn to balance trade-offs equitably among political, environmental, and the social effects of decisions.

The design process values the increasing of community members' well-being and the development of involved people and communities. The involvement of relevant perspectives in both engineering and local communities (e.g., parents, teachers, safety officers, scooter design experts, solar energy experts, etc.) and evaluating the degree of their impact in the design process, help to maintain the balance in this process. The well-being of community members involves political, environmental, and social aspects. One implication is that engineers must recognize and exercise their responsibility to society as a whole, which may sometimes conflict with their responsibility to the immediate client.

5 | EfSC EPISTEMIC TOOLS

Our approach to EfSC is anchored in two epistemic toolsets that bridge the principles of EfSC with engineering practices, to support students in integrating technological and social ideas and concerns. The epistemic tools sets include pedagogical guidelines (materialized as survey questions and the EfSC design cycle) and discursive and performative practices (embodied in community feedback conversations and students' hands-on engineering processes) that operate to support the generation of “authentic knowledge work” (Markauskaite & Goodyear,

2014, p. 241) tied to cultural contexts. We mean for the epistemic tools to be at once integrative and generative in nature. The integrative quality of the toolsets would emerge when students are directed to seek for and make sense of multiple epistemologies relevant to their engineering design, while the generative element reflect students' exploration of novel design iterations as new directionalities for problem-solving through EfSC are revealed through negotiating design trade-offs.

6 | EPISTEMIC TOOLSET #1: COMMUNITY ENGINEERING AND ETHNOGRAPHY TOOLS FOR DEFINING PROBLEMS

Teachers need support in figuring out how to move from a topic (e.g., alternative energy, transportation, etc.) to a problem space where students can develop realistic and testable prototypes iteratively, informed by technical and social data as related to technical and social design specifications. This process involves (a) identifying community problems that technology can solve, and what one needs to know about the technology to solve the problem (e.g., can I adapt my scooter to have solar-powered lights? Can it work in the dark?) and (b) identifying a range of relevant perspectives in both the engineering and local communities and evaluating their impact on the design process. This latter component requires the translation of technical language into questions, ideas and concerns that relevant stakeholders will understand. The goal is to support teachers in framing instruction around designing problems in ways that capture the problem as layered and complex. How do different perspectives constrain the problem space differently, and why does this matter?

This toolset was designed to help teachers instruct students on defining problems around multiple perspectives for the problem space and how to seek them out (social dimension), and how these multiple perspectives matter in establishing criteria and constraints (interactions). Students were supported in engaging in dialog with community members toward identifying authentic problem spaces in need of engineering solutions.

Toward this end, we cogenerated with teachers approaches to eliciting community input on classroom sustainability issues of concern. Partner teachers worked with us to come up with both survey and interview questions, grounded in a set of reflection prompts on community input (e.g., a set of five core questions related to community concerns, see Table 2) that teachers considered to be open-ended enough to elicit a range of possibilities. We also sought teacher input in how the tools would be presented to students, the “mechanics” of tool-use, so to speak. For the classrooms in this study, the three teachers decided on such a sequence: (a) Discuss with students why it is important to solicit for community input when engaging in EfSC; (b) share and explain what a survey is and gather student feedback on the teacher–researcher established set of survey questions; (c) have students practice interviewing one another; (d) discuss with students the process of collecting data through sending out both an online survey and through face-to-face interviews with other students from another class; (e) how the class would collectively analyze data results using simple descriptive statistical analyses available on the online survey platform. To facilitate survey analysis, students were provided with a data sense-making sheet (see Figure 1) as a heuristic to guide classroom discussions. A final component of this toolset is the process of soliciting for community feedback during the iterative design process. This entailed students presenting their prototype to community members (including teachers, peers, and other invited community experts such as local engineers and makerspace teachers) to gather feedback that informed the next iteration of their design process.

7 | EPISTEMIC TOOLSET #2: INTEGRATING PERSPECTIVES IN DESIGN SPECIFICATION AND OPTIMIZATION THROUGH ITERATIVE DESIGN SKETCH-UP AND PROTOTYPING

Research indicates that iterative optimization is more effective in teaching design compared to a single design cycle (NRC, 2009). However, most educational materials intended to support “designing solutions” focuses broadly on

TABLE 1 How can I make my classroom more sustainable? Unit flow

No.	Lesson	Key focus	Epistemic tools
1	Introduction	Big ideas in EfSC Lesson 1: EfSC Introduction	Examining and discussing how youth their age use community ethnography as a part of engineering design (introducing Tool 1)
2-3	Iterative design Cycle 1	Sustainable electric art: Using iterative design cycles to make electric art cards for family/friends, powered with green energy sources Lesson 2: Designing electric art Lesson 3: Sustainable electric art	Generating community narratives (Tool 1)
4-9	Iterative design Cycle 2	Sustainable classrooms: Defining problems and designing solutions through community ethnography Lesson 4: Engineering design challenge intro Lesson 5: Defining the problem: Using community ethnography to define engineering challenges Lesson 6: Initial design Lesson 7: Optimize design with community feedback Lesson 8: Prototyping Lesson 9: Refining designs through technical tests and community feedback	Surveys and observations of peers and community members (Tool 1 used iteratively) Dialogs with community on project ideas/design (Tool 2, used iteratively)
10	Community sharing	Lesson 10: Sharing engineering designs with the community	Community narratives

Abbreviation: EfSC: engineering for sustainable communities.

TABLE 2 Community survey and interview questions

1. Which category best describes you?
 - a) Student
 - b) School staff
 - c) Parent or other adult in community
2. What challenges related to a healthy and happy school community do you think are most important? Select 2 or 3.
 - a) More opportunities to celebrate accomplishments
 - b) Needs to be more fun
 - c) Needs more sense of community
 - d) Need to do more things as a class to make a difference
 - e) Need more chances to do something important
 - f) Need to feel safer
 - g) Needs to be more fair
 - h) Wasting natural resources
3. What other challenges related to healthy and happy communities do you think are important? (Open ended question)
4. What are the most important things we should be thinking about to make sure that our design idea is environmentally friendly (select 2)?
 - a) Uses recycled materials
 - b) Uses renewable energy sources
 - c) Doesn't waste materials in the final design
 - d) Lasts a long time
 - e) Helps a lot of people
 - f) Other (please specify)
5. What are your ideas for engineering designs that kids could make that could help solve these problems? (Note: Imagine that the kids had access to small LED lights among other typical class materials)

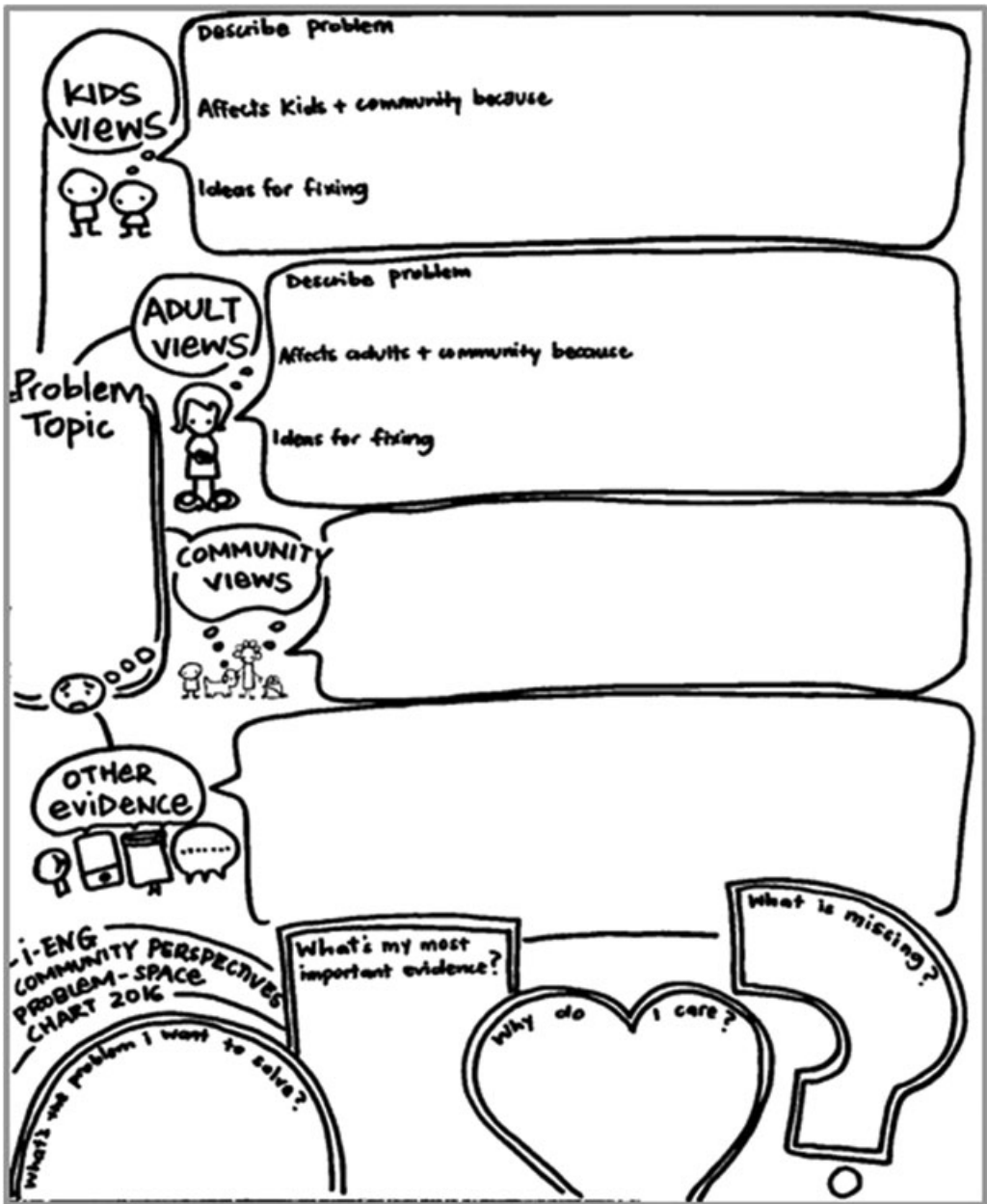


FIGURE 1 Community data analysis heuristic

the build–test–refine process, without attention to when or how multiple cycles take place, or what it means to work with data from different epistemological origins that may include conflicts. Teachers need support to help students decide on, build, evaluate, and optimize designs over several design cycles. We are concerned with four dimensions of this process: (a) How do students determine criteria (e.g., my scooter should be able to light up at night for at least three hours)? (b) How do students balance competing factors (e.g., my energy requirements demand a bigger panel, but my friends want the scooter to look sleek and cool)? (c) How do students arrive at design trade-offs that enable real and testable solutions? (d) How do students document their initial design and layer on trade-offs during the iterative design process?

We created a community-driven, EfSC design cycle for engineering design, asking partner teachers for feedback before settling on the final version shown in Figure 2a. This design cycle highlights the importance of community contributions at each stage of the design process. Our goal has been to explicitly incorporate community perspectives at each stage of the design cycle. We view this EfSC design cycle as a tool to guide teachers to support students in reflexively analyzing data toward possibilities for optimizing solutions by leveraging multiple epistemologies, explicitly recruited through attending to both technical and social specifications, and to explore and try out the most desirable possibilities given how these epistemologies might be jointly considered to reveal design trade-offs when fine-tuning design.

Balancing these different data/perspectives in one's mind is a challenge for any person, let alone a middle schooler (Schunn, Silk, & Apedoe, 2012). Therefore, as a complement to the EfSC design cycle, students also engage in iterative design sketch-up (Figure 2b). This entails putting on paper a sketch of their innovation, with parts labeled, materials required, community issue the design addresses, and questions they had going forward. Students add to this sketch-up as they engage in iterative design, layering on changes to specific design features in response to particular pieces of feedback from community members. Figure 2c,d show the increasingly complex sketch-up of the Light-Up Bingo-Cage for Fair Participation prototype.

The EfSC epistemic toolSets 1 and 2 are designed to work in a positive feedback loop to foster a generative and not merely descriptive (Gouvea & Passmore, 2017) epistemic space that work to push students' navigation of multiple epistemologies to a point of saturation toward the "border of breakdown" (Rheinberger, 1997, p. 135) when they consider design trade-offs, while weighing technical specifications against social ones. At this edge of instability because of conflicting data points, students are tipped into the next iteration of design. Through this iterative process, they are supported in engaging in epistemic work when they make decisions, about which piece of knowledge counts, why, for whom, and how to prioritize contesting data, based on what criteria. When attention is paid to multiple epistemologies, such deliberations have higher possibilities of meeting epistemic goals that are both equitable and consequential.

For example, when students weigh particular technical specifications (e.g., energy demands to power four white LED lights require more than one 3 V coin-cell battery, maybe large solar panels should be considered as energy source) with social specifications (e.g., four white LED lights are necessary so one can see the entirety of one's desk cavity, to locate specific items in the shortest amount of time, solar panels may not generate enough electricity in particular parts of the classroom where desks are located), they are forced to make epistemically oriented decisions, induced by the goal to make the prototype as easy to use as possible, so as to fulfill its purpose. In this example, it is important for one to be able to find items quickly (to avoid being late to the next class), so the energy source must be reliable and sustainable. What other renewable energy sources can be tested to see if this socially informed, technical specification can be met? Navigating between multiple epistemologies when considering design trade-offs, support student development of expertise in making epistemologically oriented decisions. Such an iterative design process serve to increase and sharpen students' range of engineering epistemologies. Figure 3 illustrates the relationships between the EfSC framework, core principles, epistemic toolSets #1 and #2, and supporting multiple epistemologies.

8 | METHOD

8.1 | Schools and contexts

Sage Middle School serves a diverse population of students with 43% Black, 38% White, 11% Hispanic, 5% Biracial, 3% Asian, and <1% each Native American and Native Hawaiian. Fifty-eight percent of the students come from low-income families. The school also serves 21% of students with a range of disabilities. Led by a dynamic school principal in his second year, Sage won the "Most Improved Middle School" award in the district and the "(Region) Signature School Award" this year, both for most improved test scores. While the school displays overt signs of

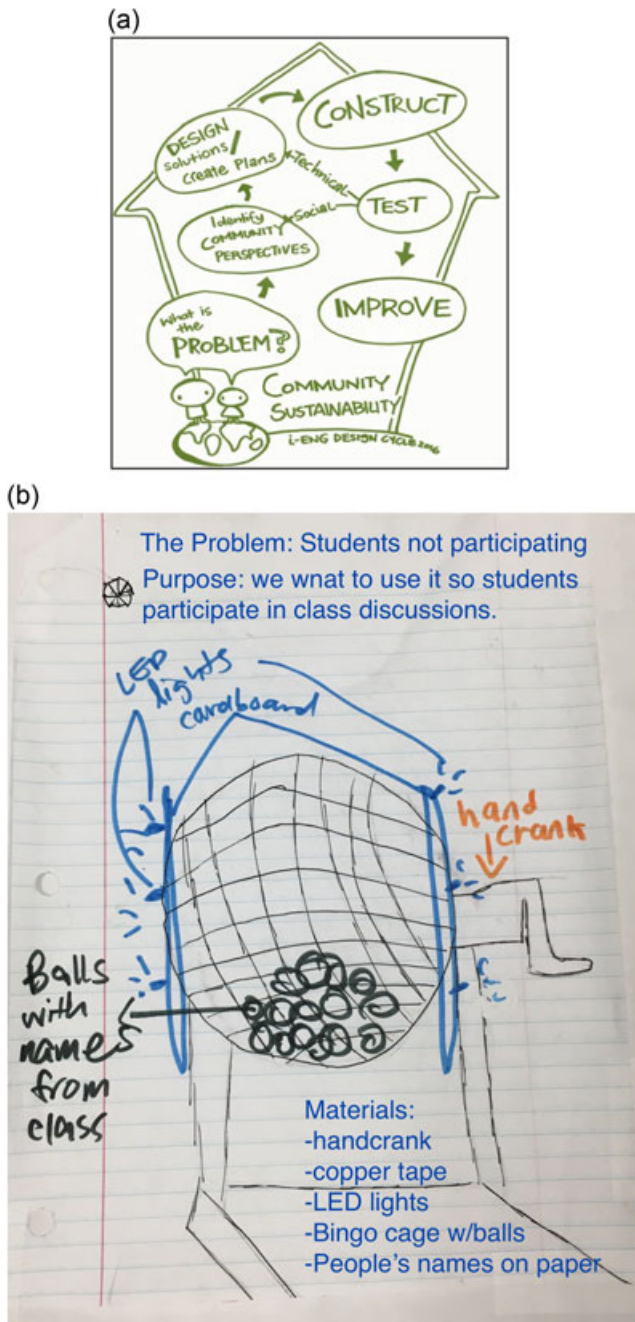
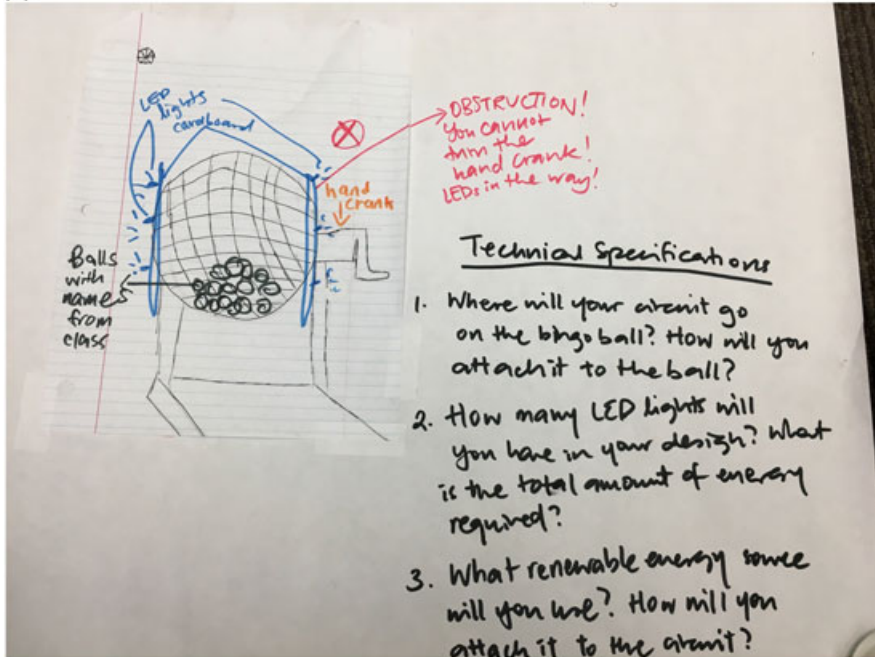


FIGURE 2 (a) EfSC design cycle, (b) initial sketch-up of Light-Up Bingo Cage for fair participation, showing design of LED light circuits on each side of the bingo cage, (c) layered sketch-up of bingo cage after iterative feedback—feedback given pointing out the LED lights placement as a physical barrier to turning the bingo cage handle, (d) layered sketch-up of bingo cage after iterative feedback, this time the circuit has been moved to the base of the bingo cage. LED, light-emitting diode [Color figure can be viewed at wileyonlinelibrary.com]

(c)



(d)

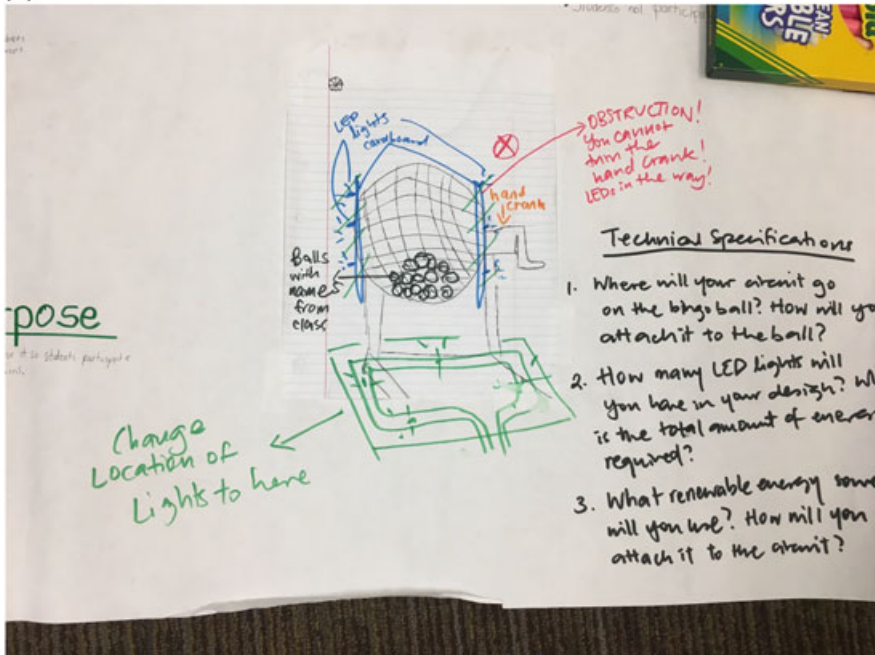


FIGURE 2 Continued

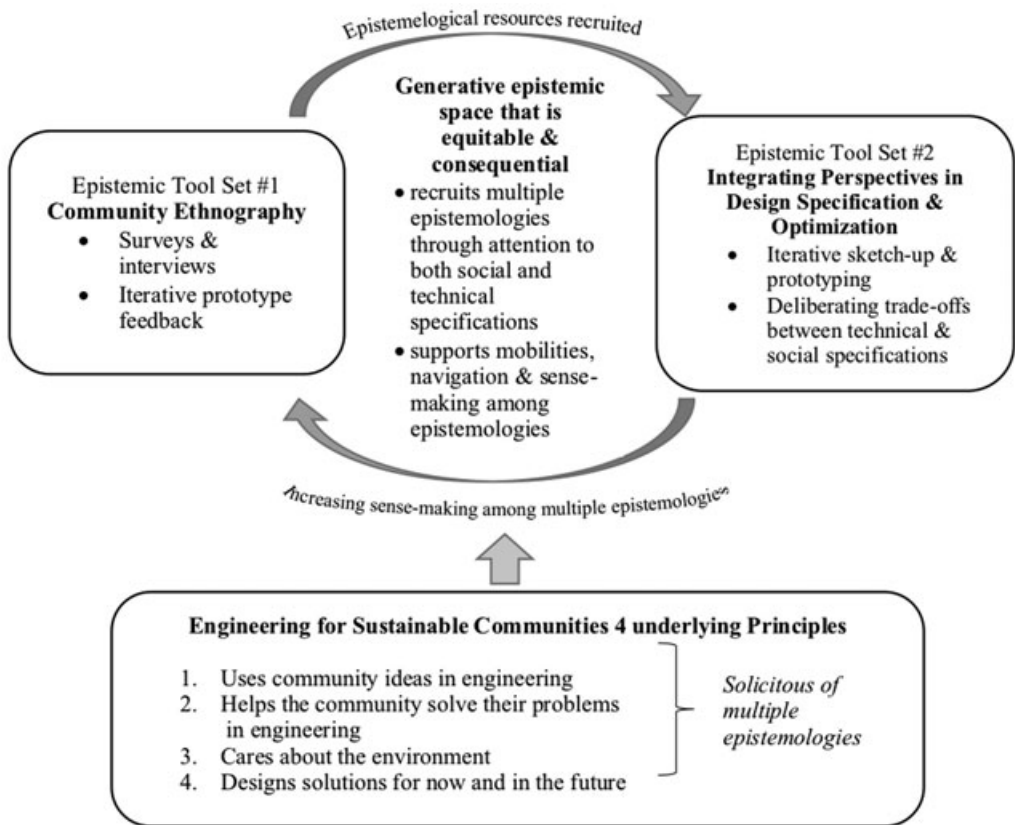


FIGURE 3 EfSC framework with underlying principles and epistemic toolSets 1 and 2

solidarity and friendship for all, such as “This school serves ALL students” posters prominently in the building, incidences of bullying regularly occur. The school also reported a disproportionate data of disciplining African American boys over all students.

We worked with three 6th grade teachers at Sage. Ms. D., a White female, has taught for 12 years at Sage Middle School. Vivacious and warm, Ms. D teaches 6th grade Science and Social Studies and is beloved by her students. One student described Ms. D as “da bomb dot com!” Ms. S., a White female, has taught for 7 years, the last 2 years at Sage. She teaches 6th grade Science and Math, and values engaging students through hands-on learning. She has a calm and measured demeanor, is well organized in her teaching, and her students showed they trusted and admired her. Mr. M., a Black male, has been teaching for 27 years, and is well loved and respected at Sage. He is organized, thoughtful, and dedicated in his 6th grade science teaching.

9 | SOCIAL DESIGN EXPERIMENT APPROACH

Being engaged with equity, we took a social design experiment approach toward social change-making because it is both critical and participatory (Gutiérrez & Jurow, 2016). Our approach is critical because our work is rooted in the belief that exposing, critiquing, and transforming inequalities associated with social structures and labeling devices are consequential and fundamental dimensions of research and analysis. We seek to collaboratively disrupt inequitable power dynamics commonly perpetuated by researchers on participants. Our work is also intentionally

participatory as we seek to include multiple voices at the research and design table, including youth, teachers, and community members.

Central to our participatory and critical approach is our effort to take an assets-driven and “desire-based” framework in refusal of damage-centered research (Tuck, 2009). This is important for students from nondominant communities who have been framed as in need of repair in science education. Thus, in this study, we codesigned our materials with youth and teachers using participatory methods, as an approach to social change-making. Our research team developed the unit and then corevised it with youth and teachers first in after-school settings and then in a summer camp before classroom implementations. As participatory researchers, we were in the classrooms during class times when the curriculum was piloted.

As students worked on innovation designs, we kept photo, video, and hard copy records of their work and progress, as well as the feedback offered by experts (engineers in the community) who were invited into the classroom. We also collected and generated digital recordings of all student and teacher work. When groups finished their prototype models, we helped them make “project postcards” as a record and information sheet of their innovation that could be posted in the school corridors. The postcard was meant to be a heuristic to help students describe the process of working on the innovations. Student groups were interviewed and making the postcards became a reflective exercise on the process of coming up with an innovation, of their mistakes and breakthroughs, and helped them to express where their ideas came from and the main idea(s) behind their innovations. Teacher interviews were also conducted that centered on (a) their general reflections of the engineering unit; (b) how the EfSC framework facilitated the engineering design process; and (c) what kinds of learning outcomes ensued from the unit.

10 | DATA GENERATION AND ANALYSIS

Detailed fieldnotes of classroom interactions were kept, along with video recordings of select lessons and group interactions. Fieldnotes were kept by more than one researcher for all class sessions to allow for multiple perspectives to inform how we understood the contexts and interactions. Mid-unit and end-of-unit “artifact interviews” with all focal groups were conducted. Here, the “artifacts” are engineering designs youth prototyped, and included their design sketches, actual prototypes, and written reflections about their prototypes. Interviews lasted about 90 min/team, and covered four categories of questions: (a) Understanding the artifact (what is it, how it works, what problem it solves, etc., materials used and why, etc.); (b) participation and engagement (behind the scenes, including a step-by-step description of the process, descriptions of interactions/support youth received from peers, educators, and community members, resources used); (c) knowledge and practices (STEM knowledge and practice needed [prior and what was learned], and community-based knowledge); and (d) Meaning and value (what this project says about oneself, etc.). We also conducted informal weekly conversations with the teachers to make sense of on-going questions, concerns, and “feel” of the enactments with a formal interview at the end of the enactment.

The 10 focal team projects are described in Table 3. Teams were comprised of two to five students each, and in each classroom, teams were assembled through self-selection based on project interest and friendship groups. These projects reflect the work of the focal groups across the three classrooms. All participants completed IRB permissions.

Data were analyzed in the grounded theory tradition, using a constant comparative approach (Strauss & Corbin, 1998). The first phase of analysis involved open coding by thoroughly perusing all generated data to surface (a) compelling episodes of engagement in the engineering design work; (b) the epistemologies that youth drew upon during critical episodes; and (c) how they iteratively defined the problems they were seeking to solve through engaging in multiple epistemologies. With the help of our theoretical framework, we worked to make sense of the range of community-based epistemologies that students brought to their engineering design process and how these epistemologies informed how, and why, youth took the actions that they did; and the meanings the artifacts youth

TABLE 3 Summary of sample projects

Selected samples of I-engineering EfSC-focused projects: Case studies as evidence of multiple epistemologies			
Project Description	Community-based epistemologies supported by the EfSC framework		
	Classroom-based	School wide-based	School-figured world based
Bingo cage Names on balls in a spinning bingo cage helped teachers call on students fairly	Very few students held up their hand to participate in classroom discussions, Paul reported only three students held their hand up to participate. Grades were partly dependent on classroom participation, fair chance to participate could boost grades	Open-ended response on survey, "equal opportunities for everyone" and "more opportunities to use more peoples' ideas," and "more chances to argue ideas and opinions"	Marginalization issue—some students felt it was an injustice to not be called upon with equal frequency and felt oppressed if they did not have a voice in discourse, this was important to this mixed-gender/mixed-race group
Good marksman boy's bathroom Solar-powered air freshener and light-up sign to remind boys to "aim for the urinal"	Class discussion of issues to address with engineering, as part of an EfSC-based design process, was animated when the subject of discussion was the problems in both girls' and boys' bathrooms at school	Open-ended responses on the survey: "I think it is important to keep the bathrooms clean." and, "CLEAN THE BATH-ROOM-S!!!!!!!!!!!!!!!!!!!!!!!!!!!!!"	Gender-based issue of bathroom smelliness and urine on the floor was seen as an injustice imposed upon the boys in this mixed-race all boy group
Hall stop sign A sign in the hall to keep students from coming into class while others exit	Some students were coming into the classroom while others were still trying to exit the class to get to their next class, preventing them from being able to leave the classroom	An idea for innovation on the community survey, "a stop sign to stop kids, so kids leaving can come out"	Respect issue—some students felt disrespected when others would barge in to the classroom as they were exiting. This was important to this all White/all-girl group
Happy box Solar-powered light-up box for notes	Low morale due to heavy testing and grade-based academic culture. Some students in the class were facing challenges in their everyday lives and needed encouragement	Survey had very frequent responses that realized a need to recognize student achievements, and an open-ended response, "I think we need to have something to make us happy in the morning"	Issue of the need for encouragement, standardized testing affected the daily culture in school and was stressful for students, and this, in addition to other challenges, felt oppressive, especially to this mixed-race, all-girl group
"Must copy assignment" lighting system powered by classroom projector light Solar panel powered LED lights in a circuit mounted on the white board to illuminate copy assignment on white board when teacher used projector	Some students were slow to copy down assignment teacher posted on white board before she turned out the lights to use the projector. When the classroom lights are off, the white board is not illuminated enough for students to jot down the "must copy" assignment, which leads to difficulties later in the lesson	Open-ended response on the survey, "equal opportunities for everyone"	Injustice issue—some students felt it was unfair to not have a "must copy" assignment stay lighted as long as it took them to write it

(Continues)

TABLE 3 (Continued)

Project Description	Community-based epistemologies supported by the EfSC framework		
	Classroom-based	School wide-based	School-figured world based
No silent lunch Light-up posters to encourage fairness in the assignment of silent lunches as a discipline measure	Class discussion of issues to address with engineering as part of an EfSC-based design process was animated when the subject of discussion was silent lunches, how they were assigned, to whom they were assigned, and perceived injustices in the assignments	Open-ended student responses to the survey question which asked for respondents to identify other problems in the school community: "I think that when most of the class is being punished and you also punish the other good students" and "the teachers need to be harder on the students because every time they say you have silent lunch but they do not actually give it to you."	Issue of racism and perceived injustice in the way silent lunch discipline was implemented, it felt oppressive to some students and at times unfair, especially important issue to the African American students in this mixed-gender all African American group
Pride slide Light-up bathroom stall door height extender to increase privacy, with decorative light-up "GIRL POWER" art to signal stall is occupied	Class discussion of issues to address with engineering, as part of an EfSC-based design process, was animated when the subject of discussion was the problems in both girls' and boys' bathrooms at school	Survey had frequent responses that realized a "need to feel safer" in school, and an open-ended response, "In the girls' bathroom the stalls are too short. Because we want more privacy and not to feel like we do not have privacy"	The gender-based issue of privacy in school restrooms highlighted an injustice to female students, and this felt oppressive, especially important issue to the girls in this group
Testing Light Indicator A sign that would indicate quiet when it lit up while the class was test-taking	The halls outside the classroom were not soundproofed and amplified sounds on tile floors, metal lockers, and on bare walls and windows	An idea for innovation on the survey was, "we can make a poster with a poster saying to be quiet when we are testing"	In this school's test-taking culture it felt like an injustice if someone made too much noise in the hall while students were trying to concentrate and take a test
Water Fountain Timer A light-up poster with a timer to limit time at the water fountain	The teacher did not allow students to leave the classroom to drink water	Open-ended answer on the survey, "everyone to have water. Some kids cannot get water after encores. Some do not even get water at all" School policy did not allow much time between classes and there were few water fountains	It was an issue that a basic right, that to drink water, was not available to some students, and this felt oppressive, especially when a few students took up too much time at the water fountain

(Continues)

TABLE 3 (Continued)

Selected samples of I-engineering EfSC-focused projects: Case studies as evidence of multiple epistemologies			
Project Description	Community-based epistemologies supported by the EfSC framework		
	Classroom-based	School wide-based	School-figured world based
What is New Board A light-up bulletin board to post new academic content on to help the class remember it	New subject content was not posted in the classroom	Open-ended answer on the survey, “equal opportunities for everyone”	The issue of understanding what was happening in class for English language learners who had a hard time keeping up with the most important new content in class was important to this all-girl Hispanic group who wanted an equal chance to learn and remember what was new

produced had for them, individually and collectively. This axial phase of coding was used to uncover relationships and connections between the multiple epistemologies and how the EfSC epistemic tools operated to support youth navigating between and multiple epistemologies.

11 | ENGINEERING UNIT

This study examined what happened during the second design cycle in an engineering unit. This study occurred during an integrated science, a 4-week unit focused on engineering for sustainability communities, grounded in the disciplinary core ideas of energy transformations, sources and systems, and sustainability, alongside engineering practices. The overarching goal was to expand disciplinary knowledge/practices identified above within a sustainability framework through incorporating community knowledge and practice (see Table 1). As a culminating design project, students were given the design challenge bounded with the following criteria: Students had to innovate something in the classroom in a way that would address a classroom sustainability concern. They were required to use a renewable energy source, such as solar panels or hand-crank generators, 10 mm gumdrop LED lights, copper tape, and any materials available in their classroom.

12 | FINDINGS

Bringing multiple epistemologies into learning and engaging with engineering in substantive ways requires more than simply making space for these epistemologies in the classroom. Opportunities for students to leverage upon and navigate multiple epistemologies with agency (Stroupe, Caballero, & White, 2018) requires that epistemic spaces be created for students to tussle with the tensions imposed by differing sociopolitical values embedded within such varied epistemologies. In school science, the conflicts and tensions that arise in relation to differing epistemologies at best are ignored, leaving students to their own devices to figure out how to make sense of such differences. However, such differences are most often rendered hierarchically in the “settled expectations” that “structure normative progressions and related judgments of students’ meaning-making” (Bang et al, 2012 p. 308).

Our findings suggested that epistemic tools that helped foster equitable and consequential learning opportunities in engineering, supported students in making sense of, and responding to tensions as a substantive

part of engineering design—as a part of figuring out “next steps” in iterative engineering design. This included supporting students in bringing in different perspectives through community members' input, figuring out how to use differing ideas collaboratively toward initial design, and revising joint-epistemologies informed designs in dialog with community members, during the iterative design process. Within these opportunities to tussle with tensions, our findings also suggested that the two epistemic toolsets, working in concert, supported students to engage in equitable and consequential engineering when their engineering process and final prototype worked to disrupt traditional engineering norms and/or oppressive school practices. We are interested in how EfSC epistemic toolsets supported such disruption, possibly leading to transformative outcomes that were both equitable and consequential. Relatedly, we are also interested in the tensions that arose in this politically-tinged process.

We present three claims to explain how the EfSC epistemic toolsets supported students in navigating multiple epistemologies, toward varying degrees of equitable and consequential outcomes. In each classroom, teachers displayed a large poster depicting the four EfSC undergirding principles, which they periodically pointed to during each lesson. Teachers also consistently referred to the two EfSC epistemic toolsets, using “community survey” as a shorthand for the Community Engineering and Ethnography Toolset. Both teachers distributed copies of the EfSC design cycle (Figure 2a) to every student and reminded them to track their progress during the iterative engineering design process, when they visited with each group during the lessons. We use an exemplar case study to more fully illustrate each claim. After the three case studies, we look across all ten cases (summarized in Table 3) to further unpack the relationships between how students and teachers took up the EfSC epistemic tools, and the degree to which both engineering process and prototype led to transformative outcomes, including the resulting tensions. Table 3 summarizes ten representative projects across the three classrooms.

Claim 1: EfSC epistemic toolsets support multiple epistemologies

In this first finding, we describe how the EfSC epistemic tools supported students in soliciting and navigating multiple epistemologies as a part of engineering design. Students brought to their engineering design deliberations meaningful ideas and insights grounded in their own, and their community members' experiences in the world. Specifically, students attended to how such lived experiences pushed back against structurally embedded ways of sense-making. This is important, for students were recognized for knowing the intricacies of complex problems that mattered in their community, and which could be responded to with engineering design. Further, when engineering for sustainable communities, one could not successfully engineer designs without deep engagement with how, or why, particular concerns mattered in their community. Thus, we suggest that epistemic tools that value multiple epistemologies in engineering design could be taken up towards promoting not only deeper engagement and learning in STEM, but also disrupting normed epistemologies in engineering by raising questions around what, and whose, knowledge counted, and why. We saw the incorporation of multiple epistemologies as valuable in opening up what it means to be an expert in STEM and what STEM projects were worthy of school attention. These tools worked to not only support the solicitation and integration of multiple epistemologies as a part of engineering design, but also awakened a need for why wider views involving community stakeholders, were necessary in design work. We illustrate these points using the case of the *No Silent Lunch*.

13 | SUPPORTING MULTIPLE EPISTEMOLOGIES

One group in Ms. S.'s class (five students, two girls and three boys, all African American) was intensely concerned about the issue of fairness related to the school-wide disciplinary practice of assigning “silent lunch” (isolated seating in the lunch room with no socialization allowed) to students. The group made two light-up posters called *No Silent Lunch*. They chose this silent lunch issue as their engineering design project, and as we discuss below, worked

to design light-up public posters meant to foster community dialog about whether or not students felt they had been punished fairly.

The group was drawn to this issue when discussing responses to an open-ended survey they administered as a part of integrating community ethnography (Tool 1) into engineering design, in an effort to incorporate community perspectives and help the community solve their own problems through engineering design (EfSC framework Principles 1 and 2). Here the youth noticed a pattern of responses related to unfair punishments, in particular, those punishments that affected all of the students. In referencing the survey responses, they called attention to this response, "I THINK (an important problem in school is) THAT WHEN MOST OF THE CLASS IS BEING PUNISHED AND YOU ALSO PUNISH THE OTHER GOOD STUDENTS." When unpacking this piece of data in whole class discussions, the conversation veered to silent lunch being the most universally meted out punitive measure in these blanket punishment situations. Students mimicked such a scenario, one of them role-playing a teacher pointing to a group of students, some of whom had been "talking when you should be working," as "you get silent lunch and you get silent lunch and you get silent lunch" (pointing at three different students in turn, who were next to one another).

The students expressed anger that silent lunch was often meted out to students who were innocent bystanders, who felt they did not deserve such a punishment. An example discussed involved students being seated in close proximity to the "kids getting into trouble" and teachers being too annoyed to find out students that were truly misbehaving. In addition, the students in the silent lunch group brought up what they had observed as "unfair targeting of Black kids" for receiving silent lunch, even for the smallest infractions, as one student explained, "Sometimes the teacher thinks you giving her a look when you are not and immediately you get silent lunch." This particular issue of silent lunch was discussed against the backdrop of other pertinent survey results, such as how 55% of the school population felt that "school was unfun" was a big problem, and how "low student morale" was a concern. When Ms. S visited with the group, she listened to their stories about who had experienced silent lunch as punishment, and for what reasons. She affirmed the students by sincerely engaging in conversation with them, at one point saying, "You really care about this. I did not know there was so much going on with the silent lunch. What are you going to do about it?" After further discussion, the group identified the need to create a safe space for a public conversation on the effectiveness of silent lunch as a deterrent to misbehavior, and whether it was being indiscriminately assigned. Using this idea as an initial design, the students decided they would make a light-up poster that could visually solicit attention to their concern and raise a sense of student solidarity around this issue to trigger a larger community dialog.

Using materials in the classroom, they worked with a large, foam-core poster board, adding two side panels. On this poster with two panels, the students built one hand-crank powered parallel circuit for each panel, to light-up five LED lights on each circuit, of specific colors. One side had green LED lights, the other red. They asked for their poster to be placed in the 6th grade hallway, so that students could use a hand crank to light up either red lights if they felt they had unjustly punished with a silent lunch, or green lights if they felt that they had justly been punished with a silent lunch. The group felt that this would provide a way for students to express how they felt about the issue visually, in public, and that materially gave their perception of justice versus injustice a voice that would attract attention in the school building.

Later, Tamira, a student in this group, decided to make an additional poster—on her own time—to complement the group poster. Her poster was bright and colorful, featuring LED lights as part of the artwork, as an attractive lure. The circuit was solar-powered, and the poster was meant to be taped to a hallway window (their 6th grade hallways were lined with windows), with the solar panel facing outward, on the back of the poster, toward the sun. Her poster invites public comment on silent lunches as a disciplinary measure with a small open cardboard 3 inches, deep, 4 inch by 8 inch box next to it that students could put a small slip of paper into with comments (see Figure 4b).

In the end, Ms. S was concerned that the "No Silent Lunch" posters, when publicly displayed as the student-engineers intended, would cause conflict among teachers and students. This led to her decision to not publicly display the posters in the hallways as the students had intended, but to post them in her classroom instead.

14 | NAVIGATING MULTIPLE EPISTEMOLOGIES AND TENSIONS

The No Silent Lunch group took on a community issue that challenged authority when they questioned the validity of silent lunch as a punishment, whether teacher practices were discriminatory towards who was punished with silent lunch, and why. Students were supported in identifying and leveraging upon this community concern through the integration of community ethnography into their engineering design work. Multiple, intersecting community-based epistemologies that were not usually sanctioned in the classroom (including punitive authoritarian practices at the class-community, school-community levels, and community-racial dynamics) were made visible and acknowledged in the classroom space, even when such dialog had not previously been a part of academic discourse in their classroom. Youth were able to talk about issues at their school they cared about as integral to science class discourse, such as the above example of the school-wide practice using silent lunch as a form of punishment. Youth discussed as relevant engineering-related data, their observations of which students, along racial and gendered lines, seemed to “get silent lunch more.”

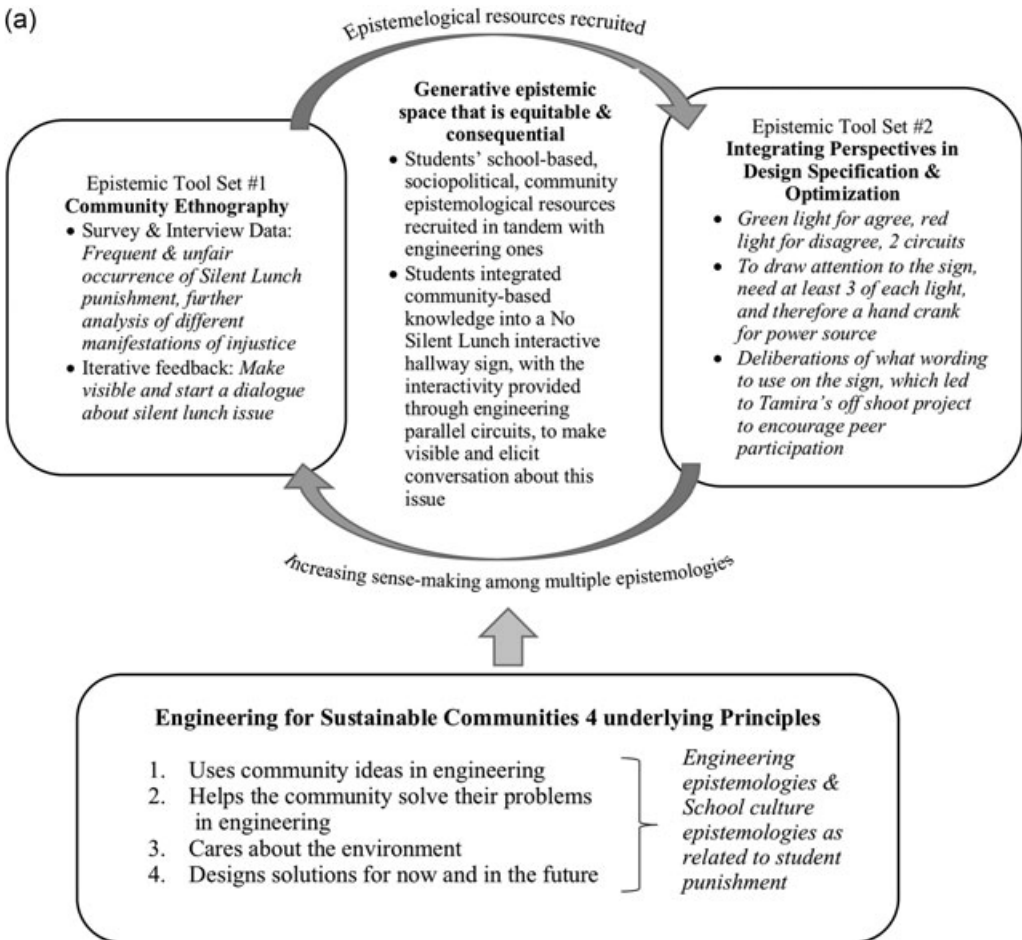


FIGURE 4 (a) Generative epistemic space for No Silent Lunch Project, (b) front of No Silent Lunch interactive poster, (c) front of Tamira's No Silent Lunch “lure” poster, (d) back of poster showing circuitry on side panels, (e) back of poster showing circuitry, (f) no Silent Lunch Comments box [Color figure can be viewed at wileyonlinelibrary.com]

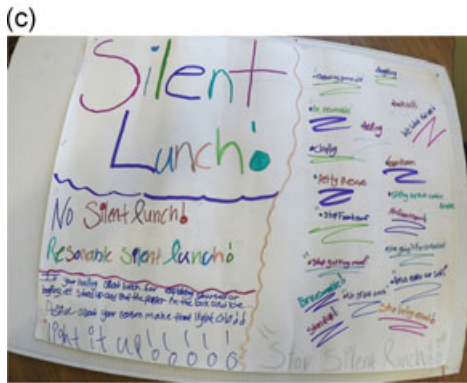
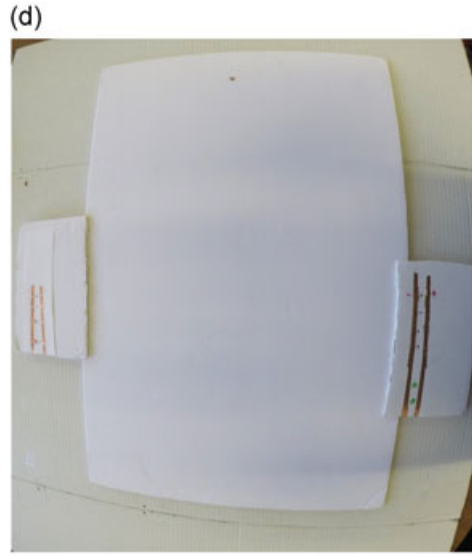
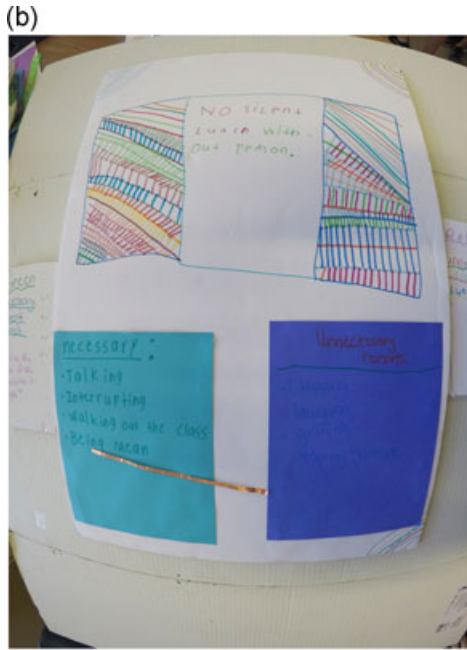


FIGURE 4 Continued

The EfSC tools made engineering epistemologies and community-based epistemologies explicitly visible as a part of the engineering design process (related to EfSC Principle 1 and 2: To use community ideas and help the community solve their problems through engineering), issues that students were not often able to talk about in the science classroom. Both posters took environmental concerns into account in the technical specification, by using renewable energy sources (related to EfSC Principle 3: Care for the environment). This was a function of Ms. S. consistently referring the students to the four EfSC principles, prominently displayed on a large poster. When using the design-cycle heuristic (Figure 2a, part of epistemic toolset #2), Ms. S. would remind students to connect the technical design elements to the four principles. When constructing their circuits each with four LED lights, students calculated the energy demands and tested which renewable energy source available was most reliable in powering the lights. 3 V coin-cell batteries were rejected on account of their short lifespans. The hand crank generator was subsequently selected over solar panels for its reliability and the poster's design feature—the red or green lights needed to be intentionally lit for the poster to serve its function. Tamira's other poster had two LED lights that powered with a solar panel because the solar panel would provide sufficient energy to keep the lights on her poster lit, serving its function as a “lure.”

It would appear, however, that though the EfSC epistemic tools helped the No Silent Lunch group consider multiple epistemologies in defining their problem space and possible prototype, the students were not more substantially supported in using the EfSC epistemic tools to wrestle with the tensions inherent in this issue of unwarranted silent lunch punishment as an injustice students experienced, and what could be created through EfSC to substantially trouble that school-wide practice. Although the project made visible and engineering-relevant, students' specific experiences with oppression and racism reflected in the classrooms at Sage Middle School, the functionality of their prototype put the onus on an aggrieved student to crank the red lights when s/he disagreed with a silent lunch punishment, without any guaranteed response that would be productive from school authority figures. Therefore, it is risky for students to use this prototype, especially when students were already in trouble with a silent lunch punishment. It is also unlikely for students to crank the green light in agreement to a silent lunch punishment. With Tamira's comment box, although less risky for students to use, the group did not consider how, and who, should respond to comments from students to further engage the collective school population in conversation. Although the intention of the group was to begin a conversation about student-perceived injustices, often along racial and gendered lines inherent in a punitive school-wide practice, how students would be positioned when interacting with this prototype, likely in ways that might further entrench them in unjust power dynamics, was not fully problematized by the group throughout the iterative design cycle. We summarize the interactions between multiple epistemologies and the design decisions the group took in Figure 4a below. Figure 4b–f illustrates the group's work.

Claim 2: EFSC epistemic toolsets support pivoting between multiple epistemologies

We noted that when epistemic tools were taken up in ways that supported pivoting of multiple epistemologies, new spaces for disrupting injustices in STEM learning and engagement were created. We purposefully use the term pivot to refer to Holland et al. (2001) notion of pivots as “mediating or symbolic devices” not just to “organize responses, but also to pivot or shift into the frame of a different world” (p. 132). From an equity standpoint this is important, given that the work of equity takes place as local practices push against and help to rewrite broader narratives, over spaces and time.

The idea of pivots conjures up imagery around the importance of new local practices grounded in the current world but oriented towards a new world, in the same way a basketball player might act—keeping one foot in place while holding the ball and moving the other foot one step to switch directionality. At the same time, it also draws attention to the pin or the point upon which something may turn. For pivots to work, both the object and the action are essential. To elaborate on these points, we draw upon the Light-Up Bingo Cage (Figure 5a,b).

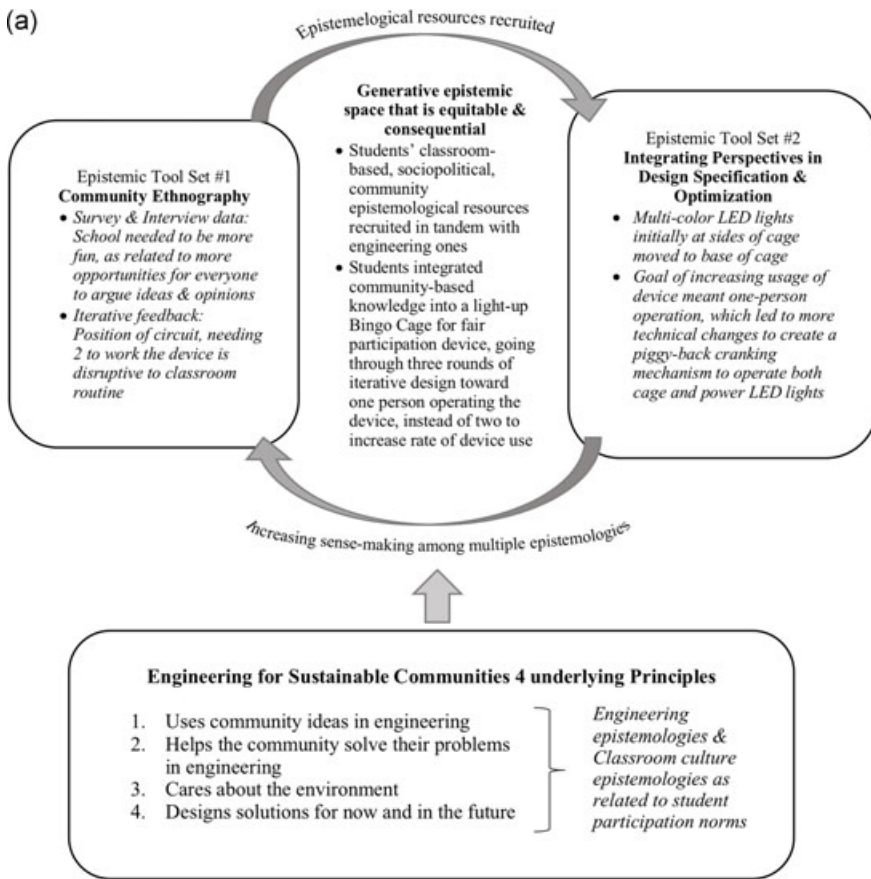


FIGURE 5 (a) Generative epistemic space for Light-Up Bingo Cage project, (b) Light-Up Bingo Cage for fair participation [Color figure can be viewed at wileyonlinelibrary.com]

15 | SUPPORTING MULTIPLE EPISTEMOLOGIES

The Light-Up Bingo Cage is an adaptation of an old family bingo game Paul brought in from home, which was engineered by a group of four students. They designed The Light-Up Bingo Cage in part in response to one of the most frequent survey findings the group noted in their analysis of their community survey—that school needed to be more fun. As the group sought to make sense of the quantitative trends, they also identified open-ended responses on the survey such as, “Equal opportunities for everyone,” “More opportunities to use more peoples' ideas,” and “More chances to argue ideas and opinions.” In class discussions, Paul noted that he was especially drawn to the idea because he said that “only three students held their hands up to participate in class discussions.” Paul conjectured that the Light-up Bingo Cage would help his class have more opportunities for everyone because “... with this, everyone has a chance to be called on, and everyone can be called on, so it is no longer, oh, I want to participate. It is more of, you have to answer because you have been called on.” He felt that he almost always held his hand up to participate in class, but he thought it would be good for the community because participation in classroom discussion was part of everyone's grade at his school, and this would help his classmates with their grades in the long run.

Student community epistemologies related to school-wide student participatory norms and grades were evident in this case. Paul also invoked classroom community epistemologies, when he noted how very few students would volunteer for participation, often the same few students. The intersection of these epistemologies inspired his bingo cage fair participation design. The Light-Up Bingo Cage would help the teacher, Ms. D., encourage all students to be part of discussions in the classroom with an equal opportunity to participate.

The group made their prototype using a class list printed out by Ms. D. of students' names, Paul's donated bingo cage, and other available materials in the classroom. They first planned on placing LED lights on cardboard disks on the two exterior sides of the spinning bingo cage. We could see part of their iterative engineering design process as the group worked on their prototype in a video taken by Ms. D. who wore a GoPro video camera during the lessons. In the video, Paul and Kaison stood side by side, behind their prototype silent, stunned, and frozen with incredulous expressions on their faces as they realized that their round-disc LED lighting circuit placement on the two sides of the spinning cylindrical bingo cage meant that the protruding LED lights were going to hit the supporting frame, thereby inhibit the cage from spinning. Ms. D., as she roamed the room giving encouragement and feedback to groups, had just pointed out this flaw in their design on their prototype they had been working on for almost two weeks. All this time, the group did not test how the decorative light-up parts of the design might interfere with operating the Bingo cage in selecting a participant (individual names on individual balls).

Throughout the prototyping process, Ms. D consistently referenced the EfSC principles poster and reminded students to check where they are in the design cycle process. She would address the students like so throughout the lessons—“Boys and girls, I want you to remember to look at the design cycle and really point out what kind of feedback you got, technical and social, we are looking at both, technical and social, that you are using to make your project even more awesome. Indicate, show us what you are changing because of the feedback you got.” After their initial design, each group presented the problem they were solving, informed by which particular pieces of the community survey data, and their proposed innovation. Peers then asked questions and offered feedback. In this way, the presenting groups had community support to improve their prototype through iterative design.

Staying after school, during tutoring time, Kaison, Paul and their group changed their design in response to feedback from Ms. D., by putting LED lights on a parallel copper tape circuit on blue cardstock at the base of the cage, instead of on the two circular sides of the cage. When the group achieved a functioning prototype, Ms. D. used the Light-Up Bingo Cage in class to encourage students to participate in class discussions who otherwise would not have been participating. She reported that Kaison and Paul would pop out of their seats when she called on them to spin the cage, one would crank a hand crank to light the base, the other would crank the cage, and in a fun game show atmosphere, the student to answer the teacher's question would be chosen from the cage. They would read the name attached to the chosen ball. In this way, one by one, all students in the classroom community could be given an equal opportunity to participate.

While pleased that Ms. D. was putting their innovation to use, Kaison and Paul considered how to further simplify the usage of the Light-Up Bingo Cage. They wanted to reduce the amount of effort required to use their innovation by “just using one crank” to turn the cage and light up the LEDs. They conjectured that their teacher would be inclined to use the Light-Up Bingo Cage more often if only one student volunteer was needed to operate it, reducing classroom disruption in the process, thereby leading to increased usage and more equal student participation in class.

Kaison enlisted the help of her father through conversation at home. She borrowed a hand crank to bring back to show her father, an electrician, to help her take it apart. She wanted to figure out how her group could use the parts to connect it directly to the basket crank and so “piggy-back” on the cranking mechanism. After more exploration and support from peers, Kaison and Paul succeeded in mounting the hand crank generator onto the cage crank, so that only one student need operate the device.

Paul and Kaison's group's engineering design process and product were informed not only by engineering epistemologies, but by multiple community epistemologies as well. These community epistemologies were school-based (the need for “equal participation for everyone” from school-wide survey), as well as contextualized in classroom-based epistemologies (Paul's knowledge and experiences in Ms. D.'s classroom, where only the same few students dominate classroom discussions), and home-based ones (Kaison's experiences at home learning with her electrician father). The students' focus on the social specifications for engineering design (e.g., how to design the innovation for maximum usage to address unequal participation problem, the attractiveness of the device) in addition to technical specifications (e.g., where to place the LED circuit, how to combine two cranks into one) were supported by Ms. D.'s constant referring to the EfSC principles poster hung on her board, as well as her reminders to consider the survey data and to use the EfSC Design cycle as a heuristic for the design process. The innovation prototype was sustainable (attending to EfSC Principle 4: design solutions for now and in the future) in that Ms. D. has continued to use the Light-Up Bingo Cage in her classroom after the unit.

16 | NAVIGATING MULTIPLE EPISTEMOLOGIES AND TENSIONS

The EfSC epistemic tools, with its combined focus on technical (attending to science/engineering epistemologies) and social elements (attending to community-based epistemologies) of engineering, supported students to pivot between the world as it is now and an idea of how the world should be. EfSC epistemic tools supported lessons coordinated with the school curriculum and social justice, provided that pivot upon which perspectives might turn. This EfSC pivot allowed the teachers and students to “swivel” their framing between what the issue is now and imagined possibilities through engineering, allowed them to “break the rules” and discuss troubling and sometimes controversial or racialized issues along with community ideas for engineering possible solutions.

In this way, the EfSC epistemic toolset supported students' recruitment of multiple epistemologies. Students were further supported in deeper sense-making of how these multiple epistemologies intersected and informed one another to surface plausible next-steps in the engineering design. Pivoting between and among different threads of epistemologies opened up new perspectives for how, and why design changes could be made toward the desettling of unjust school norms. These considerations, supported by pivoting between multiple epistemologies to first gain new perspectives with which to frame the problem space, in turn lead students to more nuanced deliberations of how, within the context of the specific problem space, these different epistemologies intersected, built on, or were in conflict with one another, further defining the problem space and possible engineering responses. Such an iterative design process of sitting with tensions, parsing out the “primary insights” from each relevant epistemological thread, led students to further consider design features such as how their prototype would be used, when it should be used, and what kinds of responses were sought for.

We see this pivoting and unpacking process in the Light-Up Bingo Cage case. To seek for more equal participation, the students worked continually to refine their design, moving toward the “improve” component of the EfSC Design cycle. The group also took into consideration technical elements of the engineering design that had to do with the environment by re-purposing an old game and by using a renewable energy source, a kinetic energy hand crank, as the source of electricity for the circuitry to light up the cage. As Paul initially described it, “We had balls with names on them. We had taped them on, and we had a hand crank. We had two cranks, and one of them was to spin the cage and the balls would come out, and the hand crank was to light up the bottom of it.”

They worked on getting the LED lights to work in a way that would not obstruct the cage-turning movement, and they also used a green energy source to power it. The prototype could have stopped at that point, requiring two students to use it, one to power the hand crank to light the lights, the other to turn the Bingo Cage lever to randomly select a student participant. But the students kept in mind their desired outcome –to make a prototype that would disrupt a certain classroom norm, that of unequal participation with Ms. D calling the same few students, while *not* disrupting other classroom norms (students are generally not allowed to get out of their seats and walk around the classroom during a lesson) that would diminish the usage of their innovation. With that tension, it was important to Kaison and Paul to make design changes so that only one person need operate the cage, with minimal disruption to the lesson, so that Ms. D would allow the cage to be used frequently. Ms. D has been consistently using the Bingo Cage in her classroom. She told us, “Yeah the Bingo Cage has been great! I call up a volunteer, sometimes Paul or Kaison who are ever ready to pop out of their seats to turn the thing and we pick a friend to answer the next question, it's been working very well.” We summarized interactions between multiple epistemologies and the design decisions the group took in Figure 5a. Figure 5b illustrates the group's work.

17 | CLAIM #3: EfSC EPISTEMIC TOOL SETS SUPPORT PRODUCTIVE DEVELOPMENT OF STUDENT ONTO-EPISTEMOLOGICAL FOUNDATIONS IN ENGINEERING

Through soliciting, valuing, and pivoting between multiple epistemologies during engineering learning experiences, students are supported in developing productive ontological leanings in engineering, thus facilitating students' onto-epistemological developments in concert, rather than in conflict, with each other (e.g., Van Horne & Bell, 2017). We noted that the concurrent development of expansive engineering and nature of engineering epistemologies, informed by varied and nuanced community-based epistemologies, supported students in taking up engineering for sustainable communities in ways that were both equitable and consequential, as we illustrate with the final case—the Portable Light-up Desk System.

18 | SUPPORTING MULTIPLE EPISTEMOLOGIES

The Portable Light-Up Desk System was June's second, solo project that she engineered during her 6th grade science engineering unit. While June was also part of a group of students who engineered a light-up candy dispensing machine in response to the survey findings that “school needs to be more fun” and needs to “celebrate more,” June herself was very drawn to other significant survey findings that indicated the low student morale in school and its heavy, punitive tone. Students often got into trouble for small infractions, such as “getting silent lunch for coming to class late.” At her middle school, students were allowed only a few minutes to transition from class to class. Teachers required that students have a pencil to participate in classwork and in June's Title 1 public school, there was insufficient funding to supply pencils to students on a regular basis, making pencils precious commodities. Teachers often took disciplinary measures when students arrived late to class, even if the reason

were to search out a lost, required pencil. When asked why she wanted to engineer a light-up desk as a second project, (even if it meant staying after school to work on it), June explained, "Kids in school keep many books and other things in their desk but have trouble finding stuff because our desk...cannot open...and you have to stretch your hands in to search for things deep inside, with no light to help you see. Sometimes kids get into trouble because they are taking too long to find their stuff. So I said, I HAVE to build a light-up desk."

Student community epistemologies related to punitive school regulatory practices inspired (attending to EfSC Principles 1 and 2) June's innovation design. Using the design cycle as a guide, June took into consideration both technical elements of her engineering (related to EfSC Principle 3: Cares for the Environment and 4: Designs solutions for now and in the future). June's prototype was designed to help students avoid punishment for arriving to class late if they had to search out a pencil in a preceding class. Pencils could be out of sight, deep in the dark desk cavity as students attempt to gather their belongings before transitioning to the next class.

Using available materials, June carefully measured two pieces of stiff cardboard that were exactly the length and breadth of the desk, with the correct "height" (thickness of the desk cavity), with a fold right at the "joint" of the desk so that the system could be quickly unfolded and fitted into the inside of the desk. Initially she used 3 V coin-cell batteries to test out her light-up desk system, to test that the bulbs and circuits worked. She tested red and blue lights for their brightness in the desk cavity and decided on white lights after gathering feedback from peers, who agreed that white lights were best "because they are the brightest."

Since June had four white LED lights, an essential technical feature, because "you need four white lights to see the whole of the inside of your desk at the same time," her system needed 13 volts of energy. Compared to the red and blue LED lights, the white ones required the most energy. June posed this energy-source problem to her classroom community during the "present prototype and gather community feedback" lesson, to her teacher and classmates. A classmate suggested that she just "stack like four batteries together" to provide the needed energy. Another reasoned that "the batteries die quickly then you need to keep changing." Ms. D. added that their school is under-resourced, so "we won't have an endless supply of batteries." While her classmates brought science and engineering-based epistemologies, Ms. D's advice was grounded in school-community epistemologies, related to funding and resources. June considered this feedback, and opined that batteries were an issue because they were costly and "bad for the environment." She also noted that for the Light-up Desk to work so kids could find items quickly, she could not be fiddling with "dead batteries and trying to find new ones" when time is of the essence to avoid punishment for being late to class because of locating a pencil.

On further discussion with classmates and Edna, June decided to test the hand crank as a green and sustainable energy source. Solar panels were considered but they did not work reliably to generate the needed voltage. June also thought the solar panels would make the lighting system cumbersome to use when her goal was for the system to be easily portable and "moved from my desk to (someone else') desk quickly so we could share." She was pleased with how easily and quickly all four white lights lit up. Using masking tape (easily removed for portability and no damage to the desk), she attached the hand crank to one of the desk legs. She explained her prototype as such, "My light-up desk system is portable and powered by a hand crank. If you want to move it to light another desk you just reach in and fold the "L" shape parallel circuit and take it out. The parallel circuits are on two hard pieces of cardstock that fit along the side and back of the desk."

Ensuring her light-up system was portable was another way June attended to the "lack of funding and resources" in the school. With a portable light-up system, "kids can share the system...you just fold it, take it out of one desk and fit it into another and do the hand crank... this way, you don't have to spend money on batteries, you just turn the hand-crank when you need to light up and see what is inside your desk." The principal, Mr. O., was very interested in June's light-up desk during the engineering unit showcase, when students presented their work. When asked which innovation left the deepest impression, Mr. O. said, "Without a doubt, the light-up desk. It is so smart, so simple, very elegant." After the engineering unit, June's Portable Light-Up Desk System was attached to a spare desk in Ms. D.'s classroom where students could fetch it for use when needed.

19 | NAVIGATING MULTIPLE EPISTEMOLOGIES AND TENSIONS

June's engineering design process and artifact were informed not only by science and engineering epistemologies, but by various school-community-based epistemologies. Specifically paying attention to both technical and social elements of the design process, as reflected in the EfSC epistemic tool (EfSC design cycle), supported June in navigating between these multiple epistemologies in productive ways. June was in Ms. D's classroom, who consistently referred the students to "check back with the EFSC poster, address both technical and social data," as explained in the previous case. The necessity of speed (student community-based epistemology), cost-saving (school community-based epistemology), green energy sources and environmental consciousness (both science and engineering epistemologies) intersected and informed one another to result in the final design of her light-up desk system prototype.

Pivoting within and between different epistemologies (as explained in Claim #2) fostered generative spaces for supporting inclusive and critical discourses of what it meant to learn and to become capable in engineering in culturally sustaining, and personally meaningful ways. Students' embodied, engineering experiences in these generative epistemic spaces worked to legitimize their development of critical, onto-epistemologies. With constructive critique, feedback and support from the community during the unit, June negotiated these tensions, informed by both engineering and community epistemologies, to refine her problem space and design features in a similar fashion as Kaison and Paul did with their Light-up Bingo Cage. June's idea and conception of her Light-up Desk system developed through the rounds of iterative feedback, when she engaged in dialog with her peers, teachers and university science educators who visited as part of the community feedback sessions. Her design changes from this iterative work led her to more intentionally address increased portability of her system (responding to lack of funds in the school, grounded in school-community epistemology) and energy efficiency with a hand crank versus a stack of 3V coin-cell batteries (a combination of school-community and engineering epistemologies). June was able to pivot between these multiple epistemologies, which helped suggest the "next-step" design consideration for her innovation.

June's engagement was transformative in both equitable and consequential ways. Individually, her decision to take on another solo project because of her deep concern about students' "being punished because you are late because you can't find your pencil" was supported by Ms. D., who enthusiastically encouraged her to "go for it, build your desk!" June was not at the epistemic center of the class usually, and Ms. D was thrilled that she wanted to take on a second engineering project. Collectively for her class, June's portable light-up desk system was put to use, to target the exact problem she intended it for. Her attention to its portability and green energy source ensured the longevity and "rate" of use of her prototype. Her innovation was able to desettle to a certain degree, the existing discipline norms in her school community among the 6th graders in her class.

June also saw herself as someone capable in engineering. In her post unit interview, she reflected on what her portable light-up desk system signaled to others about herself, and what her family's response would be: "I want them to think about me as a really smart girl, and for my product, I want them to think that it really works. (When I show my family this) my brother would be like, Oh I wish I could have done that...and my mum would be like, OHHH so that's what you were talking about! And then my stepdad would be like, cool."

As a further marker of her productive onto-epistemological foundations in engineering, June, when she was in the 7th grade, returned periodically to check on her Portable Light-Up Desk System and have since repaired the circuitry twice given the wear-and-tear of use. June also stayed after school to help Kaison and Paul figure out how to mount the hand crank onto the Bingo Cage, taking on the role of a community engineering expert. Figure 6a below summarizes the interactions between multiple epistemologies and the design decisions June undertook for her portable light-up desk system. Figure 6b shows how June's light-up system worked.

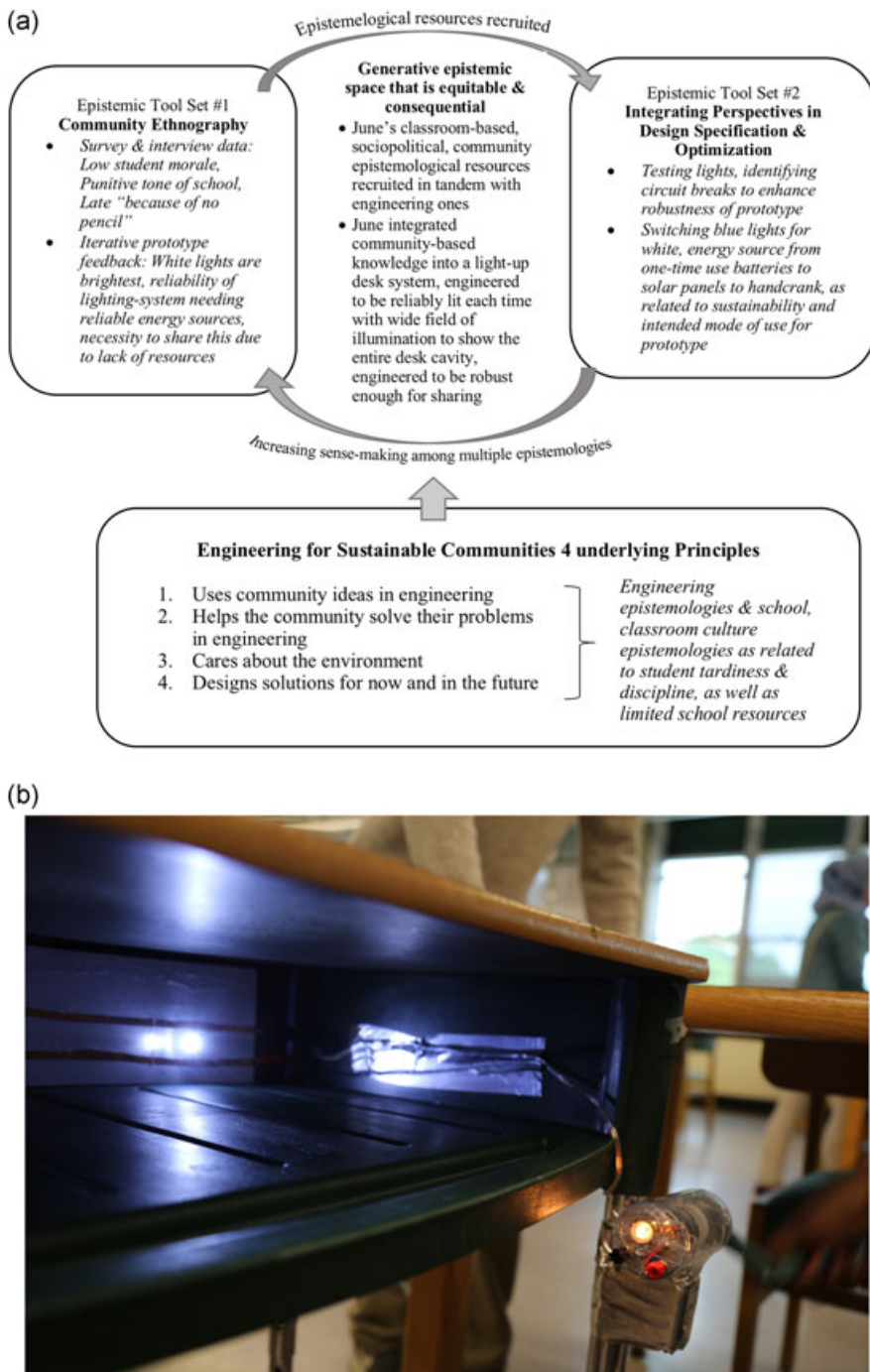


FIGURE 6 (a) Generative epistemic space for Light-Up Desk Project, (b) June's light-up desk system powered by hand crank [Color figure can be viewed at wileyonlinelibrary.com]

20 | DISCUSSION

In the findings above, we presented three exemplar case studies, each to illustrate a specific claim. We asserted that the EfSC epistemic tools sets, working in concert and in iterative fashion, generated a productive epistemic space that supported students in collaborative sense-making around epistemological questions that undergirded engineering and the nature of engineering. Such questions include: What is engineering? What do engineers do? What counts as engineering for sustainable communities? What kinds of data is relevant to engineering for sustainable communities, why are they relevant, and who gets to decide? These questions directly target students' developing understanding and increasing facility with engineering epistemologies—both pertaining to the nature of engineering (including what and *who*, engineering values), and what engineering knowledge and practices entail. It is the assemblage of discursive practices supported by the toolsets and the unfolding dialogic relationship between emerging practices and tools, that gave rise to a productive epistemic space. In other words, the “potential” of epistemic toolsets themselves were contingent on how they were taken up by teachers and students within the social dynamics of the school and classrooms.

Looking across all ten projects (Table 3), it is evident that students gained proficient mastery in standards-based engineering content knowledge and practices. Students developed robust engineering “knowledge and practice” epistemologies, reflected in their functioning prototypes, all of which utilized parallel circuits powered by renewable energy sources with at least two LED light outputs. Students further demonstrated robust discipline proficiency in their ability to explain the technical aspects of how their prototypes worked and the technical reasons behind particular design features. In the process, students displayed proficiency for the two engineering practices—defining a problem and designing a solution.

Student's epistemic gains in engineering and nature of engineering epistemologies developed in dialog with concurrent sense-making in relevant community epistemologies. The community engineering and ethnography epistemic toolset worked in concert with the iterative design epistemic toolset to continually ground each round of project feedback in both social (relating to community-based epistemologies) and technical (relating to engineering epistemologies) elements, necessitating a joint consideration of how the social informs the technical, and vice-versa. Such a mode of soliciting and navigating between multiple epistemologies, including moves of pivoting from a social angle to a technical angle, led to two equitable and consequential outcomes to students' engineering learning. First, the mobilities of ideas and resources that originated from students' lives outside of the formal science classroom were increased, when students were explicitly invited to solicit for these assets not typically legitimized in formal science settings. Second, such a mode of pivoting between technical and social angles in considering how data in one domain informs the other toward to the “border of breakdown” (Rheinberger, 1997, p. 135), necessitated “next steps” design ideas. The specific generative nature of this epistemic space supported students in progressively working out a range of ideas.

This generativity highlights three important, related points. First, students' deliberations of epistemological resources – such as survey data that indicated “school is unfun”—led them toward a more nuanced and more fully-formed understanding of community-based epistemologies in their school. Who thinks school is unfun and why does that matter? In what ways are school unfun and to whom? Who gets to decide if school is unfun is a legitimate community problem with sustainability implications? What can we engineer that could help address this problem? These deliberations are epistemological in nature, with students accruing increased expertise and nuanced understanding in community and engineering epistemologies, because they are considered together, as related and essential parts to a community engineering problem space. This is important from an equity standpoint. It is not enough for students to potentially see continuity between different epistemologies (e.g., Rosebery et al., 2010). Rather, to disrupt normative hierarchies, students needed to see and experience how such multiple epistemologies are foundational to productive engineering.

Second, because these multiple epistemologies drawn from students' experiences in different spaces were simultaneously and dialogically considered, the nature of this EfSC working process was onto-epistemological in

nature. It mattered who students were, and how that informed why they cared about particular issues in their EfSC problem definition and solution prototyping process. Similar to Barajas-López and Bang (2018), we view this as a process of supporting youth in seeing the value of themselves in their work while learning to use the tools of engineering to do so, rather than being marginalized by them. We see this process as productive in cultivating transformative views of epistemically rigorous design.

Third, students' increased understandings of these multiple epistemologies were neither uniform nor inert, but multifaceted and dynamic because of the presence of multiple voices. This point expands on Cunningham and Kelly's (2017) consideration regarding the social dimensions of epistemic engineering practices in critical ways. The elastic nature of students' developing epistemologies afforded a range of *directionalities* to their projects and allowed different angles with which students framed community-identified issues that engineering could solve. Community epistemologies related to such solicited data as "school is unfun" and "low student morale" were further pursued down different tributaries of related epistemological threads. These related, downstream epistemologies reflect more nuanced sense-making, at a finer grain-size, and collectively illustrated the complexity of community epistemologies anchored in lived experiences.

Across the ten projects described in Table 3, distinct epistemological threads related to "school is unfun" and "low student morale" were further delineated by students into: (a) The school's explicit emphasis on test-taking and overt celebration of grades. Students deemed such an environment as unsustainable to the well-being of students, inspiring a range of projects, including, (a) the Light-up Bingo Cage for fair participation (exemplar Case 2), (b) the light-up Happy Box where encouraging notes could be left for specific students, to be checked during morning announcements when test grades were being shared across the PA system, (c) the "Testing" light-up signage tacked on the classroom door, to reduce corridor noise distraction when tests were being taken by students inside the classroom, (d) the light-up "What's New" Board specifically tailored for English language learner classmate, to alert them to upcoming new content and, (e) the "Must Copy" assignment white board lighting system, to extend illumination time for student to write down what they are required to, before classroom lights are shut off to facilitate teacher's use of classroom presentation slides when teaching. These projects, all inspired from the data "school is unfun" and "low student morale" as problematic issues, were specialized in who they were intended to serve, including newcomer classmates who are emergent bilinguals, classmates who take more time to write down notes from the white board, classmates who face tumultuous home lives and need encouraging notes to help them stay positive in a stressful school environment. The specificity of these projects highlighted the distinct ways different students experienced local manifestations of these broadly defined problems gleaned from community ethnography data. The generative epistemic space provided by the two toolsets supported students in complex and layered onto-epistemological sense-making, resulting in a range of projects.

A second epistemological thread centered on the relationship between the punitive culture of school and student stress level. This thread led to projects such as (a) the portable Light-up Desk System (case study exemplar 3), (b) the Water Fountain Timer, to regulate individual students' time at the drinking fountain so no one hogs the fountain causing long wait-times, (c) the light-up No Silent Lunch interactive posters project to encourage community dialog on silent lunch as a punishment; and (d) the Light-up Hall Stop sign to more efficiently direct student traffic during class transitions. All these projects were targeted to address students receiving unfair punishments for small infractions, but why students were unfairly punished were due to a range of reasons, related to students' embodied experiences and relationships in community and made visible with the projects.

A third epistemological thread related the stressfulness of school and the low-morale of students to the state of student bathrooms at the school (Table 3). When analyzing data, students discussed the woeful state of the school bathrooms, citing the lack of privacy (e.g. too-short cubicle doors) and lack of cleanliness, as strong deterrents to the usage of the school lavatories, leading to significant student stress. In response, the "Pride Slide" project was engineered by three girls and consisted of a sliding panel, attached to the back of the girls' bathroom cubicle door that could extend the height of the door, for increased privacy. The panel was also decorated with a light-up empowering message for girls, powered by a solar panel. The "Good Marksmen" poster and solar-powered air

freshener project sought to address the lack of cleanliness in the boys' bathroom. Across the projects, salient epistemological threads emerged because of the increased mobilities of ideas and resources, leading to more equitable and consequential outcomes in 6th grade engineering.

While we intentionally integrated the codevelopment of engineering knowledge and practice epistemologies with the nature of engineering epistemologies and community-based epistemologies in the design of the EfSC epistemic toolsets, how they were deployed by teachers and taken up by students did not lead unidirectionally to pre-set outcomes but were instead fluid and flexible toward new imagined possibilities. The generativity of the epistemic space when data points intersected, converged or bifurcated pointed students towards new and up to the moment, unforeseen directions. The interactive nature of the EfSC epistemic toolsets etched connections between disciplinary epistemologies and community-based epistemologies, and in the ensuing stages of student prototyping, material traces of such multiple epistemologies informed were deposited in classrooms and school spaces as physical representations of EfSC engineering. These material representations also serve to act as continued symbols of students' epistemic agency (Stroupe et al., 2018) and the necessity of community-based epistemologies for future engineering experiences, toward more equitable and consequential learning outcomes.

The EfSC epistemic toolsets explicitly made visible and valid community issues salient to students' everyday lives at school and helped them pivot between community concerns (social elements) and needed engineering know-how (technical elements), which pushed students to dig deeper and pursue the necessary engineering practices to attend to community concerns.

Thus, the tools revealed the expansive ways in which students considered what equitable and consequential engineering entailed, the issues that mattered, to whom, and what they might engineer as a response to trouble these issues. Through such a process, the inherent epistemic nature of community cultural wealth (Yosso, 2005) is amplified.

However, the ends to which teachers and students took up these tools, related to addressing community issues and developing engineering expertise toward equity and consequentiality, remains uncertain. The degree to which students' engineering reflected how their project was equitable and consequential, fell along a continuum. To be clear, we make the argument that these EfSC projects that resulted were grounded in collectively identified justice-oriented issues, deeply contextualized to students' embodied experiences across school communities, and thus a distinct departure from benign engineering school tasks (such as exploring different bridge building approaches with popsicle sticks and weights, which can be very epistemically rigorous). Although the tools themselves could never be the "solution" for equitable and consequential engineering experiences and outcomes, they supported teachers and students in making visible what could matter in engineering, thus reshaping nature of engineering epistemologies expansively.

What the tools also made visible was the complex tensions inherent in engineering for sustainable communities process. This process not only valued multiple epistemologies, but also demanded the learning community to engage in epistemic work towards further delineating related epistemologies downstream, from what was revealed through the community survey tool. This critical analysis included figuring out how these related epistemologies bring new, sometimes conflicting insights, and how all these threads of epistemologies needed to be understood in relation to one another and finally brought to bear on the engineering design.

We saw this tension particularly clearly with the No Silent Lunch interactive posters. The political dimension residing within these particular community epistemologies –school is stressful, school is punitive, silent lunch is unfairly meted out especially to African American students—presented a dangerous terrain on which to take next steps, for both students and Ms. S. What is equitable and consequential in this project is that the students learned and developed robust engineering knowledge and practice epistemologies to meet the content standards expectations in hands-on ways, thereby positioning them as competent and smart in the engineering unit. Equally equitable and consequential is the revelation of a punitive school practice that deeply troubled students generally and a particular group of students specifically. Ms. S. was surprised at how intensely students struggled with silent lunch. As an authority figure, Ms. S. being made aware of this problem was an important step toward redressing this

injustice. However, due to the vastly unequal power held across the range of authority figures (including school teachers and administrators) in this possibly inequitable, racialized and controversial issue, the political school system proved a formidable obstacle for the No Silent Lunch posters to fulfill their intended goals, as imagined by the student engineers. These tensions remained unresolved after the engineering unit was over.

21 | CONCLUSION

To work toward equitable and consequential engineering learning experiences for all students, soliciting for multiple epistemologies and learning how to pivot between and among them, is crucial. Such pivoting can be productive towards students' codevelopment of not only engineering knowledges and practice, and nature of engineering epistemologies, but also support productive ontological developments in engineering given the explicit salience of the community issues undergirding their engineering experiences. The EfSC epistemic tools presented in this study allowed, to varying degrees, such pivoting, with a range of outcomes. Despite the tensions that would inevitably arise and that may remain unresolved, we believe that valuing multiple, even conflicting epistemologies, and learning how to pivot between them to more deeply inform students' engineering experiences, is a productive, equitable way forward in K-12 engineering.

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