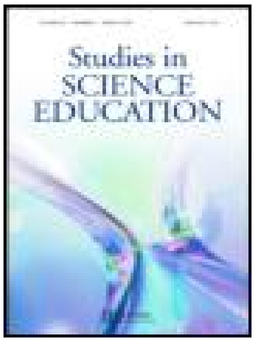

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The promise and the promises of Making in science education

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ABSTRACT

Making is a rapidly emerging form of educational practice that involves the design, construction, testing, and revision of a wide variety of objects, using high and low technologies, and integrating a range of disciplines including art, science, engineering, and mathematics. It has garnered widespread interest and support in both policy and education circles because of the ways it has been shown to link science learning to creativity and investigation. Making has taken root in out-of-school settings, such as museums, science festivals, and afterschool and library programmes; and there is now growing interest from primary and secondary educators in how it might be incorporated into the classroom. Making expands on traditions associated with Technology Education and Design-Based Learning, but differs in ways that can potentially broaden participation in science and STEM learning to include learners from communities historically underrepresented in STEM fields. STEM-Rich Making is centrally organised around design and engineering practices, typically integrating digital tools and computational practices, and positions scientific and mathematical concepts and phenomena as the materials for design. This paper takes a critical view of the claims about Making as a productive form of science teaching and learning, and reviews the current research literature's substantiation of the ways in which Making supports students' agency, promotes active participation in science and engineering practices, and leverages learners' cultural resources.

KEYWORDS

Making; STEM; practical work; tinkering; informal; broadening participation; inclusion; equity; Maker Education; Maker Movement

1. Introduction

What does the Maker Movement mean for science education? Many educators, in both formal and informal settings, are enthusiastic about the ways in which Maker Education sparks interest and can support deep engagement in learning across a range of disciplines (Bullock & Sator, 2015; Dixon & Martin, 2014; Martinez & Stager, 2013). Making has been shown to support the development of an array of learning dispositions, including resourcefulness, creativity, teamwork and forms of adaptive expertise (Martin & Dixon, 2016; Peppler, 2016; Ryan, Clapp, Ross, & Tishman, 2016). While Making is often touted as something new in STEM education, many scholars have noted that, as an educational practice, Making has deep roots in the pedagogies advanced by Froebel, Dewey, Montessori, and others who have argued for the centrality of materials-based investigations for motivating and advancing student learning (Blikstein & Worsley, 2016; Resnick & Rosenbaum, 2013). It also has many affinities with Technology Education in the UK and Design-Based Learning in the US. Yet there are also differences that, crucially, promise to broaden interest and participation for many students who do not already identify as productive STEM learners.

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While 'making' is a fundamental human practice, acts of making associated with the Maker Movement (hereinafter 'Making') generally involve the integration of digital technologies into practices of designing and constructing physical, and sometimes virtual, objects (Peppler, Halverson, & Kafai, 2016). Making is frequently characterised by an interplay of high and low technologies, producing a sense of playfulness or the unexpected. At a local Maker Faire, you might see steam-powered mopeds, LED-studded quilts, or battling robots made from refurbished kitchen gadgets from the 1960s. Making's exuberant, obsessive nerdiness celebrates ingenuity and wit in the context of exploration and invention, and thus has been championed by many educators and business leaders as a powerful way to reinvigorate innovation and entrepreneurship (Kalil, 2010; Van Holm, 2015). But while the majority of rhetoric about Making connects it with STEM learning and, ultimately, economic development, a closer look reveals that Making challenges traditional ideas of what counts as STEM, what counts as learning, and perhaps even what counts as science education.

Characterised by 'high ceilings, low floors, and wide walls', Making is argued to be profoundly accessible because of its fundamentally interest-driven nature wherein students develop and pursue their own pathways to realising their own ideas (Resnick & Silverman, 2005). As such, because it doesn't rely on prior experience with formalised design or engineering procedures or identities, it is positioned as a strategy for broadening participation in learning and particularly in the STEM disciplines (Buchholz, Shively, Peppler, & Wohlwend, 2014). Yet while some hail the Maker Movement as democratising access to the ideational and physical means of invention and production (C. Anderson, 2012; Blikstein, 2013; Hatch, 2014), others (and sometimes they are one and the same) critique its hetero-normative marketing images (Buechley, 2013), close alliances with industrial and military structures (Vossoughi, Hooper, & Escudé, 2016), and putative tone-deafness to social dynamics that privilege particular cultural ways of being and making (Chachra, 2015; Morozov, 2014). These tensions are the result, perhaps, of an under-theorised, over-marketed, and rapidly proliferating endeavour. For example, Willett (2016), in a critical review of the nascent literature on making in libraries, points to the contradiction in the ways that Makerspaces have been described as affinity spaces (Gee, 2004), organised by and for those with specialised and alike skills and interests, and, alternatively, as open-source sites democratising the means of production (Hatch, 2014). Blikstein and Worsley (2016) describe the rhetorical gap between a corporate focus on Making as a context for economic innovation and an educational focus on Making as a context for human development.

As many scholars have noted, Maker Education encompasses more than science or STEM education (e.g., Brahms & Crowley, 2016a; Martin & Dixon, 2016). It also encompasses more than conceptual learning (e.g., Bevan, Gutwill, Petrich, & Wilkinson, 2015; Ryan et al., 2016). This paper, addressed to a science education audience, distinguishes between Maker Education writ large, which encompasses a wide range of disciplinary practices, including linguistic, artistic, computational and others, and STEM-Rich Maker Education (see Figure 1 for an image of a STEM-Rich Maker activity that has also lent itself to student writing, storytelling, and diagramming activities).

STEM-Rich Making is by its nature interdisciplinary. Entailing practices of design, engineering, and sometimes mathematics, it positions science concepts and phenomena – such as electrical circuitry, force and motion, energy transfer, or cause and effect – as the central tools or materials necessary to the Making processes. As with some forms of Technology Education (McCormick, 1997) and Design-Based Learning (Kolodner et al., 2003), students develop familiarity with and understanding of science concepts and phenomena while engaging in practices of design, engineering, and mathematics (such as scaling, measuring, etc.). Science educators can use STEM-Rich Making activities to develop or formatively assess students' conceptual understanding by engaging them in the application of those understandings through design and engineering.

The definitions and distinctions I make here are not meant to narrowly construe Making as a tool of or for STEM education exclusively, because clearly it is much more than that; but rather to consider, specifically, what Making offers the fields of primary and secondary science education. In what follows, this paper will review what Maker Education is, how it is positioned to support science education, and

Figure 1. A young girl begins to diagram her Maker creation (a scribbling machine). © Exploratorium.

what the research literature says about how it advances science learning, conceptualised broadly as processes of knowing, doing, being and becoming in science (Lemke, 2001; Nasir, 2012). Because the rapid growth of Maker Education has been fuelled in part by a significant marketing machine, including the active advocacy and leadership of many Silicon Valley corporate entities as well as many branches of many governments, including the US military, the paper seeks to provide a critical perspective on claims and approaches to Making as educational practice, with the goal of informing science education strategies, including professional development for educators engaged in STEM-Rich Making. It also seeks to identify gaps in the research literature for future investigation.

2. What is Maker Education?

Many animals make things, and humans are sophisticated makers. Homo Habilis, the handy (wo)man, lived some 2 million years ago. But the 'Maker Movement', as such, might be said to have begun in 2005, in Silicon Valley, at a time when daily pursuits in industrialised nations were becoming increasingly mediated by digital devices and thus increasingly removed from materiality (C. Anderson, 2012; Hatch, 2014). Parents, educators, and the popular press began to note with concern children's increasing preoccupation with computerised technologies and tools (Smith, 2004; Subrahmanyam, Greenfield, Kraut, & Gross, 2001). This was also a time when many miniaturised digital tools and technologies were suddenly highly accessible both in terms of location (at local hardware stores or via the Internet) and cost. Microprocessors, smaller than a matchbox, now sold for less than the cost of a gourmet cup of coffee. Advances in the materials sciences led to low-cost pliable computing elements that could be sewn into garments. Thus, a person with an interest in crocheting, could now purchase conductive thread, LED bulbs, a Lilypad microprocessor, and produce entirely new genres of hand-made baby booties or winter scarves.

2.1. Beginnings

The Maker Movement has a complicated social history. Its genesis was not driven by engineers and technologists, though those fields have come to embrace it, but rather through the coalescing of a disparate set of communities organised around auteurship and craft. This grassroots collective of hackers, tinkerers, crafters, and designers share a DIY sensibility and a need for a public commons for swapping, sharing, and showcasing their skills and wares.

Traditionally associated with subversive and alternative social networks, hackers emerged from European squatter, punk, and media activist communities, surfacing later in university-based computer labs (Morozov, 2014). Tinkerers have long been associated with an economically motivated resourcefulness and skill in repurposing, recycling, and repairing. Crafters are known for their technical skills and hobby cultures. Makers, on the other hand, have been touted as the founders of whole industries and the leaders and entrepreneurs of future economies (Cognizant, 2011; LaWell, 2016). These disparate communities, with their varying degrees of normative, dominant, and counter-cultural traditions, came together under the banner of Making. To be sure makers, tinkerers, crafters, and hackers all make and all tinker, all craft and all hack; yet their distinct histories operate to make the Maker Movement something of a big and sometimes boisterous tent.

The tent was pitched in 2005 with the first publication of *Make Magazine*. The following year the publisher sponsored the first *Maker Faire* just north of Silicon Valley in the San Francisco Bay Area. This Faire brought scores of makers together to showcase their work and wares to one another, to swap tips and tools, and to collectively begin to identify not as tinkerers, hackers, quilters, mechanics, or builders, but rather, or also, as Makers.

Within a decade, flagship Faires in San Mateo and New York were drawing in over 200,000 participants. In 2014, there were over 120 public Maker Faires and mini Maker Faires held on six continents (Figure 2 shows an example of the type of active Making activities that take place at these Faires, alongside a large number of demonstrations and exhibitions of Maker wares). Libraries and museums, in Europe, South-East Asia, and the United States, have formed regional networks to support the construction of Making learning spaces (called makerspaces, hackerspaces, tinkering studios and playlabs) in their facilities. FabLabs and TechShops have sprung up around the globe as fee-based machine shops and community resources.

In the US, with active encouragement from the White House Office of Science and Technology Policy, government agencies such as the Department of Education, the National Science Foundation, the Office of Patents, and many others, have launched Maker initiatives funding spaces, programmes, or education research to advance the movement (see Kalil, 2010; National Science Foundation, 2015; Obama, 2009).

Figure 2. Soldering activity at a Maker Faire. © Exploratorium.

In the EU, Erasmus has funded a network of science museums to develop Makerspaces. The European Commission worked with the Rome Maker Faire to document 50 Maker Faires across Europe. In the UK, NESTA (the National Endowment for Science, Technology and the Arts) recently commissioned a database mapping almost 100 makerspaces across Great Britain. Google searches find Maker events happening on all continents except Antarctica (at least for now).

While research on Making has lagged practice (Herold, 2016), that too is rapidly changing. Recently Routledge published a two-volume source book, *Makeology* (Peppler et al., 2016), containing over 35 chapters by leading Making researchers and practitioners, and several other compendia are in production. The annual FabLearn conference in Palo Alto has tripled in size in its first five years, and launched conferences and fellowships internationally (Blikstein, personal communication). A broad range of popular press and grey literature on Making has been generated over the last decade. Peer-reviewed articles are slowly beginning to emerge, with the first papers appearing in 2014. What do we know so far?

2.2. Definitions

While there appears to be common agreement that Making is a broad category of activity that involves people ideating, designing, and producing physical or virtual objects in the world (Blikstein, 2013; Halverson & Sheridan, 2014; Martin, 2015), what counts as Making in educational contexts is not fully settled in the literature or in practice. While some have distinguished between making, engineering, and tinkering (Martinez & Stager, 2013) and others between design, making, and play (Honey & Kanter, 2013), these scholars and others have also noted the intertwined nature of most activities that are called Making. Peppler et al. (2016, pp. 1–2) note that Making entails 'open exploration, intrinsic interest, and creative ideas' and is 'propelled by the introduction of new technologies and … the rise of the Internet'. Martin (2015, pp. 3–4) describes Making as a 'class of activities focused on designing, building, modifying, and/or repurposing material objects, for playful or useful ends, oriented towards making a "product" of some sort that can be used, interacted with, or demonstrated'. Youth in Martin's study of an out-of-school Maker club defined making as 'building things, being creative, having fun, solving problems, doing social good, collaborating, and learning'. In another study, youth who submitted individual Maker projects to a contest, reported that they created their projects because they were 'moved by their passions and motivated, in part, by their identifications, range of experiences, and commitments they brought to the design process' (Peppler & Hall, 2016, p. 155). Almost all scholars note that Making represents an instantiation of Seymour Papert's pedagogy of constructionism. Developed in contrast with instructionism, which emphasises actions that teachers can take to produce better learning, constructionism emphasises the active role that students can take in constructing their own learning through direct physical engagement with phenomena and problems in the world. It posits the process of building something as a rich context for both the development and representation of understanding (Harel & Papert, 1991).

A review of the literature, prepared for the US National Research Council, identified three main branches of Maker Education programmes, each with distinct audiences and purposes as well as many overlapping features (Vossoughi & Bevan, 2014). The first branch is Making as *entrepreneurship*. This branch of Making is embodied in the growth of FabLabs, TechShops, and Makerspaces: Storefront machine shops, integrating high and low tech tools, where the public can, usually for a fee, rent space to prototype and manufacture small-scale quantities of a wide range of objects. These new makerspaces, like the hacker communities that preceded them, celebrate creativity and have been characterised as communities of practice in which Makers share knowledge, skills, and social networks (Sheridan et al., 2014; Van Holm, 2015). They are fundamentally organised to support the production of things – providing machines and other types of tools, such as 3-D printers, that may not otherwise be accessible. While Making as entrepreneurship is not associated with education as strongly as it is with community and economic development, some argue for the importance of imbuing entrepreneurial mindsets in young people attending secondary and even primary school (Benton, Mullins, Shelley, & Dempsey, 2013; Loertscher, Preddy, & Derry, 2013) as well as post-secondary schools (see Carlson, 2015). Within an educational context, Makerspaces in postsecondary settings are more like community-based Techshops, open for unsupervised and entrepreneurial uses; whereas in primary or secondary settings, as in libraries and museums, they are more likely to be organised to provide supervised and structured educative activities that may change from day to day or week to week.

Many entrepreneurial-oriented makerspaces have been financed by commercial industries that manufacture and sell the design and fabrication tools. In the US, they are also promoted by government agencies seeking to encourage the creation of new businesses (Kalil, 2010). Past partnerships between DARPA and MakerEd reflect efforts on the part of industrial and military leaders to leverage the open, democratic processes of design that characterise the Maker Movement towards crowd-sourcing infrastructure for the design of particular products (Mansfield, 2011; Ohab, 2010).

There is a body of research that analyses these spaces in terms of how they make tools, practices, and craft knowledge transparent, and the role of that transparency in fostering the development of new ideas (see e.g. Loertscher et al., 2013; Peppler et al., 2016; Petrich, Wilkinson, & Bevan, 2013; Sheridan et al., 2014; Van Holm, 2015). Typically, research on Makerspaces builds on Lave and Wenger's (1991) seminal analyses of butcher shops, tailor shops, and other physical communities of practice that are organised to induct individuals into the culture, history, and practice of purposeful shared activity. Willett (2016) draws on Gee's concepts of affinity spaces in her review of the literature on library makerspaces.

A second branch of Making emphasises *STEM workforce skills*. These efforts are organised around supporting young people, generally in secondary and post-secondary schools, in design and fabrication projects to develop twenty-first century skills valued in the creative and engineering industries, such as problem-solving, critical thinking, and collaboration (see Jenkins, 2009; Santo, 2011, 2013). Such programmes, when oriented towards STEM, may integrate dimensions of engineering instruction into Maker activities, either formally (see Johnson, 2014) or informally (Martin & Dixon, 2016). Frequently, the curriculum is organised around project-based activities involving advanced tools such as 3-D printers or welding equipment. These STEM workforce programmes generally take place in school buildings, and may resemble Technology Education or Design-Based Learning programmes in that they are more focused on problem-solving than on play. They are, of course, educative, but with a strong emphasis on the development and application of knowledge, skills, and design solutions. Some informal programmes (particularly when engineering or STEM-specific) have developed explicit aims of expanding and diversifying the 'STEM pipeline'. For example, the Detroit Area Pre-College Engineering Programme interleaves making and other hands-on engineering activities, academic preparation work, and engagement with role models to produce a high number (80%) of programme alumni, almost all from communities historically underrepresented in STEM, who report the programme prepared them for college and STEM majors. Industry leaders have championed such programmes for developing the workforce of tomorrow by building young people's creative problem-solving capacities and positive learning identities, as well as their technical design and engineering interests and skills (Cognizant, 2011; Intel, 2015; National Endowment for Science Technology and the Arts [NESTA], 2015).

The third branch of Making: *educative Making* is typically implemented across both primary and secondary school-aged groups, with the broader goals of developing students' interests, capacities, and productive learning identities. It has become highly popular in informal settings, such as libraries, museums, and youth development programmes. While educative Making frequently involves technologies and sometimes integrates the uses of high tech tools like 3-D printers, it is primarily a pedagogical approach to engaging students in design-build activities that allow them to explore ideas, develop skills and understanding within particular (and often interdisciplinary) disciplines, and build a wide range of learning dispositions and capacities.

Educative Making does not depend on, though it can make use of, dedicated makerspaces; instead educative Making depends on a Maker pedagogy (Bevan, Ryoo, & Shea, in press). Vossoughi and colleagues argue that such pedagogies build 'generous learning environments' involving shared activity, process, and iteration; cultivate play, imagination, and creativity; broaden 'definitions of learning, intelligence, and science'; and 'treat learning as a purposeful and social endeavour, including making STEM concepts and practices explicit in ways that are organic and meaningful' to the activity and context at hand. (Vossoughi, Escudé, Kong, & Hooper, 2013). As such, Maker pedagogies echo earlier descriptions of pedagogical practices supporting classroom design cultures. For example, in Design-Based Learning (DBL), researchers have described the need for teachers to work side-by-side with students; build a community of shared respect; help students learn that they are all responsible for each others' learning; model scientific reasoning; support students' iteration towards understanding (as well as towards improved design); design and sequence activities to support student talk and reflection in ways that build knowledge over time; and take to heart the idea of developing a community of learners (Kolodner et al., 2003).

Making as a pedagogy reflects theories of constructionism, in which learners externalise, by building and then iteratively refining, their ideas about how something works, and teachers recognise and respond to these external representations by supporting students through iterative moments of design failure and sense-making (Harel & Papert, 1991). Scholars argue that, as a pedagogy, Making can foster deep and agentive learning, in part because of the way in which it can generate reciprocal relationships among students and between students and teachers (DiGiacomo & Gutiérrez, 2016; Resnick & Rosenbaum, 2013).

Not all educative Making is alike. For example, there are many off-the-shelf kits that support Making, such as Lego kits, Robotics kits, and others, which typically come with step-by-step instructions. This *assembly* form of educative Making mandates another person's vision and plans for what should be made and how it should be made. While some caution that such approaches may be less cognitively and emotionally rich than more open-ended instruction (Espinoza, 2011; Resnick & Rosenbaum, 2013), assembly processes may allow learners to develop particular skills and fluencies with materials that can be valuable for future, more creative, processes. For example, through assembly activities, students can learn how particular building materials respond to a range of forces or learn how to wield particular tools such as soldering irons or Arduinos. As such, assembly-like activities can build the learners' skill set, preparing students to appropriate skills, tools, and knowledge for their own purposes in the future. Lego blocks, for instance, can be incorporated into entirely different plans or constructions than those that come in the box. Interleaving assembly activities into a broader making trajectory may provide important scaffolds for ultimately fostering more creative and open-ended Making.

Another type of educative making is *creative construction*, where learners are provided concrete goals, tools, and steps towards realising those goals, but along the way they have decision points requiring the exercise of creative agency. These activities don't rely on kits with step-by-step instructions, but they may have pre-determined, externally created goals and materials. An example is the cardboard automaton activity, where there is one mechanism, a cam and axle that operates the automaton. While all students build the same core mechanism, they are invited to individually determine what the mechanism will animate and how the figures will move, by scaling the dimensions and ratios of the mechanism. A wide range of personalised objects results from this process (see Figure 3). As with assembly-like making, learners become familiar with the way materials, such as cardboard or cams, work and they exercise a

Figure 3. Creative construction: Three different versions of cardboard automata. © Exploratorium.

variety of skills and dispositions, in this case measurement, persistence, and creativity. Yet the possibilities for problem solving are relatively limited because the endpoint is more or less known.

A third type of educative Making, emphasising creative and improvisational problem-solving is called *tinkering* (Berland, 2016; Resnick & Rosenbaum, 2013; Wilkinson & Petrich, 2014). In these activities, questions and goals are often open-ended or materials are intentionally selected to not fit neatly together. Tinkering is often highly playful. It requires creative work-arounds, and, from an educational perspective, it is the process of invention, testing, and iterative problem solving, more than the product being developed, that is the purpose of such activities (Quinn & Bell, 2013). An example of a tinkering project is the Marble Machine, where learners are asked to use a range of loose materials to construct ramps on a 2-m section of pegboard. The process requires significant problem solving and encompasses a large range of solutions – spanning the uses of different materials, such as duct tape for bumper guards, or technologies such as microprocessors, LED lights, or a range of sensors, to the marshalling of different physical forces and properties, such as building in turns, ricochets, and vortices (in funnels) to affect the velocity of the marble (Figure 4).

Across these different types of educative Making are varying degrees of creativity, play, and purpose. Assembly activities may typically depend on externally motivated goals whereas Tinkering may foster more intentionality and creativity. But these different Making approaches do not necessarily exist on a continuum from novice to expert. As new tools or technologies are created, as new problems are framed, or challenges posed, even the most expert Maker may benefit from engaging in assembly-like activities. An analogy is the way in which experienced cooks may sometimes reference cookbooks or equipment manuals to master a new technique or idea. Thus an education programme may include several different approaches to engaging in Making, at different times and for different purposes (Bevan, Petrich, & Wilkinson, 2014).

Some have cautioned the field to avoid over-defining Making in ways that might exclude the historical or valued Making practices of socio-economically or racially marginalised communities (Martin & Dixon, 2016; Vossoughi et al., 2016). This is an important reminder that needs to stay at the forefront of efforts to expand Making opportunities. This paper seeks to differentiate, if not define, approaches to Maker Education in the context of science learning in order to help science educators and education researchers recognise distinctions that have implications for resource allocation or assessment, and for

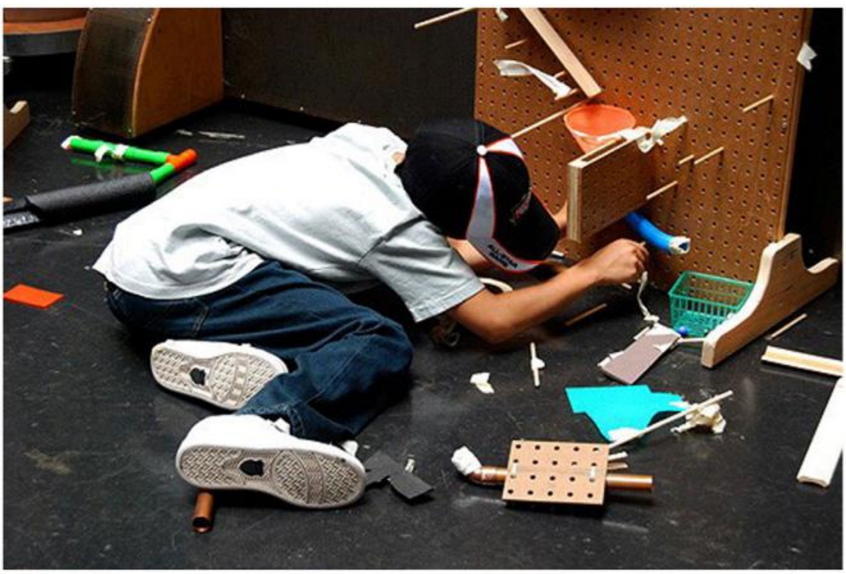

Figure 4. Young boy working on his Marble Machine project. © Exploratorium.

fully leveraging the potential of different forms of Making, including the making practices of young people's everyday and family activities.

For example, entrepreneurial Maker programmes, focused on the creation of products designed to address a market need, might require more sophisticated fabrication tools than educative Maker programmes. Entrepreneurial programmes may also need to include instruction that addresses market dynamics. Both STEM workforce and educative Making programmes may seek to broaden participation in STEM, but workforce programmes may focus more on pre-collegiate engineering skills and role models, whereas educative programmes may focus more on interest and identity development. These are not mutually exclusive goals or processes and it is not the intention of this paper to draw hard and fast lines between these different approaches. Rather the purpose of making these distinctions is to assist in planning for how such efforts can be integrated and assessed in the classroom. Programmes like Oakland California's Techbridge integrate playful tinkering with STEM workforce awareness through the involvement of female engineers as role models and volunteer assistants to help students develop ambitious, unscripted, design projects (Bevan et al., in press).

3. Making in relationship to the science classroom

Making is not new to the science classroom. Dewey's commitment to grounding education in experience with the material and social world has fostered a long history of firsthand, phenomena-rich, inquiry-based approaches to science education (e.g. Driver, Squires, Rushworth, & Wood-Robinson, 1994; Harlen, 1988; Osborne, 2014; Wells, 2002). Firsthand learning experiences in science education can take the form of laboratory investigations, field trip excursions, hands-on activities, structured problem-based learning (PBL), and other direct student engagements with the physical phenomena, social instantiations, and practices of science. The rationale for such activities is that the best way to learn science (to come to identify with, care about, know, and understand how to engage in science) is to do science and to experience its relevance and value in the world beyond the classroom. Classroom investigations, including design activities, labs, and Making, are argued to effectively intertwine scientific concepts and practices in ways that have the potential to deepen student learning of both and to shed light on the practice of science in the world (Kolodner et al., 2003; McCormick, 1997). Indeed, many state science education frameworks, such as the *Qualifications and Curriculum Authority* of England and Wales, *Science By Doing* in Australia, the *K-12 Framework for Science Education* in the US, and other state policy documents such as the 2007 European Commission's Rocard Report, encourage or even require teachers to provide students with firsthand engagements in science.

How and when to structure and implement firsthand science learning engagements, and how they contribute to student science learning is debated (Abrahams & Millar, 2008; DeWitt & Osborne, 2007). Yet there is little doubt that teachers and students, in both formal and informal settings, place high value on them. In the UK, a NESTA (2005) survey of teachers found that 84% valued firsthand experiences with science, and 99% believed that they advanced student learning. A 2003 report by Cerini, Murray, and Reiss (cited by Dillon, 2008) found that UK students highly value and enjoy (>75%) opportunities for firsthand science learning. In the US, a national survey found that students wanted more hands-on science instruction and that field trips were their second most favoured way to engage in science (Amgen & Change the Equation, 2016).

Whereas field trips or excursions are appreciated for the ways in which they allow students to see how science is practiced or valued in the everyday or professional world (D. Anderson, Kisiel, & Storksdieck, 2006), firsthand experiences in the science classroom – practical/lab work, inquiry-based investigations, and design-based learning – are seen as powerful contexts for learning because of the ways that they can engage students in the practices of science (see Table 1).

Though practical work is frequently equated with laboratory work it has also been defined as a wide range of activities including excursions, laboratory exercises, and videos (see Dillon, 2008 for a review of the literature). Millar (2004) notes the salience of practical work, in particular, when students may not have had everyday opportunities to closely observe and come to understand phenomena

Table 1. Science practices (McNeill, Katsh-Singer, & Pelletier, 2015).

Investigating	Sense-making	Critiquing
Asking questions	Developing and using models	Engaging in argument from evidence
Planning and carrying out investigations	Analysing and interpreting data	Obtaining, evaluating, and communicating information
Using mathematical and computational thinking	Constructing explanations	

they will encounter in the curriculum. Lab-based practical work generally emphasises procedures (see Lunetta, Hofstein, & Clough, 2007) and operates towards known (correct) ends. Despite the emphasis on the doing of science, Abrahams and Millar (2008) find that most practical work is usually focused on concepts and not on practices or the nature of scientific inquiry. Further, while many students may enjoy the more active engagement with science concepts and phenomena that Lab work allows, some research has found that girls find it less appealing than do boys (Murphy, 1991). While the common reasons for undertaking practical work – such as to encourage accurate observation and description; to make phenomena more real; to arouse and maintain interest; and to promote a logical and reasoning method of thought (Dillon, 2008) – are similar to rationales for Making, such practical work often relies on tried-and-true scripts for student investigations. Osborne (1993) argues that to develop students' epistemological understanding in science there is a need for engagements that are less rote than most practical work tends to be.

More akin to Maker Education is Technology Education (Fox-Turnbull, 2016; McCormick, 1997; Williams, 2013, 2016) and Design-Based Learning (DBL, sometimes called DBS or Design-Based Science) (see Doppelt, Mehalik, Schunn, Silk, & Krysinski, 2008; Fortus, Krajcik, Dershimer, Marx, & Mamlok-Naaman, 2005). These approaches involve the design and construction of artefacts or objects. Learning develops through iterative design-test-redesign, where moments of design failure are leveraged to deepen understanding. DBL is a sub-genre of PBL in which problems are identified, information is gathered, solutions are considered, and optimised solutions are designed, prototyped and developed (Hmelo-Silver, 2004). These activities root student learning in real-world situations and challenges, and can support the development of increasingly sophisticated understandings. Similar to the literature on Maker Education, such constructionist approaches are described as deeply motivating to students thanks to their authentic, iterative, and collaborative nature (Kolodner et al., 2003).

Technology Education and DBL both involve identifying problems for which solutions can be designed and constructed. As such, like with PBL, there is an authentic audience or 'client' in need of a solution; and, given the particulars of the context in which the problem/need has arisen, there will usually be an optimal or best solution. This sense of purpose is argued to lead to deeper engagement and therefore deeper learning. For example, Mehalik and colleagues describe a DBL project that replaced a 4-week unit covering a range of electricity concepts, such as 'voltage, current, resistance, parallel circuits, series circuits, batteries, lamps, resistors, and conceptual relationships in Ohm's Law' (Mehalik, Doppelt, & Schuun, 2008, p. 78). In the DBL module, students were challenged to design an alarm system, and were introduced to design processes entailing seven stages: Defining the problem and identifying the need, collecting information, introducing alternative solutions, choosing the optimal solution, designing and constructing a prototype, and evaluation (Doppelt et al., 2008). Under these conditions, the students in the DBL programme learned more than those in a guided inquiry unit; gains were particularly high for students from economically and racially marginalised communities (Doppelt et al., 2008).

The design process has been described as iterative, exploratory, and sometimes chaotic (Braha & Reich, 2003). Razzouk and Shute (2012, p. 337) cite a description of the design process by Goldschmidt and Weil (1998) as nonlinear, where 'designers follow a forward (breaking down) and backward (validating) reasoning strategy'. In another study, Stables (2002) notes that strictly adhering to design procedures and processes can inhibit the creative risk-taking essential to design thinking. But, as with Osborne's 2008 caution about laboratory activities, Technology and Design Education has been critiqued as sometimes overly rigid, when taught as a set of procedures, or transferrable problem-solving skills, rather than a set of strategies for engaging with concepts and phenomena and problems in the world (see De Vries, 1996; McCormick, 1997; Murphy & McCormick, 1997).

Making shares many features of Technology Education and DBL, but there are also differences. As with professional engineering practices, Technology Education and DBL is generally organised by creating teams of collaborating students. This is seen as a strength of such approaches, allowing students to teach and learn from one another, and to contribute their individual strengths to team efforts. Making on the other hand is often, though not always, undertaken by individuals developing their own ideas. Making thus has a stronger individualistic and creative stamp, even a kind of auteurship. But educative Making is always undertaken within a community of dedicated Makers. As such Making is both communal and individualistic; it is collaborative, but it does not always involve teams or team work per se. This difference may lead to a broader variety of artefacts and ideas being created, and possibly deeper commitment, on the part of students, to their particular ideas and approaches. This feature of Making may allow it to resist the kinds of rigidity sometimes found in DBL or Technology Education.

Making, moreover, is frequently quite playful. Whereas Technology Education and DBL are organised around a recognised problem or need, Making is often a response to an idea or a wish, and not necessarily a need. The audience for Maker activities is the individual pursuing his or her creative idea, along with the community of Makers who celebrate ingenuity and inventiveness. In other words, there is an audience for Making but it is an audience that appreciates creativity more than an audience with 'a problem to be solved'. This is not to say that some Maker projects don't solve problems. Many times Makers are motivated to solve a problem, but it is their idea of a problem. For example, in a Maker programme in California, a student built a laddivator, to help painters at the top of tall ladders access paint cans from the ground. In another Maker programme, a girl decided to build a fully self-sufficient backpack, including built-in speakers and phone. These efforts didn't involve formal processes of problem identification or analysis. They involved developing an idea, something unexpected or funny, and prototyping, testing, and developing the best version of that idea possible. This is another way that Making may resist the over-formalisation or oversimplification of design and problem-solving as a set of rigid or rote procedures.

The Making literature does suggest that students develop proficiencies, as well as interest, in design and engineering practices (Berland, 2016; Kafai, Fields, & Searle, 2014). However, the majority of the literature stresses how it develops students' identities and dispositions as creative thinkers and problem solvers (Martin & Dixon, 2016), as well as their sense of belonging (DiGiacomo & Gutiérrez, 2016; Vossoughi et al., 2013).

Finally, whereas Technology Education and DBL are likely to communicate possible professional pathways to students – i.e., students may become more aware of engineering practices and strategies, as well as engineering jobs and employers – such professional trajectories may remain invisible to students in Maker programmes unless teachers make intentional connections between students' individual goals and processes, the micro moments of design and engineering, and the larger related professional trajectories and fields in which these developing interests and skills are valued and needed.

Making has been integrated into the science classroom in different ways. There are some cases in which entire school programmes have been organised around making, such as the Brightworks School in San Francisco. Wardrip and Brahms (2016) describe three different approaches in two primary schools in the US. In one case the school created a Maker Cart, containing materials and tools for Making activities. The cart could be wheeled into classrooms at designated times, where the teacher and a partnering teaching artist, engaged students in Maker activities. The researchers note that this was the least disruptive of classroom practices, although Making activities were somewhat constrained by the materials that could fit on the cart and classroom space for storage and display (Wardrip, personal communication). In another case, a primary school created a 'STEAM room', a kind of a makerspace that teachers could use with their students, or students could use during lunch hours or afterschool. Teachers from across grade levels and content areas signed up and made use of the room. In both of these cases, the researchers note that teachers added Making activities to existing curricular activities, rather than replacing some core element of the curriculum. They note that teachers reported that Making activities helped to engage students with the curriculum units, supporting 'pro-academic behaviours' such as staying on task, asking and answering task-related questions of peers, having task-related conversations, persisting and/or completing the task, sharing knowledge with peers, etc. In other cases, teachers noted that Making activities appealed to students who were not typically engaged in classroom activities. Teachers reported that when they offered Making activities, such students more frequently attended class, came to class on time, and did not exhibit defiant or oppositional behaviours (Wardrip, personal communication). A third case involved a kindergarten teacher who replaced her science discovery centre with a Maker centre. In this case Making activities were fully integrated into the classroom experience. Wardrip and Brahms write that in addition to needing more time to plan and do the Making activities, teachers reported a need for more firsthand experience in learning through Making, so that they could facilitate it better for their students.

In a kindergarten classroom, Wohlwend and Peppler (2015) have shown that children persisted longer in circuits-based Maker activities than they did with standard circuits activities. They argue that the properties of play inherent in Making serve to engage students in the activities, whereas the aesthetic qualities of Making create constraints and challenges that serve to complexify the challenge for students.

While these examples are all for young children, Making has also been used as a context for demonstrating mastery at the secondary school level. At the Lighthouse Community Charter School in Oakland, a secondary physics teacher used Tinkering as a context for students to engage in interest-driven final projects in which they demonstrated their understanding of experimental design by building instrumentation to collect data related to their final project question. For example, one young man, who was a graffiti artist in his spare time, designed, built and tested a range of spray paint nozzles to determine the relationship between form and function (Bevan et al., 2014).

To date, there are few peer-reviewed studies of Making in school contexts, and despite the many examples of productive student engagement, educators and policymakers have questions about how exactly Making supports STEM learning (Peppler et al., 2016). Some are concerned whether or not Making deepens conceptual understanding (see Herold, 2016). Others wonder how Making engages students in the full sweep of scientific and engineering practices, including the sense-making and critiquing dimensions of science. Finally, in an era of increasing socioeconomic segregation and inequality, some are concerned that Making may reproduce rather than challenge existing inequities in schooling and society (Buechley, 2013; Vossoughi et al., 2016). The next section will provide an overview of the current knowledge base about Making and science learning.

4. Making and science learning: Claims and promise

This review of the literature is an updated and expanded version of a review originally commissioned by the National Academies of Science in the United States (Vossoughi & Bevan, 2014). The current paper has expanded the number of Making resources from 37 to 66. Methods for gathering the literature were the following:

(1) Academic database search (EBSCO, JSTOR, SCOPUS) using the search term 'maker movement' in titles, keywords, or abstracts. The terms Make and Making, and even Tinkering, are relatively common English language verbs and therefore were not helpful search terms. This search produced 95 distinct papers. Because the marketing and associated exuberance behind the Maker Movement had produced a large number of blogs and articles advocating for the movement, we filtered for academic, peer-reviewed articles, which yielded 34 papers. We omitted 13 papers focused on technical uses of 3-D printers, manufacturing, or other professional engineering processes and deleted 2 duplicate articles. This led to identification of 19 peer-reviewed articles about the Maker Movement as it relates to non-professional education.

(2) We reached out to leading researchers in Making, whose papers were included in the database and conference proceedings, and requested suggestions of other papers, or seminal reports or articles, we should include in the review. This led to the identification of 6 conference papers, 13 book chapters, and 4 reports.
(3) We included a variety of often cited resources on Making (e.g. found in bibliographies of published papers), including 9 books on the topic of Making and learning, 13 magazine, blog, press release or newspaper articles that included discussion of the origins of the Maker Movement and/or current direction in educational settings, and 2 additional peer-reviewed papers.

The vast majority of the literature, at this early stage in its development, is qualitative in nature, involving case studies, interviews, and ethnography. Some studies involve pre/post survey or other assessments. To date, most of the work has focused on out-of-school programmes and settings.

In this review, I use an analytical lens that draws on cultural historical and critical pedagogical theory – integrating work of both Vygotsky and Freire – in what has been called a *transformative activist stance* (Stetsenko, 2010).

A transformative activist stance conceptualises individual development as occurring through agentive, goal-directed efforts to make change in one's self, one's social community, and one's world (Vianna & Stetsenko, 2014). On this view, learning is an activist project. A transformative activist stance argues that it is through the agentive uses of cultural tools, within a valued community that recognises and appreciates the intellectual and cultural assets of the individuals that comprise it, that change and development occur on both the individual and social planes. As such, this approach theoretically resolves the tension between learning as a process of cultural production or reproduction, mediating between the individual and the socio-cultural by identifying a relational ontology between the two. It points, in particular, to creative (agentive) pedagogies, such as STEM-Rich Making, as powerful contexts for learning and development.

A transformative activist stance is fundamentally a situated and contextual perspective, and thus focuses on the learner's immediate purposes, the cultural tools and resources available to them, and the social or organisational power structures that support or inhibit individual agency. As students' interests, capacities (fluency with the cultural tools mediating the activity), and sense of belonging and commitment grow, shifts in their participation in community activities signal the development of productive learning identities, which become available resources for new contexts, where they may be activated or not depending on local conditions (Carlone, Scott, & Lowder, 2014; Holland, Lachicotte Jr., Skinner, & Cain, 1998).

Drawing on this perspective on learning and development, this analysis of the Making literature focuses in particular on the ways in which STEM-Rich Making as an educational practice:

- Supports students' active belonging and identity, through the relational ontology of the individual and community;
- Advances students' engagement with STEM practices and concepts; and
- Leverages students' everyday cultural resources and practices.The first section reviews how Making programmes have been documented to invite, include, and motivate student engagement in STEM learning communities as a process of forging productive STEM learning identities. The second section discusses emerging evidence about how Making programmes support students' learning of STEM practices and concepts. The third section describes research on how Making connects to and leverages students' cultural resources.

4.1. Belonging and productive learning identities

One of the factors that distinguishes Making from its roots in DBL and Technology Education is its focus on individual creativity within communities dedicated to creative agency. Cultural historical theory suggests that productive learning identities are developed through being recognised, and recognising one's self, as productive (accomplished, valued) in a given domain (e.g. Holland et al., 1998; Lave & Wenger, 1991). A transformative activist stance attends to the reciprocal relationships between individual and community, for instance the ways in which Making programmes can be organised to welcome or include learners, who come to the activities with a broad range of prior experiences and understandings; how programmes support learners to develop and pursue their own purposes; and how the learning community is organised to provide networks of assistance in which individuals can both contribute and benefit, as well as potentially transform the community itself.

Maker activities, particularly creative construction and tinkering activities, are designed to allow for multiple starting points as well as pathways (Petrich et al., 2013; Resnick & Rosenbaum, 2013). Vossoughi and Bevan (2014) note how the playful and aesthetic nature of many activities piques interest and invites learners, across age and experience levels, to pick up tools and materials and begin to play and explore. Learners develop their own ideas, building on what they know and what is made available to them within the community of learners, to launch their activity. Some learners may start a Scribbling Machine activity by focusing on stabilising the motion of the object they are building. Others may focus on the aesthetic look of the object, which then operates as a design constraint when students later seek to stabilise the motion. As DiGiacomo and Gutiérrez (2016, p. 141) note, 'Because of the playful, imaginative nature of many [Making and Tinkering] activities, the traditional notion that "science is for scientists" begins to dismantle, as children discover that they too can engage in scientific pursuits' (Figure 5).

Resnick and Rosenbaum (2013) emphasise the importance of feedback in the Making and Tinkering process. They posit that, by design, Tinkering activities provide immediate feedback to learners that clarifies the edges of what they know and what they are still figuring out. Tinkering activities have a kind of transparency that allows learners to quickly see the process and the results. The iterative nature of tinkering supports learning.

> Tinkerers start by exploring and experimenting, then revising and refining their goals, plans, and creations. Then they are ready to start a new cycle of exploring and experimenting, then revising and refining, over and over. The quicker the iterations the faster the generation and refinement of ideas. (Resnick & Rosenbaum, 2013, p. 176)

DiGiacomo and Gutiérrez (2016, p. 143) argue that the feedback loops inherent in Tinkering activities exist dialectically with the feedback loops that exist within the community of learners and educators. 'Receiving feedback in a repair-friendly context (e.g. not in a testlike setting) allows learners to feel safe to try again, engendering potential for sustained engagement in the practice.' Citing Nasir (2012), they

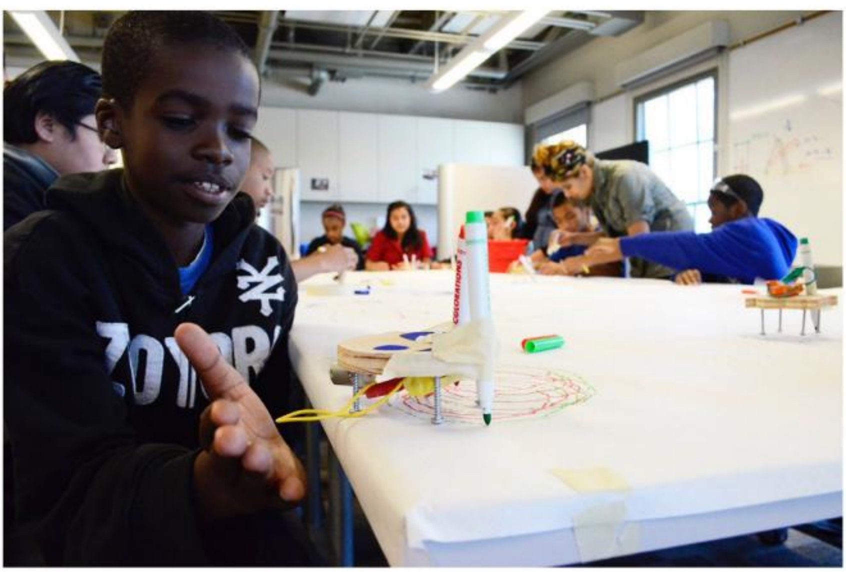

Figure 5. Testing a scribbling machine. © Exploratorium.

call out the role of consistent feedback for creating learning environments that support intellectual and creative risk-taking. In their research they have found that Making and Tinkering activities that allow young people to develop and pursue their own ideas, assisted by facilitators who follow-support rather than lead-support the activities, creates an ethos of reciprocity that deepens participants' sense of belonging within the social learning space. As they describe, the relationship between facilitators and learners during making activities:

> resembled partnerships, rather than the hierarchal [*sic*] power dynamics often seen in educational environments or mentoring relationships. … [In Making activities, facilitators] often positioned themselves as novices and learners, asked youth for guidance in activity, and developed a meaningful relationship through fluid conversation over time. (DiGiacomo & Gutiérrez, 2016, p. 150)

Within this socially reciprocal context, student self-direction, is supported by others. Sheridan and Konopasky (2016) refer to the 'resourcefulness' that emerges through such reciprocity between physical and social arrangements of Tinkering. Martin (2015, p. 37) argues that such environments 'are more motivating, support engagement and persistence, identity development, and the growth of resourcefulness'.

Some studies highlight the ways that Making can or should design for the complexification of learners' projects and explorations to advance agency (Petrich et al., 2013). While feedback may drive students to deepen or expand their initial goals and purposes, facilitation is important for stretching young people's ambitions. In their analysis of creativity in the digital realm Ackermann, Gauntlett, Wolbers, and Weckström (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 (2013, p. 18) 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 endeavours.'

Another key dimension of developing a purpose in Making activities is the availability and interest of an authentic audience (Vossoughi et al., 2013). In some cases the audience is the intended recipient of the object being made, a parent or friend, in which case Makers may take special care in the quality of the Making (Dobras, personal communication). Audiences may also be peers to whom young Makers teach particular skills, tool uses, or techniques. The audience not only propels and celebrates an individual's Making, but operates to provide important networks of assistance, and varied forms of collaboration (Kuznetsov & Paulos, 2010). Sheridan et al. (2014, p. 529) found that in Makerspaces, skills and knowledge serve as a form of social currency, and products are made to be shown, shared, and sold.

Researchers also note how transparency is valued within Maker communities and spaces. Makerspaces are generally organised to make tools and materials, as well as possible ideas and trajectories, visible (Gabrielson, 2013; Quinn & Bell, 2013; Sheridan et al., 2014; Sheridan & Konopasky, 2016). This availability of resources operates to inspire ideas and solutions, as much as it supports self-directed learning by making the necessary tools and materials immediately available to students as their needs or purposes evolve. Researchers have also argued that Making activities in and of themselves offer greater transparency into STEM disciplinary content.

> Most of today's technology designs intentionally make invisible what makes them work; yet, for educational purposes, visibility is more beneficial in promoting learning. In e-textiles, for example, the fabrication of switches, circuits, and codes reveals the underlying structures in tangible and observable ways. (Kafai & Peppler, 2012, pp. 180–181)

These authors posit that Making can allow students to 'look under the hood' and thus develop a more critical as well as visceral understanding of the concepts and technologies.

The networks of assistance that are made available in Maker communities, support young people to learn from one another. Dixon and Martin (2014) found that as youth's levels of experience with Making increased they tended to report different kinds of benefits from their interactions with Maker communities. At Maker Faires, youth who were new to making tended to focus on the experience of being in and of the Maker community – how they enjoyed it, the things they learned, how they felt accomplished through presenting their work to others. As their experience levels increased, young Makers valued opportunities to gain feedback from more experienced Makers. Those with the most Making experience linked their Maker Faire experiences to directions they could take with respect to new skills, projects and even future employment opportunities.

Similarly, Gutiérrez, Schwartz, DiGiacomo, and Vossoughi (2014) note the ways in which Making and Tinkering are accomplished in joint activity with others, and through the distribution of expertise and resources. For example, design, craftsmanship, record keeping, aesthetics, coding, communication, and many other dimensions may all be salient to a group's work. In the context of youth media production, Chávez and Soep (2005, p. 411) describe how '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', a phenomenon they refer to as a 'pedagogy of collegiality' afforded in particular through the enactment of creative communities of production.

In a museum setting, Gutwill, Hido, and Sindorf (2015) identified different ways in which participants contributed to and benefited from 'social scaffolding' within the learning environment. Building on an earlier framework about productive afterschool STEM programmes (see Bevan & Dillon, 2010), their study documented how learners frequently directly requested or offered to help one another; inspired or were inspired by others' new ideas or strategies for trouble-shooting; and physically built on or connected their own work to an existing body of work of a fellow Tinkerer (such as merging two Marble Machines). For example, when one young girl successfully built an object that could bobble around in a wind tube before softly floating out, she noticed that nearby another young girl was struggling to get hers to work. Either it wobbled aimlessly at the bottom of the tube or it shot straight out. The first girl made observations about the distribution of weight, of symmetry, and other forces that she had become familiar with through her own investigation. Working together, both girls were able to achieve success (Bevan et al., 2015).

Making frequently supports collaboration. Indeed, Blikstein (2013, p. 7) found that through the process of digital design and fabrication, students experienced 'novel levels of team collaboration'. He provides an example of three young men working for a period of weeks to design and build a table-top roller coaster. Blikstein notes how the different and complementary dispositions and skill sets of the youth were leveraged in ways that helped them succeed. One of the students was a productive idea-generator; another an optimistic problem-solver. Throughout their efforts the students' dialogue became 'increasingly complex, rigorous and compliant with the lexicon of physics' in and through the shared process of design (Blikstein, 2013, p. 12).

In sum, the literature contains many examples of how Making provides young people with social contexts and communities that foster opportunities to develop and pursue meaningful purposes, exercising and developing agency in the context of STEM-based activities. The opportunities that students have to innovate new ideas, which then ripple through and contribute to the community of learners, adding to the repertoire of Making strategies, is one way in which the individual and group capacity for creative Making is developed. Because these activities are interest-driven and student-centred they may provide authentic or meaningful opportunities for young people to demonstrate and exercise their developing understanding. However, they can also foster divergent thinking and experimentation, and therefore exact endpoints are not pre-determined, possibly complicating their use in the classroom.

Several scholars have provided a critical perspective on if and how all students are actively and equitably supported to participate, find a meaningful purpose, and complexify their investigations in ways that can expand their learning and open up new pathways and trajectories for future learning (e.g. Calabrese Barton, Tan, & Greenberg, in press; Vossoughi et al., 2016). These concerns suggest a need for attention to pedagogy in Making. Blikstein and Worsley (2016, p. 71) warn that Making's DIY culture sometimes manifests itself in a kind of anti-intellectualism that deflects attention from pedagogy and the role of the teacher. Their research has found that newcomers to Making need 'a considerable amount of onboarding and facilitation' before they can take up the process of Making. Vossoughi and Bevan (2014) warn against the dangers of side-lining the generative role of the teacher in supporting learners. Research suggests that educators need opportunities to learn through Making themselves, to understand the role of iteration (and the time needed to iterate) in developing deep understanding (and not just improved designs), and the generative nature of moments of frustration when learners are supported to engage with evidence that those moments provide. Bullock and Sator (2015) suggest that through such engagements, teachers, and in particular novice teachers, can become more critical and reflective practitioners, especially with respect to understanding the science curriculum.

4.2. Deepening engagement with science concepts and practices

Describing the relationship between Making and the *K-12 Framework* in the US, Quinn and Bell (2013, p. 17) write: 'Many varied experience associated with designing, making, and playing involve meaningful forms of STEM learning and can be conceived of as relating to important learning goals outlined for K-12 science education'. They further note that the competencies associated with designing and Making relate to the knowledge and practices of science and engineering. In particular, STEM-Rich Making is organised to engage students in design and engineering practices, where science concepts and phenomena serve as the building materials with which students work. It thus may appeal to students who do not normally identify as STEM learners, drawing them into practices in which they will deepen their understanding of and fluency with science concepts, phenomena, and practices in the service of other ends.

For example, to successfully build a Scribbling Machine, students must complete an electric circuit and grapple with symmetry, balance, and stability, although how exactly they work with these phenomena depends on their particular aesthetic goals counter-balanced by their developing facility and understanding. Experienced makers may be able to create complex machines that move exactly the way that they intend. Novice makers may create more simple machines and work more reactively: Through observing the machine's behaviour students make adjustments until they get them moving in the way that they desire (e.g., in a straight line, in circles, chaotically, quickly, slowly, etc.). In this way knowledge of or fluency with scientific concepts and phenomena mediates STEM-Rich Making activities, and engaging in STEM-Rich Making deepens knowledge and fluency of scientific concepts and phenomena (see Figure 6).

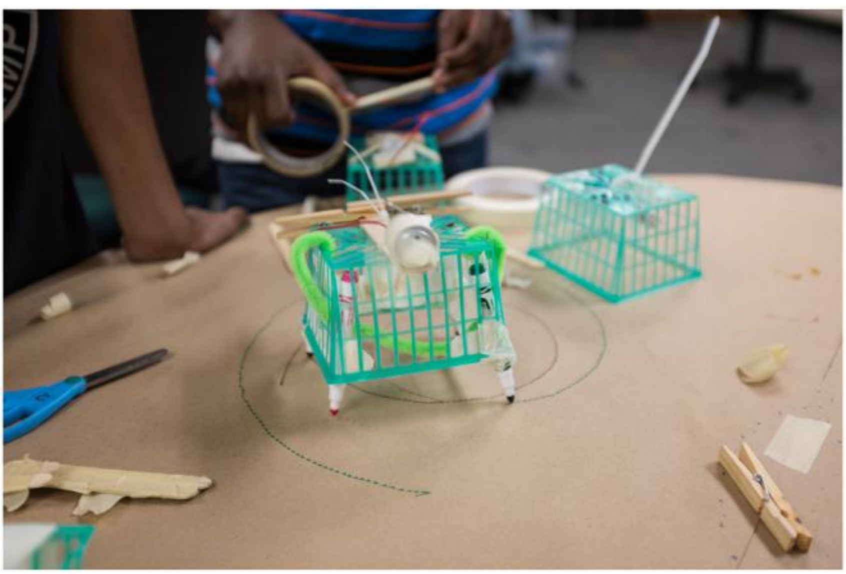

Figure 6. Designing, observing, and re-designing based on feedback. © Exploratorium.

Although much of the rhetoric about Making emphasises STEM learning, there is not yet a deep literature demonstrating conceptual learning outcomes. STEM-Rich Making, like other forms of PBL and DBL, positions science concepts and STEM practices as the means, and not the ends, to the activities. For example, describing secondary school students' experiences with digital design fabrication, Blikstein (2013, p. 18) notes 'abstract concepts such as friction and momentum become meaningful and concrete when they are needed to accomplish a task within a project.'

Martin and Dixon (2016, p. 186) describe the ways in which Making can be structured to support students' development of adaptive expertise. As they note, experts have deep conceptual knowledge. 'They understand how and why things work the way they do, and thus are able to deal with unexpected problems and innovate new solutions.' Drawing on (Hatano & Ignaki, 1986), they note that Making creates powerful conditions for the development of expertise because it provides students with multiple experiences to confront disconfirming evidence; it provides 'frequent dialogic interactions' with others in the community of practice; it takes place within a community that 'values comprehension and explanation and does not focus strictly on efficient performance'; and it is not tied to systems of reward or punishment (Martin & Dixon, 2016, p. 186).

Peppler (2013) describes how working with simple computational circuits in e-textile activities, significantly increased students' understanding of key circuitry concepts, such as current flow, circuit polarity and connectivity. In another study, Kafai and Peppler (2010) describe a wide range of computational skills – programming, interface design, animation, graphics, 3D design – developed through computer-based Maker activities. Studying family Making activities in a museum setting, Brahms and Crowley (2016a) found that young children were able to develop relevant skills and knowledge, such as successfully completing electrical circuits as well as accessing social resources within a learning space.

Buchholz et al. (2014) found, in a study that paired boys and girls in Making activities involving e-textiles (sewing puppets using conductive thread, batteries, and switches), that girls were significantly more likely to take leadership and control the materials of the investigation than were boys. The e-textile activities involved two types of activity: The crafting activity of sewing, which the authors note is 'not simply decorative or structural' but rather through the use of conductive thread, constitutes the actual circuit and the electronics activity of using a multimeter to test for conductivity and to measure electric current and voltage. Girls were significantly more likely than boys (80% of the time) to have their hands on the actual physical materials of investigation during the sewing activities, whether or not they had prior experience with sewing, and boys were significantly more likely than girls (75% of the time) to hold scientific tools such multimeters, again whether or not they had used them before. The amount of time that boys and girls spoke was about equal, suggesting to the researchers that all youth were equally invested in the activity, but taking on gendered roles in relationship to the materials at hand.

The researchers note that firsthand engagement with materials links directly to the potential for learning. Indeed they found that the girls' active engagement and consequent learning in the first activity 'rippled over' to a second activity, during which girls showed far greater efficiency in successfully completing circuits and requested less adult assistance than did boys. The findings of this study suggest that the gendered nature of the actual materials of investigation may pertain directly to the forms of participation, and consequently the conceptual learning. The authors argue that STEM-Rich Making activities integrating materials appealing to both boys and girls can challenge deficit views of girls as needing special support to do science (such as sex-segregated programmes or scaffolding to work with traditionally male gendered toys like rockets and robots) by recognising the ways in which science learning activities are often represented in male-gendered ways. In this vein, Buechley, Eisenberg, Catchen, and Crockett (2008, p. 431) note,

> In addition to asking 'how can we get girls and women to participate in traditional computer science and support them once they are there?', we should ask: 'how can we integrate computer science with activities and communities that girls and women are already engaged in?'

The limited number of studies documenting conceptual learning may reflect educators' reluctance to disrupt student creativity; or it may be because much of Maker Education has taken place in out-of-school settings or in classes or programmes devoted to design (as opposed to other disciplinary subjects) where science learning per se is not necessarily the primary goal for teachers. Most studies focus on STEM practices (see Table 1), although, unlike in PBL, DBL or Technology Education, practices are generally not presented in formalised steps or stages. For example, a study of a network of California afterschool Maker programmes described how activities involved students in processes of designing, building, testing, and refining, based on feedback, a wide range of objects such as rockets, paper circuits, or various individualised artefacts (Bevan et al., in press). This study describes how a group of girls from a low-income community decided that they wanted to build a boat to take to a community picnic. Supported by a facilitator, they worked to design, construct, test, and refine a 6-foot catamaran, out of PVC pipe and duct tape, that was ultimately able to bear the weight of two people as they paddled around the lake. Their process involved measurement, testing of multiple different strategies for ensuring a durable and waterproof 'skin' for the boat, and identifying conditions in which the boat could be tested. In a museum setting, Gutwill et al. (2015) detailed ways in which Tinkerers drew on prior knowledge, language, and practices to problem-solve and make meaning of STEM problems, practices and ideas. Indicators that learners were on a productive path towards understanding included learners' expression of new realisations, offering of explanations for strategies, tools and outcomes, applying prior knowledge, and striving to understand even through moments of struggle.

Scientific practices of formally planning and recording experiments have also been incorporated into Maker Education. 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.' Vossoughi et al. (2013, p. 5) describe how an afterschool educator introduced science journals (which students first made by hand) for students to record ideas, designs, and stories about their STEM-Rich Making creations. As in genuine uses of scientific notebooks, in this process of journaling,

> Ideas are privileged as the most valuable part of the process. … The thinking is what matters and potentially endures. … Young people are invited to see themselves as thinkers, poised to develop ideas and make significant discoveries. … [The educator] introduced the notebooks not as something you 'have to' do, but as a tool for time travel, idea-creation, and memory. The teacher's hopes are made visible, alongside what can be seen as a promise to approach the science notebooks (and activities) in ways that feel useful and meaningful.

The extent to which Makers, while they act independently and follow their own pathways, engage in the development of alternative explanations, and debate the relative merits of those explanations, is not yet documented in the literature. In the absence of verbalised explanations, it may be that documenting students' physical shifts to better design and construction solutions may serve as evidence of scientific reasoning, but not necessarily scientific argumentation (Osborne, personal communication). Yet it may be possible that when students are engaged in collaborative making activities, they may, at key decision points in the construction process, debate the merits of alternative solutions, sometimes using gesture and referencing shared experiences, in ways that may leave explanations only partially verbalised (Petrich, personal communication). Further research about the ways in which Making can engage students in scientific explanation and argumentation may be important for understanding its full potential for supporting the development of science literacy as opposed to supporting the development of readiness (interest, identity, capacity) for scientific literacy.

A core facet of learning through scientific practices relates to learning through design or experimental failures. As Makers become more experienced, they tend to reframe 'mistakes' and moments of struggle as essential to the process of learning. Indeed, Petrich et al. (2013, p. 64) argue that the process of becoming stuck and then 'unstuck' is at the heart of tinkering. Blikstein (2013, p. 8) reports that through iterative processes 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.' Calabrese Barton et al. (in press) report that moments of frustration or mistakes can serve as critical junctures for generative learning, where other makers or facilitators may intervene with ideas, strategies, or reflection to help to keep students going.

Much of schooling is organised to avoid, discourage, or even punish students for negative results. Blikstein (2013, p. 18) finds that Making contexts can provide 'visceral design experiences and new levels of frustration and excitement, which students normally do not get to experience in school.' Some frame this dimension of Making as embracing or celebrating 'failure'.

Failure in Making is seen as part of the intellectual and creative risk-taking that is essential for developing new ways of thinking. Creativity and failure go hand-in-hand, and a notable body of the research on learning through STEM-Rich Making describes, although little of it in detail, instances of students revising plans and understanding based on feedback from the objects, especially when they 'fail'. But some scholars caution against celebrating 'failure' without considering who may have the freedom to fail and who may not. For example, Martin (2015, p. 13) writes that *failure* 'is not a happy word in most educational circles'. He notes that many students, as well as schools, have been historically and systematically labelled as 'failures'. Educators must be cautious about their use of the term failure, especially for students who may commonly find themselves subjected, in direct or indirect ways, to this label.

Vossoughi et al. (2013) found that a pedagogical emphasis on the importance of *drafts* in the creative process helped to reframe 'mistakes' or 'failed attempts' as opportunities for insight and new ideas. 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, as well as support agency within the learning community and activity. As described in Vossoughi and Bevan (2014), 'they also found that students shifted their relationships with problems and drafts over time, and came to embrace the process of iteration'. STEM-Rich Making educators in their afterschool programme:

> often presented imperfect examples (a faulty scribbling machine or a sewn science notebook that artfully incorporated a 'mistake') as a way to model the power of process, invite students to publicly discuss how they might approach a problem, and emphasise the importance of ideas over final products. (Vossoughi et al., 2016, p. 216)

To productively facilitate learning through moments of design failure, helping young people to develop evidence-based design improvements and conceptual understanding, there is a need not only to provide sufficient time for youth to learn in this way, which is an important way scientists develop scientific knowledge, but also to foster a programmatic culture that supports creative and intellectual risk-taking. Under conditions in which design failures, and the tentative understandings behind them, are deeply understood as a valued part of a meaningful process, Making can help youth develop robust understandings about scientific concepts as well as the nature of scientific knowledge and investigation. Vossoughi et al. (2013) suggest that making STEM concepts and practices explicit within the playful, inquiry-led context of Making activities is an important part of equity in teaching. Supporting children to recognise the deeply intellectual aspects of their play may also help expand relationships with their own capabilities and encourage connections across settings.

4.3. Leveraging learners' cultural resources

To broaden participation in science, many scholars argue for a need to more effectively leverage the cultural repertoires of practice that children from racially and economically marginalised communities bring to the classroom (Eisenhart, Finkel, & Marion, 1996; Medin & Bang, 2014; Nasir, Rosebery, Warren, & Lee, 2006). STEM-Rich Making can provide a powerful context for such equity-oriented pedagogies because of its blending of the everyday with the scientific, and because of the way it embeds STEM concepts in socially rich discourse and practices (Halverson & Sheridan, 2014). Youth interviewed by Martin and Dixon (2013, p. 3) 'saw making as integrated across their experiences'. This comports with the call by Gutiérrez et al. (2014) for a need to question assumptions about who does and who does not engage in making, particularly with respect to the deep histories of practice and range of Making activities that exist in non-dominant communities.

Calabrese Barton et al. (in press) note the ways in which broader sociohistorical narratives about who excels in STEM fields or in Making influence how young people approach Making activities. They forefront the role of the educator in helping position youth who are new to making as central to the community by calling upon their 'salient practices and ways of being that are learned in that community, as well as from other places'. Blikstein (2013) argues that incorporating what he calls 'expressive technologies' (such as digital fabrication tools) into everyday practices positions students as capable and knowledgeable from the start, even as they work to learn how to use new tools or adopt new stances. Blikstein also found that these experiences enhanced students' appreciation of various forms of manual labour that they or their families engage in during everyday life. Vossoughi et al. (2013, p. 6) describe a case where a facilitator in an afterschool programme asked a student who was taking apart an old answering machine if she had seen people taking apart things in other settings. After some thought, the student noted that her parents dissected chickens to make family meals, which launched a group discussion about the role of dissection in everyday activities.

Fields and King (2014, p. 1), studying a university-level crafting course, noted '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.' Indeed, their study found that the university students tended to link their coursework to long-standing personal interests, bringing in skills and interests from everyday life, and building their skills in order to enhance these everyday activities.

Another strategy for leveraging young people's cultural resources is made possible through the ways in which Making is frequently deeply interdisciplinary in nature. Sheridan and Konopasky (2016) describe the ways that interdisciplinarity create multiple entry points for a broader range of learners. Peppler (2013) argues that interdisciplinary, and in particular arts-integrated, Making activities are more broadly appealing to girls than many other hands-on STEM learning activities. She notes that bringing together multiple disciplinary perspectives, from both professional and community groups can help students make connections across settings in ways that can encourage more flexible design strategies (Peppler, 2013).

Studies involving e-textiles and girls, as described above, consistently show that girls become deeply engaged in science concepts when science is encountered in activities and contexts that are familiar or of interest (see Buechley et al., 2008; Kafai & Peppler, 2010; Peppler, 2013). As Vossoughi et al. (2016) note, such framing rejects deficit orientations that focus solely on efforts to engage young people with dominant cultural norms regarding what counts as science or what science looks like, and instead recognises the ways in which young people already engage in practices that integrate a range of scientific practices, concepts, and epistemologies into their everyday or cultural making activities. This distinction, they posit, is crucial for broadening participation; further, it is:

> … particularly essential as the maker movement expands into schools and develops its own forms of assessment. The field is poised to define what counts as learning in the context of making. Situating these efforts in a deep understanding of learning as cultural activity will be crucial to challenging rather than reproducing deficit ideologies. (Vossoughi et al., 2016, p. 219)

Both in and out of the classroom, a key tension in the field of Making is the extent to which Making activities can be or should be linked to disciplinary fields or academic and workforce trajectories. There is a concern that Making will become overly curricularised in ways that eviscerate its creativity. But Vossoughi et al. (2013) suggest that having students engage with the big ideas of science and engineering without making those ideas transparent or explicit for youth can reproduce existing inequities. Through afterschool 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). Calabrese Barton et al. (in press) similarly describe participants in their study:

> Neither girl expressed interest in in-school science learning, but both enjoyed social interaction, and opportunities to get on-line during the afterschool club. [One girl], in particular, was clear that she 'absolutely hates science, math and basically anything about school.' She said she is surprised that her work in the makerspace is STEM because 'it can be fun sometimes' and it is not as 'boring' as school.

Thus, the research suggests that articulating the connections between Making and science and engineering may help to broaden students' understanding of what science and engineering are, and how they might find them enjoyable and worthy of further pursuit.

5. Discussion

As demonstrated in the above summary of the current literature on Maker Education, both research and practice brim with an enthusiasm that reflects both the nature of the learning activities themselves and a sense of liberation from a generation of text-centred, test-driven instruction. As the review shows, there is a growing body of evidence that details the many ways in which Making can motivate and support learner's purposeful activity, position STEM practices as a powerful cultural tool for engaging in interest-driven activity, and leverage cultural resources and assets with a goal of deepening engagement and learning. Brokering connections between science in Making to science in academic and career trajectories can help students to envision possible STEM futures for themselves. In particular, the relational ontology between individual and community, the diversification of what counts as STEM, science, or science learning, and the leveraging of learners' cultural resources, position Making as a potentially powerful context for science learning.

But there are also tensions in the literature described above. For example, an emphasis on tools and makerspaces risks a fetishisation of tools that could obscure fully participatory and interest-driven learning. Blikstein (2013) references this danger when he discusses the Keychain Syndrome, in which the sheer ability to design and turn out, using a 3-D printer, a vast number of 'products' risks becoming an end unto itself. Martin (2015) describes 'a seductive, but fatally flawed conceptualisation of the Maker Movement that assumes its power lies primarily in its revolutionary tool set.' He argues for a need to focus on creating Maker communities in which tools and mindsets are also a means of participation. Without such a 'tri-partite' focus, Martin worries that the movement will be declared a failure.

There is also a tension between high and low technologies that are found in many Makerspaces vs. classroom and other spaces that have been converted for Maker communities and activities. In one paper, Blikstein (2013, p.7) argued that high tech tools can accelerate design cycles, allowing students to 'focus their attention on improving the design rather than taking care of mundane issues with the materials. He also noted that the high tech tools, and the resulting professional-like quality of the products, enhanced students' commitment to the work: 'It wasn't "school stuff," it was the "real thing"' (Blikstein, 2013, p.7). These approaches contrast with the use of more everyday materials, which Vossoughi et al. (2013) argue can create opportunities for young people to continue to explore and engage in Making outside of the designed learning opportunities, as they return to their home and community settings.

There are also many practical issues to contend with. Making is materials-rich, it requires time, and benefits from spaces organised to ensure cross-pollination of ideas and interactions. Informal programmes can create dedicated spaces but classroom teachers must grapple with logistical as well as curricular implementation issues. These are compounded by the need to shift pedagogical strategies to support more reciprocal, less hierarchical, ways of investigation. Yet many teachers are taking the plunge, based on the positive responses of students. Blikstein and Worsley (2016, pp. 76–77) argue that the moment is now for progressive pedagogies to move into the classroom: 'We have the once-in-a-generation opportunity to establish something truly new in schools, make it sustainable, and deeply integrate it into the school day.'

Vossoughi and Bevan (2014) note a need for more explicit and detailed analyses of pedagogy in Making environments. Because much of the research to date has focused on out-of-school settings, there has been a reluctance to refer to mentors or facilitators of Making programmes as 'teachers'. While the focus on more learner-centred activities is essential to constructivism and the Maker Movement in general, this trend risks de-intellectualising the educative potential of Making by paying short shrift to the critical role that educators can play in creating the generative settings and teaching and learning moments in which young people can deepen their understanding and skills in Making. For example, in a study of design thinking in an urban classroom serving young women of colour, Norris (2014) found that, at times, students experienced Making activities as invasions of their privacy. She notes the key role of the teacher in recognising the sometimes racialised and gendered processes of Making in order to ensure full participation and inclusion of all students. More clearly articulating the role of teaching in student-driven learning may be one way in which schools can enrich and deepen Maker Education.

The literature also tends to position Making as superior to the routine practices of schools, perhaps reflecting its position as a counter-narrative for what counts as learning. But this positioning, when it slips into pejorative views of teaching and schooling, can backfire by undermining the ways in which many classroom educators and school leaders seek to thoughtfully expand the curriculum and pedagogical repertoire of contemporary STEM education. As Making is scaled and adapted into classrooms and non-classroom settings, it is important that it recognise and leverage existing and earlier forms of design activities, including everyday and community crafting activities, many of which have been the subject of extensive research and documentation from which the Maker Movement can learn.

Additionally, unless adequate time, vision, and professional preparation are a part of its implementation, in STEM-Rich Making (like other forms of inquiry) students can remain deeply engaged in the realm of investigation, without shifting to scientific practices of sense-making and critique. With such attention, Making may have the potential to provide deep, unscripted opportunities for students to engage in science practices.

Although it is beginning to change, to date there has been little focus on how Making can be adapted into educative environments serving youth who 'bear the brunt of narrow educational policies – working class students and students of colour' (Vossoughi & Bevan, 2014, p. 40). This issue includes but also goes beyond the question of who has access to Making as educational activity (to date, such activities have been primarily located in private schools, museums, and higher education, although there are efforts to change this). Fundamentally, it involves the ways in which the pedagogical organisation of Making recognises and leverages the cultural learning resources of young people (Vossoughi et al., 2016). Calabrese Barton et al. (in press) caution that as Making expands into school settings, 'a lack of dialog on how to [integrate it] in equitable and consequential ways may disadvantage schools and communities for whom the risk, and potential reward, remain high.' Although certainly this discussion has begun, Vossoughi and Bevan (2014) note that there is a need for 'a more direct engagement with the history and contemporary manifestations of educational inequality and the literature on equity and learning [to] help this emerging field address the pedagogical *how* of creating equitable environments and wrestle with some of the tensions apparent in the maker movement'. They note that such tensions include:

Representations of Making and Makers

Several scholars have remarked on the overwhelming use of middle class white men, their images, ideas, and projects, in depictions of Makers and Making found in materials such as *Make Magazine* (Brahms & Crowley, 2016b; Buechley, 2013). While the Maker Movement promotes a sense of counter-culture, or of rebellion and transformation, such depictions surface a central contradiction. Is Making simply a new avenue for members of economically dominant social groups to craft and exercise new forms of capital, whether social or financial? Or is there space within the Movement to recognise and leverage ideas, activities, and images from groups who have been largely excluded from historical forms of STEM, STEM education, and STEM enterprises? Key questions include: Whose forms of Making count as 'Making'? Whose values and goals define Making? The growing socio-cultural literature on culture, race, identity and epistemology (Bang, Warren, Rosebery, & Medin, 2013; Nasir et al., 2006) may be key to examining such questions.

Creative/open-ended vs. standardised/test-centric education

As Making begins to engage with schooling, there is a need for educators to directly address the ways in which 'issues of remediation, segregation and tracking have shaped and continue to shape the schooling experience of working class students and students of colour' (Vossoughi & Bevan, 2014, p. 40). Such schooling policies reflect deep cultural assumptions about who can benefit most from creative and open-ended approaches vs. more back-to-basics teaching strategies (Cole & Griffin, 1983; Gutiérrez, 2008). Thus, while the focus on learner-centred activity, and 'celebrating failure', is common in the promotional rhetoric on Making, Vossoughi and Bevan (2014) note that in communities with histories of narrow and high-stakes testing regimes, this rhetoric can easily devolve into deficit views of young people when they are not fully supported to leverage their cultural resources and experiences within Making programmes. They note a need for researchers to more directly engage with the historical debates about progressive educational movements and issues of equity (e.g. Delpit, 1986) and about the academic/vocational divide (Rose, 2005).

Making to support learning or consumption

The Maker Movement's focus on entrepreneurship and future industries can seep into pedagogical environments in both school and out-of-school settings. This may or may not be problematic, but suggests a need for STEM educators to be explicit about *why* they are introducing Making activities. Is it to create producers and consumers or is it to leverage meaningful questions and contexts for exploration of STEM phenomena, practices, and concepts? As a mode of interaction with the physical world, the purpose of Making, and Making as a learning activity, is imbued with social and political values. Some researchers have noted that Making programmes that emphasise workforce may de-emphasise interdisciplinarity, social contexts for making, and a close consideration of consumerism and creativity (Blikstein & Worsley, 2016; Vossoughi et al., 2016). As such, Vossoughi and Bevan (2014, p. 41) call for a more nuanced stance that makes connections between inquiry, creativity, and youth agency:

> 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 [students and teachers are working towards or making].

6. Conclusion

As science educators consider ways to make their instruction more stimulating and inclusive, more rich in STEM practices, and more culturally responsive and relevant to a broader number of students, the research suggests that there is great value in considering the integration of Making into the classroom curriculum. At times Making may augment other forms of firsthand learning activities. At times it may, as with the Oakland teacher described above, provide a context for assessing understanding of key STEM practices, such as experimental design, within the context of interest-driven projects. It can also be used to introduce lessons (Schneider, Wallace, Pea, & Blikstein, 2013) or to replace them, as in the elementary classroom described by Wardrip and Brahms (2016).

But many questions remain and there is a need for further programme development, documentation, and research. In some cases entire schools are reorganising their curriculum around Making. In the San Francisco Bay Area there are three disparate schools – the pricey independent Nueva School, the state-funded Lighthouse Community Charter School, and the alternative private Brightworks School. Each of these schools is beholden in different ways to state testing, but all are accountable for preparing college-ready students. These schools may offer promising models for how Making can enhance STEM learning in the primary and secondary contexts. Additional research is needed on how individual teachers integrate Making into their classrooms as a form of firsthand learning. Also of great interest is how Making fosters students' STEM interest, identity, and capacity in the out-of-school time setting and how these developments flow into and are recognised and leveraged in the science classroom. Research in this domain is just beginning. What seems to be imperative is that, as with all educational movements, great care is taken in terms of preparing and supporting teachers to implement Making in thoughtful and relevant ways to engage their students. Schools serving students from communities historically underrepresented in STEM fields may present a particularly interesting and promising opportunity in that Making can be organised to leverage students' cultural resources and family practices, positioning them to make transformative contributions to their own and the learning community's repertoires of practice. But it should not be assumed that 'high ceilings, low floors, and wide walls' are perceived or experienced equally by all learners. As educators continue to experiment in this realm of activity, practitioner knowledge may lead the way in this regard.

The hype and promises about the Maker movement, some of it the product of a marketing machine associated with various for-profit businesses, and some of it the by-product of corporate and government promotion, suggest that educators and researchers need to carefully explore the ways in which the promise of Making is optimised for youth, especially for those from communities historically underrepresented in STEM fields. Making as an educational practice has emerged in the early part of this century from the innovation culture of the notoriously non-diverse MIT-Silicon Valley axis. An overreliance on makerspaces and maker tools, rather than on pedagogy and relationships, reflects the contemporary technocratic currents transforming much of social life around the globe and leaving many behind. As this promising and exciting way of engaging with STEM is further developed and researched in educational settings, it is paramount that its fundamental purpose – liberatory learning and creative self-expression in ways that reflect the traditions of Dewey, Vygotsky and Freire – remains a key focus and area of inquiry.

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