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Engineering Education as the Development of Critical Sociotechnical Literacy

Veronica Cassone McGowan[1] · Philip Bell[2]

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Abstract
Recent policy documents position engineering as a way to broaden participation for students in STEM fields. However, a recent review of the literature on engineering education found that fewer than 1% of reviewed articles focused on issues of equity and broadening participation. For this reason, there are few frameworks to build on when designing for equitable engineering instruction in K-12 settings. Diversifying participation in engineering means that we need to not just bring learners into existing engineering practices, structures, and ways of knowing, but that we take a critical look at the field of engineering education and challenge researchers and educators to create learning opportunities that build on diverse ways of knowing about engineering and being engineers in the world, with a focus on relating course materials to learners' everyday lives. In this paper, we leverage the diverse histories, epistemologies, and ways of knowing in engineering to outline the possibilities for learners to critically engage with engineering in K-12 settings and we ask the question, "How can we design learning environments to help students critically understand the intrinsic and systemic sociotechnical relationships between people, communities, and the built environment?" To answer this question, we propose an instructional framework for developing learners' critical sociotechnical literacy, which is a place-based approach for critically engaging learners in understanding the impacts of engineering and technology on their own communities and everyday lives in order to restory these spaces for a more equitable and just future.

✉ Veronica Cassone McGowan
vmcgowan@uw.edu

Philip Bell
pbell@uw.edu

[1] School of Educational Studies, University of Washington Bothell, Bothell, WA, USA

[2] College of Education, University of Washington, Seattle, WA, USA

1 Introduction

Recent policy documents position engineering as a way to broaden participation for students in STEM fields, noting that engineering gives students the opportunity to deepen their science knowledge by engaging them in problem-solving practices around locally relevant issues (National Research Council. Committee on a Conceptual Framework for New K-12 Science Education Standards 2012; NGSS Lead States 2013). However, a recent review of the literature on engineering education found that fewer than 1% of reviewed articles focused on issues of equity and broadening participation, noting that "starkly limited was research on diversity and inclusion with respect to engineering" (Hynes et al. 2017, p. 460). Existing engineering curricula tend to engage learners in highly structured, recipe-like building activities that often foreground science content knowledge as a way to connect engineering design pursuits to classroom learning goals (Chabalengula et al. 2017; NAE 2009; Roth et al. 2001). This approach to engineering draws narrow boundaries around the types of knowledge and practices that students can use during engineering activities, and is out of sync with the transdisciplinary and synthetic nature of professional engineering design (Adams et al. 2011a; Cunningham and Kelly 2017; Duderstadt 2010; Sheppard et al. 2009). For this reason, there are few frameworks to build on when designing for equity and justice-centered engineering instruction. The inclusion of engineering as part of the *Next Generation Science Standards* (NGSS Lead States 2013) opens the opportunity for more students to engage with engineering learning in the classroom. It invites research and design work that guides equitable approaches to engineering learning that build on students' everyday knowledge, interests, and identities, and encourages learners to use engineering practices to critique the impacts of the designed world on their own lives and communities, and to leverage their learning for constructing a more just and equitable future.

Restrictive models of learning that limit what counts as engineering knowledge further marginalize learners that have been historically underrepresented in STEM disciplines and tends to reify cultural assumptions about engineering as a field (Claris and Riley 2012). For example, while research on equitable approaches to K-12 engineering is limited (Chabalengula et al. 2017; Hynes et al. 2017), similar research from the learning sciences and math and science education offer insights for what these models of instruction should look in a classroom setting. Equitable learning builds on learner's everyday and lived experiences (Gutiérrez 2008; Nasir and Hand 2006; NRC 2012; Rosebery et al. 2010). As learners move through a variety of contexts throughout their lives, they bring diverse practices, knowledge, and experiences to the classroom that serve as foundation for personally consequential learning (Nasir et al. 2006; Riley 2008; Roth et al. 2001; Vossoughi and Bevan 2014). Formal instruction designed to empower learners places experiential knowledge at the center of learning (Yosso 2005). This expansive view of knowledge creates horizontal learning opportunities for students to bring diverse ways of knowing to the classroom (Gutiérrez 2008), and also engages learners in critical conversations and reflections about the role that engineering, technology, and science have played in their own communities and lives (McGowan 2018).

Engineering has historically taken a deficit stance toward minoritized learners (Smith and Lucena 2016), and neoliberal discourses in favor of broadening STEM participation advocate for assimilation models of instruction that bring learners into existing and inequitable visions of engineering, rather than supporting learners' agency and action in their own communities (Claris and Riley 2012; Lucena 2005; Philip and Azevedo 2017; Riley 2003). Public narratives for recruiting new engineers from diverse backgrounds tend to focus on individual benefits (i.e., salary and career options) and national economic growth and security (i.e., patriotism and public service) (Lucena 2005). This privileges the owners and operators of STEM enterprises, rather than empowering individuals and communities historically underrepresented in these fields (Basile and Lopez 2015). Diversifying participation in engineering means that we need to not just bring learners into existing engineering practices, structures, and ways of knowing (as defined by the exposure and access notions of equity), but that we take a critical look at the field of engineering education and challenge researchers and educators to create learning opportunities that build on diverse ways of knowing about engineering and being engineers in the world, with a focus on relating course materials to students' everyday lives (Claris and Riley 2012; Kelly et al. 2017; Riley 2003).

In this paper, we leverage the diverse histories, epistemologies, and ways of knowing in engineering to outline the possibilities for learners to critically engage with engineering in K-12 settings, and we ask the question, *How can we design learning environments to help students critically understand the intrinsic and systemic sociotechnical relationship between people, communities, and the built environment?* In order to answer this question, we first surface the diverse histories and epistemologies of engineering and argue that its origins in craft and trade provide a pathway for engaging learners in authentic engineering design in nondisciplinary and transdisciplinary contexts. Second, we describe a set of five principle elements of engineering found in professional contexts that relate to designing instructional models that build on learners' everyday and experiential knowledge. Last, we describe an instructional framework for developing learners' *critical sociotechnical literacy*, which is a place-based approach for critically engaging learners in understanding the impacts of engineering and technology on their own communities and everyday lives in order to restory these spaces for a more equitable and just future. In this work, we hope to advance a critique of the ways K-12 engineering education may limit or expand the possibilities for broadening participation and addressing equity, particularly given the history of engineering in formal educational contexts, and to present a framework for designing equitable engineering experiences that addresses this critique.

2 Images of Engineering Through History

In this section of our paper, we briefly review the history of engineering to surface which aspects can be leveraged to expand the development of critical design capacities and design more equitable learning environments in K-12 settings, as well as to surface the historical narratives that continue to limit participation in engineering, particularly for individuals and communities underrepresented in STEM fields. Historically, engineering is rooted in arts and crafts trades such as masonry and building (Crismond 2001; Lawson 1997; Razzouk and Shute 2012; Rowe 1987; Stokes 1997; Vincenti 1990) and dates back to humans' earliest efforts to alter their space to meet desired esthetic, safety, structural, and nutritional needs (Lawson 1997; Stokes 1997; Vincenti 1990). The enlightenment, industrialization, and World War II all marked multiple bottlenecks, where engineering became more narrowly defined, and engineering roles became separated between builders, who used tacit and everyday knowledge to perform their work, and designers, who followed formal disciplinary learning pathways and translated disciplinary knowledge and their designs to builders (Pawley 2009; Riley 2008; Schön 1983; Stokes 1997; Vincenti 1990). This separation of expertise was superficial at best, as builders continued to engage in iterative cycles of designing solutions as they engaged in their everyday work, but the assumptions about the differences between builders and designers became deeply embedded in how our broader culture views engineering work and formal educational pathways. These divisions are clearly described by the Accreditation Board for Engineering and Technology's (ABET) guidelines for educational programs in engineering vs engineering technology:

"Engineering programs often focus on theory and conceptual design, while engineering technology programs usually focus on application and implementation. Engineering programs typically require additional, higher-level mathematics, including multiple semesters of calculus and calculus-based theoretical science courses, while engineering technology programs typically focus on algebra, trigonometry, applied calculus, and other courses that are more practical than theoretical in nature." (ABET Engineering Accreditation Commission 2005)

Although these divisions exist at programmatic levels, in reality, engineers and technicians work together at the intersection of theory and practice, as both spheres of work inform each other. In learning contexts, these divisions become problematic as students branch into divergent professional trajectories that correspond with power, income, and long-term job security. Research on engineering careers suggests that theory is only relevant in some professional and problem-solving contexts (Jonassen et al. 2006) yet becomes a barrier to participation in professional engineering fields and trajectories. These distinctions become distilled in K-12 settings where students are asked to make course decisions that impact long-term professional trajectories.

Divisions between technical and disciplinary career pathways exist because of historic efforts to integrate engineering into traditional university disciplinary structures (Tadmor 2006). The rise of western universities and modern disciplines during the Enlightenment and Scientific Revolution positioned science as a separate and superior discipline to applied design trades, and this division was wrought with embedded cultural assumptions about intelligence, class, and working with one's hands (Pawley 2009; Riley 2008; Schön 1983; Stokes 1997; Vincenti 1990). The construction of science knowledge became formalized in institutions and associated with privilege, while engineering knowledge remained situated in apprenticeship models of learning and military training schools and what eventually became trade schools (Lewis 2006; Pawley 2009; Razzouk and Shute 2012; Riley 2008). In addition, the conception of engineering as an applied science emerged from these historical and hierarchical understandings of knowledge construction that became further engrained with positivism in the late nineteenth and early twentieth centuries (Schön 1983; Stokes 1997; Vincenti 1990). Within the framework of positivism, disciplines became distinguished between major and minor studies. Major professions included the sciences and classics that had stable and generalizable knowledge bases, and minor professions were flexible, changing, and situated in nature (Schön 1983). Applied fields of study, such as engineering, education, and other social sciences, fell into the minor category and became subordinate to the "facts" of science and philosophy. From this positivist perspective, technical knowledge preceded application (Schön 1983), and early conceptions of engineering and design positioned decontextualized content knowledge and scientific theories before the doing of design work.

Translational research-to-practice models of learning emerged from this paradigm and still dominate applied science fields today, including engineering, medicine, and teaching (Schön 1983; Tadmor 2006; Woolf 2008). The positioning of engineering as an applied science has implications for how and when learners are able to engage in engineering-related pursuits in K-12 settings, as it implies that students need to develop a considerable depth and breadth of science knowledge in order to solve engineering problems. This is why prior to the adoption of the Next Generation Science Standards (NGSS Lead States 2013), fewer than 10% of learners participated in formal engineering learning in K-12 settings, and most engineering was situated in upper high school science classes, such as Physics (NAE 2009). Bringing engineering instruction to younger students requires a broadening of what counts as engineering knowledge, so that it is accessible to all students regardless of their science content background knowledge and age.

Emphasis on theory also centralized the role of science and math in engineering programs in higher education. This became magnified by the post-Sputnik science revolution, which researchers argued defined engineering education throughout the second half of the twentieth century (Lucena 2005; Schön 1992; Tadmor 2006). In the May 1971 issue of *Science Magazine*, Joel Cohen wrote, "Physics-envy is the curse of biology." The same can be said for engineering, and the "physics-ification" of engineering after World War II has had lasting impacts on approaches to engineering education, as well as public perceptions about what engineers do and what they are required to know. The public visibility and success of government-funded physics projects during World War II and the Soviet's launch of Sputnik led to the integration of physics in a number of institutional contexts including K-12 science classrooms, undergraduate engineering instruction, and engineering professions in general (Crismond 2001; NAE 2009; Stokes 1997). The emphasis of math and physics in engineering instruction continues today, even though research on engineering expertise suggests that engineers do much less math in their professional work than their training would suggest (Jonassen et al. 2006). This is particularly true in fields where computational tools and programs have automated rote mathematical practices. This suggests that there is a disconnect between engineering instruction and what engineers do in the field, and a lack of awareness of how these practices have changed over time (Duderstadt 2010; Jonassen et al. 2006; NAE 2009).

Further, most engineering faculty hold doctorates in math and science so engineering epistemologies often get positioned out of engineering classrooms in favor of math and science frameworks; this is one of several reasons why generalizable theories over practical knowledge and experiential learning became the focus of twentieth century engineering programs, and remains the focus to this day (Duderstadt 2010; Tadmor 2006). This disconnect between the learning of engineering and the doing of engineering was the driving force behind the recent restructuring of engineering courses in higher education settings toward more experiential studio-based learning (Claris and Riley 2012; Jonassen et al. 2006; Tadmor 2006). In contrast, K-12 engineering education has remained largely framed and constrained by post-WWII aims of instruction (Sullivan 2006). Despite rapid advances in technology and its deeper integration into everyday life, researchers note that little has changed in K-12 engineering education in the past 30 years, and that the public remains largely "unaware of the role of engineers in medical advances, in alleviating human suffering, or even in creating the iPod that puts 10,000 tunes at our fingertips" (Sullivan 2006, p. 18).

Foregrounding science and math content knowledge out of the context of doing design is deeply rooted in schooling and historical notions of major disciplines (Schön 1983). In Schön's words, "the normative idea of curriculum places general principles and methods before skills and application," and Schön argued that these content-first models reflect a positivist epistemology of practice that conflicts with design-based ways of constructing knowledge through action. While universities and agencies thought they were increasing the rigor of engineering by foregrounding instruction in physics, math, and other science disciplines, by the 1970s, engineering employers began to complain that recent graduates "couldn't do anything" in professional contexts and lacked the experience, creativity, and communication skills that were necessary for successful design, and that students need to be provided with hands-on and practical experiences to successfully prepare them for professional engineering work (Crismond 2001; Razzouk and Shute 2012; Tadmor 2006). Since that time, some engineering schools have begun to reintegrate hands-on engineering practices and vocational models of instruction into their undergraduate programs through design-based pedagogies that diversify traditional classroom participant structures (Crismond 2001; Litzinger et al. 2011). However, in K-12 contests, studio-based design instruction is often relegated to informal and opt-in learning spaces and is largely absent from engineering curriculum and instruction that takes place in the classroom.

In addition to the emergence of engineering from craft and trade-based fields, engineering also has deep roots in military history that continue to shape contemporary narratives around who gets to be an engineer and what types of problems are addressed through engineering. The historical connection of engineering and military pursuits predates the enlightenment with military training institutions as the primary supporters of engineering education (NAE 2009; Pawley 2009; Riley 2008; Schön 1983; Stokes 1997; Vincenti 1990). The division of civil engineering is a lexical symbol of the reality that most engineering is for state rather than civic purposes. Even today, over 75% of university graduates in engineering go on to work for military-affiliated agencies and corporations (NAE 2009), which shapes how students are prepared at the undergraduate and graduate levels, and shapes notions of engineering for reifying historical norms rather than for restorying possible and more equitable futures (Pawley 2009; Riley 2008). For example, in *Engineering for Social Justice*, Riley (2008) argued that the militaristic foundations of engineering impose hierarchical, top-down design processes that devalue creativity, intuition, and exploration during the design process. Riley argued that this produces conservative design processes that perpetuate the status quo and often advance the needs of those in power over the collective good (Pawley 2009).

The associations between the military and engineering colleges have also had major impacts on how engineering is portrayed as a profession to the public and prospective students. Prior to World War II, engineering was still considered a trade profession and recruiting college-bound undergraduates to engineering schools proved difficult as undergraduates were more inclined to pursue degrees in the Arts and Sciences, which were historically more prestigious. In response to this lack of interest, engineering programs constructed public narratives aimed at recruiting young men from this era into the field. Narratives of military service, masculinity, technical triumph over nature, and working in extreme environments successfully recruited undergraduates to emerging engineering programs (Pawley 2009; Riley 2008; Stokes 1997). These narratives persist in engineering today and may be responsible for the low recruitment and retention of women and individuals from nondominant groups (Bardzell and Bardzell 2013; Nieusma and Riley 2010; Pawley 2009; Razzouk and Shute 2012; Riley 2008). Additionally, these narratives perpetuate dualistic notions of technology as separate from natural systems and limit the future possibilities for engineering to be used for ecological renewal and for recognizing the universality of engineering in our natural world as a set of practices used by humans as well as nonhuman species (McGowan 2018).

As higher education programs in engineering are trying to integrate more authentic design practices into their instructional models, K-12 engineering education continues to perpetuate the limited, hierarchical, and analytical notions of engineering described above. The narratives used to recruit young, male engineers into engineering in the past, today exclude women and other individuals from nondominant groups from identifying as engineers and participating in engineering learning and professional pathways (Capobianco et al. 2011, 2015; Nieusma and Riley 2010; Pawley 2012; Riley 2008). Further, the physics-ification of engineering and rigid, top-down design models position engineering as subordinate to science learning, which has three implications for K-12 settings. First, it devalues the intuitive and creative aspects of design thinking, which positions out students who are drawn to more creative fields and displaces everyday knowledge from the design process. Second, it induces anxiety around teaching engineering for elementary school teachers and teachers with less training in math and physics, making them less likely to integrate relevant aspects of engineering into their instruction (Boesdorfer and Greenhalgh 2014; Capobianco et al. 2011). And third, it restricts the degree to which students engage in authentic engineering endeavors until they have completed advanced science and math courses, and withholds these opportunities from students who do not pursue these courses (NAE 2009). Reframing engineering learning as synthetic and emergent has the potential to situate engineering in more K-12 learning contexts, including elementary and nonscience classrooms. Further, surfacing the distributed nature of engineering design knowledge eases pressure on teachers who have less experience and confidence teaching engineering, and allows students to be positioned as emerging experts in the classroom, through the course of engineering design work. Critical approaches to engineering teaching and learning will require K-12 settings to highlight emerging engineering fields and to center engineering and engineered artifacts within larger sociotechnical systems. For example, critical approaches to engineering might ask learners to think about how infrastructure projects have impacted and continue to impact the health and safety of their and other's communities, and how policies such as "eminent domain" shift power and agency regarding development decisions from individuals and communities to government agencies. Similarly, critical approaches to engineering may invite learners to think about what sociotechnical structures limit their own agency and decision-making in everyday life, such as the availability of public transportation to reduce fossil fuel consumption and transportation expenses.

In *Towards an Epistemology of Engineering*, Figueiredo (2008) proposed a framework of four epistemic dimensions of engineering knowledge that include social science, basic science, design-based practices, and real-world applications, which intersect and intertwine in ways that make engineering a transdisciplinary field when practices are situated within a problem-solving context. This vision of engineering as a transdisciplinary field (Adams et al. 2011a; Gibbons et al. 1994; Figueiredo 2008; Yu and Strobel 2012) contrasts the dichotomous images of engineering in K-12 settings. It also provides a framework for how we can build more inclusive and equitable engineering learning environments that enable learners to draw on a wide range of knowledge to solve novel engineering design problems in the classroom that are more representative of professional engineering practices. Recent research has argued that the disparity between engineering education's notion of epistemic practices and professional accounts of what engineers do is responsible for students disidentifying with engineering as a potential career pathway (Cunningham and Kelly 2017). In order to connect student to the opportunities inherent within diverse engineering professions, Cunningham and Kelly (2017) outlined core engineering practices to guide authentic classroom engineering instruction. These practices build on Figueiredo's framework using language that is more accessible to both teachers and students by describing engineering practices within the following four categories: engineering in social contexts, use of data and evidence to make decisions, tools and strategies for problem solving, and finding solutions through creativity and innovation. Significant in each of these frameworks is the socially situated nature of engineering design work that invites learners' critical engagement with engineering problem solving and invites students to critique the impacts of designed artifacts in their own lives and communities.

The history and epistemologies of engineering offer both opportunities and challenges as we try to design more equitable engineering learning environments that support a vision of engineering that is inclusive and empowering to learners and invites learners to use engineering to solve personally-consequential sociotechnical challenges in their own lives and communities. K-12 settings are already moving beyond the narrative of engineering as an applied science but continue to support narrow framings of engineering as a profession or disciplinary course of study. In contrast, research suggests that students are more likely to identify as engineers and with engineering when engineering is shared as a set of practices that move across settings and over time rather than as a fixed field in a distant future (McGowan 2018). In particular, leveraging synthetic, transdisciplinary, and learning-by-doing models of engineering similar to early craft and trade-based foundations in the field provides authentic examples of engineering that we can use to design more inclusive instruction today. In this sense, we argue that equitable models of engineering are not simply designed to give students more access to engineering opportunities at earlier ages, but about re-envisioning engineering as a situated set of practices that depend on diverse types of knowledge to solve novel problems both in and outside of K-12 settings.

3 Principle Elements of the Enterprise of Engineering for Equitable K-12 Engineering Instruction

In professional contexts, the term *heterogeneous engineering* describes the integral role that diverse types of knowledge, including tacit knowledge and lived experience, play in designing and situating engineering design solutions in particular contexts (Adams et al. 2011b; Suchman 2000). However, in K-12 settings, diverse approaches to problem solving become constrained by the narrow educational goals and recipe-like structures of many engineering design projects (Roth et al. 2001). Although research on equity-oriented instruction describes the social, cultural, and historic aspects of STEM learning (Bang et al. 2010, 2012; Calabrese Barton et al. 2008; Nasir and Hand 2006; Nasir et al. 2006), attrition in engineering is most often described as a "leaky pipeline" model of students leaving STEM fields as coursework becomes more challenging, or a "chilly climate" that is unwelcoming and unresponsive to individuals from historically underrepresented communities (Riley 2008). These models place responsibility on the individual to adapt to traditional engineering learning structures and equate equity with access. The continued focus in the engineering education community on access as the main form of equity is disconnected from the breadth of similar research from science education that recognizes the need to ground instruction in students' everyday experiences and community knowledge as foundations for equitable learning (Aikenhead and Jegede 1999; Bell et al. 2012; Brown et al. 1989; Greeno and Engeström 2014; Penuel 2014; Zimmerman and Bell 2012).

Equitable models of engineering instruction would invite learners to build on their own interests and identities to broaden what counts as engineering and who gets to be an engineer. Qualitative studies of professional engineers are challenging historic and translational models of engineering as an applied science by providing thick descriptions and long-term observations of engineers' professional practices in and across contexts (Bucciarelli 1994; Cross 2000, 2011; Koretsky et al. 2014; Razzouk and Shute 2012; Schön 1983; Stokes 1997; Suchman 2000; Vincenti 1990). It is from these studies that accounts of design thinking and methodologies have surfaced. In a review of research on design thinking, Razzouk and Shute (2012) described design thinking as a nonlinear process that uses synthesis of everyday knowledge, prior experience, and precedent (as opposed to theoretical abstractions) to address real-world, practical problems. The practical and material nature of designed artifacts means that design thinking practices become embodied in the people and places in which they are created (Adams et al. 2011b; Suchman 2000). As an embodied practice, engineering ideas take form in artifacts in ways that are performative and invite users to leverage these artifacts as examples for learning through observation, consumption, and critique. However, the materiality of engineered artifacts also means that they serve as models that perpetuate the cultural and historic patterns that are valued within the field itself. Without engaging learners in critically examining what values and power structures are embodied in designed artifacts, these ideas become taken up and reified over time. For this reason, equitable approaches to engineering instruction require that students engage in multiple dimensions of engineering learning that include "reading" the designed world to understand the history and values embodied in artifact, as well as having access to the practices and pathways for imagining and redesigning future possibilities. In this next section, we propose five principle elements of the enterprise of engineering that can be used to ground equitable approaches to engineering education by broadening what types of knowledge are recognized as essential to using engineering to solve situated engineering design problems and relate them to tensions in existing K-12 engineering instruction. Later, in the final section of our paper, we leverage these principle elements to build our framework for developing learners' critical sociotechnical literacy to understand the social, cultural, and historical contexts of engineering and engineered artifacts on people and communities in ways that allow for new models of engineering to emerge.

3.1 Engineering Is Situated and Place-Based

Engineering solutions are designed for context using available knowledge and resources and are therefore situated in nature (Cross 2000, 2011; NAE 2009). There are tensions between the situated nature of engineering and the fact that engineering curricula are designed for scale rather than context. Classroom engineering projects are often decontextualized from the people and places involved in the iterative problem-solving process. For example, in classroom settings, engineering problems are often predefined and the criteria and constraints are already outlined for students (Jonassen et al. 2006). This overstructuring of the engineering design problem anonymizes the role that people play using engineering methods to solve problems. It creates engineered artifacts that are separate from their creators, and perpetuates historic notions of designers making the design decision and builders following construction guidelines (Riley 2008). However, place-based pedagogies can guide local adaptations of engineering curriculum in K-12 settings to locate engineered solutions within their own communities and reposition people at the center of the engineering problem-solving process. Place-based pedagogies engage learners in exploring the cultural knowledge, ecosystem resources, and opportunities within their own lives and often engage learners in participatory design work to take action in their own communities (Bang and Vossoughi 2016).

3.2 Engineering Knowledge Is Embodied and Distributed and Therefore Performative

The designed world serves as a template for learning, as engineering knowledge is embodied in the people, places, artifacts, and participatory structures of everyday life (Hutchins 1995; Suchman 2000). In this sense, engineering knowledge is available and accessible to students across settings through its performative nature (Pickering 1995; Suchman et al. 1999). The performative aspects of design and construction of objects in the world allow individuals to engage in a relationship with them and the knowledge embodied by their construction, which Fenwick and Edwards (2013) described as a "performative ontology" inherent in design-based work. Therefore, engineering artifacts are models for disciplinary learning through precedent; by looking at the design world, we can physically see many design solutions as they are written into artifact form and can leverage these performative design solutions in our own work.

Engineering knowledge is not only embodied and visible in the world, but also in the people involved in the engineering problem-solving process and related artifacts (Papert 1980; Bell and Winn 2000; Hall and Stevens 1994; Jonassen et al. 2006; Penuel 2014; Suchman 2000). This aspect of design surfaces the need to broaden perspectives of engineering education to include more social, cultural, and historical dimensions of learning (Gutiérrez and Rogoff 2003; Lave and Wenger 1991). Situating engineering learning within these contexts would surface the ways in which engineering knowledge is embodied in communities of practice and the material resources and historical patterns of construction rooted in places.

3.3 Engineering Is Synthetic

Braha and Maimon (1997) argued that synthesis is at the core of design thinking. Through synthesis, designers leverage a wider range of knowledge that includes disciplinary, cultural, emergent, and embodied ways of knowing to solve novel engineering problems in specific contexts. For this reason, the synthetic nature of engineering knowledge connects activity across time and space (Roth 1996; Suchman 2000), and engineered artifacts embody the evolution of an idea and the collective knowledge of communities (Sarlemijn 1993; Suchman 2000). The siloed nature of school subjects can place implicit boundaries around what types of knowledge get counted during the engineering design projects in K-12 classrooms as does the normative approach of teaching engineering as an applied science in these settings.

However, approaches to engineering problem solving that recognize engineering knowledge as distributed and embodied in the world (rather than in texts or disciplinary experts) invite synthesis and broaden the types of knowledge and ways of knowing that get counted in K-12 settings. This is a critical space for repositioning power structures in engineering as it positions learners as experts in using the visible and available resources within their own communities to solve locally and personally relevant engineering problems. In addition, this is a pathway for broadening participation in engineering for youth by inviting engineering into informal and non-STEM learning spaces. Teaching learners to read this embodied knowledge in the designed world is a foundational step in developing critical sociotechnical literacy among students.

Through synthesis, engineering design activities also enable students to blend experiential and disciplinary knowledge to create hybrid learning environments (Jonassen et al. 2006; Vossoughi and Bevan 2014). In this way, engineering design mediates learning in ways that are personally relevant, agentic, and community oriented (Quinn and Bell 2013; Rolf 1996). In addition, the design of artifacts is a meaningful context for learning because it enables learners to represent their thinking in a physical and collaborative way (Papert 1980; Roth 1996; Vossoughi and Bevan 2014). Through collaborative discourse around physical objects, learners are able to leverage the intuitive, experiential, and disciplinary knowledge embodied in the artifact even in the absence of formal, disciplinary instruction (Roth et al. 2001; Puntambekar and Kolodner 2005). This shift from abstract principles to embodied artifacts distributes expertise among all learners engaged in project work and provides common experiences to ground problem-solving discourses in the learning space.

3.4 Engineers' Knowledge Is Tacit, Emergent, and Experiential

Almost universally, literature on design thinking emphasizes the central role of tacit, emergent, and experiential knowledge in engineering problem solving (Sarlemijn 1993; Stokes 1997; Vincenti 1990). Pushing back on positivist frameworks that emphasize science over experience, Schön (1983) argued for an "epistemology of practice" for design-based fields that honors intuitive and experiential learning, and the knowledge that emerges from the doing of design work. Engineering-related knowledge emerges through reflective conversations with the materials used in the process of artifact construction and the "doing" of design work and through the iterative co-evolution of product production and knowledge construction (Cross 2011; Koretsky et al. 2014; Pickering 1995; Roth 1996; Schön 1983, 1992; Stokes 1997; Suchman 2000; Vincenti 1990). Additionally, Vincenti (1990) argued that much engineering knowledge is created in the absence of science, and Sarlemijn (1993) described the design process and its products as cultural alloys that connect and embody everyday and disciplinary expertise in artifact (Sarlemijn 1993).

The nature of tacit knowledge changes with lived experience, and therefore, its role in problem solving also evolves over time. For youth, tacit knowledge refers to knowledge gained through everyday, nondisciplinary learning, often referred to as cultural funds of knowledge (Moll et al. 1992). Research has found that play, working with family members, and prior classroom experience can all provide knowledge and experiences that students are able to leverage in novel situations (Rosebery et al. 2010; Zimmerman and Bell 2012). Individuals who pursue engineering degrees and engage in professional engineering practices gain disciplinary knowledge through their lived experiences, and over time, the gap between everyday and disciplinary knowledge narrows, as experts draw on professional experience to solve engineering design problems. In the context of equity-oriented engineering instruction, the central role of tacit knowledge in the enterprise of engineering points to the need to engage learners in engineering design work as a means for learning related content knowledge rather than as an end point or measure of that learning. It repositions power and instruction from the curriculum and teacher to the relationship between learners, each other, and material artifacts and allows for diverse types of knowledge to emerge from situated problem solving.

3.5 Engineering Is Part of a Complex Sociotechnical System

As a situated, synthetic, and place-based endeavor, engineering knowledge and engineered artifacts exist within complex sociotechnical systems (Adams et al. 2011a). In professional contexts, the criteria and constraints that guide engineering solutions include economic, political, and social aspects of design work (Bucciarelli 1994; Cross 2000, 2011; Jonassen et al. 2006; Lawson 1997; Petroski 2011; Vincenti 1990). Yet, the social aspects and implications of design are often left out of engineering instruction and project work in K-12 settings (Cunningham and Kelly 2017). Duderstadt (2010) used this aspect of design to argue for broad-based training beyond STEM fields in engineering undergraduate education, which suggests that engineering can and should be integrated into diverse contexts in K-12 settings, particularly in courses examining the political and historical dimensions of human invention and community development.

Research in support of socially situating engineering note that engineers and designers often design artifacts, space, and processes for public use but do not always take into consideration the greater public good or the social impacts of their designs (Nieusma and Riley 2010; Riley 2003, 2008). Riley (2008) wrote that client-driven design often means that designers and engineers are solving problems that benefit institutions and people in power at the cost of the broader community, and argued that when framing engineering as solving problems, students need to be taught to ask, "Solving problems for whom?" In addition to providing more supports for design thinking, K-12 engineering opportunities should also provide supports that help teachers employ equitable interdisciplinary approaches when engaging students in the design practices of modeling, synthesis, and systems thinking that include asking students to think about the impacts of their design solutions on people and places, in addition to their functionality (NRC 2012). Teaching learners of all ages to reflect on the human dimensions of engineering design is central to critical and equity-oriented approaches to engineering instruction, as well as for decolonizing engineering education in K-12 settings in order to surface the types of knowledge, structures, practices, and solutions that have been prioritized in these spaces.

As a socially situated and transdisciplinary field, engineering has the potential to connect learning across disciplines, time, and space. Equitable engineering and design instruction should allow students to build on their own experiences and expertise as the foundation for integrated learning while also engaging in a distributed and synthetic model of engineering problem solving. Incorporating social practice theories into research on engineering learning and identity development is necessary for creating learning opportunities that engage all students and build on the social and situated nature of engineering design work (Kelly et al. 2017). Further, diversifying participation in engineering means that we need to not just bring students into existing engineering frameworks and structures, but that we need to take a critical look at the field of engineering education, and challenge researchers, educators, and curriculum designers to create learning opportunities that build on a diverse way of knowing about engineering and being engineers in the world, with a focus on relating course materials to students' lived experiences and surfacing the human decision-making and powered relationships embodied within the designed world (Claris and Riley 2012; Riley 2003). In the next section, we use these elements of equitable engineering to propose a framework for developing learners' critical sociotechnical literacy in K-12 engineering.

4 A Framework for Using Engineering to Develop Learners' Critical Sociotechnical Literacy

As participation in engineering has broadened in professional contexts, there has been a rise in socially conscious design practices, symbolized by the rise of critical design theory and humanitarian engineering (Bardzell and Bardzell 2013; Claris and Riley 2012; Nieusma and Riley 2010; Pawley 2009; Riley 2008). Critical and humanitarian approaches to engineering shift empathy, agency, and social justice toward the communities affected by design solutions and away from client-driven practices. Community-based models of engineering are now emerging from these critical frameworks, as well as the increasing emphasis in higher education on the social implications of artifact construction (ABET Engineering Accreditation Commission 2005). Engaging learners in the sociotechnical aspects of engineering means cultivating their critical sociotechnical literacy. In this section of the paper, we propose a framework for cultivating critical sociotechnical literacy, which is an approach to engineering instruction that engages learners in the practices of critically reading their designed world by situating engineered artifacts in the social, cultural, and historic contexts of their construction in order to imagine new and future possibilities for community-centered engineering design work in K-12 settings.

Traditionally, technological literacy has referred to the purely technical aspects of our designed world. Louis Bucciarelli (1994) began his ethnography, *Designing Engineers*, by recalling a phone survey of technological literacy that asked users to explain how a telephone worked. Bucciarelli used this example to note that there are multiple dimensions of technological literacy that can include knowing "how things work," but argued that it should also include knowledge of how designs are used and applied in the world (Bucciarelli 1994; Wells 2013). The *Next Generation Science Standards* adopted both of these views in outlining standards for Science, Technology, Society, and the Environment (NGSS Lead States 2013). The three strands of learning for these standards are as follows: students understand that engineering, technology, and science are interdependent; that society guides the adoption of these principles; and that their application can have impacts on the natural world. These standards address the transdisciplinary nature of engineering (Figueiredo 2008) and surface the impact that technology can have on the natural environment. However, these standards do not explicitly surface the impacts that engineering and technology have on individuals and communities due to how societal power structures guide the allocation of resources, development of engineered projects, and evaluation of projects in and on communities. For this reason, technological literacy should be expanded to include the critique of designed spaces to surface how infrastructure (the built environment) shapes culture, which is a central aspect of developing learners' critical sociotechnical literacy.

The Framework for K-12 Science Education (NRC 2012) and the Next Generation Science Standards (NGSS Lead States 2013) implicitly connect engineering and social science by advocating that designed solutions should be oriented toward solving human problems and fulfilling human needs and wants. There are advantages and disadvantages to this framing of design. The advantage is that this situates engineering within a sociotechnical system. However, there are few existing instructional models for how equitable approaches to problem solving through engineering and technology would look at scale. Research in support of positioning engineering as a sociocultural endeavor note that engineers and designers often design artifacts, space, and processes for public use but do not always take into consideration the greater public good or the social impacts of their designs (Nieusma and Riley 2010; Petroski 2011; Riley 2003, 2008). Further, researchers argue that many philanthropy models of engineering take on neocolonial constructs as they impose top-down solutions on communities, rather than including community voice as central to the problem-solving process (Bardzell and Bardzell 2013; Nieusma and Riley 2010; Pawley 2009; Riley 2008). Riley (2008) noted that client-driven design often means that designers and engineers are solving problems that benefit institutions and people in power at the cost of the broader community, and argued that when framing engineering as solving problems, students need to be taught to ask, "Solving problems for whom?" In addition to providing more supports for design thinking, next generation engineering curricula should also provide supports that help teachers employ equitable interdisciplinary approaches to problem solving, which invite students to consider the systems-level impacts of their designed solutions.

The built environment can both afford and constrain the way communities and individuals are able to construct their everyday lives and can perpetuate oppression through the anonymity of artifact (Riley 2008). However, professional engineers receive little to no training in the social aspects of their work and often self-identify as working in purely technical fields (Adams et al. 2011a; Bardzell and Bardzell 2013; Nieusma and Riley 2010; Stevens and Hall 1998). Young learners are also brought into a purely technical view of engineering through traditional engineering education frameworks, in ways that limit their ability to both identify with the field as future professionals, and to critically engage with the impacts of the built environment on their everyday lives (Bardzell and Bardzell 2013; Nieusma and Riley 2010; Riley 2003, 2008). Bang and Vossoughi (2016) noted this trend in education by arguing that:

> "Without expansive views, equity work becomes directed toward more effective forms of compliance and participation in inequitable systems and forms of life. More simply, these efforts become singularly focused on increasing non-dominant students' mastery of dominant forms. In our view undertaking equity-oriented work driven by a commitment to epistemic heterogeneity demands theories of change, forms of praxis, and axiological commitments to be more carefully examined, articulated, and theorized as part of scholarship and practice" (Bang and Vossoughi 2016, p. 175).

Our framework for developing learners' critical sociotechnical literacy builds on the praxis foundations of engineering as a craft and trade-based field that draws on tacit, emergent, and diverse ways of knowing to solve novel and socially-situated engineering design problems. It invites learners to critically reflect on *who* defines what counts as technology and engineering, and *who* benefits from its implementation in the world in order to situate technical phenomena in its social and historical contexts. Historically, engineering in the guise of social and technological progress has been used as an engine of oppression by dominant groups (Claris and Riley 2012; Riley 2008); disrupting these historic patterns requires that we critically engage learners in critiquing and reconstructing the designed world by surfacing issues of power, history, and culture in engineering instruction. We begin to do this by engaging learners in discourses both about and with designed artifacts in their everyday lives in ways that support noticing and exploring the how, why, and for whom related to the designed and built world.

Schön (1992) argued that design is a cultural practice as it is primarily a social and dialogic activity, noting that dialog can be exchanged with people and materials. Design calls for normative judgments in the process of creation by defining what a "need" or "solution" is. For this reason, structural inequalities are written into our designed world. Equitable engineering learning and the development of engineering-linked identities require that learners are able to "read" the sociotechnical landscape in order to derive meaning about the self in relation to historical and present representation of space. In this portion of our paper, we use the lens of critical theory to argue that learners can and should actively critique and seek to understand the historic and everyday ways that engineering, technology, and the designed world impact their own lives, communities, and society in general (Kellner 1989). Cultural Historical Activity Theorists (CHAT) argue that infrastructure, or base, determines the nature of superstructure, or broader cultural paradigms, through a unilateral relationship between infrastructure and society. Critical theorists differ from earlier CHAT ideologies in that they see the potential for a two-way relationship between infrastructure and superstructure through agency and empowerment of citizens. For the framing of critical sociotechnical literacy, we leverage critical design theory (Bardzell and Bardzell 2013; Nieusma and Riley 2010; Pawley 2009; Riley

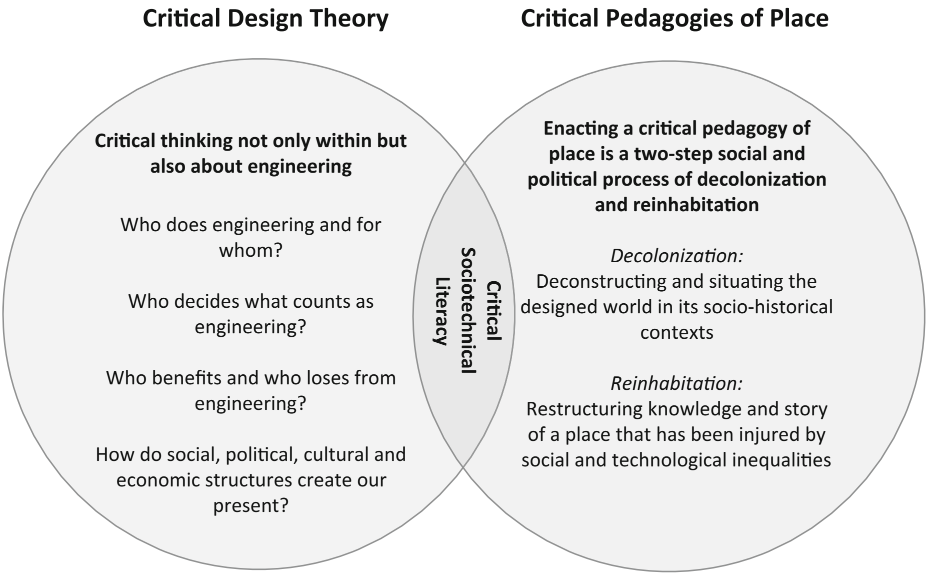

Fig. 1 Locating critical sociotechnical literacy at the intersection of the critical design theory (Dunne and Raby 2001; Nieusma and Riley 2010; Pawley 2009; Riley 2008) and critical pedagogies of place (Gruenewald 2003)

2008) and critical pedagogies of place (Gruenewald 2003) to argue that critical sociotechnical literacy lies at the intersection of these two theories (as shown in Fig. 1) and is a two-way process of decolonizing the designed world by reading the inequities embodied in designed and constructed spaces in order to restory these spaces for more just and equitable redesign that looks at engineering problems holistically and with a lens on their differing impacts on individuals within communities.

The critical design theory (Nieusma and Riley 2010; Pawley 2009; Riley 2008) asks learners to think critically not only within engineering, but also about engineering. It invites learners to ask the following questions: “Who does engineering, and for whom?”; “Who decides what counts as engineering?”; “Who benefits and who loses from engineering?”; and “How do social, political, cultural, and economic structures create our present?” (Pawley 2009; Riley 2008). The field of critical design asks designers to think about the social implications of their designs and their impact on the social structures and sustainability of communities. It shifts the problem-solving process away from just addressing clients’ needs to including the long-term needs and concerns of all those impacted by design decisions (Bardzell and Bardzell 2013; Dunne and Raby 2001; Nieusma and Riley 2010; Pawley 2009; Riley 2008). In this framework, Riley and Pawley encourage designers to not only “define the problem” and “design solutions,” but to ask, “Who is this a problem for?” and “Who does this solution serve?” In partnership with the critical design theory, enacting critical pedagogies of place is a two-step social and political process of decolonization and reinhabitation. Decolonization asks learners to deconstruct and situate the designed world in its sociohistorical contexts, and reinhabitation empowers learners to restructure knowledge and story of a place that has been injured by social and technological inequities.

Although knowledge used in the problem-solving process is distributed, engineering designs themselves are situated in place (Cross 2000, 2011; NEA 2009). In this sense, local knowledge, community desires, and the history of place are all central to creating equitable and socially just engineering solutions. Therefore, models of engineering learning can be productively thought of as a form of place-based learning that can draw on the instructional frameworks and guidelines for learning with specific places, people, and their histories in mind. This approach has been previously used in K-12 landscape architecture lessons to develop learner's place-based identities and agencies around redesigning spaces within their communities (Johnson 2009). Gruenewald's (2003) theory combines both place-based and critical pedagogies in what he calls "the best of both worlds," as these two pedagogical approaches are intrinsically linked when we ask students to critically evaluate the infrastructure–culture relationships in their own communities (Gruenewald 2003). The performative nature of engineering designs can be leveraged to teach students how to critique the designed world in ways that enable them to see how broader sociological constructs are related to quality of life, health, and personal agency. The act of critiquing the built environment involves restorying individual agency in places in order to reinhabit exploited spaces and direct change-making efforts toward the base structures that shape culture.

Below we outline a framework for and provide an example of cultivating critical sociotechnical literacy in K-12 engineering. This framework emerged from a 2-year, design-based ethnographic study in a linguistically and culturally diverse fifth-grade classroom, in which the authors iteratively designed and tested engineering curriculum and instructional approaches that were aimed at critically engaging learners with sociotechnical issues related to technology and engineering design in their everyday lives (McGowan 2018). Our underlying belief for this research is that all engineering instruction is ultimately a political endeavor (Freire 2013), and therefore, engineering learning environments should invite learners to surface and critique the social and political implications of engineering design on local, national, and global communities. Below are the steps that emerged from our research that can be used and adapted to support equitable instruction for K-12 engineering instruction in different contexts (Fig. 2). These steps include using self-documentation or other instructional techniques to invite students home-based knowledge into K-12 engineering lessons, adapting the curriculum to build on students' everyday knowledge and to engage learners in the practices of engineering, anchoring learning in engineering design pursuits and allowing learning to emerge from the doing of design work, connecting students to community and disciplinary experts as partners in learning, connecting learning across settings through field trips and community explorations, and using emergent, contemporary, and sociotechnical phenomena to surface the impacts of engineering and technology on people and places.

4.1 Anchor Learning in Learners' Everyday Knowledge, Interests, and Identities

Research on learning how cultures, such as home and school, interact to produce learning outcomes provides examples for the development of equitable instructional frameworks that can be adapted for use at scale (Gutiérrez and Penuel 2014; Nasir and Hand 2006; Penuel 2014; Philip and Azevedo 2017). Findings from this body of research suggest that overlaps between learners' everyday experiences and disciplinary practices of science can open access points for students who might not otherwise participate in STEM fields (Nasir et al. 2006), and learning environments that build on students' everyday experiences are central to equitable instruction (Calabrese Barton et al. 2008; Bell et al. 2013; Claris and Riley 2012; Kelly 2014; Roth and Barton 2004). Our overall curriculum arc was guided by a district-level scope and sequence for 5th grade science (see Fig. 2 headings). We used self-documentation activities (Tzou and Bell 2010) at the start of each unit to ground instruction in students' everyday

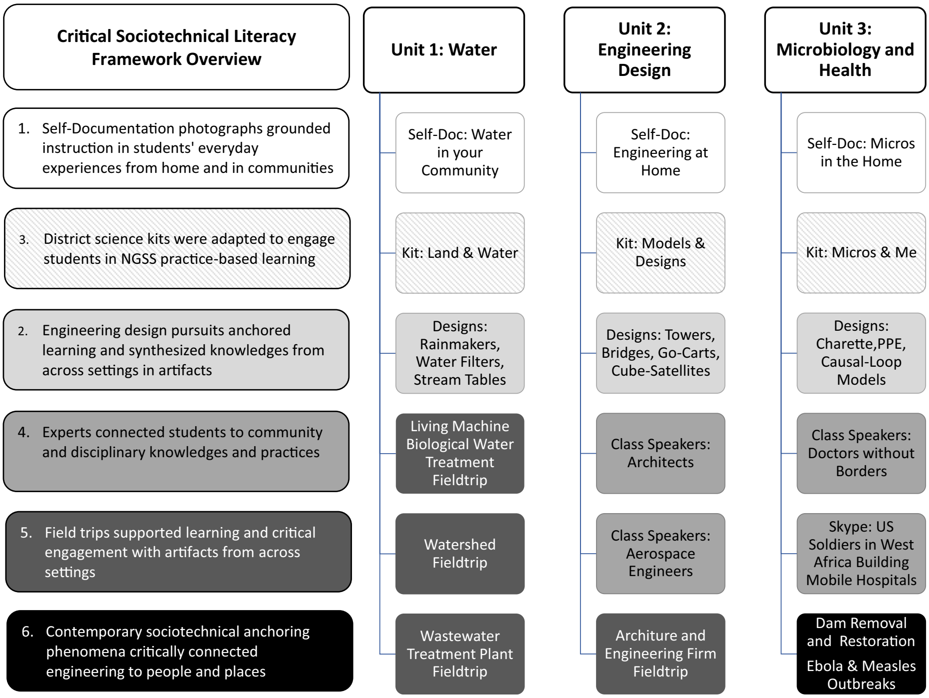

Fig. 2 Developing critical sociotechnical literacy framework overview with examples of our yearlong unit arcs

knowledge and experience. Self-documentation is a qualitative data collection and sharing activity in which leaners collect photographic data of course-related topics outside of the classroom. For example, the engineering self-documentation activity task asked students to collect, label, and share pictures of how, when, where, and with whom they did engineering in their everyday lives. In partnership with the fifth-grade teacher, we used self-documentation photos as formative assessment tools to adapt our critical engineering unit in ways that incorporated and built on students' everyday knowledge and experiences (Bell et al. 2012). Self-documentation guided the major topics that emerged in our work, including our focus on contemporary news topics of the time including construction and removal of the Elwha Dam, the Ebola outbreak in West Africa, and the 2015–2016 Measles outbreak in the USA. These three topics served as anchoring phenomena for the district science kits related to Land and Water, Models and Designs, and Micros and Me (microbiology and health).

4.2 Use Complex Anchoring Phenomena and Include Community and Disciplinary Experts to Surface Critical Sociotechnical Aspects of Learning and to Connect Learning Experiences Across Settings

Students' self-documentation photos guided our overall unit and yearlong course design by locating students' experiences at the center of learning about complex sociotechnical systems in which individual agency and actions are both afforded and constrained by aggregate system structures. Complex, sociotechnical anchoring phenomena emerged from students' interests and were used to connect learning across design projects, people (including community members, experts, and the teacher), places (home, field trips, and school), and district science kits. For example, we used the building and subsequent removal of the Elwha Dam and restoration of the Elwha River in Washington State to discuss community health, wildlife conservation, and land and water rights in the context of earth science, erosion, and deposition. For this investigation, students asked: “Who benefited from the construction of the Elwha dam?”; “Who was most impacted?”; and “Will dam removal and habitat restoration restore power and health to historically impacted communities?” Students visited their local watershed, which had previously experienced a dam failure, to see the impacts of dams and dam failures on ecological and human communities, and students modeled these phenomena on land and water tables in their own classrooms. Students then researched ways to treat and store water in their own communities to create more sustainable ways to store and process water for human use.

In addition, the 2015 Ebola outbreak in West Africa and the 2015–2016 measles outbreak in the USA emerged as anchoring phenomena that tied together each of the three district learning strands of water, engineering design, and health. Through the Ebola investigation, students learned about the transmission of disease and how the rates and severity of transmission are related to the availability of clean water and water-related infrastructure. We visited multiple sites, including a local wastewater treatment facility, a “living machine” to show smaller-scale wastewater treatment, and spoke with experts from Doctors without Borders and the United States Army to understand the connections between clean water, engineering, and health. For this investigation, students asked, “Why did Ebola become an epidemic in West Africa when it did not even spread to family members in the U.S.?” Experts from Doctors without Borders who had recently returned from working with Ebola patients in West Africa and members of the U.S. military who were in quarantine after building mobile hospitals in Liberia surfaced the connections between infrastructure and health for students. Both guest speakers noted that the lack of effective wastewater treatment facilities and indoor plumbing in West Africa allowed Ebola to spread rapidly among family members and even to healthcare workers in hospitals, and speakers related the lack of infrastructure in this area to ongoing civil wars and political instability throughout the 1980s and early 2000s. This expert knowledge enabled students to make connections between political structures, poverty of individuals as well as nations, infrastructure and the built environment, and its connection to health and disease. Similarly, during our measles investigation, students interviewed family members about their views on vaccines and compared demographic data from our region to understand which communities are least likely to vaccinate their children. Students surfaced the pattern that White, privileged families who had the greatest access to healthcare were more like to forego vaccinations, putting those without access to healthcare at the greatest risk for the most severe impacts of measles. Critical design approaches including the use of individual, small-group, and whole-group systems diagrams and causal-loop diagrams (see Figs. 3 and 4) surfaced the role of power, politics, and engineering in relation to community health. In each of our case studies, community and expert knowledge and field trips were central to understanding the nature and complexity of technology in social and historical contexts.

4.3 Leverage Engineering Practices for Critical Engagement

In our research, we designed practice-based approaches to learning that situated engineering design pursuits in social and historical contexts. Throughout this research, students engaged in

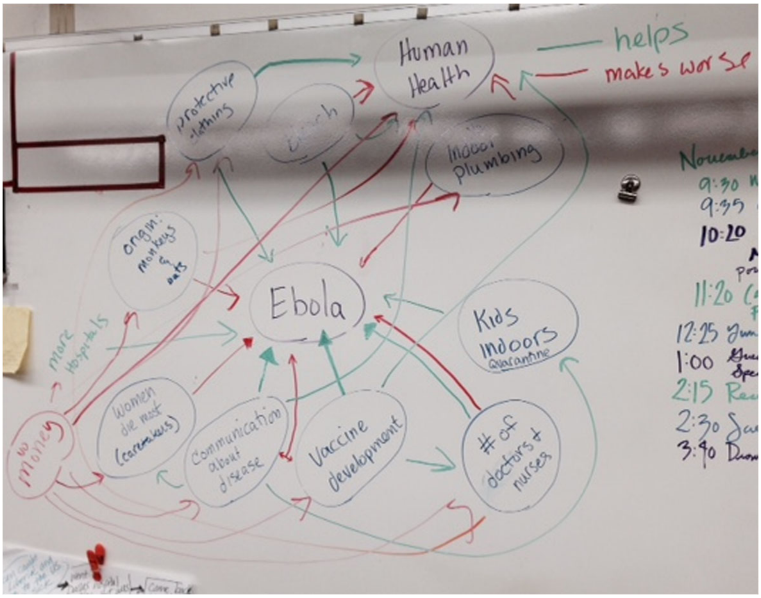

Fig. 3 Whole-group causal-loop models engaged students in critical classroom conversations around the relationships between technology, engineering, people, and places. In this image, circles indicate components within a sociotechnical system and arrows show increasing and decreasing relationships. For example, in this image, students made connections between human health, resources (PPE, money, doctors and nurses, etc.), and Ebola prevention and treatment (vaccine development, hospital construction, infrastructure, etc.)

engineering practices in which they synthesized distributed knowledge around sociotechnical anchoring phenomena. Each engineering investigation launched with and revisited the questions, “Who is defining the problem,” “Who decided on the criteria and constraints,” and “Who do the solutions benefit and impact?” We layered human-centered components of decision-making into our systems and causal-loop models as we developed and revised them throughout the year. Throughout our engineering design pursuits, we had students use self-documentation techniques to research the diverse ways that similar solutions have been constructed and/or solved in their own communities. At the start of and throughout engineering activities, students shared and revisited their photographs to both critique and build on the knowledge embodied in community artifacts. For example, students were able to use examples of local, constructed wetlands from a field trip to propose low-cost and sustainable solutions for water management and purification in regions that lack wastewater treatment infrastructure.

4.4 Engage Learners in Participatory Design Solutions

In addition to surfacing and modeling connections among sociotechnical systems, systems-based and causal-loop models enabled learners to situate engineering phenomena within complex sociotechnical systems (Adams et al. 2011a). Students constructed and regularly revised causal-loop models (Figs. 3 and 4) in order to identify variables for change and agency within the complex network of actors and artifacts in the sociotechnical systems they investigated. These models supported students’ ongoing sensemaking of complex sociotechnical topics and grounded students’ action projects. In this work, students used their critical engagement with these topic and systems models to participate in restorying their designed world. In

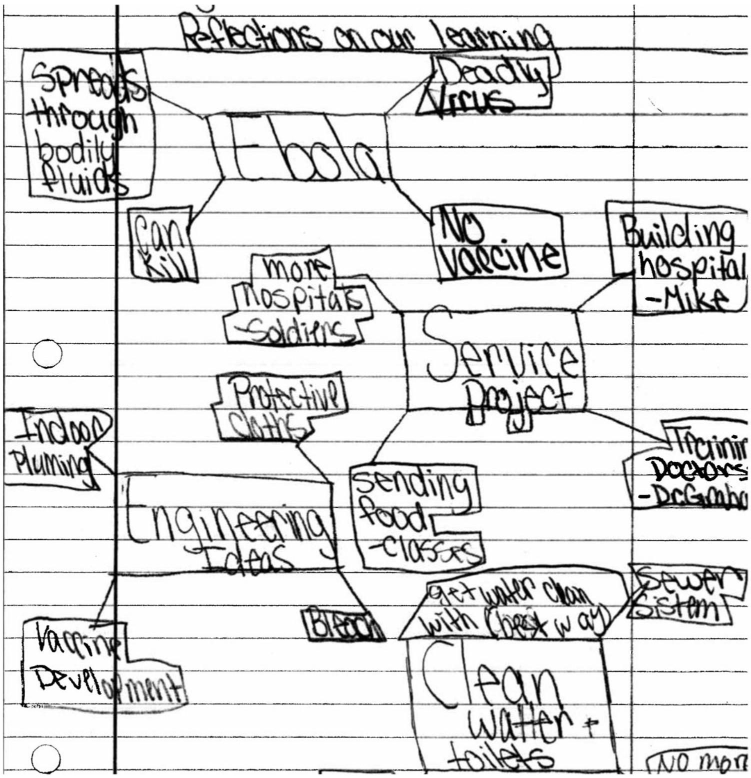

Fig. 4 Individual and small-group causal-loop diagrams engaged students in critical reflections about their learning across topics (units 1, 2, and 3), settings (home, school, field trips, and guest speakers), and engineering design pursuits (stream tables, community service projects, etc.) and connected this learning to our sociotechnical anchoring phenomena

our Elwha Dam study, students followed the Elwha Dam restoration process and constructed diagrams that showed how increasing salmon stocks would impact both wildlife and human communities in the region. They surfaced the limits of restoration as well as the possibilities for reimagined future in the space. As part of the Ebola outbreak investigation, learners collected and sent supplies to volunteers constructing mobile hospitals in West Africa and engaged their parents and family members in discussions related to public health. For example, several parents were concerned that Doctors without Borders volunteers who had assisted with the Ebola outbreak in West Africa were in the classroom to talk about the Ebola epidemic. Students used evidence from expert visits and from classroom discussion to alleviate their parents' worries and to advocate for learning about public health issues from experts who had direct experience in the field. Finally, students advocated for increasing vaccination rates in their school and shared information to debunk myths about the risks associated with vaccines.

5 Conclusions and Implications

Contemporary images of engineering emerged from multiple and diverse historical pathways, which have increasingly narrowed what counts as engineering and who gets to be an engineer over time. However, we can leverage engineering's historic roots in craft and trade to build distributed and synthetic models of engineering that allow learners to use diverse ways of knowing for solving problems within their community contexts. The performative nature of engineering designs can be leveraged to teach students how to critique the designed world in ways that enable them to see how broader sociological constructs are related to quality of life, health, and personal agency. In this paper, we used the history and epistemologies of engineering to identify elements of the nature of engineering that can be used to support equitable instruction in K-12 engineering settings. We then described how these elements can be used to develop learners' critical sociotechnical literacy and introduced a framework for using engineering to cultivate critical sociotechnical literacy in the classroom. The act of critiquing the built environment involves reframing the assumptions of individual agency that undergird neoliberal discourses in K-12 settings. Critical sociotechnical literacy surfaces the interconnectedness and complexity of living in a sociotechnical world, which privileges some individuals at the cost of others. The NGSS Science, Technology, Society, and the Environment standards (NGSS Lead States 2013) engage students in investigating *how things work* and *how designs are used and applied*. Critical sociotechnical literacy adds to this framework by encouraging teachers and students to ask, "Who benefits from this design, and at what cost?" Longer-term studies are needed in diverse contexts to understand the heterogeneity of engineering in practice (Penuel 2014) and to provide design principles for inclusive engineering instruction that situates the technical aspects of this work in cultural, social, and historical contexts.

Research from the informal making and tinkering community has designed contexts that situate the informal design work of learners within larger historical and social contexts, leveraging the diversity of cultural practice and knowledge that learners bring to these spaces as foundations for knowledge and artifact production (Bevan et al. 2015; Calabrese Barton and Tan 2018; Vossoughi and Bevan 2014). These studies serve as models for similar research related to engineering and design-based learning in the classroom. Social practice theory perspectives on learning attend to how the socio-material arrangement of places, actions, and positions can lead to specific learning outcomes including future participation, interest, and identity in design-related learning (Bell et al. 2013). Sociocultural perspectives of learning in engineering would aim to situate learners along the boundaries of engineering communities of practice through partnerships, field trips, and the use of technology to extend learning beyond classroom walls, and to situate students' engineering practices within a larger social context. In addition, there is a need for empirical and observational research that locates engineering practices and epistemologies across diverse learning settings, including formal and everyday. Two recent studies called for "innovative" approaches to research with regard to engineering education filling these gaps. Case and Light (2011) called for an increase in studies using "emergent" methodologies in engineering education, such as case study, grounded theory, ethnography, action research, discourse analysis, and narrative analysis. Douglas et al. (2010) surfaced the long-standing bias of engineering educational research toward positivist research paradigms, noting that few engineering and engineering education researchers have been trained in qualitative methodologies. This gap provides opportunities for ethnographic studies of learners' engineering practices across settings, including at home, after school, in community settings, and at school to highlight the heterogeneity of learners' engineering practices as they show up across settings and over time. Lastly, there is a need for research that includes critical approaches to engineering teaching and learning that surface and disrupt historical practices that continue to marginalize historically underrepresented learners in these fields, and situates engineering design solutions within community contexts. These approaches would shift the focus of engineering learning from neoliberal framings of economic production and assimilating diverse workers into the existing industry to empowering learners to leverage engineering practices and ways of knowing to engage in the critique and restructuring of their designed world. Employing critical approaches to engineering means situating engineering as a sociotechnical field of study.

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Compliance with Ethical Standards

Conflict of Interest The authors, Veronica Cassone McGowan and Philip Bell, certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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