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Fostering heterogeneous engineering through whole-class design work

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ABSTRACT

Background: Design problems have long attracted researchers' attention for their potential to provide authentic learning opportunities. While we have methods for supporting students to learn through relatively simple engineering and design tasks, supporting students to address complex problems that they find and frame remains poorly understood. Designing for the real world presents opportunities to understand how heterogenous engineering practices emerge from students' experiences, how problems are negotiated and reframed, and the forms of learning such experiences support. Descriptions of engineering practice often privilege technical aspects, where heterogeneous engineering emphasizes the active coordination of social and material dimensions as well.

Methods: We present two cases from large, complex design projects: (1) a design-based research study in a school-based making space and (2) an extended participant observation in a design-build school. We used interaction analysis to characterize the forms of participation.

Findings: We identified ways students negotiated social and material elements of design, how they coordinated these activities, and how the instructional environments contributed to developing heterogeneous practices.

Contribution: Designers and materials both operated as agentive actors in dialogic conversations that coordinated the multitude of considerations involved in heterogeneous engineering. We argue for the importance of fostering sociomaterial entanglements to support learning in design.

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The purpose of this paper is to jointly elucidate the learning potential in heterogeneous engineering design projects and discuss the advantages of studying such settings for revealing learning-in-process. We characterize heterogeneous engineering as a legitimate phenomenon that happens in large, complex design challenges, where sociality (that is, interactions between humans), and materiality (that is, interactions humans have with materials), and instructional design come together to support learners' engagement in engineering and design practices. Our goals are to examine complex, ill-structured design contexts to identify how learning occurs in these settings.

Law (1987) argued that close examination of engineering *in the wild* reveals a more complex and multifaceted activity than technical descriptions of engineering might suggest (Trevelyan, 2010). He argued that engineering challenges and solutions in the real world are distributed across social, material, economic, and political domains as well as the technical. Working across this complex array of considerations, engineers must develop, direct, and coordinate particular design practices that can account for and contend with these heterogeneous conditions. This conceptualization of "heterogeneous engineering" (Law, 1987, p. 113) expands notions of engineering and design practice—and it expands possibilities for learning by design.

Heterogeneous engineering describes how the production of artifacts is organized across the space of diverse and complex considerations (Law, 1987, 2002; Suchman, 2007). We see clear relevance in how engineering, making, and design can be understood to involve the coordination of multiple, often competing, and "unruly" (Suchman, 2000b) contingencies and emerging considerations. Design studies pay particular attention to how individuals communicate and negotiate possibilities, how design is entangled with material possibilities, and how the production of artifacts is organized (Schön, 1983, 1992). Turning these considerations to learning spaces, heterogeneous engineering provides us with a lens for examining the complexity of learning through problem framing and solving, just as we see in engineering design and making contexts.

In this paper, we investigate how students work on large, messy, collaborative kinds of design problems—ones requiring an entire class or large group of students to solve—as heterogeneous engineering practices. These ill-structured and complex problem spaces, shown to be productive for learning through problem solving (Jonassen, 2000), require navigations and coordination of social and material factors, as well as instructional supports. Our paper shows, through cases, that heterogeneous engineering offers students expanded opportunities for learning to coordinate and direct their work, and that our framework for exploring learning in these settings holds potential for structuring future investigations into the particulars of learning in heterogeneous engineering and design contexts. We do this by first exploring the literature on learning through problem framing and problem solving. We build from that to describe the learning practices in heterogeneous engineering with a focus on coordination and negotiation as crucial in managing competing considerations in sociomaterial design activity. We offer a means of conceptualizing *sociality* and *materiality* in these activities, borrowing from Shotter's (2006) notion of "withness" and expanding on foundational studies that articulate design as a "conversation with the situation" (Schön, 1983, p. 95). Finally, we articulate the theoretical perspectives that describe conversations among people and materials, with respect to the multiple ways designers engage with each other and materials. Taken together, our theoretical framework situates this paper and its contributions as describing rich possibilities for learning in what we call sociomaterial entanglements, endemic in heterogeneous engineering design.

Learning through design, problem framing, and problem solving

Jonassen (2000) argues that ill-structured, complex, and domain-specific—or situated—problems are best suited for students learning through problem solving. Jonassen's description of structuredness and complexity in design problems has traction in the engineering education community (e.g., Brophy et al., 2008), but less attention has been paid to the situated nature of problems (see Nieusma & Riley, 2010). For instance, while it is common to integrate engineering with science or mathematics, it is less common for authentic sociality and materiality to imbue the problem (Gunckel & Tolbert, 2018). Of interest in this paper is how large, situated, and complex problems identified and framed by groups of students can present opportunities to engage in heterogeneous engineering.

Past research in project-based classrooms focused on problem solving has hinted at the potential of whole-class engagement with complex problems. For instance, the breadth and depth of engagement visible when students wrestle with how to treat a classmate's missing data (O'Connor et al., 1998) reveals both a diversity of thinking and that collective progress can be made. Likewise, in a 5th grade classroom, computer tablets signal the onset of a simulated earthquake, prompting students to take up various roles to map out the plate boundaries of their classroom (Moher, 2008). These examples demonstrate the possibilities of designing for large format inquiry in terms of surfacing sociomaterial dynamics, where differing perspectives, roles, and negotiation become important to students' problem solving. However, the typical problem contexts in engineering and design curricula remain limited in scope (Sadler et al., 2000) and usually limited in terms of complexity, in part because of instructional barriers. Our past research (Svihla et al., 2016) in a design-build school showed how teachers struggled to engage students in large-format problems, but ultimately enacted particular instructional moves that shifted agency to the students. This transfer of control, through a focus on problem framing and reframing, opened up opportunities for students to learn how to negotiate with each other and to navigate problem framing and solving processes. Ultimately, these studies point to a need for more intentional and explicit research concerning the instructional environment and how it contributes to supporting students' engagement in authentic design and engineering work, and specifically with an aim to not just solve problems, but to frame them.

Research on the disciplinary practices involved in framing and solving complex problems, like in heterogeneous engineering, has gleaned insight from comparisons between new and experienced designers. In the engineering education literature, studies of practicing and beginning designers reveal both similarities and differences between practices enacted in educational environments and those observed in professional settings (Atman et al., 2008; Crismond & Adams, 2012; Daly et al., 2012). Crismond and Adams (2012) argue that beginning designers launch into solutions, usually just one or two, without adequate time spent researching, understanding, and framing problems, and that they tend to view problems as well-defined rather than embracing the ill-defined and complex nature of problems. Atman et al. (2008) show that students in design courses can take up the language of engineering design in ways that support the development of their design knowledge. However, students do not always put that knowledge into practice. These studies reveal a need to revisit the instructional contexts within which design practices are studied (Bornasal et al., 2018). Over-prescribed problem spaces and relatively inauthentic challenges can mask what students are capable of doing when designing, if given the kinds of complex, ill-structured problems that Jonassen (2000) recommends. Thus, here, we pay explicit attention to the instructional designs of large-scale, situated, and messy problem contexts to better understand students' engineering practices and the ways design and learning interact.

One line of research looking at the intersections of design and learning focuses on the forms of science content that students learn in engineering design situations (e.g., Kolodner et al., ; Wendell & Lee, 2010). Though our focus is not on learning science, design practices in the sciences—such as when scientists *design* their studies, data collection and analysis workflows, models of phenomena, and data representations—offer insight into how design can focus students' attention. Schauble et al. (1991) found that students' approaches to experiments in science often took the form of what they called the "engineering model of experimentation," (p. 862) whereby students' decisions about variables and materials in experiments were driven by desired outcomes. This "engineering model" positions students as inquirers of the variables or materials and their properties as they relate to specific outcomes. Interaction with the materials becomes a form of conversation, where students' inquiry with the materials is organized around an interest in making something work, less so around understanding *why* something works. While Schauble et al. (1991) acknowledge that the scientific model (i.e., focusing on why things happen as they do) emerges from these engineering approaches to experimentations, we point to this as further evidence of how those practices for engaging with questions, problems, and materials contribute to one's learning. These studies suggest that learners can direct their efforts toward phenomena and first principles, as well as toward the materials and how they behave, interact, and respond. The more opportunities learners have to explore materials within the problems of their choosing, the more opportunities there are for them to "bump up against the world" in interesting ways that support learning in a variety of contexts (Bransford & Schwartz, 1999, p. 82).

Examining these intersections of design and materials in school settings has led many in the Learning Sciences to explore the promise of making as a context where students may pursue problems of their own choosing and where they may engage in meaningful and disciplinary inquiry and design activities (Martin, 2015; Papert & Harel, 1991). In making, multidisciplinary, multimodal ways of knowing and working provide opportunities for youth to engage with problems of personal interest and community need (Calabrese Barton & Tan, 2018). We argue that making—bringing together engineering, the arts, and design—may reveal the ways learning occurs in heterogeneous engineering contexts and might create the conditions for approximating forms of authentic professional practice in ways that can be useful for youth learning to become designers, engineers, and problem solvers. Making presents opportunities for authentic, student-authored forms of work and problem solving (Peppler et al., 2016; Tucker-Raymond & Gravel, 2019). Many examples from the making literature showcase projects within relatively confined timeframes such as a series of after-school workshops (e.g., Ryoo et al., 2016), or classroom interventions (Ball et al., 2017), which is understandable considering the constraints on time in schools. And yet, the promise of making for engineering education seems relatively well-established (Martin, 2015). Within these constrained settings, the heterogeneous nature of engineering and design may look different from more complex projects in authentic or professional practice (e.g., the construction of a bridge; Suchman, 2000b). Thus, there is great potential for learning in instructional designs that involve large ill-structured problems, a focus on sociomaterial aspects of problem framing and solving, and making. Furthermore, the importance of the instructional environment—how activities are organized, the pedagogical moves of the teacher, and forms of support for students—also requires attention. We argue that further exploration of how multiple dimensions of complex design work are coordinated and organized will advance conversations about learning through and in design.

Theoretical framework: Learning practices of heterogeneous engineering design

Learning to engage in particular forms of activity means enacting practices developed by communities of individuals who have shaped those activities over time (Lave & Wenger, 1991), whereby those practices become the ways of learning, for example, within a discipline (Engle & Conant, 2002). In engineering, practicing disciplinary experts have long emphasized the technical aspects of their work, often masking other requirements, such as social or political dimensions (Trevelyan, 2010). However, the real work of engineers and designers solving complex, situated problems extends well beyond oft-emphasized technical domains of engineering. For instance, building a bridge that connects two communities is a technical feat, but success requires social and contextual understanding (Suchman, 2000b); designers engage the communities where the bridge will be built, soliciting and addressing concerns, and they explore issues like esthetics, traffic flow impacts, and how the new bridge will affect the community. Law (1987) called this conceptualization of engineering-in-practice "heterogeneous engineering" (p. 113) to acknowledge the complex and interrelated collection of factors influencing authentic design problems and the production of artifacts. Heterogeneous engineering attends to the "(1) the heterogeneity of the elements involved in technological problem solving, (2) the complexity and contingency of the ways in which these elements interrelate, and (3) the way in which solutions are forged in situations of conflict" (Law, 1987, p. 111). Law argues that the malleability and interconnectedness of social, material, and technical considerations makes the process contingent, and thus designers must attend to all elements jointly. Furthermore, privileging the technical over social and material elements narrows what we consider as real engineering work, making the entanglements between multiple dimensions challenging to observe (Orlikowski, 2005, 2007). Yet, integrating social and material considerations requires a certain kind of organizing act or a coordination of performances that span these domains (Suchman, 2000a). To make progress and to design solutions to real problems, Suchman (2000b) argues, "the focus is on organizations as ongoing performances involving heterogeneous modes of action and materialization, both of which must be actively affiliated and aligned across a range of often unruly contingencies" (p. 313). These "unruly contingencies" both define complex activities like engineering and design and require acts of coordination that are central learning practices of heterogeneous engineering design.

Coordination of the social and material alongside the technical is not how engineering work has historically been perceived (Bornasal et al., 2018; Bucciarelli, 1994; Vincenti, 1990), nor how engineering educators have typically described engineering practices. In recent descriptions of engineering practices for educational contexts, many of the nontechnical aspects of engineering are flattened, relegating the human elements of engineering to categories like "working effectively in teams," "communicating effectively," and "seeing themselves as engineers" (Cunningham & Kelly, 2017). We agree that these categories are important, but at the same time they are neither comprehensive nor complex enough to understand the potential of heterogeneous configurations. Others have acknowledged that the historical separation of the social and technical domains of engineering work presents an artificial and incomplete image of what is involved in engineering practice (Entwistle & Slater, 2019; Stevens et al., 2014; Styhre et al., 2012). Suchman (2000b) centered what some engineers consider peripheral in arguing that the real work of design involves the "organizational activities of sense-making, persuasion, and accountability" (p. 315). And increasingly, scholars are attending to the social elements of engineering practice (Bornasal et al., 2018; Sheppard et al., 2006; Stevens et al., 2014; Styhre et al., 2012). We seek to contribute to the conversations about learning in engineering by considering the sociomaterial work of the discipline, specifically the design practices of heterogeneous engineering.

Rethinking sociality: "Withness" conversations in heterogeneous engineering

If learning in design involves acts of sense-making, persuasion, and accountability between people, materials, and situations, we need a lens through which to examine how these entanglements unfold in practice. First, we use the term "social" to point at interactions between humans and "material" to point at human-material engagements. As artificial as this parsing may be, it supports our efforts to uncover a structure for how the acts of coordination and sensemaking in design unfold, a move not unlike the practice in interaction analysis of tagging interactions as talk-driven or physical (Jordan & Henderson, 1995). While this simplification creates a somewhat false dichotomy, it serves to draw attention to material agency and its role in design decisions. Talk is already well-validated in the Learning Sciences, yet comparatively little attention is paid to materials and interactions with them; our distinction expands the sense of conversation to include materials in how we think about interactions.

We find the foundational notion of "design as a reflective conversation with the situation" (Schön, 1983, p. 95) useful in understanding the interplay of social and material aspects of heterogeneous engineering. However, at the same time, we argue, as have others (Leonardi & Rodriguez-Lluesma, 2012), that the structure or nature of those conversations requires further consideration if we are to understand how they contribute to learning in design. Taking the designer's perspective, exchanges with others and with materials are crucial to understanding the nature of the problem and design space. The designer's job is to learn all they can from the available sources of information—other people, materials, regulations, and even imagined users (Ivory, 2013)—so they may harness the properties for their intended needs and uses. As such, these are typically understood as *monologic* conversations, in which the designer learns about and from different sources, including the materials themselves, to explore their possibilities. The designer reaches out, through directed forms of inquiry and attention, to have these conversations in service of advancing their design goals.

We contrast this with a very different kind of *dialogic* conversation (Bakhtin, 1986), one where the designer orients to these sociomaterial engagements as time to learn *with* and alongside other elements of the problem, materials, and collaborators. This kind of co-constitutive conversation suggests agency is distributed across the problem space, shared among designers, materials, and the situation. These dialogic conversations maintain possibilities for learning about material properties, constraints of the situation, and tensions between competing visions, but they also serve as opportunities to learn about both the problem and solution spaces. When thinking specifically about sociomaterial engagements, the conversations that designers have with materials (Schön, 1992) become sites for understanding how heterogeneous engineering unfolds for learners. A structure for these specific sociomaterial discussions needs to be articulated to understand what we observe in the interactions between designers and materials.

We turn to Shotter's (2006) arguments for a "withness" approach for understanding these engagements. Most processes, like engineering design, are described from the outside looking in (e.g., Crismond & Adams, 2012), what Shotter (2006) calls a cinematographic perspective that employs "aboutness" thinking. From this detached vantage point, observers theorize about participants' actions and motives, which are covert and strange. And, as researchers, making sense of these performances involves imposing order, often reducing them to their barest components. This "aboutness" thinking produces models of design processes and practices that not only fail to account for the complexity of design work, but also provide meager and misleading guidance for newcomers. Shotter argues "aboutness" thinking strips away the intimate and constantly evolving relationships that actors have with each other, with materials, and with the situation. When thinking about materials, we run the risk of ignoring or even silencing forms of conversations designers are having with them. Instead, focusing on the complexity of the interrelated nature of conversation—as a two-way exchange of ideas, meanings, agreements, and disagreements—positions such sociomaterial conversations as dialogical. Thus, we adopt Shotter's stance of "withness" because it restructures our understanding of socio-material conversations as dialogical, co-constituted by designers and materials. The dialogic form presumes exchanges among designers and materials are cooperative and interpretive in nature, expanding the possibilities of shared design spaces.

Shotter draws from Bakhtin's (1986) descriptions of language as a structure for considering "withness," using the example of two people in conversation, where one poses a question to another, who responds. In doing so, this person displays *responsivity* to the questioner, such that the active construction of a response is an *entanglement* with the original question, not simply the articulation of a position. Shotter argues real conversation requires that "we must continually tack back and forth between 'listening to the questioner's voice', so to speak, and 'answering to' its calls." (p. 590). Thus, this conversation requires response and listening, both to the original question but also to the ways that responses are taken up or received. Bakhtin's (1986) *dialogic* approach foregrounds that one's expressions are responsive to, entangled with, and mutually co-constitutive with the others in conversation. This conceptualization of sociality in heterogeneous engineering reframes conversations as much more than people talking or discussing ideas. Sociality understood through the perspective of "withness" means engineering practices like "communicating effectively" (Cunningham & Kelly, 2017) involve deep dialogic entanglements, where designers listen to, interpret, and imagine design possibilities together. Conversations of this nature, among designers and with the situation, require a complimentary consideration of the design possibilities garnered through listening and being "with" the materials as well.

Material "withness": Being, doing, and becoming conversations

As designers move through a moment, they are in conversation with the materials of that moment, be it wood or words, in "unfolding movement, they always inevitably 'point toward' future possibilities in some way" (Shotter, 2006, p. 591; paraphrasing Bakhtin, 1986). The exchange of suggestion and response between designer and material is a process of unfolding, and the possibilities for what the two can agree upon emerges from this tacking back and forth. In the sciences, Pickering (1993) described conversations of the sort we consider here as "the mangle," situating material agency as "temporally emergent in practice" (p. 564) and emphasizing the unpredictable contributions materials make through a "dialectic of resistance and accommodation" (p. 567). In engineering and design, the entangled nature of materials and designers suggests a dialogic, or a "withness," that positions the designer not as someone who forces the materials into submission, but rather as someone who listens and is responsive to the material's "question," or suggested possibilities. In this image, the materials are designers' companions and provocateurs (Turkle, 2007). Withness thinking suggests that the designer and materials are co-constitutive of the possibilities, constraints (or "resistances," Pickering, 1993), and imagined ways that choices can be made about the design itself. This frames the role of materials in design not as dormant objects, but as interlocutors in acts of heterogeneous engineering required to solve particular kinds of problems. This "withness" helps to describe how learning unfolds in dialogics of design, those among humans and materials.

Though long acknowledged that social and material aspects are not simply a backdrop for understanding how individuals act, situative approaches have made little progress in theorizing the social role materials might play (Greeno, 1998; Lehrer, 2009). In considering the ways materials have agency in design, we draw inspiration from design characterizations of materials as "being," "doing," (Manzini & Cau, 1989) and "becoming" (Bergström et al., 2010). Traditional materials, such as clay, wood, and glass, that have stable and known material properties were characterized as "being" materials for their abundance, accessibility, and knowability. Engineered materials, such as composites, were characterized as "doing" materials because they were designed for specific applications. With advances in engineered materials, the notion of "becoming" materials was introduced to characterize materials, such as nanomaterials and smart materials, that could change over time in designed ways.

We co-opt these terms to consider the kinds of conversations designers have with materials, and how materials tell designers what they want to be, do, or become. We therefore define these terms to characterize how we see designers interacting with materials. Especially in learning settings, we expect to see being and doing material conversations; to be in sociomaterial entanglements opens opportunities for becoming material conversations. We conjecture that these distinct kinds of material conversations reveal much about the kinds of learning happening amidst heterogeneous design—specifically, learning to direct framing problems.

Being materials

Being materials are abundant, knowable, and sometimes invisible in the design process. Being material conversations involve treating the materials as well known, literal, and not improvable or repurposable. Consider, for instance, LEGO bricks (see Figure 1). As a being material, LEGO bricks tell designers to assemble them, studs facing up, locking tightly together; in this way, they seem somewhat coercive in their conversations with designers. When designers work with materials that do not

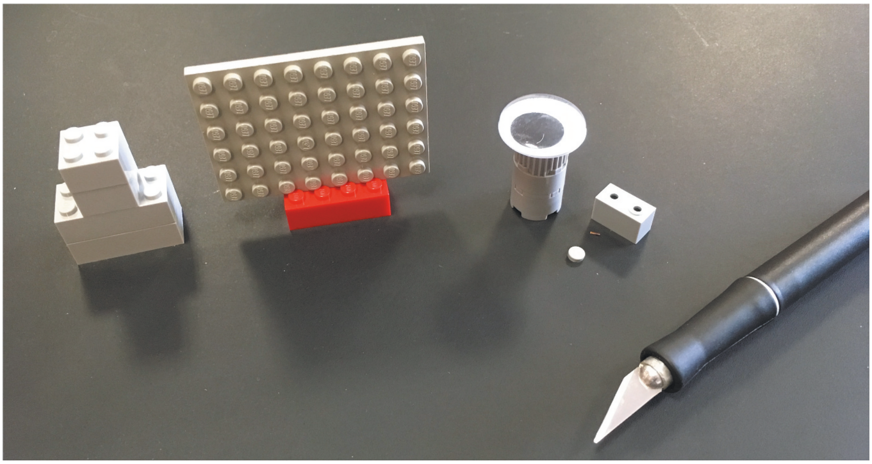


Figure 1. LEGO bricks as being, doing, and becoming materials.

seem to afford modifications, or that get treated as part of the landscape, rather than as part of the design, the conversations they have are *being* material conversations. In this way, the materials have high agency compared to the designers.

Doing materials

Doing materials *do* something in the design. Often, *doing* material conversations involve known characteristics of the materials—what they afford, what they can accomplish in the design problem or solution space. For instance, a designer might recognize that LEGO studs can be rotated 90 degrees simply by wedging a LEGO plate on its side between the studs on another LEGO. While “designed into” LEGO bricks, this insight is missed by most; LEGO bricks only whisper this secret to some. When designers work to accomplish some goal or property and reach out for a specific material to *do* that work, both they and the materials have agency.

Becoming materials

Becoming materials change or transform during the design process or through use in the designed solution. A *becoming* material conversation involves transformative or significantly changed uses and reconfigurations of materials, sometimes as a means to understanding or proposing tentative solutions. Such materials may be stand-ins for envisioned designs, with a complementary consideration of use. Continuing the LEGO example, a more irreverent designer might fundamentally alter the nature of a LEGO brick, such as by slicing the studs off, or gluing googly eyes onto them, resulting in a material reconfiguration that is itself a design; and as a result of this reconfiguration, the material becomes something new, for both designer and user. In both *being* and *doing* conversations with LEGO bricks, the material is unequivocally telling the designer not to do such a thing. But not all designers listen to this; some opt for becoming conversations as they see the new possibilities in a material's use. Such conversations involve shared agency, as the designer asks questions of the material and the material responds.

Being, doing, and becoming material conversations are all endemic to designing, but the ways in which designers chat with materials to shift from being to doing or becoming conversations is a learning process. Of interest in the present study are the ways in which materials—some familiar and some not—speak to learners as they design solutions to authentic problems. Heterogeneous engineering practices are the lens through which we can examine how learners navigate and coordinate sociomaterial entanglements within instructional settings.

Research purpose and question

Our broad goal in this paper is to explore how heterogeneous engineering design practices unfold as dialogic, sociomaterial conversations when the problem spaces are expanded, deepened, and complexified in ways that parallel authentic engineering and design in the world. By foregrounding relationships between sociality and materiality in this context, we attend to the ways in which materials—some familiar and some not—speak to learners as they design solutions to authentic problems. Heterogeneous engineering practices are the lens through which we can examine how learners navigate and coordinate sociomaterial entanglements within instructional settings. We showcase what learning is made possible when large and ill-structured problems are the tasks students take on, to explore the dimensions of heterogeneous engineering practices. We characterize heterogeneous engineering as a legitimate phenomenon that happens in large, complex design challenges, where materiality, sociality, and instructional design come together to support learners' engagement in engineering and design practices.

In this study, we ask: In what ways do large, complex design problems present opportunities for students to engage in, develop, and learn with heterogeneous engineering practices?

Methodology

We employ a case study methodology (Merriam, 2007) to present a comparative case analysis from curricular enactments at two different sites. Each case was developed from analysis of design and engineering projects with students in high school. The two focal projects for this paper, *Frankenstein* and the *Shake Table*, were selected to elucidate the emerging framework in particular ways. First, each project exhibited the characteristics of the framework set out by Jonassen (2000) for learning through problem solving. The problems were ill-structured, sufficiently complex, and domain-specific (see Table 1). In foregrounding the relationships between sociality and materiality, additional criteria were applied to consider each project's inclusion for analysis. The criteria were: (1) evidence that the designers imagined their artifact in use, where there was evidence that they were not making decisions based solely on the materials available or a solution preferences, but that these considerations were informed by how they imagined people might use their design; (2) the cases present both social and material considerations, where agency appears distributed across people and materials; and (3) the projects had clear evidence of how instructional designs and facilitation decisions supported the ways these sociomaterial entanglements were coordinated and organized. These criteria, coupled with Jonassen's (2000) characteristics of problems that support learning, comprise a means for identifying heterogeneous engineering in high school learning contexts.

Research contexts: Two classroom design and engineering projects

Frankenstein

The Frankenstein case draws from data collected as part of a larger design-based research (DBR) project focused on design pedagogies, making spaces, and disciplinary inquiry in a large urban high school in the Northeastern US. The project explored the installation of a making space in the high school, coupled with professional learning opportunities for teachers, exploratory design courses for students, and summer design and making programs. The full data corpus for the DBR project includes over 1,000 hours of observations, 355 fieldnotes, 396 video recordings (totaling approximately 227 hours of video), and over 2,000 images of student work. The Frankenstein case was developed from an 11/12th grade English classroom project, co-designed by the teacher and first author, an outcome of the professional development and curricular design activities situated within the larger project.

The case draws from a high-school English elective called "Monsters," in which students read and analyzed books about monsters. The culminating text was *Frankenstein* by Mary Shelley, which scholars have argued is about humanity, the consequences of our actions, of our love, and of what it means to be humans in the world (Ferguson, 2018). The teacher engaged the students in the learning activities customary in her English class (i.e., close reading, essay writing, argumentation) to refine their interpretations of the novel. The teacher recounted, "the [students] were slacking on the reading, so we slowed down a bit and had a couple of close reading essays thrown in to

Table 1. Cases in the study, with a description of the ways in which students address ill-structured, complex, domain-specific problems.

Cases	*Ill-structure* (multiple possible outcomes and solution paths)	*Complexity* (multiple variables and relationships between variables)	*Domain-specificity* (relevant disciplinary and contextual knowledge)
Frankenstein	Students (n=18) in an English classroom explored ways of expressing their understandings of Mary Shelley's *Frankenstein* by producing a piece of interactive public art that would engage the viewer with the themes of the novel.	Their design involved themes (animation, creativity, connectedness, and, interaction) embodied in a complex multi-touch light and sound object. User interactions involved touch, sound, controls, and structural elements. Assembly required coordination of all parts into a coherent piece of functioning multimedia art.	*Socio-political context*: Public art as medium for expressing issues related to youth lives culled from a novel, attending to the user experience with the piece. *Domains*: English language arts, engineering, computer science, physics.
Shake table and seismic retrofits	Students (n=8) designed a more accurate shake table to test other students' (n=18) spaghetti skyscrapers (with and without seismic retrofits). They wanted to produce destructive surface waves that were reproducible and controllable.	The notions of control and reproducibility influenced design ideas about seismic wave production in their model. Material properties related to one another: the spaghetti skyscrapers had to stick well enough to the surface of the shake table; the material had to transmit waves across the surface.	*Socio-political context*: A social component emerged through two competitive moves the facilitators made: pitching the students who made towers against those who made the shake table, and another group of students who wanted to make a shake table using a motor. *Domains*: physics, geology, and architecture.

ensure they could defend and discuss their interpretation of the text." They had discussions about "coming to life," "connecting and interacting," and they lamented the impersonal nature of social media, saying that there was not enough "face-to-face" communication. These discussions contributed to the distillation of core themes: animation, creativity, connectedness, and interaction.

The students were challenged to design and build an artifact to express those themes, a radical departure from essays and other expected final projects in an English class. The students accepted the challenge and agreed the themes would guide the design and construction of a piece of public art. According to their teacher, they decided to "bring people together to create something new." They set out on a process of activity-centered design (Norman, 2005) to build a piece of interactive art that would engage their community with the themes of the novel.

Shake table

The *Shake Table* case was developed from data collected through a 9-month participant observation at a design-build, project-based, not-for-profit charter high school in the Southwestern US. The school has a social justice mission, providing significant social and wellness support to reengage students who previously dropped out or were habitually truant; a higher than average percentage of students qualify for special education services. A majority speak a language other than English at home and qualify for free/reduced meals. Teachers designed and co-taught interdisciplinary, cross-grade projects that engaged students in designing and constructing, while meeting state curricular standards. The full data corpus comprises over 1,000 hours of audio and video recordings, over 3,000 pages of field notes, and over 9,000 images of student work. We selected one case with three co-teachers—a science specialist in his probationary first year, a special education teacher with a science endorsement, and a history specialist. The sustainable skyscraper project, which included physics, history, mathematics, and English, typified heterogeneous engineering as students developed case studies on the history of skyscraper innovation, considering social, political, scientific, and technical developments that led to changes in skyscraper construction and legal requirements—like seismic retrofits to compensate during earthquakes. They investigated the physics of skyscraper design, building a city of different skyscrapers from spaghetti and testing their capacity to withstand simulated earthquakes. They proposed new skyscraper designs for their city, considering local context, especially water shortages and climate change effects. From this, we chose to focus on the capstone (senior) students' task about three weeks into the project. While the rest of the students were tasked with creating their own spaghetti skyscrapers, with and without seismic retrofits, the capstone students were tasked with designing a shake table to test the skyscrapers.

Data sources

Data for the two cases includes audio and video records, field notes, photographs, artifacts of design work, and ethnographic interviews (Table 2), each

Table 2. Details about data sources by case.

	Frankenstein	Shake Table
Timing and duration of project	3/30/16-5/15/16; 21 sessions; 25 hours*	1/11/16-3/17/16, 40 sessions; 80 hours
Audio & video records sampled or selected from corpus	Selected 6 episodes, 5 total hours	Selected 10 hours that covered shake table scope
Pages of field notes	12	20
Artifacts (number of photos)	46	17

* plus additional after-school and study hall hours.

set specific to these curriculum projects. Specifically, we documented students' design process and conversations, including discussions about ideation, planning, disagreements, fabrication, and evaluation and reflection. Some discussions were instigated by teachers, while others emerged from collective, heterogeneous design work. Student design process and products were documented as students iterated across designs; this includes photographs of notes, drawings, and models, as well as video recordings. A participant observer made field notes to document the broader classroom activities and specific instances of student work. The researcher debriefed with teachers during or following the sessions and interviewed teachers about their perceptions of the design work.

Analytic approach

Given the overall density of the data corpus, the analysis began with a comprehensive content logging of the data sources (Jordan & Henderson, 1995) for each case, making specific note of design negotiations, ideational conversations, and particular forms of interactions including student-student and student-teacher dialogue. From these logs, the authors collaboratively constructed a set of criteria for identifying moments that contained explicit material considerations and deep sociality, guided by our theoretical framework. The inclusion criteria for identifying moments in the data logs included: observable deliberations about design decisions; explicit use of materials in conversation—students talking with, and through materials; evidence of a division of labor (including ideational dialogue) between designers; and evidence of shared agency (Pickering, 1993) looking specifically at patterns in discourse (borrowing from the *Agency Toolkit*, Konopasky & Sheridan, 2016).

From the set of identified moments, we nominated specific episodes where sociomaterial entanglements were evident and began a process of repeated viewings (Derry et al., 2010), complemented by transcripts of conversations that included descriptions of actions and behaviors. Where possible, we added screen shots from video data to the transcripts to illuminate aspects of these sociomaterial entanglements. These viewings were used to identify focal episodes for further analysis.

We conducted interaction analysis of these focal episodes (Jordan & Henderson, 1995), with particular attention to segmentation (the rhythm and flow of longer events, as well as ruptures in norms) and the temporal organization of activity. In this, we were guided by notions of micro, meso, and macro scales, and how these influence each other (Lemke, 2000, 2001).

Because each case represents multiple weeks of activity—the macro level—looking across levels is particularly important for understanding the complex processes of learning in design, sometimes made visible in the evolution and emergence of new meso scale routines or micro-scale discourse patterns. In much research on learning, the commonplace short durations of hours or days can relegate macro-scale phenomena to "context," but in studies that trace learning over weeks or months, the macro scale can make particular meso and micro scale phenomena salient. In our case, mapping out the macro scale as timelines helped us identify data to focus on for more detailed analysis, and in turn, to anchor that analysis to the specific meso scale routines set within the broader macro-scale arc of activity, even as we focused on microscale sociomaterial conversational turns.

We attended to interactional patterns and divergences displayed in turn-taking in talk and with materials, trouble and repair in talk (Goffman, 1983), and the spatial organization of and access to materials and activity. In this process, we sought to uncover differences in talk-driven and instrumental interactions; we anticipated this would reveal differences between the kinds of design work that happen in planning versus reflection-in-action designing (Schön, 1992). Likewise, with a design context, we wondered about the degree to which participants had agency to make changes to shared design work, how instructional factors contributed to shifts in agency, and together how this supported learning. Our analysis made use of video segments and transcripts supplemented by screenshots from the video,[1] supporting simultaneous consideration of social and material elements of discourse.

The interaction analysis provides fine-grain detail and to address more macro-timescale arcs we conducted a thematic analysis (Braun & Clarke, 2006) for each case, building from our initial framework considering material, social, and instructional dimensions of the data. These analyses helped to elucidate aspects of the framework and the relationships between heterogeneous engineering and learning, across timescales. This analysis was used to produce macro-timescale arcs of the cases that illuminate the interplay of social and material conversations, situated within the instructional settings of each project.

[1]Following the tradition of interaction analysis, transcripts are numbered by turns of talk. We offer additional information to support readers' interpretation of certain lines in the transcript using parentheticals, and we use brackets to describe gestures and actions. The transcript segments for Case 1 are numbered continuously, to reflect the continuous nature of that conversation. The transcript segments for Case 2 are numbered to reflect discontinuity, with each segment numbered as a contained set to mirror the timing of the discussion over the course of 4 days of work. For example, segments 110 and 145-156 both happened on the first day, segments 200-201 and 207 happened on the second day. Transcript conventions include (.) for short pauses,//for interruptions,::: for drawn out sounds, and [...] to reflect a discontinuity in turns of talk within a moment.

Our findings present analysis of our two cases to highlight heterogeneous engineering in high school classrooms. We worked from the smaller moments that exhibit the characteristics of heterogeneous engineering in action, which we argue allows us to hone the analysis of sociomaterial entanglements.

Findings

Our comparative case analysis of the two design challenges illustrates how materiality, sociality, and coordination brought about through facilitation comprise a design problem ecology that emulates Law's (1987) conception of "heterogeneous engineering" for high-school students. Our findings suggest that in large-format design problems, students enter into multiple conversations with different components of the design problem ecology: conversations with the materials, with the framing of the problem, and with the coordination required to enact designs. Both cases illustrate the complexity of sociomaterial entanglements, but the first (Case 1) puts sociality at the fore and the second expands on conversations with materials (Case 2). For each case, we first display an analysis of the macro-timescale arcs of each design team's work, highlighting how materiality and sociality within the instructional context played interrelated roles in shaping the progress the students made toward solutions (Figures 2 & 4). These arcs demonstrate the breadth and complexity of these *big problems* that we claim are central for heterogeneous engineering in the classroom. The focal episodes are used to examine specific aspects of our argument, but it is important to remember that they are instances within the larger timescale arcs of these intense and substantive design problems.

Case 1: Frankenstein

This case focuses on the Frankenstein project. The macro-timescale arc presented in Figure 2 illustrates the overall scope and sequence of the project. The project was ambitious, incorporating many nested and complicated elements; a scale that was daunting for mostly first-time designers. The teacher, Ms. B noted "We struggled with visual metaphor, more than expected. They got really stuck on a literal image." Their themes were expressed with specific words—animation, creativity, connectedness, and interaction—and Ms. B. noted that the students focused narrowly on literal translations of those words, which she thought was stunting their progress in developing design possibilities. These challenges revealed the need for significant problem framing and scoping in order for students to develop a design, and facilitation by Ms. B and the research team helped to coordinate the sociomaterial considerations.

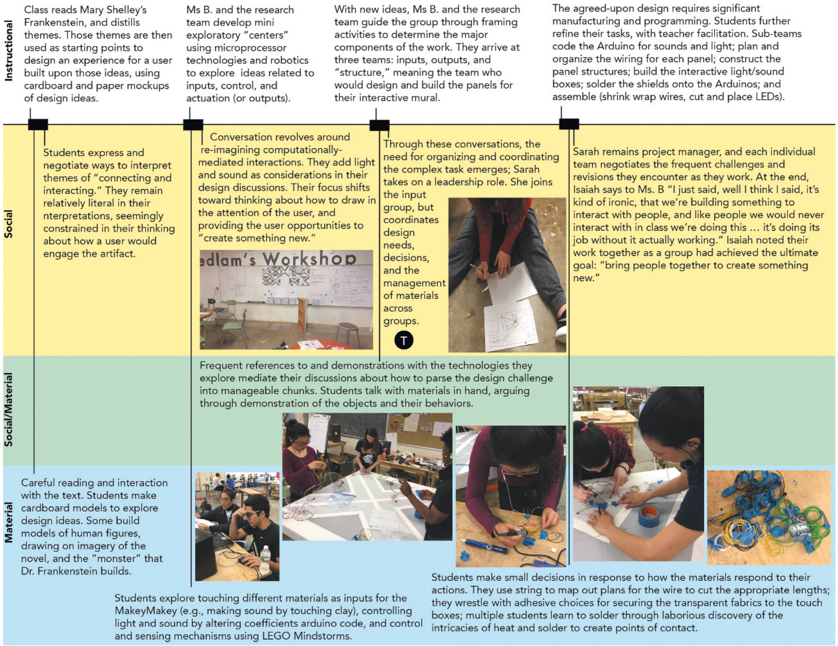


Figure 2. Macro-timescale arc of instructional, social, and material interactions in Case 1. The T indicates where transcript reported in the paper originated.

To support the students' coordination of multiple design elements, Ms. B first showed pieces of art, including a mixed media collage based on Frankenstein, to explore how artists blended message and material. In addition, the research team developed a series of short activities for students to explore *sensing-control-actuation* paradigms with different tools. Students played with simple adjustments of code on pre-programmed Arduinos to change colors and frequencies of blinking LEDs. They explored "fruit pianos" with Makey Makeys, where touching bananas controlled a computer piano simulator. And they played with pre-built LEGO Mindstorms robots to examine proximity, light, and touch sensors.

These activities were designed to support the students in coordinating elements of the proposed project, and they were followed by continued design conversations. Ms. B emailed her reflection on their ideational discussions, "They'd like to go biggish. Lights, they want to incorporate lights (Frankenstein/electricity/brings creature to life), they said 'people are drawn to flashing lights and will think it is cool.'" Going "biggish" resulted in rough plans for three large interactive light and sound panels where multiple users collaborate to play music with the piece (the final project is shown in Figure 3). Completing this design meant tackling distinct yet interrelated components like building the frame, programming the microelectronics,

Figure 3. Images of the completed Frankenstein project, (left) a three-panel interactive public art mural that lights up and plays sounds as groups of individuals pressed the copper strips along the outside of each of the cubes; (right) the cubes were the objects that Sarah, Kavi, and Chunhua were designing in the focal episode of Case 1.

constructing the interface, and wiring and assembling the panels. As mentioned, the scale of the task was daunting.

The class separated themselves into three design teams: Inputs, Outputs, and Structure. Each team was responsible for designing that element of the project (e.g., Input group was responsible for the user interface), and with Ms. B's help, they worked to synchronize the three components. The focal episode from this case specifically illustrates the interplay of sociality and materiality in design conversations. The students wove together their desired impact for the piece and the material possibilities by conjuring a user in an example of heterogeneous engineering in practice.

Focal episode: How will people interact with the Frankenstein?

Three students in the Input group, Sarah, Kavi, and Chunhua, were charged with designing the "box" that users would touch to play music and sound. Ms. B, asked them to "come up with a model of what we can use for this little box, thinking about what we'll be touching specifically, and what's in this (the front face of the box) space." Implicit in their charge was the need to consider materials, structures, and user interactions.

The design was only minimally framed at this point. The students sat around a table in the school's makerspace and began discussing the possibilities for their design, centered around the idea of a box that users would touch. Just before the transcript begins, the teacher checked in with the group, and Sarah shared the group's collective agreement that the "boxes" (or cubes) that people will touch as part of their piece of art should have some kind of transparent front so that the light can shine through (see Figure 3). The three students sat silently for a few minutes, looking things up on their computers and phones before Sarah started:

1 Sarah: Let's make decisions today.
2 Sarah: OK, so, for us … do you want to touch the face *[pushes hand forward simulating pressing the front of the cube]* or the sides? I think the sides would be more comfortable…

3 Kavi: Like the sides of the cube? *[Uses hands to simulate the sides of the cube]*

4 Sarah: Yeah, like, it's gonna be 3D. So, think of it like…
5 Kavi: Cause I feel like people won't understand that…
6 Chunhua: I think it would be easier to touch the face, but then have the pull…
the lights come out the side.

7 Sarah: Yeah, we could do that. The ones I guess, I don't know how to make that work… I mean, cause we could do a piece of cardboard front *[grabs a square piece of cardboard]*, or something metal, whatever, and then we could have like posts kind of. Right? Posts? And then the lights could shine through the sides. Because if you put like woods on the sides, you're not going to see the lights.

8 Kavi: I feel like, like, the, a cube sticking out, can be floating a little bit off, so the light can still come out.
9 Sarah: Yeah, that's what I mean, it's going to be like 3D//
10 Kavi: //Ok (.) yeah.
11 Sarah: //so it's still coming off (.) So you'll have sides to touch, like, you can touch, like, it'll be thicker than this *[holding the cardboard square]*. You can touch the top, the bottom, whatever. And the front, you really only can't touch the back. Er, whatever.
12 Kavi: I don't, ah, yeah [inaudible].
13 Sarah: Ed's (another student in the class, but not in this group) idea is of course more obvious (using large buttons instead of boxes of light), but I think, the lights won't happen.
14 Kavi: Like, for me, the whole thing, OK, like around it. It'll shine onto it, and bounce off. It'll still have impact.

Sarah was interested in making decisions (turn 1), and the possible configurations she offered for the boxes satisfied two primary, yet still ill-defined, requirements: the user must be able to touch the box, and light will shine from it. She suggested that touching the sides of the box might be more "comfortable" than the front of the box (turn 2). However, in earlier discussions she wondered about using a transparent material covering the front of the box that would let light shine through. Her proposal to touch the side of the cube accounts for the transparent front, meaning the users hand would not impede the light from the LEDs. We interpret her proposals as managing several questions simultaneously: how do you touch it, where does the light shine from, and what are the material considerations? The array of concerns suggests she is imagining the materials in use by conjuring a user. She, Kavi, and Chunhua are engaged in a design dialogue where they are negotiating ideas among themselves, the materials, and this conjured user.

Touching the sides of the box clashed with Kavi's sense of that conjured user's experience. He asked Sarah for clarification (turn 3), gesturing how this conjured user might touch it, "Like the sides of the box?" Sarah confirmed his interpretation, and Kavi continued to wonder how the user would respond to that design (turn 5). Chunhua stepped in to suggest that touching the face seems "easier," aligning with Kavi's concerns. She also suggested that the lights could shine out of the sides of the box. Her comment surfaced a possible assumption that the light would come from the front face of the box. Her suggestion to touch the front opened the option that the lights could also shine from the side of the box (turn 6). Sarah built on that idea—light can come out of the sides of these "cubes"—by grabbing a piece of cardboard to represent the front face of the cube. She described possible ways of making this "3D" cube, including using "posts" (perhaps instead of opaque sides) and ideas for front materials (turn 7).

Kavi built on Sarah's ideas, clarifying that the front face, represented by the cardboard square, could be raised off the surface of the frame to allow lights to shine from the sides. Sarah talked through where the user might be able to touch it—the sides, top, bottom—and Kavi offered a tepid approval of these suggestions (turn 12), now seeing how it might work to have the the lights come from the side. Moreover, he seemed to think the light would shine from the sides, and that "It'll still have impact" (turn 14), which we interpret to mean that he thought the conjured user will experience the intended interaction.

In this short exchange, three students on the "Input" team negotiated the conjured user's experience, the intended "impact" of the piece, the required functional aspects of the cube, and potential material options. The groups' ideation introduced multiple dialogics, not only among members, but with the materials and a conjured user. Thinking *with* each other, the materials, and the conjured user involved the designers negotiating disagreements or inconsistencies regarding the ways they imagined this object would behave. This kind of deep sociality—exhibited by the sociomaterial entanglements—is germane to heterogeneous engineering. To further explore these ideas, we continue with Sarah, who turns to ask Ms. B a question:

15 Sarah: Yeah, I'm thinking, Ms. B, I have a question (.) Do we have to constantly be touching to keep the circuit complete? If we take our hand off, will the light motion stop? Or, do we have to like put our hands on it

and hold it? Or can we touch it and take it off and leave the circuit on?
16 Ms. B: No, I think you have to hold it.
17 Sarah: Ok. So 'Cause, I'm like, um. 'cause, like, if we do the front transparent, we'd have to touch the sides, but then it would be less obvious to people. But if we do the sides, no, the front where you touch, and the lights will come off the sides, I feel like it would be harder to do 'cause you'd have wood or something (.) how would you do it on the sides?

Achieving the desired "impact" of illuminating the cube meant understanding possible configurations for the materials. If the front of the cube is transparent, Sarah argued (turn 15), the user must touch the sides, which is less obvious as Kavi had already pointed out. If the user touches the front, the cubes must be strong enough to withstand a push. In both cases, the user must "hold it" (turns 16–17) to keep the cube illuminated. Sarah's questions represent attempts to clarify the requirements of their design, directing explicit attention to the materials as understood through the conjured user's actions. Sarah's questions suggests the group treated the available materials—wood, cloth—as knowable, readily available options for the design. The purpose and possibilities were evident in the designers knowledge of and history with these commonplace materials. The circuit materials, perhaps less familiar and in need of clarifying, were assessed as though their function was predetermined by the material itself. The group's exchange, led in this segment by Sarah, amounts to engaging with the known and designed natures of these materials to shape the possibilities of design. This exchange *between* Sarah and Ms. B, but also *with* the materials and conjured user, continued.

18 Sarah: Like if you have, if you have, if you touch the front, lights would have to come out the front so you could still see it, right?
19 Ms. B.: Well, then you're thinking about size, so maybe you make something bigger than hand size, so your hand isn't covering…
20 Sarah: That's true too.
21 Ms. B.: Or maybe you think about shifting it to the side, and maybe the color of your sides are…
22 Sarah: I mean, we could also have like a little, kind of, plate.
23 Kavi: 'Cause the problem is, is that, like, if you want the front to be able to touch and also to light up, then it has to be somewhat clear (.) or, the thickness of it has to be slim.
24 Sarah: Yes, 'cause the cloth could be conductive.

Sarah, Kavi, and the teacher navigated this space of material realities together, within the scope of the imagined input: the user touching the front of the cube. One danger is that touching the front with an open palm would cover where the lights shine from, diminishing the "impact" of the piece (turn 18). Ms. B suggested they could remedy that issue by having a large enough square so that light shined around the hand (turn 19). But Kavi worried again about the structural requirements (turn 23), that whatever you touch is thin enough to allow light to come through, but strong enough to receive the push from the user's hand. Sarah reminds the group of the need for the material to be conductive (turn 24).

25 Kavi: Yeah, but the problem with that is that usually things that are thin and that we could use are not really conductive.
26 Ms. B: Yeah, I remember…
27 Sarah: And you don't want it this way *[places palms close together, indicating a thick material]*
28 Ms. B: Like, you could use electric spray-paint, like, you put that on something and you turn it into what?
29 Kavi: The paint? Yeah. Like, that works. But that would have to be on the outside. In order to touch that, and sort of grab it.
30 Ms. B: Right, so anything you have will have to be on the outside.
31 Sarah: Like the sides?
32 Ms. B: Yeah.
33 Sarah: So the face can light up?
34 Ms. B: Yeah, like anything you pick, like if it's aluminum…
35 Kavi: So, like the lights might have to go front… the sides… *[gesturing light coming out the sides and top]*
36 Sarah: No the light will be in the front, and you'll have to touch the sides.

This exchange illustrates the group's active coordination of the myriad considerations in their design. Options for where to touch the cube and where the light will shine were complicated by the issue of conductivity (turn 25). Playing with the Makey Makey earlier convinced them that touching an object to play music and lights was a behavior they wanted their piece to perform. Incorporating that action into their design involved serious functional and material considerations. Perhaps their limited or nascent understanding of conductivity encouraged them to treat some materials as having specific design functionality, whereas other more familiar materials, such as wood and cloth, were treated with more flexibility and possibility. In this exchange, they began to narrow the set of possible materials using two criteria—transparency and conductivity. Cloth was floated as an idea for the front face of the cube, satisfying Kavi's concerns about "thinness." Sarah seems to confirm the interest in a thin material by gesturing as she says "you don't want it this way" (turn 27), holding her palms at a distance to perhaps indicate thickness. At the same time, materials "thin" enough to let light through may not be conductive. Ms. B offered paint as an option, and Kavi agreed that could work (turn 29), but it had to be in a place that is easily touched. The exchange ends with Sarah confirming that the light will come from the front, and the user will touch the sides, essentially locking down the functional requirements at the end of this long negotiation and sociomaterial conversation. As they continued to discuss how to realize this design concept, Kavi reiterated that he is uncomfortable with the idea of touching the sides of the cubes (turn 37):

37 Kavi: I'm not liking that you have to touch the sides to make it work. I feel like people won't understand that. And, because if you see something cubed, and then, there's light around it… then they go, Oh!, I can probably touch this and they go *[gestures putting his flat open hand on a button in front of him]*.

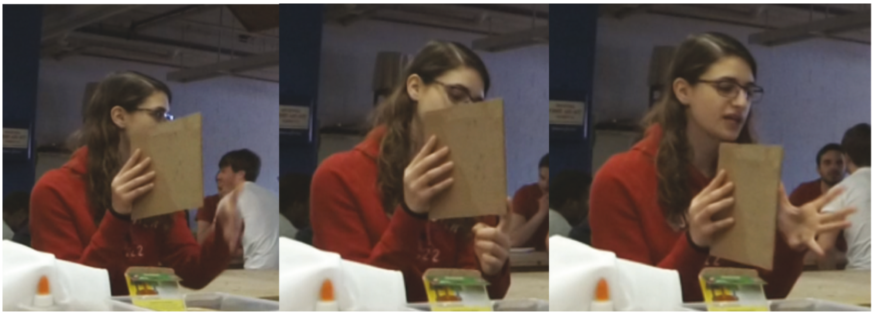
Kavi continued to invoke the actions of the conjured user in his thinking about how to design the interactions for the cube. Suchman (2000a) writes about the acts of persuasion in complex design, and this episode reflects the challenge these designers faced in determining how their idea would be realized given multiple human and material constraints. Kavi's persistent reminder of the user's experiences worked to continually organize the system to align with the many "unruly contingencies" of authentic design in practice. In other words, Kavi, along with his group, was trying to bring material, social, and technical considerations into conversation with each other.

As the students continued to discuss, Ms. B said, "So I think you have to kind of, like, accept that you have some material limitations, and make a compromise with the materials that you have." In effect, she offered them some reassurance, or allowance, to move forward with their ideas even if they were not neatly stitched together in ways that made complete sense to them; she let them know that their work as designers was a constant conversation among each other, the problem, and the materials at hand. The group finally arrived at an idea that seemed to reconcile all of the concerns raised across the conversation:

38 Kavi: Like a, like a little or metal or something to make up like a plate on the front that you could… but, you could… I mean I like the edges. 'Cause all you need is a finger.
39 Sarah: 'Cause like how much of the, how much of the edge are we talking about?
Is it going to be super thin, or is it going to be…
40 Ms. B: So when you were doing your, um, when you were playing around with the materials, think about well what, how much of it did you need to touch to make it work? Did it work with like a finger?
41 Kavi: Yeah, it worked with a finger or a whole hand. So it doesn't really matter…
42 Sarah: So, like, you could do, like, a little *[she grabs a square piece of cardboard and holds it up with one hand]* (.) so say this was the block *[points to the cardboard with her other hand]*, and then, it's like, it's 3D *[runs her fingers around the edge]*.
43 Kavi: Yeah. *[Ms. B walks away]*

Kavi suggested that "all you need is a finger," (turn 38) and that realization by the group supported them in seeing how the tensions between design ideas and constraints could be resolved. This marks a convergence of the goals for the design with the materials available and known to the designers. Now realizing that the touch was for conductivity, and that it only required a finger, touching the "sides" meant different things (turn 37). A finger along the edges of the cube could work as a point of contact, for example, and Sarah, Kavi, Chunhua, and Ms. B worked that out together. Their work entailed ensuring the technical considerations of conductivity met the aesthetic and user demands, evidence that they were exploring ways these materials *could* be used in their design. This was conducted between members of the group in a multidimensional, yet harmonious interweaving of considerations and constraints. Sarah's move (turn 42), grabbing a piece of cardboard to describe her proposal to Kavi with a performance, put the material into conversation with the designers.

44 Sarah: So picture the sides of it. If you touch, like, the sides of it or something…
Right? Like right here on the corner. So, this will be the face where the light comes out, and there will be like a frame around it



45 Kavi: Are you talking about… hold on… *[he walks around the table to get the material from Sarah]* So, let's say, like, if we fold this here, here, here, and here *[showing how he would fold each side of the square over a bit]*. Like, fold it like that?

46 Sarah: No.
47 Kavi: No?
48 Sarah: No, so…
49 Kavi: So, you're talking about, like, actually touching this part? *[He runs his finger along the edge of the square]*
50 Sarah: Hmm, hmm. Of the front. So, like, we can put a frame around the cloth *[Kavi hands square back to Sarah]* … too lock, like, say, like, we have the sides. It's hard to say without… I, like, know what I want to say, but I don't know how to say it to make sense. So, like, we have, like, the sides… I need like a diagram. I wish we had…
51 Ms. B.: Yeah, take some paper.
52 Sarah: No, I wish we had like a proto-thing I could just draw on, like a box. Do we have a box?
53 Ms. B.: So make one.

In this final exchange of the episode, Sarah took a material object—the square piece of cardboard—and began gesturing to describe how she imagined it could work (turn 44). She appeared to be convincing Kavi and Chunhua that touching the sides while the light comes out the front could still work. Kavi took the material at one point to contribute to the imagined design, bending the sides slightly, but Sarah confirmed that move was not even required; the strip of conductive material is thin (the class had already explored copper tape as a conductive element), and it could be layered around the edge (turns 45–49). It is through this material manipulation that the disagreement around design solutions was resolved; the materials played a role in supporting the collective reconciliation of many factors, including issues of structural integrity, material functionality, and user experience. Sarah motivated the need to move from discussion to construction when she said, "I wish we had like a proto-thing," suggesting her imagination of new sociomaterial possibilities.

After weeks of work, the groups' design was realized as a constructed piece of art (Figure 3), where users could touch thin strips of copper along the sides of different panels to play different tones and colored lights. The piece of art was functional, and it was displayed in the school's common area just before the end of the term.

Case 1 discussion

The Frankenstein case draws from a whole-class collaborative design and engineering project, of the sort we argue can embody heterogeneous engineering practices. In this English class, the students embarked on a large-scale, complex, and multidimensional making project. The focal episode showcases one of three teams working on one element of the overall design. Kavi, Sarah, Chunhua, and Ms. B. engage in a sophisticated dance of deliberation and coordination. Their task was designing the "cubes" that serve as user inputs for their overall piece. Their discussion illustrates a competent organizing and managing of multiple, interrelated constraints that emerged from their design conversations with each other and with materials. Of particular note is the role of the *conjured user* in their sociomaterial entanglements. Kavi first introduced the imagined user as a means of drawing his co-designers into the space of imagining how people would respond to their artifact. We see this conjuring of a user as a signal of authentic deliberation, and as evidence of the designers' entanglement with each other and the materials and their imagined use. The *conjured user* functioned to coordinate multiple, sometimes competing, considerations including where to touch the cube, where the light will shine, how the cube will be built to withstand the interactions, and how it will conduct electricity, all while keeping the imagined experience—the "impact"—in mind. This conjured user became another participant in their sociomaterial conversations, and served to organize their attempts to coordinate the social, material, and technical aspects of their design.

The simultaneous coordination of issues of material, use, design, and intended "impact" captures what we mean by a sociomaterial entanglement. Tacking back and forth between ideas, responses, and tensions is a dance of coordination, which is characteristic of how Law (1987) and Suchman (2000a) described heterogeneous engineering. Design comes through the continual framing and reframing of the problem and possible solutions. We see the designers first constrained by perceived limitations of fabrics, wood, and the need for conductivity. These discussions treated the familiar materials as *being*, and more novel materials as *becoming*, for example, how the limits of conductivity and opacity were considered features of designed purposes of the materials themselves. However, their discussions evolved to where cardboard became the substrate for an imagined configuration, blending conductive tape, transparent fabrics, and a new way of interacting with the object that achieved the "impact" for the piece. In this way, the cardboard was a *doing* material, occupying a function of allowing the designers to imagine possible uses and designs as they worked to reach an agreement about how to build the input. In this instance, the cardboard square took on the imagined properties of conductivity, illumination, and shape as they talked with it and through it. The tacking back and forth between ideas, responses, and tensions now involved materials and what they might become in the design.

We also acknowledge how Ms. B. contributed to the decision to parse the design work into groups. Working on the project as a whole class surfaced the need to distribute design responsibilities focused on the major elements of the project. Ms. B played a role supporting the students' decision to separate into input, output, and structure groups. She also supported Sarah's bid to serve as a "project manager," after she expressed interest in coordinating the multiple threads of the class project (e.g., ordering materials, attending to the interfaces between components, managing schedules). Shifting the structure of how the groups worked, how coordination was distributed, and who had decision making power reconfigured how agency functioned during the project. In the focal episode itself, Ms. B. encouraged them to explore different materials (turn 34), while also directing attention to prior experiences they had with materials they were considering (turn 40). Both through decisions or suggestions about how to structure the instructional context, and through discursive moves, Ms. B. contributed to the acts of organizing in this example of heterogeneous engineering. Taken together, the case and episode illustrate a keen navigation and coordination of the sociomaterial entanglements of the situation, where the designers engaged in authentic design practices with associated opportunities to learn with and make sense of the materials in their hands.

Case 2: Shake table

This case, drawn from the design-build project-based school, traces capstone (senior) students' design work within a project focused on sustainable skyscraper design. We chose to focus on the third and fourth weeks, as this highlighted the role of the conjured user and coordination (see the macro-timescale arc in Figure 4). During this time, as the students designed two identical skyscrapers from spaghetti, adding their seismic retrofits to one, the

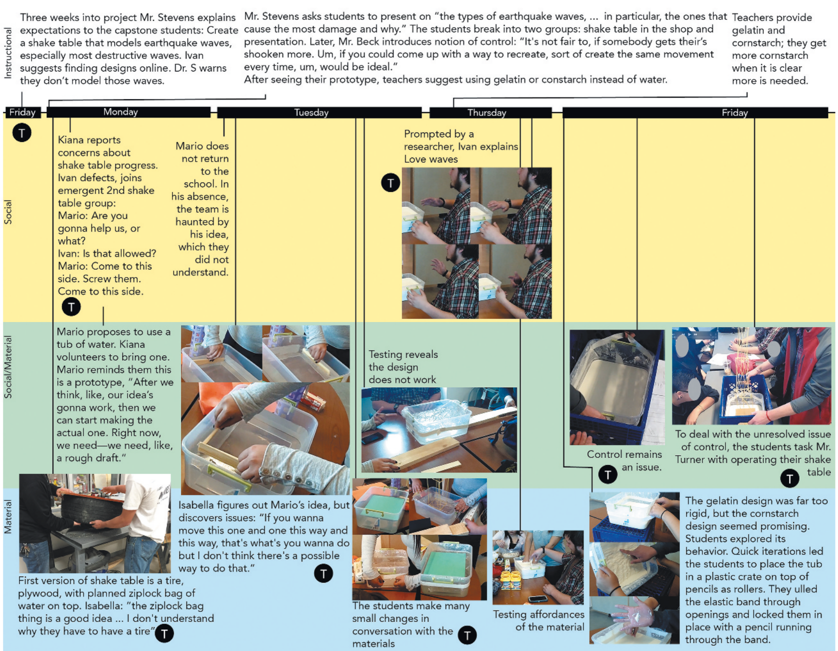


Figure 4. Macro-timescale arc of instructional, social, and material interactions in Case 2. The T indicates where transcripts reported in the paper originated.

capstone students were tasked with designing a shake table on which to test the skyscrapers. The capstone students included Isabella, Susannah, Kiana, Jorge, Mario, Ivan, and four others who did not provide consent.

Focal episode: How can damaging earthquake waves be reproducibly simulated?

Mr. Stevens and Mr. Turner gathered the eight capstone students present to discuss their plans for designing a shake table:

1 Mr. S: You're gonna need to figure out whatever types of earthquake waves—which ones cause the most damage and then figure out how to model those on a small scale.
2 Ivan: Yeah.
3 Mr. S: You saw the spaghetti towers [skyscrapers] that they're gonna build. They're gonna be no taller than three spaghettis high. […] You've gotta have multiple drawings that show the design of your shake table that include materials, how and why it recreates the waves that you're looking for, a perspective drawing of the table and an exploded drawing of the parts of the table, alright. […] How do you guys wanna do it? You guys have been here long enough to make that decision. You guys are capstone. Figure this shit out. Talk to each other. What are you gonna do.

The students then discussed how to tackle the work, which in addition to creating a shake table included formal design drawings explaining how the shake table recreates the damaging waves and case studies of buildings that failed in earthquakes. They decided to split into two groups along friendship lines: Isabella, Kiana, Jorge, and Mario focused on preparing the case studies while Ivan, Susannah, and the other students focused on building a shake table.

On the following Monday, Mr. Stevens spoke to Isabella, Susannah, Kiana, Jorge, and Mario while the others were working in the shop. He added a twist —a presentation to the rest of the class about seismic waves:

110 Mr. S: I need some, like a small group of you guys in here, and doing a presentation on the three types of—or the types of earthquake waves and which earthquake waves cause damage alright, because in:: looking at this, I'm just realizing that we don't have the—that information yet. I'm gonna get them started on a reading with how much uh how much buildings move and like the bigger picture, like what happens. But what I need you guys, is to do is help me out by doing a presentation and yeah the types of earthquake waves in particular the ones that cause the most damage (.) and why they cause the most damage.

In this request, Mr. Stevens showed trust in the students to provide an informative presentation. By explaining "I'm just realizing that we don't have the—that information yet" his request positioned the students as sharing some ownership over teaching their peers. Yet, the presentation also served to motivate capstone students' efforts and provided a means to assess their understanding. After checking in with the other students, Isabella expressed concern that "what's gonna take the longest is making the shake table. So, we need, like, enough hands back there to get it done by tomorrow." She then checked with Mr. Stevens about "What kind of presentation do you want?" and when he responded, "Don't lecture" she explained she had a plan and organized the remaining students to begin working on the presentation. After about an hour, she sent Kiana to check in on Ivan and the others, finding them reticent and working with a tire and a piece of plywood. After presenting to the class, Isabella and the other students who presented discussed the shake table with the teachers. This surfaced several concerns that would influence the remainder of their work:

145 Mr. T: The shake table- How are they trying to make it?
146 Isabella: They're trying to put a TIRE? (.) Ziplock (bag filled with) water. (.) Move. (.) Yeah. (.) So, like they're gonna have a tire and then, they're gonna have—put like this piece of wood on it.
147 Mr. T: What I was thinking was//
148 Isabella: //and then they're gonna like shake it with the ziplock of water on top because it supposubly moves the way Love waves *[damaging surface waves]* moves but they didn't listen to me when I was trying to explain Love waves so they don't know what Love waves are.
149 Mr. S: So
150 Mr. T: I have some different ideas I could just point out over there maybe
151 Mr. Stevens: So why don't you guys
152 Mr. Turner: Maybe make a box and like on one end do some sort of vibration or something to it
153 Isabella: And on the other end
154 Mr. Beck: You know the problem with doing that, if you do that, it just depends. It's not the same thing every time, it's um
155 Jorge: Different
156 Mr. Beck: And it'd be different for everyone

In turns 154–156, Mr. Beck raised concerns about reproducibility, a move that would later conjure a user for the capstone students. Mr. Stevens then described how the design Ivan, Susannah, and the others proposed addressed this issue, "The cool thing about the rheostat, the variable resistor, is that you can set it," but Isabella asked, "And how is that project looking right now. Is it almost done?" Thus, the students expressed doubt that the others would be able to finish the shake table successfully, and Isabella asked, "Is there any way we could do a box idea [building on Mr. Turner's suggestion]. And then just have two different groups and let them do theirs and us do ours?" With permission granted, they brainstormed ideas, and Susannah and Ivan defected to this second group. After a brief conceptual design session, the team seemed confident about a design proposed by Mario, who then never returned to the school.

The next day, with materials in hand, they attempted to create Mario's idea, which had involved a tub of water and wood shims. One of the researchers brought in some craft supplies, and upon deciding the promising idea was not so clear to them—as Kiana explained, "I really wish Mario was here cause he had a really good idea, like he didn't really explain it to us, but it was really good"—the students quickly iterated on designs. They filled the tub with water and tried various ways—floating a foam sheet, covering the water with plastic wrap—to stand up one of the partially completed spaghetti skyscrapers and test whether they could create particular types of waves. While the spaghetti skyscrapers might be thought of as the direct users of the shake table, the capstone students conjured the designers of those skyscrapers as they evaluated their shake table. They imagined those designers interacting with the shake table, and they expressed concern that if they could not reliably reproduce waves of the same strength, their own bias could impact students' grades:

200 Isabella: So we can't screw up people we don't like, and give people that we do like great grades.
201 Ivan: Have consistent results (during this, Ivan repeatedly pushes in the sides of the tub)
[…]
207 Isabella: And then you need to move these sides (indicating the ends of the tub) but it's not consistent because, (the teacher) can say that we're giving people we do like good grades and people we don't like bad grades.

As they tried various means to model the most damaging earthquake waves, they abandoned even promising approaches, repeatedly conjuring "people we don't like" and "people we do like." These means included: wrapping an elastic band around the tub as a means to wedge in wooden shims, pulling them back and releasing them; dropping a ball suspended from above such that it swings into the tub; hitting the tub with a wooden stick from one or two directions from a controlled distance, among others. By the end of the day, they discussed their realizations with the teachers: their approach lacked a means to control the strength of simulated earthquakes, and the water, even with various surfaces placed over it, was not working well. The teachers offered to acquire gelatin and cornstarch, and the next day, the students mixed up two designs, a mixture of ~4 cups of water and 10 packets of gelatin and a mixture of water and cornstarch (sometimes known as oobleck, a non-Newtonian fluid). While the gelatin mixture was too firm, the cornstarch mixture seemed promising to the students.

Across iterations, Ivan had repeated exchanges with the plastic tub. Although overlooked by others, these exchanges reveal his understanding of both material affordances and technical knowledge needed for the design to succeed. Even when the design was still purely conceptual (on Monday), Ivan brought up concerns, “How much water displacement do you need?” and “We need enough volume—we need to take up enough volume of the water to cause a disruption through the water.” As Isabella and Kiana worked to understand Mario’s idea (the student who did not return) in his absence, Ivan had a quiet conversation with the plastic tub, squeezing the sides repeatedly. This was not picked up by the others in talk or replicated in their gestures, and though for one moment Isabella indicated the ends of the tub as Ivan pushed in the sides, she did not seem to notice his idea. He contributed other ideas to their design, such as adding plastic wrap to cover the water surface, while still periodically pushing the sides of the tub in (Figure 5).

Before they prototyped their gelatin and cornstarch designs, Ivan explained his ideas to some of his friends who were not part of the project, revealing this conversation he’d had with the materials, which had not been heard by Isabella and the other capstone students.

Figure 5. Ivan had repeated material conversations with the tub.

325 Ivan: The first prototype—so basically—hit it with a piece of wood. Basically cause some movement here
326 *[Ivan snaps the elastic on the side of the tub, showing the first approach taken to make waves, that he was initially skeptical about]*
327 Ivan: Here. Here.
328 *[The water in the tub moves very slightly]*
329 Ivan: As you can see. Pretty much causes no surface reflection and I was—kept on telling them 'We need somebody who does this job.'
330 *[Ivan pushes forcefully on the sides of the tub, pressing them quickly, producing noticeable waves]*

331 Ivan: So we get the arc-shape
332 *[Ivan stares into tub watching the waves]*

In this brief exposition, Ivan claimed that he "kept on telling them" (turn 329), suggesting that his conversation with the materials seemed like a literal conversation, external and available to those in earshot, even though we found no instance of him putting this idea into words. While we recorded many instances of Ivan pushing on the sides of the tub in front of others, we found no evidence that the other students he worked with ever heard this material conversation. No other student ever pushed on the sides of the tub as he did nor suggested it as a strategy. For them, the plastic tub was there only to hold the primary materials of their design. In this way, Ivan had more insight into the broader system than the students he was working with, who treated the plastic tub as fixed.

Later, as Susannah and Isabella made their two designs—cornstarch/water in one, gelatin/water in the other—an embedded researcher asked Ivan about their plan.

375 Ivan: The way, uh Love waves yeah, so they have the rolling effect on the ground plus the compression and the tension
376 *[Ivan jabs the tub of water and cornstarch with his middle finger]*
377 Ivan: Yeah.

In this brief exchange, we see Ivan's understanding of the waves they aim to simulate (turn 375). Ultimately, Susannah and Isabella further revised their cornstarch-water mixture, and Ivan explained that although their model did not faithfully recreate the waves in the manner earthquakes do, the spaghetti skyscrapers still experienced the same type of damage due to the scale of the model. Indeed, as they tested the skyscrapers, the originals failed, while those with seismic retrofits survived. However, they never resolved the issue related to fair treatment of the conjured users whom they liked and disliked. Right before testing, Isabella showed this lack of resolution by explaining their design to Mr. Turner, "Our goal is to put golf balls (for the tub of cornstarch/water mixture to roll back and forth on, inside of a larger crate) in there and then it'll shake it." In saying "it'll shake it," the lack of a shaking mechanism is masked, but not yet assigned to a particular person. In the absence of golf balls, Isabella suggested glue sticks, and Mr. Turner offered a cup full of pencils. He then offered a way to anchor the elastic wrapped around the tub through handles of the crate. The students handed off the task of shaking the table to Mr. Turner simply by literally handing it to him. He took up his role, selecting a spaghetti skyscraper and testing it.

450 Mr. Stevens: It broke down there *[pointing to one of the spaghetti beams that broke in testing]*
451 Several: OOOooohhh!
452 Isabella: Good job guys. We made our project.
453 Mr. Beck: We broke it
454 Isabella: I broke it!

After the success of their shake table, Isabella and Ivan high-fived (Figure 6), and Isabella offered to share the cornstarch-and-water mixture with the other students who contributed to the design, a material that had become a prized possession.

Mr. Turner discussed the configuration of the final design with Ivan, who argued that "It's pushing actually, physically" (Figure 7). In this design, the waves came from the shaking motion, rather than from collisions, which

Figure 6. Ivan and Isabella high-five over their successful prototype.

Figure 7. Mr. Turner and Ivan discuss how their design functions.

contrasts with many of the prototypes they generated that involved hitting the sides of the tub to create the waves. Although their design traversed many forms and mechanisms—from tire, to water, to cornstarch and water—Ivan maintained a focus on the kinds of waves and means to produce them, evaluating the system of materials.

Case 2 discussion

Case 2 presents a project where students connected their design work to the history of skyscraper innovations, including cases of seismic failure and policy intended to prevent additional failure, and preceded to develop innovations related to local context and sustainability. The Shake Table focal episode exemplified heterogeneous engineering in how the designers' efforts were coordinated to build a city full of spaghetti skyscrapers to be tested on a shake table, designed by the capstone students. Because the capstone students designed their shake table to test the other students' spaghetti skyscrapers, their design work was inherently social and material. They contended with the scale of the spaghetti skyscrapers, which made them tip over too easily on the initial water-based designs. They considered, through iterative designs, ways to produce waves of an appropriate scale that could be controlled and reliably reproduced. This was driven by the instructional design, when Mr. Beck introduced concerns about bias (turns 154–156). We argue that an earlier instructional decision, presented by Mr. Stevens (turn 110), positioned these capstone students as co-teachers presenting key information to the students who were designing spaghetti skyscrapers. As such, the concern that the shake table must be controllable and reproducible led the students to conjure visions of those students they liked and did not like, and whom they might give "good" and "bad" grades to by shaking the table gently or vigorously. In turn, this led to rapid iterations in their design. The concerns about fairness were ultimately resolved by figuratively handing the power back to a teacher, and literally making the teacher part of the design. This sociomaterial entanglement, therefore, traversed concerns about bias and simulating scientific and technical information with materials that were both familiar and unfamiliar.

The instructional design supported the coordination of students creating their spaghetti skyscrapers and capstone students creating a shake table. At the same time, the instructional designs and decisions made space for capstone students to re-coordinate their design work in response to their concerns that those initially tasked with creating the shake table were not making sufficient progress—even though the teachers appeared to see value in the original idea and using a rheostat to control the shaking. The students' efforts to reconfigure and reorganize the groupings and design ideas is evidence of their shared agency with instructors, and it allowed for deep conversations with the materials of the situation.

These conversations involve *being*, *doing*, and *becoming* conversations. We argue that the plastic tub was a *being* material for most of the students—it held whatever they wanted to put in it—while also bringing attention to how it was a *becoming* material for Ivan. Ivan repeatedly pressed the sides of the tub inward to create surface waves, but this suggestion was never directly considered for the design by others in the group, though he remained committed to simulating these means for producing the waves as the design changed. In this, we see that he and others treated the water as a *doing* material, selected for its capacity to transmit the kinds of surface waves they sought to replicate. As they iterated their design, bringing in different surfaces to place onto the water, they likewise treated these as *doing* materials—materials that should support the spaghetti skyscrapers and move with the liquid underneath to form damaging waves. When they decided water would not *do* what they wanted to it do, they shifted to gelatin and cornstarch mixtures, both of which could be considered *becoming* materials, as they behaved in ways the students did not predict and they suggested possibilities that students had not previously considered. The gelatin was unexpectedly (to the students, but not the teachers) firm and barely wiggled, even when the entire container was dropped. The cornstarch mixture was new to them, and they spent time showing each other things it could do that violated their expectations of how it should behave, yet confirmed its usefulness for their purposes. They were surprised by how well it held onto the bottoms of the spaghetti skyscrapers, a stability issue they had not really addressed. Ultimately, Mr. Turner, the teacher who ran their shake table, also became a material component in their design. While we might view this as a *becoming* conversation, as a teacher became a trustworthy shaker, the straightforwardness of handing off the design for him to shake suggests they treated him as a *doing* material, performing a clearly understood functional role in their design.

Across these examples, some of the material conversations were quiet and despite being on display, were not heard by other students working on the design. Other material conversations were shared and provoked new insight. In this way, we see many forms of individual designers' conversations can become visible within heterogeneous work.

Discussion

We presented cases from two design projects to address our research question: In what ways do large, complex design problems present opportunities for students to engage in, develop, and learn with heterogeneous engineering practices? We argue that heterogeneous engineering practices involve designers simultaneously contending with social and material aspects of the problem spaces. To do so requires a particular kind of organizing, where different performances are coordinated and aligned across a large range of "unruly contingencies" (Suchman, 2000b, p. 313). In both the Shake Table and Frankenstein cases, students worked together with their teachers, within a particular instructional environment, to achieve these forms of sociomaterial design practices. Our discussion addresses how learners engage in sociomaterial entanglements as forms of heterogeneous engineering, the *conjured user* as an organizing act, and the role of instructional design and facilitation considerations in maintaining these kinds of productive learning environments.

Sociomaterial entanglements

Both cases demonstrate how conversations among people and materials opened space for group members to access and evaluate different aspects of their design. For instance, Ivan's conversation with the plastic tub surfaced opportunities for him to explore and understand the form of the waves that a shake table should simulate to mimic seismic activity. Similarly, as students designed the Frankenstein art piece, the conjured user helped them reconcile their confusions about functionality and design, and a cardboard square moderated their negotiations. In both episodes, as students immersed themselves in framing and designing solutions to their problems, new issues emerged requiring them to attend to deeper aspects of their problems. We understand these situated, authentic design discussions as sociomaterial entanglements, where people, materials, and ideas tangle to produce the kind of complex and ill-structured situations that Jonassen (2000) showed are important for learning. Embracing work within sociomaterial entanglements means engaging in heterogeneous engineering, forming authentic and engaging disciplinary contexts for learning in design.

When students take up this challenge of working within the entanglements, materiality can be understood in new ways. In the Frankenstein case, the initial considerations of the material possibilities could be characterized as *being* and *doing* material conversations. Sarah suggested using wood or metal to stabilize the cubes, treating them as familiar and available *being* materials, where their material possibilities remained relatively invisible. Discussions of conductivity cued *doing* conversations with copper tape and conductive fabrics. The conductive features of these materials were discussed, focusing the designers' attention to particular characteristics of the materials themselves. All throughout this evolving conversation, the students continually refined how they framed their design problem. These entanglements produced a need to consider materials in ways outside their *doing* or *being* natures, to find a way to bring stability, conductivity, and the user experience together into a suitable solution. The cardboard square surfaced as a *becoming* material in their deliberations. It was a proxy for reconsidering how different elements could fit together, and the *becoming* conversations emerged as the designers imagined new possibilities for achieving their design.

We wonder what might have been different if their conversations had entailed only *being* and *doing* conversations, leaving much agency with the materials. We conjecture that the becoming conversations were instrumental to reframing the problems. However, we are also not suggesting that productive design only involves *becoming* material conversations. In the Shake Table episode, we argued the plastic tub housing the cornstarch and water mixture was largely a *being* material for most of the students—it held the liquid—but for Ivan, it was a *becoming* material, offering new possibilities for how to generate specific kinds of forces. This case complicates how being, doing, and becoming aspects of materials are understood, and how different forms of conversation might be coordinated, calling into question how designers comprehend the requirements and boundaries of their problems. While we might relegate *being* material conversations as tied to constraints, we note that Pickering (1993) discussed constraints as nonemergent. The same material, in the hand of another designer, might offer emergent possibilities—as was the case with the plastic tub in Ivan's hands—suggesting that rather than being a constraint, it offered resistance. Designers relax constraints in their work, as a means to think around sticking points. In this way, it is important to acknowledge the dynamic and contextual nature of sociomaterial conversations. The learning opportunities are contingent on managing these dynamics and complexities that sociomaterial entanglements present. The moves designers make to coordinate these tensions and organize their processes are, thus, the heterogeneous engineering practices that promote learning in design.

The conjured user as an organizing act

Both communities of designers—students and teachers together—operated as organizations tasked with the persistent challenge of coordinating multiple challenges and decisions. Their sociomaterial conversations became the spaces to both organize and negotiate possibilities, where we argue the materials played active roles in the discussions. This tacit coordination achieved through conversations like the one Sarah, Kavi, and Chunhua had is one example of how people and materials design together, in ways that mirror the authentic practices Law (1987) and Suchman (2000a, 2000b) describe. One particular organizing act worthy of elaborated discussion is that of the conjured user. In both cases, designers introduced a "user" to propel their design decisions. We discuss two aspects of considering the *conjured users* as an act of coordination and organization.

The first involves the ways in which conjuring a user places the perceived needs of those who will actually interact with the artifact at the fore of deliberations. In so doing, the imagined user becomes a participant in the discussion, serving to mediate and support how designers listen and respond to each other. Kavi continually evoked the user in both suggesting and critiquing ideas. In so doing, proposals and critiques were relocated to the shared sociomaterial space of the problem, often organized around how a user would engage with the artifact. Surfacing the needs of the user, and bringing that user into the conversation, means negotiations among designers have a sustained authenticity and conviction. The designers want their artifact to work for the user they conjured; conflict and persuasion become valued qualities of the conversations. Students challenge each other's ideas in constructive and generative ways, using the conjured user to punctuate their impassioned arguments. Their disagreements lead to more informed design decisions, as Suchman (2000a) highlighted, and give rise to iterations, as Piccolo et al. (2019) have noted. This was especially true in the Shake Table case, where the conjured user was invoked to raise concerns about the potential for bias produced by their design. As the students tested various means to simulate seismic waves reflective of damaging surface waves and scaled to the spaghetti skyscrapers, many of their attempts were clearly not controllable and reproducible. This led to rapid iteration.

A second aspect concerns how the conjured user focuses students' attention on how users will interact with the materials under consideration, those that comprise the overall solution. By bringing specific attention to materials into the conversation, through the lens of the intended user experience (or as Kavi said, the "impact"), sociomaterial entanglements emerge as a central characteristic of debate. The conjured user asks designers not only to think about interfaces, but also about specific materials and their possible uses. This both surfaces the complexity of the sociomaterial challenges of heterogeneous engineering, while also providing structure for coordinating and organizing decisions. We see this as particularly evident in the Frankenstein case, in terms of how Kavi introduced the intended "impact" felt by a conjured user. In the Shake Table case, considering the human "tester" contributed to Ivan saying "we need somebody who does this job," focusing on the user's specific interactions with the materials. These sociomaterial interactions serve to amplify the opportunities for the materials to "speak back" to the students, where their properties and responses assist the designers in their decision-making.

Instructional design and facilitation

Finally, within the sociomaterial circumstance, we see tangible implications of instructional designs and facilitation moves serving to organize the activities. Designing for authentic problems, where heterogeneous practices emerge, means offering students ample space to negotiate, frame, and stumble their way through solving the problem. We found that carefully designed entryways into the complexity of these ill-structured and complex problems supported students' engagements in sociomaterial entanglements.

In the Frankenstein case, the "stations" designed and implemented by the teacher, with support from the research team—where students explore inputs, control, and outputs on model systems—influenced how the students conceived of the problem space. Each of these designed activities operated like sociomaterial playgrounds, providing space for students to engage with different ways of constructing notions of input and output, while introducing them to different kinds of technology platforms and new possibilities for material configurations. What emerged from this was the collective decision to break into input, output, and structure groups. These small, scaffolded experiences helped open space for framing, negotiation, and deliberations about the larger, messier problem context of Frankenstein which was organized into the three groups. The students and teacher agreed on this structure, and an outcome was the discussion in the focal episode from the input group. While shared, the teacher's endorsement of parsing the problem space was an instructional decision that maintained heterogeneous possibilities. An alternative structure may have been smaller groups, each producing their own installations. Constraining the scope and size might provide benefits in terms of narrowing the technological and conceptual landscape, but that smaller scale misses the need for coordination embedded in working as a whole class on cooperative elements of one larger project. The large scale makes the management, coordination, and organization central, which in turn elevates the material conversations. Leaving problems ill-structured, but still contextualized, centers deliberations that surface sociomaterial entanglements, asking learners to frame, scope, and imagine the problem and possible paths forward. In thinking about instructional environments, care placed in how structures—grouping, entryways, etc.—support sociomaterial entanglements are crucial to surfacing heterogeneous engineering practices.

Another dimension is the specific and careful attention to how instructional decisions respond improvisationally to issues that emerge within design conversations. The discussion about the need to reliably control the strength of simulated earthquake waves in the Shake Table case was one of both design and instructional decisions—how the final spaghetti skyscrapers were tested on the Shake Table was endemic to the class's structure and expectations. Mr. Stevens might have denied the request from the students to re-organize and start a new shake table design, one that lacked a clear plan for control. Allowing this meant the students had to make their own decisions and plans, to coordinate themselves and materials across multiple iterations. Engaging in heterogeneous engineering means embracing the complicated intersections of people, materials, and ideas. Sustaining the discussions of potential for bias and bringing a human actor into consideration as the “tester” contributed to Ivan’s discovery of new ways of seeing the familiar plastic container. Making space for sociomaterial entanglements means materials can agentively shape design ideas as learners grapple with complexity. Thus, facilitation requires listening to the multiple conversations happening during design activities and encouraging acts of coordination and organization genuine in heterogeneous practices.

Finally, both projects asked the entire class to collaborate on designing and building something. While the focal episodes highlight smaller group discussions, those were situated within larger, shared, and collaborative efforts to frame and solve large-scale problems. We argue that the complexity of these kinds of problems, coupled with the open-ended nature of designing a piece of interactive art, or developing both a city of earthquake resistant skyscrapers and mechanisms for testing them, are necessary if we are to foster heterogeneous engineering. Big problems make space for multiple and varied possibilities. As students dig more deeply into the material possibilities, they bring in sociality, considering how stakeholders would experience their designs and refining them based on their sociomaterial conjectures. Those conjectures fuel their continued engagements as well as the emergence of acts of coordination and organization, which are authentic practices when engineering in the wild.

Alternative instructional designs for engineering design projects may foreground particular content. For example, building paper bridges to hold as many paperclips as possible foregrounds physics concepts and backgrounds esthetics. In this example, the scope of relevant phenomena is constrained and the material options are limited; as such, the commonplace challenge in design of balancing tradeoffs is lost. Engineering projects of this sort strip problems of their social context, in favor of instructional efficiencies and fidelity of implementation. Suchman (2000b) wrote specifically about bridge building as a quintessential example of Law’s (1987) “heterogeneous engineering.” She argued the structural elements—which show up as physics content in the paper bridge and paperclip challenge—of bridges are one element of much larger problem contexts, factoring alongside consultation with communities that the bridges connect, bridge esthetics, economic considerations, and issues of construction and disrupting public spaces (e.g., Menn et al., 2004). Engineers and designers of complex socially-contextualized projects navigate numerous related decisions spanning technical, social, and material considerations. Without this complex social context, learners working in design problems have little need to direct their own problem framing and solving processes. That agency—making decisions about what the problem is, imagining the material possibilities, and conjuring a user to assess design ideas—is what the heterogeneous nature of these larger, messier problems encourage. The cases presented demonstrate how ill-structured large-scale problems support these kinds of authentic engineering practices.

Coupled with the sociomaterial opportunities in heterogeneous engineering contexts are the need for instructors to have familiarity and expertise with design, making, and elements of the disciplinary ideas at play. Ms. B spent significant time in the making space at the school honing her own skills before enacting this project. We would be remiss if we did not acknowledge the importance of her expertise in the overall consideration of the instructional environment. Likewise, the effort to plan and design the sustainable skyscraper project, along with the frequent recalibrations was central to its success. As we have noted in previous work at this school, the teachers are improvisational experts (i.e., Brown & Edelson, 2003), skilled at developing projects that appeal to their students and adept at recognizing when to draw out or deepen an activity (Svihla & Reeve, 2016), and when to pivot. Such pivots typically mean sharing instructional control with students in response to issues that emerge in the process of designing (Svihla et al., 2016). Improvising and pivoting, in consultation with industry professionals, researchers, and students reflects an instructional agility that we found crucial to the collaborative organizing and coordinating work of heterogeneous engineering. We note below that opportunities for teachers to continue learning in similarly messy problem contexts is a place for future research as well.

In summary, large, whole-class kinds of challenges are shaped by different factors—social, material, and instructional—and we argue they provide promising opportunities for students to develop heterogeneous engineering practices, when supported by thoughtful instructional designs and knowledgeable instructors.

Conclusions and implications

The cases highlight the learning potential when we treat designing as collective human performance. In order for a design problem to support this type of heterogeneous work, it must be difficult enough, complex enough, and situated enough to actually necessitate collective effort. This means finding problems that are too big to be solved by a team of two, four, or even six students. This extends past work on collaborative problem solving that makes similar arguments (e.g., Brown & Campione, 1994). It likewise extends our past work on how to support students to learn not just to solve problems, but also to learn to frame them (Svihla et al., 2016). This underscores that rather than learning concepts or principles, or even learning to solve well-framed problems and carry out disciplinary practices when directed to, heterogeneous engineering provides opportunities to learn to coordinate and navigate sociomaterial entanglements. And, rather than the kinds of learning made possible from engaging with fragmented disciplinary practices—e.g., reasoning with data—where practices are discrete and disconnected from other practices, we conjecture that sociomaterial entanglements invite students to direct their own practices, thereby providing opportunities to build knowledge of how and when to deploy a particular practice. Such coordination requires a high degree of agency so they can make decisions that are consequential to both how the problem is framed and what else is learned in this process (Svihla et al., 2019). Efforts by teachers to maintain instructional control by narrowing the scope of the problem fundamentally remove opportunities for students to learn to wrestle and tame these “wicked problems” (Rittel & Webber, 1984).

Heterogeneous work is how design happens in the world, and opportunities to embrace this expanded notion of engineering learning hold pro- mise for the design of more equitable and ethical learning spaces. Heterogeneous engineering relies on divergent experiences in/with/of the world and its materials (Vossoughi et al., 2016; Wilkerson & Gravel, 2020), and we call for increased attention to designing learning environments that realize and amplify the possibilities of sociomaterial entanglements. The K-12 arena is both promising and under-realized in terms of engaging and sustaining the forms of participation we present in this paper. We see this research as launching an agenda of studies that investigate ways to reach this vision, including the instructional supports that make such practice feasible for teachers. For one, more research is needed on forms of professional development that can support educators' efforts to design and facilitating making projects that foster heterogeneous engineering (e.g., Gravel et al., 2020).

Finally, we believe there are implications for this research in terms of methodology when studying engineering design and making. The literature on making highlights that making is messy (Peppler et al., 2016). And studying the learning in making is nontrivial. However, within these instructional contexts—extended project-based design challenges—we see making and engineering unfold in ways that give us opportunities to describe learning. This requires meticulous data collection and methods for constructing both the arcs of these projects and also for selecting and analyzing data across time-scales to better understand the dynamics of learning. Our focus on the instructional, material, and social aspects provides one possible framework through which we can continue to study learning in making—both in terms of how practices contribute to learning, but also future descriptions of the disciplinary nature of students’ learning in these contexts. Interaction analysis is a complementary tool for operating across these timescales. Using these tools to further explore heterogeneous engineering as a phenomenon, perhaps using emerging frameworks for exploring how making and learning intersect (e.g., Tucker-Raymond & Gravel, 2019; Vossoughi et al., 2020), will hopefully advance our shared understanding of learning through design. We hope this paper contributes to future studies of both capturing and analyzing the complexities of learning in heterogeneous engineering projects.

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