Making and Tinkering: A Review of the Literature

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Introduction

The Maker Movement, a grassroots movement of backyard and kitchen tinkerers, hackers, designers, and inventors, has been dramatically expanding over the past several years. Since the first Maker Faire in 2006, making festivals, spaces, activities, conferences, and studies have multiplied (Bevan, Gutwill, Petrich & Wilkinson, in revision). A growing number of researchers and educational leaders see in making the potential to engage young people in personally compelling, creative investigations of the material and social world (Blikstein, 2013; Martin & Dixon, 2013; Martinez & Stager, 2013), to democratize tasks and skills previously available only to experts (Blikstein, 2013), and to expand participation in STEM fields by leveraging the strengths of interest-driven, multi-disciplinary STEM learning environments (Brahms, 2014; Martin, 2014; Sheridan et al., in press). In a June 2014 meeting at the White House, numerous agencies (including the National Science Foundation and the US Department of Education), and corporations (such as Local Motors, Google and Intel), made commitments to supporting the expansion of making activities into community settings (White House, 2014).

In this paper, we draw on the research literature to consider 1) what is known about the impact of tinkering and making experiences on school-aged children's learning (interest in, engagement with and understanding of STEM in particular) 2) the emerging design principles and pedagogies that characterize tinkering and making programs and 3) the specific tensions and possibilities within this movement for equity-oriented teaching and learning.

Historicizing Making & Education

Though branding and marketing (largely driven by O'Reilly Media, publisher of *Make Magazine*) has recently highlighted making as a novel form of activity, making has deep socio-historical roots—first and foremost as fundamental human activity, and second as a form of educative practice.

As noted in the literature (Blikstein, 2013; Martin, 2014; Sheridan et al., in press), making reflects the practical, physical, and playful modes of inquiry advanced by educators such as John Dewey (1938/2007), Friedrich Froebel (1887), Maria Montessori (1912), and Seymour Papert (1980). As Paulo Blikstein argues, these theoretical approaches (and their attendant technologies, such as Logo programming and Lego Mindstorm) "revealed how the ideas and intellectual passions of children could be powerful and generative, and that the perceived difficulties of [previous] tasks were due to deficient design rather than learners' cognitive deficiencies" (2013, p. 6).

Emerging research also documents the ways in which making environments support novices and experts to work side-by-side, assist one another, and continually shift roles through processes of investigation and invention. Making therefore has the potential to challenge deficit views and support learning and development in ways that resonate with the theories of Lev Vygotsky (1978) and Jean Lave and Etienne Wenger (1991). The notion that making ought to be grounded in personally and socially meaningful problems, and position students as producers rather than consumers of knowledge and technology, also draws from the critical educational theories of Paulo Freire (Blikstein, 2013; Freire, 1970).

In this sense, making as educative practice is largely a return to earlier learner-driven, inquiry-oriented pedagogies, much of which have been sidelined by the last two decades of accountability era schooling (Resnick & Rosenbaum, 2013). A broad range of researchers have documented how these learner-driven practices support student participation, learning, and conceptual understanding (e.g., Driver et al., 1985; Minstrell & van Zee, 2000; Monk &

Osborne, 2000; National Research Council, 2002). To be sure, making adds a specific dimension of design, design-thinking, and frequently the use of new technologies (such as Arduinos or other micro-computational devices). But in many ways making mirrors, or at least echoes, traditional forms of scientific and artistic investigation in which devices are built, tested, and used for purposeful activities and exploration.

Based on a review of the literature, we posit that in addition to the well-documented pedagogical power of learner-driven inquiry, the aesthetic and playful qualities of many making activities may operate to create a particularly low barrier for participation. Making thus *looks and feels* different from more traditional open-ended inquiry activities. Its invitational potential may be a part of what is driving so much interest in making as an important innovation in teaching and learning practice, particularly after the predominance of text-based, test-driven, teacher-centered STEM instruction.

But educators have many questions about making. For example, after decades of defining learning as conceptual recall, some are concerned about the ways in which making activities relate (or do not relate) to existing curricula and/or lead to the development of conceptual understandings. Others are examining if and how making can support student engagement in the scientific and engineering practices elucidated in the recent *Framework for K12 Science Education* (NRC, 2011). Finally, in an era of increasing socioeconomic segregation and inequality, some researchers are concerned with ensuring that making is leveraged to challenge rather than reproduce existing inequities.

Current Trends within Making & Education

The Maker Movement, as it is currently being realized and branded, might be grouped into three categories: making as entrepreneurship and/or community creativity, making as STEM pipeline and workforce development, and making as inquiry-based educative practice.

Entrepreneurship & Community Creativity: Over the last five years there has been an investment (by Autodesk and others) in the creation of publicly accessible fabrication facilities (e.g., TechShops, Fablabs, MakerSpaces) outfitted with tools and technologies such as metal cutters, lathes, and 3-D printers. These spaces are made available to the general public for a fee. Artists, designers and others use these sites for access to the tools, skills, and community that support their creative purposes (Brahms, 2014). As the research shows, activities and interactions in these contexts are generally characterized by collaboration and innovation, and such spaces are often highly valued resources in local settings. Another driving force behind these spaces is providing individual entrepreneurs with access to the means of production. These facilities allow individuals to build and test ideas and objects that can, in some cases, be brought to market (White House, 2014). Further, recent partnerships between DARPA, Make and hackerspaces represent efforts on the part of industry and military leaders to leverage the open, democratic processes of design that characterize the maker movement towards crowd-sourcing infrastructure for the design of particular products (Mansfield, 2011; Ohab, 2010). We return to the tensions and contradictions of these developments below.

STEM Pipeline and Workforce Development: A second category of work in the Maker Movement is STEM workforce development. These efforts generally engage high school and university students in engineering and design projects (Blikstein, 2013). Here, the focus is largely on providing opportunities for young people in school environments (such as the

FabLab@School project at Stanford University) or as part of an extended high-school/university STEM curriculum. Some informal settings (particularly targeted programs) also focus on expanding and diversifying the STEM educational and workforce pipeline. Rooted in design and construction, these courses and programs often emphasize the development of students' "21st century skills," such as problem-solving, critical thinking, and collaboration. Frequently, the curriculum is organized around project-based activities that involve using advanced tools such as 3-D printers or welding equipment. The goal of these programs is generally to support the development of engineering and other STEM skills, capacities, and interests. Industry leaders have championed such programs for developing the workforce of tomorrow by building young people's creative problem-solving capacities and positive STEM learning identities (e.g., Cognizant, 2011).

Inquiry-based education: A third category is making as inquiry-based educational activity. These programs may or may not be located in spaces outfitted with expensive technologies and tools. For instance, they may take place in classrooms, libraries, museums, after-school or community settings that have been pedagogically transformed into "making settings" as groups of individuals participate side by side or collaboratively in making a range of artifacts while drawing on interdisciplinary tools and modes of inquiry. The goals of these programs are generally to inspire interest, foster engagement, develop understanding of the processes and concepts at the center of making activities, and support students' identities as thinkers, creators and producers of knowledge. These programs frequently draw upon youth development principles such as developing supportive relationships, building on children's prior experiences, and supporting leadership, confidence and agency.

Though these three categories often overlap in practice, it may be useful to tease apart the various motivations and ends that inform the broader movement. For example, entrepreneurial maker programs that focus on the creation of products designed to address a market need might require more sophisticated fabrication tools than are needed in an inquiry-based maker program, alongside instruction that addresses market forces and dynamics. While making is generally defined as interdisciplinary, activities undertaken in inquiry-based maker programs often integrate art, science, technology and literacy practices, whereas workforce development programs may focus more specifically on STEM skills and practices. Both may endeavor to broaden participation for young people who may not self-identify as science learners.

In what follows, we review the literature pertaining to these three categories in the context of Out-of-School Time (OST) STEM. The published literature that specifically references the Maker Movement or making and tinkering as such (as opposed to inquiry-based learning, project-based learning, or other forms of practice that are closely aligned with, and pre-date the maker movement) is not extensive. The majority of peer-reviewed papers pertains to the third category: Making as Inquiry-Based Practice, with some important connections to the first two. Research on existing “makerspaces” for example, seeks to identify the forms of thinking and learning common in these community settings as a way to design for and evidence learning in educative practice (Brahms, 2014; Brahms & Crowley, 2014b; Sheridan et. al., in press). Similarly, Bowler’s (2014) work on making in libraries characterizes makerspaces as “offering a place where everything from STEM learning to critical expression to future start-ups can be nurtured” (p. 59).

Conceptualizing Learning and Making

In this section, we consider how researchers in the field are defining making and tinkering, and the potentials for learning therein. The research literature consistently references both constructivism (Piaget) and constructionism (Papert) as core pedagogical drivers of making (e.g., Martinez & Stager, 2013; Resnick & Rosenbaum, 2013). *Constructivism* refers to the ways in which understanding is constructed by the individual learner through a wide variety of experiences; this mode of learning is contrasted with what Papert called *instructionism* which views understanding as being developed through transmission of facts from one person to another. *Constructionism* posits that the experience and process of *building* something physical or digital provides a rich context for developing and representing understanding.

Martinez & Stager (2013) describe three "ways of knowing" that characterize constructionist approaches to classroom learning: making, tinkering and engineering. They describe making as active construction that entails working on a planned "product." They describe tinkering as a "mindset" involving a playful approach to solving problems through "direct experience, experimentation, and discovery." Finally, they describe engineering as extracting "principles from direct experience," bridging intuition and formal aspects of science by supporting students' capacity to "explain, measure, and predict the world around us." From this perspective, tinkering is a mindset that can cut across intentional building (making) and disciplinary construction activities (engineering). Honey & Kanter (2013) distinguish between designing, making, and playing, describing making as "building or adapting objects by hand for the simple personal pleasure of figuring out how things work" (p.4).

These characterizations of making (and its differentiation from tinkering, designing or playing) are not consistent in the research literature. Indeed, much of the literature represents tinkering as a kind of making activity, not just a mindset (Petrich et al., 2013; Resnick & Rosenbaum, 2013) and stresses core activities of play and design as integral to the process of making (e.g., Resnick & Rosenbaum). For example, to make their own wooden pinball machines, children in one after-school tinkering program first visited a local pinball museum, playing, noticing and diagramming a diverse range of designs. They were then supported to build their own machines, starting with a flat piece of wood that served as a blank canvas—an invitation to imagine, test and develop their own playing field (Vossoughi, et al., 2013). Here, the process of making involved a subjunctive mode of thinking (What if we try this? How might this piece change the movement of the pinball?) and an exploration of multiple possibilities characteristic of both play and design (Ackermann, 2010).

These voices caution that making can sometimes be implemented as step-by-step, recipe-like, construction activities, running counter to the inquiry-based explorations that the maker movement espouses (Resnick & Rosenbaum, 2013). To call out this distinction, some researchers describe tinkering as a sub-category of making characterized by improvisational, creative problem-solving. Others distinguish making from *assembling.* As Espinoza (2011) writes, "Making seems to be cognitively and socially richer than assembling as it involves more active testing and fitting and less routine following of directions" (p. 17). Similarly, Blikstein (2013, p.3) distinguishes between engineering and the modes of thinking traditionally involved in science: "Notwithstanding the natural content overlaps amongst science and engineering disciplines, they are fundamentally different. While a scientific investigation typically concerns with finding the one law to explain many natural phenomena, a technological investigation typically finds many solutions for the same problem (Atkin, 1990)." These distinctions can be useful, particularly considering the differential value placed on linear approaches to engineering and the historical predominance of the "scientific method" in schools.

At the same time, the range of practices involved in making can and often are viewed as mutually generative, and the forms of meaning making embedded in the process of creative problem solving and design can productively blur the lines between science, engineering and the arts. Some engineering activities may involve following a recipe for how to construct a robot or a lego spacecraft, or meeting a challenge such as building a bridge that can bear a particular weight, or a tower than can reach a particular height. More broadly, engineering practices generally involve both making (constructing) and tinkering (creative problem-solving) activities. As defined in the Next Generation Science Standards and the Framework for K-12 engineering is an open-ended yet systematic process of defining and solving problems.

As making takes root in educational practice, there appears to be an interest in defining terms. Such definition may be of special importance to educators seeking to ensure that making does not become a practice of recipe-like instruction (e.g., Resnick & Rosenbaum, 2013); but there is a parallel concern that narrow definitions could exclude some historical or community practices, raising questions about who gets to define what counts as STEM and what counts as making (Vossoughi et al., 2014). Narrow definitions may also overlook subtle distinctions between rote forms of assembly and moments when following a model or recipe may be intellectually generative.

There does appear to be common agreement that making is a broad category of activity that involves people ideating, designing, and producing physical or virtual object in the world (Blikstein, 2013). For Martin (2014) making refers to a "class of activities focused on designing, building, modifying, and/or repurposing material objects, for playful or useful ends, oriented toward making a "product" of some sort that can be used, interacted with, or demonstrated" (p. 3). Martin's research in an out-of-school making club found that participants defined making as "building things, being creative, having fun, solving problems, doing social good, collaborating, and learning" (p. 4). The literature on making, tinkering and engineering also shares an emphasis on interdisciplinarity, as reflected in efforts to advocate for STEAM rather than STEM (Peppler, 2013), to highlight the intersections and generative back-and-forth between virtual and physical realms (Ackermann, et al., 2009; Kafai & Peppler, 2010; Martin, 2014) and to define making as a mode of creative production that exists at the "crossroads and fringes of disciplines such as science, technology, engineering, art and math" (Brahms & Crowley, 2014b, p. 3). In this vein, Sheridan et al. (in press) define "makerspaces" as "sites for creative production in art, science and engineering where people blend digital and physical technologies to explore ideas, learn technical skills and create new products." They argue that the heart of making involves "taking an idea and constructing it into some physical or digital form."

Summarizing the research on making/tinkering as educative practice

There is a great deal of literature supporting the value of learning in out-of-school time settings (NRC, 2009). Martin (2014) draws on this literature to summarize the ways making can support the development of interest, identity and content area knowledge: Gee (2007) and Ito et al. (2010) have shown how informal, leisure activities can provide foundational experience with sophisticated language and transactional processes necessary for later engagement in academic discourse. Heath (2012) has highlighted the importance of playing a role other than "student" in the development of identity, while noting that "formal learning environments cannot easily give groups of young learners either truly meaningful roles or opportunities for participation in longitudinal projects" (p. 257). Barron (2006) has shown that interest in technology typically develops across a web of out-of-school experiences that extend over time and space.

In out-of-school time making communities, Martin suggests, "analytically separable categories like identity, agency, and expertise are deeply intertwined (NRC, 2009)." He elaborates: "the ways that young people identify with a domain such as engineering can have substantial influence on the kinds of choices they make for future educational experiences, including courses and majors, and can partly predict the likelihood that they will pursue a career in that field (Tai et al., 2006). When young people are interested in the things they are working with, when they feel like their activities align with their sense of themselves and their possible futures, and when they feel connected to the community they are working within, tremendous amounts of learning can occur" (p. 10).

Indeed, the literature suggests that making can provide a powerful context for integrating the socio-emotional and disciplinary dimensions of learning, and broadening interest and engagement in STEM. Drawing on existing frameworks for high quality STEM programs (National Research Council and Institute of Medicine, 2002; National Research Council 2009, 2012) our review of the evidence considers how making as educative practice can:

(1) ***Position and support young people to participate in science programs and learning activities***, including how making programs support opportunities for belonging and mattering (NRC & IOM, 2002); developing interest and identity (NRC, 2009) and expanding experiences and skills in communication, leadership, and the negotiation of differences (NRC, 2012).

(2) ***Structure and implement program activities to support young people's learning and development***, including providing opportunities for skill building and connections to

community and school experiences (NRC & IOM, 2002), the development of conceptual understanding, STEM skills, scientific ways of knowing, an understanding of how science is practiced in the world (NRC, 2009), and critical thinking, reasoning, and innovation (NRC, 2012).

(3) ***Create a supportive community of learners that can leverage the interests and skills of each member of the group towards shared goals***, including opportunities to develop supportive relationships and positive social practices (NRC & IOM, 2002) as well as flexibility, initiative, appreciation of diversity, and metacognition (NRC, 2012).

Research Findings

The emergent research literature takes a largely qualitative (ethnographic, case study, interview, descriptive) approach to studying teaching and learning in the context of making. There are also a smaller number of studies that incorporate surveys, pre-post assessments and quantitative forms of measurement. While the research primarily focuses on out-of-school maker spaces/clubs and designed museum settings, there is also a growing effort to study making in after-school, school and library settings. We draw on the above framework to summarize existing evidence for the impact of making/tinkering. We have not tested the validity of the study designs or data analyses, but instead summarize the claims made by researchers from papers published in peer reviewed journals or conference proceedings. While each learning dimension (**A1-C2)** necessarily blends elements of design and impact, we conclude each sub-section with a summary of the claims researchers have made about the evidence for learning through making.

A. Making programs can be intentionally designed to position and support young people to participate in science programs and learning activities. The literature highlights several ways in which making has been organized to position and support young people's participation and sense of belonging. These include (1) supporting new intellectual dispositions, identities and future trajectories, (2) connecting making activities to familiar practices, and (3) advancing young people's agency and authorship.

A1. Supporting new intellectual dispositions, identities and future trajectories

Though the literature has yet to provide evidence for the influence of making/tinkering experiences on young people's long-term trajectories, a number of researchers identify expanding roles, dispositions and identities among participants. Most of the evidence here is observed or self-reported during or soon after making experiences, and focuses more on the nature and impact of extended participation than on the reasons some people may choose not to continue participating. Sheridan et al. (in press) noted a "dispositional shift that was often identified by regular participants" in one makerspace: "They repeatedly highlighted how they were thinking about and doing things they had never even thought about before." Here, "regular" participation often involved ongoing and deepening engagement and expanded roles, such as supporting newer participants. Depending on the space, regular participation might range from attending a series of workshops to becoming a core member of a setting for a number of years.

Fields and King (2014) observed "how college age and adult women changed the way they viewed themselves as well as how they took up new practices that integrated computational media with existing interests through connected learning in the craft technologies course. All interviewed students acknowledged that they considered themselves —if only as beginning or hobbyist—programmers by the end of the course" (p. 7). In a study of making with children in a library space, Bowler (2014, p. 60) described shifts in confidence, such as one participant who felt that if she could program and build a robot, she could pursue more technical challenges in the future. In a survey- based study of 25 maker programs, Dorph & Cannady (2014) found that young people increased their *activation* towards STEM over the course of their participation in maker programs. Here, “activation” refers to dispositions, skills, and knowledge that position an individual for current or future success in STEM learning, such as fascination with and valuing of STEM, competency belief, problem-solving and creative thinking.

In an interview-based study of young makers, Dixon and Martin (2014) asked participants (3 young women and 8 young men, aged 11-15) what was valuable about being part of Maker Faire. Based on ‘the reported number of times participants visited or presented’ at Maker Faire, their findings revealed that the least experienced makers emphasized the benefits of seeing and absorbing the experience—having fun, learning (generally, not a specific skill or topic) and gaining a sense of accomplishment. Youth with more Maker Faire experience connected their choices to longer-term interests and emphasized the importance of connecting with mentors and showing people what they did to get feedback or to display particular skills. Participants with the most experience at Maker Faire linked the development of skill within making activities to future work and enduring commitments, and thought of next steps with regards to the building skills they wanted to develop rather than the next thing they wanted to build. Importantly, Dixon and Martin note that the most experienced participants also wanted to prompt action, inspire or create experiences for others.

A2. Connecting to (rather than replacing) familiar practices

While making can offer youth access to new tools for building and thinking, a number of researchers found that connecting making with existing practices created more powerful and equitable learning experiences. Based on observations and conversations with students in digital fabrication workshops, Blikstein (2013) argues that “building onto students’ familiar practices and adding a layer of expressive technologies, a digital fabrication lab, which merges computation, tinkering and engineering, had the potential to augment rather than replace familiar and powerful practices that students already possess, therefore they can recognize their own previous expertise in the lab, rather than acquiring a whole new identity altogether" (p. 7). Blikstein also found that "students reported having gained a new appreciation for the 'manual' labor they used to do, and also for the occupation of their parents" (p.7). Vossoughi et al. (2013) reported similar connections in an after-school tinkering setting that designed for cross-setting learning. In one example, a facilitator asked a student who was taking apart an old answering machine if she had ever seen anyone dissect an animal. She responded that her "mom and dad do that," describing the ways her parents take apart chicken for cooking purposes. This sparked a discussion with other children about the role of dissection in cooking and other everyday activities.

In the context of a university course on craft technologies, Fields & King (2014) found that "aspects of 'making' that draw on knowledge and skills that people build at home, in community and religious groups, and with friends may hold particular promise for creating spaces of connected learning related to programming and engineering" (p. 1). Their findings revealed that university students pursued longstanding personal interests in and beyond the course and integrated new with older knowledge.

In an interview based study of young makers, Martin and Dixon (2013) found that participants viewed making in a "highly integrated, 'life wide' fashion." Rather than treating making as a set of discrete skills or an activity that takes place in certain settings, youth in their study "saw making as integrated across their experiences" (p. 3). More broadly, these findings resonate with Gutiérrez et al.'s (2014) argument that the ingenuity and creativity central to making are fundamental human practices, and that making and tinkering are “indigenous” to non-dominant communities, particularly to communities in “tight circumstances” (McDermott, 2010). As Gutiérrez argues, it is important not to essentialize forms of making born of necessity, but rather to question our assumptions about who does and who does not engage in making, particularly with regards to the deep histories of practice and range of making activities that exist in non-dominant communities. As we will argue, these frameworks are essential to countering the deficit views underlying narrow or hierarchical definitions of “making” and “makers,” and to recognizing and leveraging deep connections between the scientific and the everyday.

A3. Advancing Agency and Authorship

Across the literature, youth are positioned as active producers rather than passive consumers of knowledge, media and technology. According to Martin (2014, p. 16), “Making environments typically give youth substantial say in what and how they make. Learning environments that support youth autonomy and control of their endeavors are more motivating, support engagement and persistence, identity development, and the growth of resourcefulness (Azevedo, 2011; Barron, 2006; Ryan & Deci, 2000).” Through interviews with 17 young makers (3 girls and 14 boys, ages 12-18), Martin and Dixon (2013) found that young people positioned making in contrast to consuming, and framed the products makers like to produce as typically creative and not ordinary. These interviews took place early in the Maker Club program, “as participants formulated project ideas and began to build” (p. 2). Petrich et al. (2013) contrast the ways participants in tinkering author their own goals and ideas with engineering and design competitions where the goals and constraints are externally determined. Embedded in this approach is an understanding of goal development and problem finding as cognitively rich activities, and as potential sources of ownership (Vossoughi, et al., 2013, p. 3).

Some researchers explicitly connect this dimension of making with the development of **critical literacies** (Kafai & Peppler, 2010; Norris, 2014; Santo, 2013). Kafai and Peppler write that while most school activities are concerned with using rather than producing technologies, “media education needs to foster both critical understanding and creative media production of new media to encourage urban youth to be consumers, designers, and inventors of new technologies” (2010, p. 25). Based on their review of existing research on youth, technology and DIY (Do-It-Yourself) they argue that the emphasis on writing within creative media production empowers individuals to insert their selves and redefine their position within existing power structures. At the same time, they caution against drawing a strict line between production and consumption in ways that frame the active play and consumption of technologies as necessarily unproductive or non-serious: “The traditional role of formal media education still remains in media consumption because it involves stimulating critical reflection on a greater variety of media texts and engendering youth to write and reformulate those ideas critically” (p. 24). In their research and teaching of youth media production, Chavez and Soep (2005) argue that “the process of transforming lived and imagined experiences into original expressive works for significant audiences can provide a resource for young people to rewrite the stories that are told about them, against them or supposedly on their behalf” (p. 410). Complicating simplified and decontextualized notions of “youth voice,” Soep (2006) also suggests the need for more fine-grained research attention to the “actual moment-to-moment discourse young people use to produce original media” (p. 209).

In summary, with respect to positioning young people to actively participate in and commit to learning activities, researchers claim that making supports students to:

- Integrate knowledge and experiences across settings (Fields & King, 2014; Dixon & Martin, 2014) and draw connections between new and familiar practices (Blikstein, 2013; Vossoughi et al, 2013)
- Develop confidence, persistence, authorship and resourcefulness (Brahms & Crowley, 2014b; Petrich et al., 2013)
- Develop new dispositions and ways of thinking (Sheridan et al., in press)
- Become activated towards STEM ("activation" includes dispositions, skills, and knowledge such as fascination with and valuing of STEM, competency belief, problem solving and creative thinking) (Dorph & Cannady, 2013)
- Develop critical literacies, including distinguishing between making and consuming (Martin & Dixon, 2013) and rewriting narratives about oneself and one's community (Chavez & Soep, 2005)
- Develop new ways of viewing themselves and their STEM capacities (Bowler, 2014; Dixon & Martin, 2014; Fields & King, 2014) and a growing interest in and pursuit of future making related activities and skills (Fields & King, 2014; Dixon & Martin, 2014)

B. Making programs can be structured and implemented in ways that support young people's learning and development. The literature highlights several ways in which making programs and activities are structured to support young people's learning and development. These include (1) contextualizing STEM concepts and practices in meaningful activity, (2) cultivating interdisciplinary practices, and (3) encouraging Intellectual risk-taking, experimentation and iteration.

B1. Contextualizing STEM concepts and practices in meaningful activity

In contrast to teaching STEM concepts and skills in the abstract, researchers argue that making can support relevant and purposeful engagement with STEM. Describing middle and high school students' experiences with digital design fabrication in predominantly school based "fab labs," Blikstein (2013) writes, "students have the opportunity to come across several concepts in engineering and science in a highly meaningful, engaging, and contextualized fashion. Abstract concepts such as friction and momentum become meaningful and concrete when they are needed to accomplish a task within a project" (p. 18). In a study of students' engagement with simple computational circuits through e-textile materials (textile artifacts that are computationally generated or that contain embedded computers), Peppler (2013) found that students significantly increased their understanding of key circuitry concepts, such as current flow, circuit polarity and connectivity. Peppler concludes that "stitching circuits seems to demystify ideas that can be elusive to students using traditional electronic toolkits" and that "e-textile toolkits underscore basic circuitry principles in tangible ways as well as allow for novel aesthetic possibilities" (2013, p. 40). Gutiérrez et al. (2014) found that different forms of mediation presented opportunities for participants in after-school tinkering activities to extend their STEM practices, take on new roles and identities and engage affective and cognitive dimensions of learning. Drawing on Quinn and Bell (2013), Martin (2014) argues that making is therefore well-aligned with the Next Generation Science Standards (NGSS): "Some points of alignment with making are clear, such as the inclusion of 'defining problems' and 'designing solutions' as core engineering practices. Others are more subtle, but equally important. For instance, the framework's emphasis on problem solving and sensemaking will require a shift toward greater student agency and autonomy, as is often seen in making-centered learning environments" (p. 2).

Sheridan et al. (in press) found that learning in community and museum makerspaces "is deeply embedded in the experience of making. These spaces value the *process* involved in making—in tinkering, in figuring things out, in playing with materials and tools...The makers we observed learned skills to create things that are beautiful, useful, marketable, and fun." They also found that participants "iteratively work with ideas, materials, tools, and processes in increasingly complex ways" suggesting a relationship between authentic projects/activities and participants' inclination to complexify and deepening their participation over time. Studying family learning in a museum setting, Brahms (2014) found that young children were able to form meaningful trajectories of participation with respect to maker community practices, including the development of relevant skill and knowledge. In another museum setting, Gutwill et al. (2014, p. 4) identified particular "indicators" of participants' growing understanding, including the ways tinkering activities helped learners express new realizations, offer explanations for strategies, tools and outcomes, apply prior knowledge and strive to understand even through moments of struggle. Gutwill et al. also noted the high degree of museum visitors' emotional investment in their work (p. 9).

Finally, Martin (2014, p. 12) suggests that makers typically **focus on skills rather than abilities**: "the discourse of the community emphasizes assets and the ability to learn, over deficits - an orientation sometimes missing in schools (Gutiérrez & Rogoff, 2003)." Kafai and Peppler (2010, p.24) connect this notion to the interest-driven nature of learning in DIY settings: "When youth are 'messing around' or 'geeking out' in DIY, they invariably begin to use and master design languages—programming, interface design, animation, graphics, 3D design, and more (Ito et al., 2013)." Collectively, these studies point to an educative practice that treats concepts and skills as tools to achieve desired ends, rather than ends in and of themselves.

B2. Cultivating Inter-disciplinary practice

Though making and tinkering are often tied to STEM learning, a number of researchers identify the interdisciplinarity of making as fundamental to its power and potential as educative practice. Sheridan et al. (in press) found that disciplinary boundaries are "inauthentic to makerspace practice" and that the "blending of traditional and digital tools, arts and engineering can create a learning environment with multiple entry points that foster innovative combinations, juxtapositions and uses of disciplinary content and skill" (Brahms & Crowley, 2014b; Sheridan et al., in press). They also suggest that the multi-disciplinary design work often seen in makerspaces resonates with arguments that learning to design and make as children will yield more interest in science and engineering and a more active stance towards learning. Similarly, Peppler (2013) suggests that "design thinking provides a common ground for both the arts and STEM," (p. 41) and that such disciplinary intersections contribute to broadening participation, particularly for women. In a video-based study of e-textiles in middle schools settings, Peppler found that within mixed-gender pairs, projects were positioned in front of the girls 81% of the time, and that the girls spent 58% of the time directing the activity, trouble-shooting and deciding next steps. Peppler therefore argues for authentic combinations of STEM and the arts whereby "students garner expertise in several content areas as well as the skill sets to think across traditional disciplinary boundaries." She elaborates: "With e-textiles, this might mean requiring students to understand Ohm's law in the context of circuit design as well as the various stitching techniques in order to choose the most appropriate one, both technically and aesthetically" (2013, p. 41). Further, intentionally involving a range of disciplinary experts (including artists and professionals from students' families and communities) and purposefully contrasting multiple media, tools and materials can encourage students to reexamine what they know in one context when they see the same phenomenon play out in a new context, think across physical and digital domains, and approach their designs flexibly (Peppler, 2013). Kafai and Peppler (2010) connect this interdisciplinarity to equity-oriented changes in the field of computer science as it grows to include a greater focus on arts and design.

B3. Encouraging Intellectual risk-taking, experimentation and iteration

Researchers note that in the context of making and tinkering, “mistakes” and moments of struggle are often reframed as essential to the iteration and experimentation valued in design and problem solving. Petrich et al. (2013) argue that “the process of becoming stuck and then ‘unstuck’ is at the heart of tinkering” and that “having an artifact to point to, an artifact that may be rickety or lopsided, but yet has resolved the problem that so puzzled the learner” is part of what makes tinkering activities compelling for participants (p. 55-56). Vossoughi et al. (2013) found that the emphasis on *drafts* helped to reframe ‘mistakes’ or ‘failed attempts’ as moments in the process of creation that offer insight and fertile ground for new ideas. They also found that students shifted their relationships with problems and drafts over time, and came to embrace the process of iteration. Similarly, Martin (2014) draws on Okita and Schwartz (2013) to note that “production can lead to powerful forms of learning driven by *recursive feedback*, where people learn from the actions of their creations” (p. 16).

Researchers also suggest that these contexts can provide “visceral design experiences and new levels of frustration and excitement, which students normally do not get to experience in school” (Blikstein, 2013, p. 18). Some frame this dimension of making as embracing or celebrating “failure.” As Martin (2014, p. 13) writes, “Failure is not a happy word in most educational circles, particularly when attached to schools, students, or initiatives. Yet within the maker mindset, failure is celebrated...Failures in school setting can be “productive” as well, helping students to better understand the structures and constraints of problems, so that they can learn better when given another chance (Kapur, 2008).” At the same time, Martinez and Stager caution against confusing “iteration with failure when in fact any iterative design cycle is about continuous improvement, keeping what works, and improving what doesn’t.” (p. 70) As they argue: “This is learning, not failure” (p. 70). Because, as Martin notes, some students and schools have been historically and systematically labeled as “failures,” the term may (legitimately) carry negative connotations and may not be so easily reframed – particularly within an isolated activity or context.

In summary, with respect to young people’s learning and development, researchers claim that making supports students to:

- Engage in meaningful and contextualized STEM concepts and practices (Blikstein, 2013; Gutiérrez et al., 2014; Gutwill et al., 2014) including problem finding, solving, testing and iteration (Petrich et al., 2013; Vossoughi et al, 2013)
- Deepen understanding of scientific concepts (Blikstein, 2013; Gutwill et al., 2014; Peppler, 2013)
- Develop fabrication skills and dexterity with a range of tools (Sheridan et al., in press), including design languages such as programming, interface design, animation, graphics, 3D design (Ito et al., 2013; Kafai & Peppler, 2010)
- Develop innovative combinations, juxtapositions and uses of disciplinary content and skill (Brahms & Crowley, 2014b; Peppler, 2013; Sheridan et al., in press)
- Develop new roles and trajectories of participation (Brahms & Crowley, 2014b; Gutiérrez et al., 2014) including working with ideas, materials, tools, and processes in increasingly complex and iterative ways (Sheridan et al., in press), experiencing new levels of

frustration and excitement (Blikstein, 2013), and embracing the process of iteration (Vossoughi et al., 2013).

C. Orchestrating programs to create a supportive community of learners that can leverage the interests and skills of each member of the group towards shared goals. The literature highlights several ways in which making has been organized to create supportive communities of practice. These include (1) encouraging collaboration and sharing and (2) treating expert/novice roles as fluid.

C1. Encouraging Collaboration & Sharing

Many researchers point to the value making and tinkering environments place on collaboration and the sharing of tools and ideas. Martin (2014) describes a "community infrastructure" that includes online resources and in-person spaces and events. He identifies the relationships and community built through the process of making as central: "Participating in these community spaces, both in person and online, centers topically around making, but is otherwise similar to other communities: people socialize, read, share project details, watch videos, joke around, and engage in other forms of hanging out and geeking out (cf. Ito et al., 2010; Kafai & Peppler, 2010)" (p. 9). Martin also suggests that "people share to exchange information, to educate others, to get feedback, and to feel connected (Kuznetsov & Paulos, 2010)… Scardamalia and Bereiter (2006) note that this is different from the typically competitive and replicative nature of classroom learning, where the (sometimes tacit) goal is to acquire a set of pre-existing knowledge, and to do so more effectively than ones' classmates" (p. 9).

In their study of after-school tinkering settings, Vossoughi et al. (2013) consider the ways tinkering supports "socially rich activity" (Espinoza, 2011). Within projects that culminated in a collective pinball arcade or musical composition, individual artifacts took on new meaning as part of a larger social creation. As they argue, “finding meaningful opportunities for participants to share their work both in the process of making and as a culminating social activity can deepen engagement, encourage connections across artifacts and their makers, and create openings for children to stretch into new roles and practices.” In a museum tinkering setting, Gutwill et al. (2014) identified three indicators of social scaffolding across participants: direct requesting or offering of help, inspiring new ideas or approaches, and physically connecting to others’ work. Sheridan et al. (in press) noted that participants in makerspaces found venues to share creations with a wider audience: “In this way, skills and knowledge are treated as tools that allow you to create new things and access new communities and learning opportunities. Things made are meant to be shown, used, sold, or shared. This deepens participants’ experiences, since production-based work is more authentic and learning outcomes focused on representation more robust when audience is an embedded component of the design process (Halverson, 2012).”

Blikstein (2013) found that through the process of digital design and fabrication, students “experience new ways of work and novel levels of team collaboration…through several cycles of failure and redesign, students not only achieved incredibly original and complex designs, but also became more persistent, learned to work in heterogeneous teams, and became better at managing intellectual diversity” (p. 7). For instance, Blikstein (2013) describes the distributed and collaborative process through which three students went about designing and building a table-top roller coaster: “While Tyler, Bob, and John worked together for almost the entire program, they had very different styles in going about their projects. As a team, Tyler’s optimism in the face of adversity worked as a great balance to John’s aptitude for ideating. While John often drove the start of projects, it was Tyler who would use the inevitable failures to advance their goal. Tyler would often tell John ‘Things never work the first time, and that’s okay.’

Almost every day they hit a fundamental problem with their design, and consistently came up with means to work through it. While Tyler took the constant setbacks in stride, accepting them as part of the engineering process, John considered them instead as embarrassing failures. Despite these differences, the team showed remarkable perseverance throughout in the project, and was able to use their different approaches to failure as a feature of their collective strategy of problem solving, rather than a difficulty" (p. 13). Blikstein also found that the students' dialogue became "increasingly complex, rigorous and compliant with the lexicon of physics" in and through the shared process of design (p. 12).

C2. Treating expert/novice roles as fluid

Researchers note the fluidity of expert/novice roles that often characterize learning in making and tinkering environments. In the context of youth media production, Chavez and Soep (2005) identified a "pedagogy of collegiality" whereby "young people and adults mutually depend on one another's skills, perspectives and collaborative efforts to generate original, multi-textual, professional quality work for outside audiences" (p. 411). Sheridan et al. (in press) found that becoming a member of a making community involved "participating in a space with diverse tools, materials and processes, finding problems and projects to work on, iterating through designs, becoming a member of a community and taking on leadership and teaching roles as needed and sharing your creations and skills with a wider world." Vossoughi et. al. connect the fluidity of expert/novice roles to opportunities for authentic audiencing (such as when children "hosted" the pinball machines they had made in an arcade open to neighborhood children and families) and to the intentional moves facilitators make to position students as experts (2013). As Gutiérrez et al. (2014) write: making and tinkering are accomplished in joint activity with others, and through the distribution of expertise and resources.

In summary, with respect to developing communities of learners that can leverage the interests and skills of all participants, researchers claim that making supports students to:

- Develop collaborative relationships - learning to work together, share tools and ideas, provide assistance to others and embrace intellectual diversity (Blikstein, 2013; Chavez & Soep, 2005; Gutwill et al., 2014; Vossoughi et al., 2013)
- Develop skills and practices involved in audiencing and sharing projects (such as confidence, communication, drawing connections across artifacts, giving and receiving feedback) (Martin, 2014; Vossoughi et al., 2013) as tied to the deepening of authentic intellectual activity (Halverson, 2013; Sheridan et al., in press)
- Develop community (Sheridan et al., in press; Vossoughi et. al., 2013)
- Take on new leadership and teaching roles (Sheridan et al., in press)

Pedagogy and Facilitation

The research described above offers initial evidence for the impact of making and tinkering experiences and emergent principles for the design of learning environments. In what follows, we connect these dimensions to the specific forms of pedagogy or facilitation named in the research literature, and articulate possible implications for professional development.

Hybrid pedagogical models

In contrast to the formal/informal binary that often frames distinctions between teaching and learning in and out-of-school, Sheridan et al. (in press) found that the three makerspaces they studied blended aspects of a “communities of practice” model with aspects of more formal education environments such as studio arts and engineering design courses. As they describe: “we saw evidence in each makerspace of a hybrid model that incorporates many of the ways of seeing, valuing, thinking, and doing found in participatory cultures, yet incorporates pedagogical structures found in more formal studio-based settings, such as demonstration, facilitated workshops, and critique (Hetland et al., 2013).” Sheridan et al. suggest that hybrid pedagogical approaches create flexible environments that support a range of solo or group projects, privilege relationships and community building and provide the “just-in-time access to STEM and arts based skills and habits of mind (Hetland et al., 2013) required to successfully complete a project.” Vossoughi et al. also found fruitful intersections between formal and informal pedagogical practices in after-school settings. These include the ways teachers made skills and concepts *explicit* (naming tricks of the trade or sharing the ‘why’ of a practice) and engaged children in whole-group discussions about their ideas, questions, explanations and plans, and about the role of tinkering in scientific and artistic pursuits. Their research also complicates common pedagogical axioms within the field, such as the notion that teachers should pose questions rather than offer explanations, or avoid academic language. Rather, they argue for a more nuanced approach that attends to moments when well-crafted explanations or strategic uses of scientific language are generative, and serve as a form of intellectual inclusion or respect (Vossoughi et al., 2013).

Explicit discussions of **making and maker identities** are also addressed in the literature. Dixon and Martin (2014) found that becoming a “maker” was integrally tied up with how participation was framed in practice. They suggest that it is “critical to attend not only to the knowledge and skills that youth may acquire through making, but also to their sense of themselves as participants within a broader community.” Norris (2014) argues that teachers should support the development of positive self-concepts and identities as part and parcel of the design process. Of relevance to professional development, Brahms and Crowley (2014b) found that museum educators in a museum-based makerspace “identify as being members of the maker community, and each bring deep knowledge, skill and personal interest in a particular area or medium of making, as well as training in inquiry-based facilitation." As we return to below, the question of whether young people and/or educators must identify as "makers" (versus as people who are engaged in making, science, art, writing, etc.) to participate meaningfully in making as educative practice also needs to be considered in relation to broader issues of culture and equity.

A number of researchers describe the **pedagogical skills and understandings** that support meaningful participation in making and tinkering. Brahms and Crowley (2014b) suggest that effective facilitation involves: "skill and knowledge of the materials, tools, processes, and practices of making; strategies for facilitating children's development of accurate knowledge, skill, and progressive engagement in the learning practices of the making community; and an understanding of the child as a learner, his or her prior experiences, interests, intentions, and temperament." This view is consistent with the literature on effective teaching in other contexts and disciplines (e.g., Darling-Hammond & Bransford, 2005). Similarly, Peppler (2013, p. 42) suggests drawing "upon a wide variety of domains, including digital arts, physics, and crafting, in conceptualizing what and how to teach and in organizing the learning space." Of relevance to professional development, Peppler further states that "to successfully transform classroom and after-school learning environments, it is important to relay these types of insights to preservice teachers and informal educators as well as provide rich cross-disciplinary training" (p. 42). This includes offering STEAM-powered tools and materials that allow for open-ended exploration, a high degree of personal expression, and aesthetically compelling possibilities (Peppler, 2013). Blikstein (2013) and others (Petrich, et. al., 2013) note the importance of teachers having opportunities to experience activities and tools as *learners* prior to and alongside engaging young people in making activities. Bowler considers the skills, knowledge and aptitudes librarians need to organize makerspaces that reflect the core mission and values of libraries (2014, p. 60).

Brahms and Crowley (2014b) speak to the distinct and potentially complementary roles played by educators and family members in supporting children's making. In one example, Brahms and Crowley describe the interactions of a young boy, Owen, who's mother facilitated and supported his participation in a museum makerspace based on her sense of his deep interest in scientific explorations, such as taking apart electronics at home. In the setting, Owen worked closely with Dustin, a museum educator, who invited Owen to investigate materials and facilitated his understanding of how a circuit works. At one point in the interaction, Owen and Dustin were discussing the concept of a switch and the conservation of energy (i.e. saving the batteries energy life by switching the circuit "off."). Brahms and Crowley describe how Owen related this idea to an electronic toy he has at home, which sparked his Mom to participate in interpreting this connection for Dustin. A little later in the interaction, Owen's sister Anna intervened. She had been building her own circuit block with Kurt, another educator in the exhibit space. As Brahms and Crowley write: "Anna constructed a fan circuit block component out of wooden blocks, a motor and zip ties. After completing her construction, and testing it a number of times, Anna prepared to share her creation with her brother, explaining to Mom, 'I'm going to show it to Owen. He's gonna think it's the coolest thing in the universe!'" Based on a range of examples of family learning in the museum makerspace, Brahms and Crowley conclude that, "As informal learning environments and opportunities are designed for learning through making, we must be thoughtful about how the relative expertise of consequential adults in a child's learning experience is drawn upon and positioned relative to others' expertise. This suggests that children, adult family members, and educators must work together as learning partners in order to foster young children's meaningful learning experiences through making in designed informal learning environments."

Pedagogical Practices

Gutwill et al. (2014) found that facilitators in the Exploratorium's tinkering studio engaged in three kinds of facilitation moves: *Sparking* or orienting learners to the space and activity at hand, while establishing the safety needed for participants to take risks and unleash creativity; *Sustaining* participation by offering new tools or suggestions, welcoming learners' ideas, re-engaging participants when interest waned and revoicing ideas to help clarify the nature of the problem; and *Deepening* participation by fostering reflection or challenging learners to complexify their work. Vossoughi et al. (2013) attend to the **specific forms of pedagogical talk and gesture** used by educators in after-school tinkering settings. They found that phrases such as "that's a nice draft" or "test it and see what happens" reflect and reaffirm the value placed on iteration and experimentation. They connect these moves to a broader set of **equity oriented design principles**, such as building generous learning environments, cultivating play and imagination, widening definitions of learning, intelligence and science, and treating learning as a purposeful and social endeavor. Peppler (2013, p. 42) writes about the importance of **helping students document and share their work,** suggesting that "as students work with new tools and materials to render aesthetically compelling work with STEM content, it is important to document the process and products of creation, celebrating failures as well as successes as learning experiences." As touched on above, documentation and sharing can also create rich opportunities for meaning making and feedback.

Some studies highlight the need to design for and support **the complexification of learners' project and explorations over time**. In their analysis of creativity in the digital realm, Ackermann et al. (2009, p. 82) note the importance of “enabling the act of creating to evolve with increasing levels of user sophistication and thus supporting this progress towards mastery with personally relevant inspiration and content based on one’s previous creations, stated interests, alongside inspiration from one’s groups and affiliations.” Blikstein suggests that while “digital fabrication machines might generate aesthetically-pleasing products with little effort, educators should shy away from quick demonstration projects and push students towards **more complex endeavors**” (2013, p. 18). Drawing on Papert’s work, Resnick (2011) argues for the importance of developing technologies with a low floor (easy to get started), a high ceiling (opportunities to create sophisticated projects) and wide walls (supporting many different types of projects).

Researchers also note pedagogical approaches that seek to build on the **transparency** of materials to make the processes of making more transparent. Based on a pilot study (referenced above) in which students significantly increased their understanding of key circuitry concepts, Peppler (2013, p. 40) argues that e-textiles “are not only effective tools for broadening participation in computing but might also offer greater transparency into STEM disciplinary content” such as circuitry. Based on their analysis of teaching and learning in tinkering after-school settings, Vossoughi et al. (2013) suggest that engaging with the big ideas of science and engineering without making those ideas transparent or explicit can reproduce existing inequities. Through observations and interviews, they found that a number of children drew sharp distinctions between play and science (the more fun it is, the less scientific, the more scientific, the less fun). Based on these findings, they argue that equity-oriented pedagogies work to make STEM concepts and practices explicit within the playful, inquiry-led context of tinkering activities. Supporting children to recognize the deeply intellectual aspects of play may also help expand relationships with their own capabilities and encourage connections across settings. Similarly, Nasir et al. (2006) write that recognizing the overlap between everyday activities and the "official" activities of science can highlight valuable access points to science for learners who might not otherwise engage in scientific activities.

Cautions, Recommendations & Tensions in the Field

Here, we summarize some of the cautions and recommendations voiced by researchers, particularly with regards to the ways making experiences may be incorporated into schools and other educational settings. This is followed by a brief discussion of the tensions and gaps we note in the literature. While we recognize the *potential* of making to provide an inclusive and productive pedagogy that can expand participation in science and engineering practices, we also note the need to attend to if and how making is in fact being implemented or studied as equitable practice, for whom, and under what conditions.

Narrow focus on STEM: Martin and Dixon (2013) caution against "a reductive treatment of making as a set of component knowledge and skills" and argue that "efforts to tie making more narrowly to STEM outcomes or to assume uniform outcomes in any particular area of learning may limit the openness of maker definitions, leave less room for exploration and personalization, and erode the value youth see in participation" (p. 3). Based on their interviews with young makers, Martin and Dixon advocate for "a more holistic, youth-centered view of the role and value of making as an educative experience" (p. 1). Similarly, a number of researchers (Peppler, 2013; Sheridan et al., in press) assert the interdisciplinarity of making and the importance of creating substantive connections across STEM and the arts. Artistic pursuits involve their own disciplinary practices and dispositions and must not be reduced to a vehicle for STEM learning.

Fetishizing tools: Martin (2014) writes, "There is a seductive, but fatally flawed conceptualization of the Maker Movement that assumes its power lies primarily in its revolutionary tool set. In this view, deploying these tools in school settings will lead to transformations in education. Given the growing enthusiasm for making, there is a distinct danger that its incorporation into school settings will be tool-centric and thus incomplete…. Without [a] tripartite focus [on tools, community infrastructure and maker mindsets], implementation will likely follow a pattern whereby tools are purchased, but the community and mindset are given too little attention. When this truncated effort does not create substantive change, it will be labeled a failed experiment." Martin connects this tension to the ways technology was conceptualized as a stand-alone agent of change, and to the challenge of meaningfully incorporating making in schools: "The difference between the Maker Movement and what is typically seen in schools represents an opportunity to create change, but also a distinct challenge, as schools struggle to accommodate differing structures, goals, and incentives. Herein lies an important area in need of research: to examine the ways in which an integrated vision of making can and should mesh with the practices of schooling." The fetishization of tools (and activities) also conflicts with the need to integrate the socio-emotional and disciplinary dimensions of learning noted in section III. While relationships and community are often studied as contexts for learning, shared experiences of making and tinkering also need to be studied as contexts for deepening relationships and building community (Gonzalez, personal communication).

High versus Low Tech: Some argue that digital fabrication accelerates invention and design cycles in ways that quickly transform an idea into product such that students “can focus their attention on improving the design rather than taking care of mundane issues with the materials” (Blikstein, 2013, p. 7). Blikstein observed that “unlike asymmetric or fragile cardboard prototypes,” products generated by laser cutters and 3D printers were aesthetically pleasing and had a strong impact on students’ self-esteem: “It wasn’t ‘school stuff,’ it was the ‘real thing’” (p. 7). Such acceleration may contrast with approaches that privilege working with **everyday and familiar materials** in ways that bring participants into close contact with the moment-to-moment processes of design and building and allow for expanding familiarity with a range of tools and materials (Petrich et al., 2013). Vossoughi et al. (2013) also suggest that the use of everyday materials may support students to extend and deepen their explorations across contexts. It is an open question as to whether experiences of iteration and problem solving are qualitatively distinct (and/or complementary) across these modes of making. Drawing from and engaging in research that examines how students *think and work across* physical and digital design will help illuminate these processes (Hooper & Freed, 2013).

Age groups: Though the research literature includes studies of all age groups, the educational or school focused applications of making tend to focus on middle and high school students. Research on younger children and families (Brahms & Crowley, 2014b; Gutwill et al., 2014; Gutierrez et al., 2014; Vossoughi et al., 2013) offers an important counterpoint and raises questions about the distribution of making and tinkering programming across age groups. While some caution against a narrow focus on adults in makerspaces, Fields & King’s (2014, p. 7) study of a university craft technologies course suggests that “opportunities for self-expression and creativity can be very limited in the lives of busy working adults—kids are ‘allowed’ this kind of play (in many circles at least) but adults are often excluded from this through commitments to work and family. The course opened up a space for older students to pursue personal interests and learn new techniques."

Duration of Funding: Though few researchers focused on questions of program support and sustainability, Dorph & Cannady's analysis of 25 maker programs indicated that "one year is not long enough for a new program to figure out the business model and investors needed to keep the program alive... On the other hand, when investments land in an established organization with existing capacity for program development and funding, a year may be sufficient. Accordingly, it might be worth considering two-year investments in new programs that are catalyzed by these grants within new organizations" (2014; p. 4-5)

Though not explicitly addressed by the research, we note an additional set of **tensions and gaps in the literature**.

While there is growing research attention to design and facilitation, we see a need for **more explicit and detailed analyses of pedagogy** in making/tinkering environments. As we have written elsewhere, educators in making spaces or informal STEM learning environments are frequently described as "facilitators." This shift away from the word "teaching" is often meant to distinguish the support offered by adults from more didactic or teacher-centered approaches. While this is important, we worry about swinging to the other extreme in ways that make "teaching" or "pedagogy" taboo words within the realm of tinkering/making. Minimizing the role of the teacher can shortchange the many generative aspects of pedagogical talk and interaction and forego opportunities to share valuable knowledge with other educators (Vossoughi et al., 2013).

The literature also tends to position making over and above the routine practices of schools. While this reflects the role of making as a critical response to narrow forms of curriculum and pedagogy, we also worry about slipping into pejorative views of schools and teachers in ways that work against the kinds of change researchers are interested in advancing. As reflected in section III, the elements of high quality making and tinkering programs are not developed from scratch. Rather, they build on existing pedagogical traditions and evidence-based design principles. Thus, similar to the value of connecting to (rather than replacing) the familiar practices of students, approaches to scale and professional development would do well to recognize and leverage the existing expertise of teachers rather than presenting making/tinkering as entirely "new" or superior to other rich forms of STEM and artistic activity. Similar tensions emerge when the maker movement fails to recognize and learn from existing histories of craft, artistic and professional practice.

Equity: Though the recent upswell of investment in tinkering and making signals both a need and hope for re-imagining the educational status quo, particularly in STEM education, the question of how to best serve students that bear the brunt of narrow educational policies—working class students and students of color—is not at the center of the discourse on making and education (Vossoughi et. al, 2013). A more direct engagement with the history and contemporary manifestations of **educational inequality** and the **literature on equity and learning** would help this emerging field address the pedagogical *how* of creating equitable environments and wrestle with some of the tensions apparent in the maker movement (Vossoughi et. al, in preparation). These tensions include:

Representations of making and makers: Scholars have noted that *Make Magazine*, and the attendant Maker Faires, widely seen as a central organizing forces of the Maker Movement, are overwhelmingly dominated by the work, ideas, and images of middle class white men (Buechley, 2013; Brahms & Crowley, 2014b). This presents a central contradiction if making is positioned as an inclusive or potentially transformative practice. Whose forms of making count as "making"? Whose values and goals inform definitions of making? In what ways are young people being invited to identify as the type of maker represented by the brand in order to participate in making? The growing socio-cultural literature on culture, race, identity and epistemology (Nasir et al., 2006; Medin & Bang, 2014) and equity beyond access or "sameness as fairness" models (Gutiérrez & Jaramillo, 2006) offers important conceptual resources for examining these questions.

In this vein, Norris (2014) identifies gaps in the literature with regards to **the connections between design thinking processes and identity processes**. In a study of design thinking in an urban classroom serving young women of color, Norris found that "Although some students were able to make meaning as they designed individual projects that helped them to develop more positive identities, other young women did not make tangible projects... social constructions and the need for privacy overshadowed their willingness to design and their need to share their designs." Norris therefore highlights the key role of the educator in recognizing the often racialized and gendered processes of identity construction as they intersect with making and design, and the importance of supporting students to develop positive self-concepts.

We also note that while some researchers describe the demographic and socio-economic contexts of their studies, others describe student populations or program participants by age and gender but not race/ethnicity or class. When this information is not offered, it becomes difficult to adequately assess the equitable distribution of making experiences as well as the full meaning and applicability of research findings. Researchers also risk treating dominant groups as an unmarked "norm."

Creative/open-ended vs. standardized/test-centric education: While efforts to shift education in the direction of hands-on, project-based and creative learning experiences are important, the maker movement has not, to date, substantively engaged with issues of remediation, segregation and tracking as they have shaped and continue to shape the schooling experience of working class students and students of color. These policies are deeply tied to cultural assumptions about ability and intelligence, such as the notion that students who are constructed as "underachieving" should be given a more basic set of tasks, rather than intellectually rich tasks with ample support (Cole & Griffin, 1983; Gutierrez, 2008). Thus, while phrases like "self-directed" and "independent" learning, or "celebrating failure" are common in the literature on making (and are often meant to signal a shift away from didactic models of education) we worry that they are out of touch with the realities of schooling for students of color and can easily lend themselves to deficit frames. If making is to challenge rather than reproduce existing hierarchies, research may benefit from a deeper engagement with the history of ideas and debates around progressive educational movements and issues of equity (e.g. Delpit, 1986). Similarly, efforts to incorporate making in schools (such as the movement to reclaim shop classes as makerspaces) may benefit from a more explicit engagement with the academic/vocational divide (Rose, 2005).[1]

Making towards what ends? Finally, the Maker Movement is replete with buzzwords like "innovation" and often aligns itself with the policy emphasis on "workforce development" and "global competitiveness." These discourses have implications for teaching and learning. For

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[1] See in particular the 2014 edition of Rose's *The Mind at Work*, which includes a new preface and discussion of the maker movement.

example, the artifacts or objects young people make are often referred to as “products,” and making is touted as an opportunity to revitalize the American economy. While the emergent literature focuses on the *what* and *how* of making, it may risk paying inadequate attention to the *why*: the larger *purposes* of making and how those purposes are tied to particular social and political values. In this vein, Vossoughi and Vakil (2014) express concern with corporate and military investments in making and problematize narratives that “tout innovation yet de-emphasize critical thinking, the questioning of authority, social analysis and the arts.” They argue for a more “nuanced stance that embraces inquiry and problem solving but critiques notions of innovation that are divorced from youth agency and activism.” Engaging more explicitly with the goals of making would bring the literature into conversation with critical theoretical traditions that treat learning as a political process and consider the values and social futures being designed for (Barton, 2003; Booker, et al., 2014; Medin & Bang, 2014; Santo, 2013).

Case Study: Tinkering After-School

We conclude with a case study that looks more closely at one after-school tinkering/making environment. The Tinkering After-school program**,** an ongoing partnership between the Exploratorium and the Boys & Girls Clubs of San Francisco, offers tinkering programming for clubhouses serving urban communities. Adult and youth educators (ages 15-20) join elementary aged children in a weekly workshop setting to design and co-create artifacts such as stop-motion animation films, wooden pinball machines, wearable circuits and musical instruments. While these activities have particular parameters and goals, they are intentionally designed to support multiple pathways and to imply a range of solutions. Educators work to develop a sustained tinkering curriculum that engages youth in inquiry and meaning-making by blending STEM practices and concepts with artistic pursuits.

The clubhouses where workshops take place serve low-income youth from immigrant and diasporic backgrounds (African American, Latin@ and Asian American) and generally include an equal mix of boys and girls. The tinkering program staff is also comprised of adults and youth from immigrant and diasporic backgrounds. Since its inception, the program has prioritized equity, working to design inclusive and intellectually respectful learning environments that expand conceptions of intelligence and science and incorporate students' cultural and intellectual histories. Building on the work of the Exploratorium’s Tinkering Studio, the Tinkering After-School Program aims to develop teaching and learning practices that cultivate “tinkering dispositions” and shared experiences of intellectual possibility. In collaboration with the program's director, Meg Escudé, educational researcher Shirin Vossoughi has been conducting ethnographic research since the program's inception in 2012. This research focuses on the nature of teaching and learning in the after-school tinkering settings**,** the ways these settings design for equity, and the kinds of shifts in participation and identity that emerge among participants (children, teens and adults) over an extended period of time.

Program routines and pedagogical practices

A typical day in the after-school program begins with the pedagogical staff (adults and youth) setting up the room and organizing tools, materials and a configuration of chairs and tables that supports the activity for that day. During this time, educators (including the embedded researcher) discuss specific plans and ideas for facilitation and refresh our collective memory about the activity, which we usually engage in as learners during professional development trainings. When the children arrive (typically about 15-25 students, including long-time members and newer drop-in participants) everyone gathers together in what participants refer to as "circle time." During circle time, Escudé and other staff engage children in a community building activity, introduce and demonstrate the day's project, and facilitate a discussion based on children's questions, ideas, discoveries and plans. For example, in an activity involving tools and gears, educators might ask: "Where else have you seen gears?" or "Who uses tools in your family? What kinds of tools do they use?" In an extended unit on circuits, children were invited to share what they discovered or contemplated in the process of working with circuit boards the prior week as preparation to make wearable circuits. Educators also make efforts to connect tinkering practices with a range of professional and everyday activities, such as art, science, writing, cooking, construction and architecture.

After about 10-15 minutes, one of the regular participants usually takes the collective temperature and suggests that the kids are ready to build. "Workshop time" begins, with participants figuring out who they will work with for the day and how they will approach the activity. Facilitators move around the room, sometimes engaging in extended building with a particular child or ensemble, sometimes making their own project alongside the children and providing assistance as needed. Adult educators simultaneously work with the children and support younger facilitators to complexify and deepen children's investigations. All participants are encouraged to collaborate and support one another in the process of making. Accordingly, ideas and solutions often "travel" around the room. As the day winds down, children are invited to record and reflect on the building process in their science notebooks. Sometimes there is a second circle time to share artifacts and new discoveries. After the children are picked up by family members or return to other club activities, facilitators clean up and prepare for their debrief. This usually involves about 10-15 minutes of sustained writing in our own notebooks.

Adults encourage youth to write not only about the kids' investigations but also about the interactions they had, the pedagogical moves they made, or ones they would have made in hindsight. These reflections are then used to engage in a collective discussion about the day, what went well, what could be improved, the types of learning we witnessed in the children, and in ourselves.

Vignette: Circuit boards

During one circuit board activity, Arthur (7 years old, participating in the program for about 6 months) worked with Walter (an adult facilitator) to explore circuitry. Arthur's exploration began with a review of his previous experience with circuit boards in the after-school program. He first tried a simple circuit by connecting a switch to a light bulb. Noticing that he did not have a power source, Walter drew Arthur's attention to another circuit that included a light, a switch and a battery pack. Arthur quickly realized the need for power and incorporated a battery himself. He then deepened his investigation, first adding a switch, then adding a board with multiple lights, and finally adding more boards with different simple machines and lights.

Arthur became very excited when he realized that some of his lights were lit even though they weren't directly connected to the battery. This prompted him to call others over to see his circuit, pointing out that some lights worked "without even batteries." Using Arthur's own phrasing, Walter affirmed and then re-framed this statement, helping to clarify what was happening, "without even batteries going directly to those light bulbs." At this point, another facilitator walked by and said (excitedly), "look at his parallel circuits!" This casual initiation into relevant terms and concepts continued to build as other students came by to witness Arthur's work and ask questions. Arthur then tried out the term "short circuit," which he had picked up in a previous circuit activity. Pointing to his (by now giant) set of circuits, Arthur exclaimed, "look, these are not even short-circuiting!"

Arthur then asked Walter about a battery tester that was available on the table. After Walter explained the uses of the tool, Arthur became fascinated and took a break from his circuit building in order to test all his batteries and compare their power. After this detour, he periodically switched off his circuits and spoke about the need to save their energy. While building and testing out his circuit, Arthur also mentioned to Walter that he is “getting smarter and smarter” because he comes to tinkering every week. Another productive pathway emerged when Arthur decided to move around the room to check out the work of others, a practice that is encouraged in the setting. He became especially excited to see some of the ideas he had been working on showing up in others' circuits. He spent some time as a guest at Aeden’s circuit (9 years old, participating in the program for about 2 years) who had earlier stopped by to witness Arthur’s parallel circuit. Aeden pointed out interesting aspects of his own investigations (such as a small fan with rapidly spinning foam blades) and Arthur joined in the experiment. Aeden’s own engagement with circuits seemed to ebb and flow on this day, which facilitators later discussed as potentially stemming from his need for a greater challenge. During the end-of-the-day debrief, one facilitator committed to working more closely with Aeden the following week.

Once back at his original circuit, Arthur continued to investigate the idea of lights that work “without even batteries,” adding more and more boards to his long parallel circuit. This opened up new questions and challenges as the lights furthest from the battery pack grew dim or did not light up at all. Walter commented that Arthur had built an “elegant circuit” and offered suggestions for ways to test and try out solutions. This created an occasion for Arthur to apply his battery-testing skills as he considered adding more batteries. Some of Arthur’ solutions surprised Walter, who expressed that he was also learning from Arthur’s ideas, showing camaraderie in the effort. Arthur then picked up a circuit board with a motor, held it up and asked, “Who made this?” before working it into his circuit. When the motor was added, Walter pointed out that it was effecting the intensity of light from some of the light bulbs. This threw Arthur into his final investigation of the effects his circuit boards were having on one another other. As the day winded down, Arthur joined other students to draw and write about his circuits in his science notebook.

Conclusion

Based on our observations and analyses of such interactions, our emergent findings highlight the empirical intersections between tinkering, equity and the development of STEM practices. Our research on pedagogy reveals the ways educators actively work to build intellectual safety, and offer specific forms of guidance as they engage children in the joint process of tinkering. These include: making efforts to learn about children’s ideas or goals, modeling and encouraging valued STEM practices (such as questioning, testing and iteration), and supporting participants to draw connections to previous investigation and experiences. As illustrated in Arthur and Aeden’s interaction and in Arthur’s comments during his exploration, we also found that participants came to support one another in ways that reflect the social and scientific practices valued in the setting and developed new relationships with the act of learning. These shifts include: new orientations towards iteration, drafts, and mistakes; increasing curiosity about the process through which artifacts and machines are made; the appropriation of tinkering practices across activities/settings; growing confidence with regards to problem solving, tool-use and scientific language; and new forms of collaboration. As reflected throughout this paper, we also address tensions that have emerged in our work, such as the relationship between learning in and out of school, and the need to address equity and pedagogy in the discourse of the larger “maker movement.”

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