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Keywords

Maker Movement, making, tools, community, mindset

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Abstract

The Maker Movement is a community of hobbyists, tinkerers, engineers, hackers, and artists who creatively design and build projects for both playful and useful ends. There is growing interest among educators in bringing making into K-12 education to enhance opportunities to engage in the practices of engineering, specifically, and STEM more broadly. This article describes three elements of the Maker Movement, and associated research needs, necessary to understand its promise for education: 1) digital tools, including rapid prototyping tools and low-cost microcontroller platforms, that characterize many making projects; 2) community infrastructure, including online resources and in-person spaces and events; and 3) the maker mindset, aesthetic principles, and habits of mind that are commonplace within the community. It further outlines how the practices of making align with research on beneficial learning environments.

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The Maker Movement represents a growing movement of hobbyists, tinkerers, engineers, hackers, and artists committed to creatively designing and building material objects for both playful and useful ends. The name and the idea of a Maker Movement can be traced to the 2005 founding of *Make* magazine and the first Maker Faire in 2006 ("Leading the Maker Movement", n.d.), but the basic activity of *making* grows out of longstanding hobbies and crafts such as woodworking, sewing, and electronics. These pursuits have been reinvigorated and opened up in recent years through the advent of digital fabrication tools and online networks that make it easy to share, critique, and compare ideas, designs, and project information.

While the Maker Movement has developed in out-of-school spaces and has mostly involved adult participants, there is growing interest among educators in bringing *making* into K-12 education to enhance opportunities for students to engage in design and engineering practices, specifically, and science, technology, engineering, and mathematics (STEM, or STEAM when art is included) practices, more generally. This growing interest can be seen in increasing coverage in the popular press (e.g., Finn, 2012; Giridharadas, 2011) and in investment in maker spaces by a number of science and technology museums (e.g., Tinkering Studio at the Exploratorium in San Francisco, Ingenuity Lab at the Lawrence Hall of Science in Berkeley, Maker Space at New York Hall of Science, and MAKEShop at Children's Museum of Pittsburgh). The US government has also expressed interest in making, through funding agencies (e.g., NSF and DARPA calls that mention making and maker spaces) and at the White House, which recently hosted a Maker Faire (Kalil & Miller, 2014).

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The Maker Movement is a new phenomenon, but it is built from familiar pieces, and its relevance to education has deep roots. It has long been argued that children and youth can learn by playing and building with interesting tools and materials (Montessori, 1912). Making and building can foster learning in a variety of ways that mesh with long-established theories of how learning unfolds. For example, testing ideas out in the world allows one to check expectations against reality, a process that can create conceptual disequilibrium, and can in turn lead to conceptual adaptation (Piaget, 1950). Physical creations can also create a context for social engagement around a shared endeavor. This can bring more- and less-experienced participants together around a common task—a configuration that often proves fruitful for learning (Lave & Wenger, 1991; Vygotsky, 1978).

The growing excitement around making and the Maker Movement is understandable. The inventiveness on display at Maker Faire and related events feels like a good antidote to gloomy forecasts of the decline of American innovation and competitiveness (e.g., National Research Council, 2007). The sight of youth actively engaged in designing, tinkering, and building brings hope to those who worry that today's youth are disengaged from engineering and design. The playful quality of many projects provides a counterpoint to the perception that school curricula are too rigid and formulaic. The potential value of *making* for K-12 education is perhaps most directly seen in relation to the new *Framework for K-12 Science Education* (National Research Council, 2011). Quinn and Bell (2013) argue that making is well aligned with the new standards, which bring engineering into the K-12 curriculum at a national level for the first time (see Carr, Bennett, & Strobel, 2012). Some points of alignment with making are clear, such as the inclusion of "defining problems" and "designing solutions" as core engineering practices. Others are more subtle, but equally important. For instance, Quinn and Bell suggest that the centrality of "individual agency" in many maker activities could help foster student autonomy, which in turn can help support the framework's emphasis on problem solving and sensemaking.

The purpose of this article is to introduce making and the Maker Movement to engineering education researchers, and to argue for its promise to bring playful, but rich, engineering and design activities into K-12 education. To do so, I first describe three elements of making and the Maker Movement that are critical for understanding its promise for education: 1) *digital tools*, including rapid prototyping tools and low-cost microcontroller platforms, that characterize many making projects, 2) *community infrastructure*, including online resources and in-person spaces and events, and 3) the *maker mindset*, values, beliefs, and dispositions that are commonplace within the community. I then argue that the nature of making is well aligned with research recommendations on fruitful learning environments. I conclude by arguing that the full potential of making for education can only be realized when all three critical elements are in focus.

A Working Definition

What exactly is *making*? There is no set definition. As part of what they call "*design-make-play* learning methodologies," Honey and Kanter (2013) emphasize the personal, hands-on nature of making, saying that to make is "to build or adapt objects by hand, for the simple personal pleasure of figuring out how things work" (p. 4). Sheridan et al. (2014) describe making as the activities that take place in the maker spaces they have studied: "creative production in art, science, and engineering where people of all ages blend digital and physical technologies to explore ideas, learn technical skills, and create new products" (p. 505). Blikstein (2013a) focuses on what he terms "digital fabrication labs," saying that they merge "computation, tinkering and engineering" (p. 7). Kuznetsov and Paulos (2010) define DIY (do it yourself) practice, of which they see making as a part, as "as any creation, modification or repair of objects without the aid of paid professionals" (para. 3). I draw from these conceptions to form a working definition of *making* as a class of activities focused on designing, building, modifying, and/or repurposing material objects, for playful or useful ends, oriented toward making a "product" of some sort that can be used, interacted with, or demonstrated. Making often involves traditional craft and hobby techniques (e.g., sewing, woodworking, etc.), and it often involves the use of digital technologies, either for manufacture (e.g., laser cutters, CNC machines, 3D printers) or within the design (e.g., microcontrollers, LEDs).

What then is a *maker*? A maker is someone who makes things, of course, but like the term artist, it can be difficult to offer a precise definition of what it means to be a maker. Kalil (2013) defines makers as "people who design and make things on their own time because they find it intrinsically rewarding to make, tinker, problem-solve, discover, and share what they have learned" (p. 12). Dougherty (2013) describes his realization when founding *Make Magazine* that "makers were enthusiasts who played with technology to learn about it" (p. 7). In my research in an out-of-school making club in the San Francisco Bay Area, participants said that being a maker means building things, being creative, having fun, solving problems, doing social good, collaborating, and learning (Dixon & Martin, 2014).

In this article, I refer to *making*, a class of activities sharing a family resemblance, and the Maker Movement, a community of self-identified *makers*. I chose these terms because they are commonly used and meaningful within the communities I have studied, but there are many variants in use. Others refer to digital fabrication, rapid prototyping, hacking, or tinkering. These naming differences represent regional differences as well as differences in intellectual

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heritage. "Making", as a term, has been popularized by *Make* Magazine and Maker Faire (Anderson, 2013), but has been embraced by many groups including US government agencies like DARPA, NSF, and the White House (Kalil & Miller, 2014). "Hacking" was popularized by Whole Earth Catalog publisher Stewart Brand and was intended to connect technological enthusiasm with counter-cultural and rebellious tendencies (Morozov, 2014). The word "tinkering" is most associated with the MIT Media Lab and, in particular, Resnick's Lifelong Kindergarten group (Petrich, Wilkinson, & Bevan, 2013; Resnick & Rosenbaum, 2013). Resnick and Rosenbaum (2013) contrast tinkering with more planful, engineering-oriented approaches, and connect tinkering to Levi-Strauss' notion of *bricolage*. Differing terms can also represent differences in the kinds of tools and design practices being emphasized: *digital fabrication* evokes images of laser cutters and 3D printers (e.g., http://fablabatschool.org/), *tinkering* suggests disassembled appliances and glue guns (e.g., http://tinkering.exploratorium.edu/), and *hacking* and related words (hack-a-thons, hackerspace) are more strongly associated with programming practices (Sheridan et al., 2014). These distinctions can represent meaningful contrasts between activities, but they should not be taken as absolute. As I argue below, when the focus moves away from the tools employed to the mindset at work, these distinctions become less important.

Digital Tools for Making

One of the most readily apparent features of the Maker Movement is the celebration and use of new and newly affordable digital tools. As these tools provide new ways of interacting with physical materials, they also offer new opportunities for learning. Much of the technology youth encounter in day-to-day life has a black box quality: it works (usually), but its workings are hidden (Resnick, Berg, & Eisenberg, 2000). Tech-savvy youth are often those who excel at dealing with breakdowns in technology, or who actively disassemble black box technologies to see how they work. The recent explosion of accessible digital tools represents an expansion, in the commercial space, of a long established program of research and development of digital materials and artifacts specifically designed to allow young people access to the inner workings of sophisticated technologies (Blikstein, 2013b; Papert, 1991; Resnick & Rosenbaum, 2013). Resnick's Lifelong Kindergarten lab, for example, has created programmable blocks that allow children to build, explore, and program with materials that can sense and act in the world in a contingent and interactive fashion (Resnick & Silverman, 2005). These and other digital toolkits can substantially lower the barriers to engaging in physical computing, while still offering robust pathways for learning about engineering and programming through design and play.

These efforts involve sophisticated technologies, and as such provide opportunities to learn about circuits, microcontrollers, and programming principles. Beyond this, these tools are often seen as providing access points to powerful ideas about mathematics, logic, computational thinking, and scientific experimentation. Transformative tools, the theory says, can lead to transformations in thinking. Blikstein (2013a) extends this vision to making (within what he calls fabrication labs): "What Logo did for geometry and programming—bring complex mathematics within the reach of schoolchildren—fabrication labs can do for design and engineering. Digital fabrication is Logo for atoms" (p. 2).

There are many types of digital tools in use within the Maker Movement, but two classes of tools are the most prominent. Paraphrasing Gershenfeld (2005), I call these classes *digital physical tools* and *digital logic tools*.

Digital Physical Tools

Digital physical tools (also called rapid prototyping tools or digital manufacturing tools) shape materials or material objects into new forms. With hand tools, a person guides the tool to cut away or deposit new material to create the desired shape. With digital tools, a design file is loaded onto a computer which controls the moving parts of the tool. A common distinction is between additive tools, like 3D printers and digital embroidery machines, which add material to a substrate, and subtractive tools, like CNC machines and laser cutters, which take material away. Table 1 summarizes the properties of some of these technologies. Many of these tools have existed for some time, but costs have dropped sufficiently in recent years so as to make them affordable to serious hobbyists, small-scale maker spaces, and schools.

Computer-controlled tools have a number of important qualities. First, newcomers can produce objects with a relatively high level of finish. Students often feel proud when working with computer-controlled tools, as they can make "real" products that look good (Blikstein, 2013a). Second, compared to hand crafted objects, making multiple identical or nearly identical items is easy and fast. An analogy can be made to desktop printing compared with hand drawing or typing a document. These multiples can be identical, or they can be customized in systematic ways (e.g., varying color, size, or material). Third, digital design files are shareable with complete fidelity through computer networks. Analog designs can also be shared, but doing so is effortful for both the original designer and the person hoping to reproduce the design. With digital tools, the original designer must create a digital file to create the original object, but once completed, the file can be easily used to create an exact or modified copy on another digital tool. This allows people to download finished designs (e.g., a replacement part for a washing machine) or designs that

Table 1
Common consumer-level digital physical tools.

Tool	How it works	Basic application
Desktop 3D printer (fused filament)	A digital design file contains a model of a 3D object, created with computer-aided design (CAD) software or from a 3D scan of an object. Software decomposes the model into virtual cross-sections. In the 3D printer, computer-controlled motors move a print head left and right while depositing small amounts of molten plastic onto a surface, creating a layer of material that corresponds to a cross section of the digital file. The print head then move slightly away from the print surface, so that the next layer is built on top of the previously printed layer. In this way, a 3D object is slowly built up, layer by layer.	Creating small plastic parts for use in projects. Prototyping parts in plastic that will be later manufactured in another material.
Computer numerical control (CNC) router	A digital design file contains a model of a piece of stock (e.g., metal, wood, or plastic) as well as areas where material will be removed. The CNC machine contains computer-controlled motors that move a rapidly spinning cutting head left and right, and up and down, that can cut away material from the piece of stock. Software translates the digital design file into tool paths that specify how the cutting head should move in order to carve out the desired form.	Creating small parts from metal, wood, or plastic stock, for use in projects or for prototyping. Carving words or decorative patterns into stock. Carving stock so that pieces can be joined together (e.g., with a dado joint), as in the woodworking practice of joinery.
Laser cutter	A digital design file contains a model of a piece of stock (e.g., wood or plastic) as well as lines and areas where the stock is to be cut or etched. The laser cutter contains a bright, highly focused laser capable of burning through thin materials. Computer-controlled motors can move the laser in two dimensions over a piece of flat stock, cutting or etching the material as the laser moves. Software translates the digital design file into tool paths that specify how the laser should move, and when it should be in high power (cutting) or low power (etching) in order to carve out the desired form.	Cutting stock into shapes used in a project (e.g., gears, lever arms). Carving words or decorative patterns into stock. Carving stock so that pieces can be joined together, as in the woodworking practice of joinery.
Digital embroidery machines	A digital design file contains a model of a piece of fabric as well as lines where thread will be added. The embroidery machine contains a sewing machine head that can deposit thread onto the fabric. Computer-controlled motors move the fabric in two dimensions under the sewing head. Software translates the digital design file instructions that specify how fabric should move in order to sew the desired form.	Decorating cloth; sewing circuit designs into cloth with conductive thread.
Vinyl or paper cutters	A digital design file contains a model of a piece of stock (e.g., vinyl or paper) as well as lines where the stock is to be cut. The vinyl or paper cutter contains a sharp knife capable of cutting through the material. Computer-controlled motors move the knife in two dimensions over a piece of flat stock, cutting the material as the knife moves. Software translates the digital design file into tool paths that specify how the knife should move in order to cut out the desired form.	Creating stencils and stickers; creating templates for circuit board designs.

they then modify to suit their needs (e.g., a dollhouse table, which can be scaled to fit the room).

Manufacturing

While educators tend to focus on ways in which digital tools can support student projects and small-scale making, others see within the Maker Movement the beginning of a much larger social and economic transformation. Anderson (2012) argues that shifts in computer-controlled, customized manufacturing tools, and the rise of participatory, open-source hardware designs (where companies open up their design process to their community of customers) have the potential to dramatically shift the future of manufacturing. Comparisons are sometimes made to the rise of personal computing, propelled by hobbyists working in garages, later to transform the global economy ("More than just digital quilting", 2011). Compared to traditional manufacturing technologies (e.g., injection molding), these technologies are much more efficient for making a small batch of items, and there is no additional cost to customizing each item. As such, makers can create items that are neither homogeneous nor hand crafted. This creates important business opportunities for entrepreneurs who can pursue "mass customization" (Anderson, 2012). Only time will tell if such claims are prescient or overstated, but they are worth noting as a possible justification for the incorporation of making into the curriculum—if this is the wave of the future, the argument goes, we should get youth in on the ground floor to help create that future.

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Digital Logic Tools: Microcontrollers, Mini-computers, and Other Electronics

The second class of digital tools in common use in the Maker Movement is low-cost, hobbyist-friendly microcontrollers. A microcontroller is a small, programmable computer on a chip which can process input from a variety of input devices, including sensors, switches, internet data, and so forth, and control various output devices, including motors, LEDs, screens, and speakers, and can save data to a memory card or webpage. The landscape of available microcontrollers is constantly evolving, but popular options today include Arduino, BeagleBone, and Raspberry Pi. Each of these platforms has an associated online community where people can read manuals and tutorials, watch videos, converse through forums, and share code.

The possible uses of microcontrollers are endless, but an example may help to clarify. Consider a project completed by one of the participants in our recent study of making in an out-of-school club (Martin, Dixon, & Hagood, 2014). This young woman created a kinetic sculpture of a dragon–horse hybrid, with wings that would flap faster and faster as the viewer approached. She built a skeleton from wire, sculpted a body from clay, and carefully decorated the body with paint and copper foil. She then made wings from paper and wire, attached them to a mechanism scavenged from a broken toy, and attached this to a motor powered by an Arduino microcontroller. She added a light sensor to the Arduino and wrote code so that when light levels dipped lower—when a viewer approached and blocked ambient light—the Arduino moved the motor faster, thus flapping the wings more rapidly. This project captures the basic capacity of a microcontroller: it monitored an input (a sensor) and modulated an output (a motor) based on a set of user-specified instructions (code). It also exemplifies a common maker practice of integrating traditional art practices with interactive electronics.

Community Infrastructure

The second critical aspect of the Maker Movement, as its moniker suggests, is the community that has arisen around making. This community emerged not only because of shared interests, which are longstanding, but also because of the infrastructure that supports community engagement. This infrastructure includes person-to-person meetings, at museums (e.g., Exploratorium's Tinkering Social Club, http://tinkering.exploratorium.edu/taxonomy/term/8634; workshops at New York Hall of Science's Maker Space, http://nysci.org/programs-main/maker-space-folio/), maker spaces (e.g., Hacktory, http://thehacktory.org; NYC Resistor, http://www.nycresistor.com/), and events like Maker Faire (http://makerfaire.com), as well as in online settings such as social network sites (e.g., Facebook, http://facebook.com; Twitter, http://twitter.com) and maker-oriented websites (e.g., Instructables, http://instructables.com; DIY, http://diy.org). Participating in these community spaces, both in person and online, centers topically around making, but is otherwise similar to other communities: people socialize, read, share project details, watch videos, joke around, and engage in other forms of hanging out and geeking out (cf. Ito et al., 2010; Kafai & Peppler, 2011).

One way to conceptualize the value of the community is to imagine what youth making would look like without the broader community. Without websites, magazines, and events that showcase projects, inspiration and ideation would be diminished. Without access to websites that host samples of code, digital design files, support forums, and how-to videos, it would be much more difficult to build project components and to troubleshoot the inevitable problems that arise. Without mentors in the community, the expertise available for teaching and problem solving would be reduced, and youth would lack expert roles to which to aspire. Finally, even those youth who finished projects would lack an interested audience with whom to share their work.

There is a rich body of literature that supports the intuition that out-of-school learning communities, like the Maker Movement, can provide powerful contexts for the development of interest, identity, and content area knowledge: Barron (2006) has shown that interest in technology typically develops across a web of out-of-school experiences that extend over time and space. Gee (2007) and Ito et al. (2010) have shown how informal, leisure activities can provide foundational experience with sophisticated language and transactional processes necessary for later engagement in academic discourse. Heath (2012) highlights the importance of playing a role other than "student" in the development of identity, while noting that "formal learning environments cannot easily give groups of young learners either truly meaningful roles or opportunities for participation in longitudinal projects" (p. 257).

In informal learning communities, analytically separable categories like identity, agency, and expertise are deeply intertwined (National Research Council, 2009). The ways that young people identify with a domain can have substantial influence on the kinds of choices they make for future educational experiences, including courses and majors, and can partly predict the likelihood that they will pursue a career in that field (Tai, Liu, Maltese, & Fan, 2006). When young people are interested in the things they are working with, when they feel like their activities align with their sense of themselves and their possible futures, and when they feel connected to the community they are working within, tremendous amounts of learning can occur (National Research Council, 2009). Although youth identity is often conceptualized as an important predictor of future career choices (Tai, Liu, Maltese, & Fan, 2006), it is also important on shorter timescales. The way that youth think of themselves, as mathematicians, scientists, designers, or makers, guides the knowledge, skills, and practices they draw upon

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to solve the problems they encounter (Dixon & Martin, 2014; Engle, Lam, Meyer, & Nix, 2012; Heath, 2012).

The Maker Mindset

The third essential aspect of the Maker Movement concerns the values (Dewey, 1929), beliefs (Elby & Hammer, 2001), and dispositions (Perkins, Tishman, Ritchhart, Donis, & Andrade, 2000) that typify participation in the community. Following Dougherty (2013), I refer to this collection of attributes as the *maker mindset*, and I consider four elements I believe are critical to its value for education: it is playful, asset- and growth-oriented, failure-positive, and collaborative. This list is not meant to be exhaustive nor final, but is intended to be a parsimonious account of commonly professed beliefs that connect well with issues important to educators.

1. Playful

Dougherty (2013) notes that, while the growth of the Maker Movement has been bolstered by the emergence of new tools, easier access to components, and growing online communities, at the heart of its emergence is something he calls "experimental play." Gershenfeld (2005) shares that the artists, architects, and engineers who showed up for his seminal "How to make (almost) anything" class were motivated not by professional desires, but "their own pleasure in making and using their own inventions" (p. 6).

Play, fun, and interest are at the heart of making. Petrich et al. (2013) note that in activities at the Tinkering Studio in the Exploratorium, where they work and conduct research, learners "author" the goals and constraints active in the activities. As such, the learners' goals, interests, and sense of what is fun and cool are primary. This stands in contrast to many other hands-on engineering or problem-based learning activities, such as robotic competitions, where the goals and constraints are externally determined. Working within external constraints is an important skill for engineers and designers, they argue, but it is not necessarily an ideal starting point for engagement.

Play is a complex construct, but researchers have long considered it to be a fundamental developmental activity for children and adolescents (Pellegrini, 2009; Piaget, 1945; Vygotsky, 1978). Fun, playful activities are intrinsically motivating, and intrinsic motivation is associated with a variety of educational benefits, including persistence in the face of challenge (Vansteenkiste, Simons, Lens, Sheldon, & Deci, 2004). Moreover, a playful learning environment encourages experimentation and experience of variation, prerequisites for the development of conceptual knowledge and adaptive expertise (Hatano & Inagaki, 1986).

2. Asset- and growth-oriented

Makers are free to focus their activities where they want to. They can focus on developing their areas of strength and experience, or venture into new territory when they want to learn something new. Rhetoric in the Maker Movement often focuses on skills rather than abilities: Dougherty (2013) describes the maker mindset as a "growth mindset that encourages students to believe they can learn to do anything" (p. 10), and summarizes it with the question, "what can you do with what you know?" (p. 9). There is a strong sense that anyone can learn the skills needed to make things. Because making is free-choice, there is little talk of areas of weakness, or even areas in need of improvement: there is no sense that everyone needs to code, or knit, or use a 3D printer.

Dweck (2000) and colleagues have shown that youth who see intelligence as a fixed entity adapt a variety of strategies that are poorly suited to learning, such as avoiding challenges that may lead to failure. In contrast, youth who believe that intelligence is muscle-like, and can grow with exercise, tend to follow a more adaptive learning pattern that embraces challenges. This growth mindset is more robust to experiences of failure, because failure is interpreted as an indicator that more effort is required, rather than a cue to disengage.

The asset- and growth-oriented nature of the maker mindset aligns well with Dweck's growth mindset as well as asset-based views of youth. In addition, free choice learning environments, including making, can soften deficit-based views of youth that emphasize what they cannot do rather than their competencies (Gutierrez & Rogoff, 2003; McDermott, 1993; Vossoughi, Escudé, Kong, & Hooper, 2013). This is not to say that youth involved in the Maker Movement never doubt whether they can learn, if their skills will be valued, or if they may be judged for their ignorance. Youth can experience the failures of making as demoralizing (Soep, 2014). Rather, discourse in the community, and the free-choice nature of making, emphasize assets and the ability to learn over deficits—an orientation sometimes missing in school settings (Gutierrez & Rogoff, 2003).

3. Failure-positive

Failure is not a happy word in most educational circles, particularly when attached to schools, students, or initiatives. Yet within the maker mindset, failure is celebrated. This celebration shows up in a variety of places. For example, a 2011 blog post on *Make* magazine declared, "Failing is the new winning" as it introduced the "Most Spectacular Failure Award" for an annual race called the Handcar Regatta (Mohammadi, 2011). One maker I spoke with shared a story of how disappointed he and his sons were when an engine they had completely disassembled and reassembled started up on the first try. The unanticipated success ruined their planned weekend of tinkering, troubleshooting, and learning. Adam Savage, host of the popular TV show Mythbusters, often wears a shirt on screen that says, "Failure is always an option," and has spoken on the importance of failure to the creative process, and in one's personal and professional development (Branwyn, 2009).

While "failure" is an often used term in making circles, overcoming small obstacles is equally important. Petrich et al. (2013) state that "the process of becoming stuck and then 'unstuck' is the heart of tinkering" (p. 55), and they find that such moments are often among the most salient in participants' post-activity interviews. Failures in a school setting can be "productive" as well, helping students to better understand the structures and constraints of problems, so that they can learn better when given another chance (Kapur, 2008). More broadly, the process of facing and adapting to multiple sticking points may be important to the development of adaptive expertise (Chi, 2011; Martin & Schwartz, 2009).

4. Collaborative

The fourth element of the maker mindset is that it embraces sharing and collaboration. This is not to say that most maker projects involve a group working together on a common goal, as projects can be completed individually or in teams. Instead, the collaborative nature of the maker mindset comes from an embrace of sharing ideas and projects, and helping others. While not everyone who makes things shares their knowledge or their creations, the existence of large online communities shows that many do (Kuznetsov & Paulos, 2010), and among youth, sharing one's knowledge is associated with greater technical sophistication (Barron, Walter, Martin, & Schatz, 2010). People share to exchange information, to educate others, to get feedback, and to feel connected (Kuznetsov & Paulos, 2010).

The Maker Movement, with its macro-level sharing, helping, and collaborating, can be conceptualized as a *knowledge building community* (Scardamalia & Bereiter, 2006). A knowledge building community is one that, like the scientific community, works collectively to build and share new knowledge. Scardamalia and Bereiter note that this is different from the typically competitive and replicative nature of classroom learning, where the (sometimes tacit) goal is to acquire a set of pre-existing knowledge, and to do so more effectively than one's classmates. In particular, making focuses on enacted knowledge and a non-competitive discourse, both central to the definition of a knowledge building community.

The maker mindset, as presented above, represents a synopsis of commonly held beliefs, but it should not be taken as monolithic or unchanging. As schools work to incorporate making, they will need guidance on how to construct their own version of the maker mindset appropriate to the local context. For example, research suggests that having students choose their own projects is a powerful motivator (e.g., Blikstein, 2008), but some schools may prefer a more highly packaged approach to making, with allowable projects pre-specified. Further research is needed on when and how autonomy, and other aspects of the maker mindset, are essential for learning.

Learning Through Making

An obvious and important question about making and its role in education is, what do youth learn through making? Because interest in making as an educational activity is new, empirical evidence specifically about making is still limited. Nonetheless, a rich body of research from the learning sciences and engineering education suggests that, given the properties of making described above, there is good reason to believe that it is a beneficial learning environment of interest to engineering education researchers. Depending on the particular aspects of practice, and the learning outcomes of interest, a variety of literatures are relevant. Those interested in the contexts in which making typically occurs might look to the robust literature on science learning in out-of-school contexts, such as after school programs, museums, and families (see National Research Council, 2009, for a review). An interest in community-driven processes of learning and identity development suggests examining research on online learning communities (e.g., Buckingham, 2008; Ito et al., 2010), while researchers interested in the development and maintenance of interest, engagement, and identity development will find a robust literature on these topics in hobbies, technology, and science (e.g., Azevedo, 2011; Barron, 2006). Those interested in particular aspects of engineering and design expertise, such as computational thinking (Grover & Pea, 2013) or use of design thinking (Dym, Agogino, Eris, Frey, & Leifer, 2005), will find ample useful literatures as well.

A full review of these relevant literatures is beyond the scope of this paper, but in the service of making connections between *making* and learning more clear, I present in outline form seven reasons why making is a valuable learning activity.

1. Making aligns with the curricular demands of schooling, in particular the engineering practices seen in NGSS (Quinn & Bell, 2013). Alignment between learning activities and learning outcomes is a commonsense and effective way to increase learning (Krajcik, McNeill, & Reiser, 2008).
2. Making gives youth access to sophisticated tools for building and for thinking. Transformative digital tools have been shown to empower youth to engage in new forms of thinking, including computational thinking (e.g., Blikstein, 2008; Resnick & Silverman, 2005).
3. Making involves creating things, seeing how they perform, and sharing them with others. Research has shown that, in Papert's (1993) words, learning "often happens especially felicitously when it is supported by construction of a more public sort 'in the world'"

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(p. 143). Okita and Schwartz (2013) note that production can lead to powerful forms of learning driven by *recursive feedback*, where people learn from the actions of their creations.

4. Making is playful and highly tolerant of errors. Playfulness begets experimentation, which leads to the development of conceptual knowledge and promotes adaptability in the face of challenges (Hatano & Inagaki, 1986). Failures, small and large, can drive learning, as they bump people out of routines and into a reflective mode that can prepare them to learn more (Kapur, 2008; Koschmann, Kuutti, & Hickman, 1998).
5. Making advocates a growth mindset, where, given effort and resources, anyone can learn the skills needed to complete any project they can imagine. Learning environments that advocate a growth mindset encourage persistence, challenge seeking, and learning (Dweck, 2000).
6. Making environments typically give youth substantial say in what and how they make. Learning environments that support youth autonomy and control of their endeavors are more motivating, support engagement and persistence, identity development, and the growth of resourcefulness (Azevedo, 2011; Barron, 2006; Ryan & Deci, 2000).
7. Making occurs within linked learning communities, spanning in-person and online contexts, and involving people of a wide range of ages and knowledge. Such environments help youth integrate their interests with robust social support to create powerful contexts for learning (Heath, 2012; Ito et al., 2013).

Connecting the Maker Movement to Education

The purpose of this article is to introduce making and the Maker Movement to the broader educational research community and to argue for the promise they hold for education. In doing so, it introduces three aspects of the Maker Movement: two types of digital tools, community infrastructure, and the maker mindset. Just as a stool requires three legs to stand, all three aspects of the Maker Movement are critical to understanding the role it can play in education. An explicit emphasis on the tripartite nature of making is necessary because of the pervasive desire in education for silver bullets that can solve big problems through simple means.

Consider the history of computers in classrooms in the United States. Although thoughtful researchers have long argued (and continue to argue) that the social architecture of activities surrounding technology is at least as important as the devices themselves (e.g., Mercier, Higgins, & Joyce-Gibbons, 2014), policy documents have often tacitly assumed that the computers themselves are the real agents of change, and that placing them in classrooms will catalyze large shifts in teaching and learning (Culp, Honey, & Mandinach, 2005). The logic underlying investment in computers for schools said that access would lead to increased use, and increased use to improved learning (Cuban, 2001). Schools that fully integrated computer technology into teaching and learning did see gains (Means, Penuel, & Padilla, 2001), but in most schools, computers sat unused or were put into service only to advance existing practices of schooling, resulting in little to no real change in teaching and learning (Cuban, 2001).

Although thoughtful researchers of and advocates for bringing making into education, such as those cited throughout this article, uniformly argue for a multifaceted understanding of making, the history of the adoption of computers in schools suggests a lurking danger: a seductive, but fatally flawed conceptualization of the Maker Movement that assumes its power lies primarily in its revolutionary tool set, and that these tools hold the power to catalyze transformations in education. Given the growing enthusiasm for making, there is a distinct danger that its incorporation into school settings will be tool-centric and thus incomplete. In my view, a tool-centric approach to integrating making into education will certainly fail, as it will neglect the critical elements of community and mindset. As we consider the promise of the Maker Movement for education, we must actively resist this tendency to oversimplify.

With continued focus on the three essential elements of making, and research to address gaps in our understanding of how making can align with the goals and needs of schools, bringing making into school settings has the potential to bring the creative, playful, engineering- and design-relevant learning activities of making to a wider and more diverse audience than ever before. Doing so will be of benefit to both the Maker Movement and to the schools and classrooms that embrace making.

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References

Anderson, C. (2012). *Makers: The new industrial revolution*. New York, NY: Random House.

Anderson, C. (2013, April 16). The Maker Movement: Tangible goods emerge from ones and zeros. *Wired*. Retrieved from http://www.wired.com/2013/04/makermovement/.

Azevedo, F. S. (2011). Lines of practice: A practice-centered theory of interest relationships. *Cognition and Instruction*, *29*(2), 147–184.

Barron, B. (2006). Interest and self-sustained learning as catalysts of development: A learning ecology perspective. *Human Development*, *49*(4), 193–224.

Barron, B., Walter, S. E., Martin, C. K., & Schatz, C. (2010). Predictors of creative computing participation and profiles of experience in two Silicon Valley middle schools. *Computers & Education*, *54*(1), 178–189.

Blikstein, P. (2008). Travels in Troy with Freire: Technology as an agent for emancipation. In Noguera, P., & Torres, C. A. (Eds.), *Social justice education for teachers: Paulo Freire and the possible dream* (pp. 205–244). Rotterdam, Netherlands: Sense.

Blikstein, P. (2013a). Digital fabrication and 'making' in education: The democratization of invention. In Walter-Herrmann, J., & Büching, C. (Eds.), *FabLabs: Of machines, makers and inventors*. Bielefeld: Transcript Publishers.

Blikstein, P. (2013b). Seymour Papert's legacy: Thinking about learning, and learning about thinking. Presentation given at Interaction, Design, and Learning conference, New York. Retrieved from: https://tltl.stanford.edu/content/seymour-papert-s-legacy-thinking-about-learning-and-learning-about-thinking.

Branwyn, G. (2009, June 5). Adam Savage, at Maker Faire, talking on the importance of failure. *Make Magazine Blog*. Retrieved from http://makezine.com/2009/06/05/adam-savage-at-maker-faire-talking/.

Buckingham, D. (2008). *Youth, identity, and digital media*. Cambridge, MA: MIT Press.

Carr, R. L., Bennett, L. D., & Strobel, J. (2012). Engineering in the K-12 STEM standards of the 50 U.S. states: An analysis of presence and extent. *Journal of Engineering Education*, *101*(3), 539–564. doi: 10.1002/j.2168-9830.2012.tb00061.x.

Chi, M. T. H. (2011). Theoretical perspectives, methodological approaches, and trends in the study of expertise. *Expertise in Mathematics Instruction*, 17–39.

Cuban, L. (2001). *Oversold and underused: Computers in the classroom*. Cambridge, MA: Harvard University Press.

Culp, K. M., Honey, M., & Mandinach, E. (2005). A retrospective on twenty years of education technology policy. *Journal of Educational Computing Research*, *32*(3), 279–307.

Dewey, J. (1929). The quest for certainty: A study of the relation of knowledge and action. New York, NY: Minton, Balch and Company.

Dixon, C., & Martin, L. (2014). Make to relate: Narratives of, and as, community practice. In Polman, J. L., Kyza, E. A., O'Neill, D. K., Tabak, I., Penuel, W. R., Jurow, A. S., O'Connor, K., Lee, T., & D'Amico, L. (Eds.), *Proceedings of the International Conference of the Learning Sciences (ICLS) 2014.* Boulder, CO (pp. 1591–1592).

Dougherty, D. (2013). The maker mindset. In Honey, M., & Kanter, D. E. (Eds.), *Design. Make. Play. Growing the next generation of STEM innovators* (pp. 7–16). New York, NY: Routledge.

Dweck, C. (2000). *Self-theories: Their role in motivation, personality, and development*. Psychology Press.

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education*, *94*(1), 103–120.

Elby, A., & Hammer, D. (2001). On the substance of a sophisticated epistemology. *Science Education*, *85*(5), 554–567.

Engle, R. A., Lam, D. P., Meyer, X. S., & Nix, S. E. (2012). How does expansive framing promote transfer? Several proposed explanations and a research agenda for investigating them. *Educational Psychologist*, *47*(3), 215–231.

Finn, H. (2012, Oct. 5). Amateurs to the rescue. *The Wall Street Journal*. Retrieved from http://online.wsj.com/news/articles/SB1000087239639044376880457803436060456545 2.

Gee, J. P. (2007). *Good video games + good learning*. New York, NY: Peter Lane.

Gershenfeld, A. (2005). *Fab: The coming revolution on your desktop—from personal computers to personal fabrication*. New York, NY: Basic Books.

Giridharadas, A. (2011, May 13). The kitchen-table industrialists. *The New York Times*. Retrieved from http://www.nytimes.com/2011/05/15/magazine/the-kitchen-table-industrialists.html.

Grover, S., & Pea, R. (2013). Computational thinking in K–12: A review of the state of the field. *Educational Researcher*, *42*(1), 38–43.

Gutierrez, K., & Rogoff, B. (2003). Cultural ways of learning: Individual traits or repertoires of practice. *Educational Researcher*, *32*(5), 19–25.

Hatano, G., & Inagaki, K. (1986). Two courses of expertise. In Stevenson, H., Assume, H., & Hakuta, K. (Eds.), *Child development and education in Japan* (pp. 262–272). New York, NY: Freeman.

Heath, S. B. (2012). Seeing our way into learning science in informal environments. In Tate, W. F. (Ed.), *Research on schools, neighborhoods, and communities: Toward civic responsibility* (pp. 249–267). New York, NY: Rowman & Littlefield Publishers.

Honey, M., & Kanter, D. E. (2013). Design, make, play: Growing the next generation of science innovators. In Honey, M., & Kanter, D. E. (Eds.), *Design. Make. Play. Growing the next generation of STEM innovators* (pp. 1–6). New York, NY: Routledge.

Ito, M., Baumer, S., Bittanti, M., Cody, R., Herr-Stephenson, B., Horst, H. A., Lange, P. G., Mahendran, D., Martínez, K. Z., Pascoe, C., (2010). Hanging out, messing around, and geeking out. Cambridge, MA: MIT Press.

Ito, M., Gutiérrez, K., Livingstone, S., Penuel, B., Rhodes, J., Salen, K., … & Watkins, S. C. (2013). *Connected learning: An agenda for research and design*. Irvine, CA: Digital Media and Learning Research Hub.

Kafai, Y. B., & Peppler, K. A. (2011). Youth, technology, and DIY: Developing participatory competencies in creative media production. *Review of Research in Education*, *35*(1), 89–119.

Kalil, T. (2013). Have fun—learn something, do something, make something. In Honey, M., & Kanter, D. E. (Eds.), *Design. Make. Play. Growing the next generation of STEM innovators* (pp. 12–16). New York, NY: Routledge.

Kalil, T., & Miller, J. (2014, February 3). Announcing the first White House Maker Faire. *The White House Blog*. Retrieved from http://www.whitehouse.gov/blog/2014/02/03/announcing-first-white-house-maker-faire.

Kapur, M. (2008). Productive failure. *Cognition and Instruction*, *26*(3), 379–424.

Koschmann, T., Kuutti, K., & Hickman, L. (1998). The concept of breakdown in Heidegger, Leont'ev, and Dewey and its implications for education. *Mind, Culture, and Activity*, *5*(1), 25–41.

Krajcik, J., McNeill, K. L., & Reiser, B. J. (2008). Learning-goals-driven design model: Developing curriculum materials that align with national standards and incorporate project-based pedagogy. *Science Education*, *92*(1), 1–32.

Kuznetsov, S., & Paulos, E. (2010). Rise of the expert amateur: DIY projects, communities, and cultures. *Proceedings of NordiCHI*, Reykjavik, Iceland.

Leading the Maker Movement (n.d.) Retrieved February 1, 2014 from http://makermedia.com/.

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge, UK: Cambridge University Press.

Martin, L., Dixon, C., & Hagood, D. (2014). Distributed adaptations in youth making. Paper presented at *FabLearn: Conference on Creativity and Fabrication in Education*, Stanford, CA.

Martin, L., & Schwartz, D. L. (2009). Prospective adaptation in the use of external representations. *Cognition and Instruction*, *27*(4), 1–31.

Means, B., Penuel, W., & Padilla, C. (2001). *The connected school: Technology and learning in high school*. San Francisco, CA: Jossey-Bass.

Mercier, E. M., Higgins, S. E., & Joyce-Gibbons, A. (2014). The effects of room design on computer-supported collaborative learning in a multi-touch classroom. *Interactive Learning Environments*, 1–19. doi: 10.1080/10494820.2014.881392.

McDermott, R. (1993). The acquisition of a child by a learning disability. In Chaiklin, S., & Lave, J. (Eds.), *Understanding practice* (pp. 269–305). New York, NY: Cambridge University Press.

Mohammadi, G. (2011, September 28). Most spectacular failure award at handcar regatta. *Make Magazine Blog*. Retrieved from http://makezine.com/2011/09/28/most-spectacular-failure-award-at-handcar-regatta/.

Montessori, M. (1912). *The Montessori method*. New York, NY: Frederick Stokes Co.

More than just digital quilting. (2011, December 3). *The Economist*. Retrieved from http://www.economist.com/node/21540392.

Morozov, E. (2014, January 13). Making it. *The New Yorker*. Retrieved from http://www.newyorker.com/arts/critics/atlarge/2014/01/13/140113crat_atlarge_morozov.

National Research Council (2007). *Rising above the gathering storm: Energizing and employing America for a brighter economic future*. Washington, DC: National Academies Press.

National Research Council (2009). *Learning science in informal environments: People, places, and pursuits*. Washington, DC: National Academies Press.

National Research Council (2011). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Committee on Conceptual Framework for the New K-12 Science Education Standards, Board on Science Education, National Research Council. Washington, DC: National Academies Press.

Okita, S. Y., & Schwartz, D. L. (2013). Learning by teaching human pupils and teachable agents: The importance of recursive feedback. *Journal of the Learning Sciences*, *22*(3), 375–412.

Papert, S. (1991). Situating constructionism. In Papert, S., & Harel, I. (Eds.), *Constructionism*. Cambridge, MA: MIT Press.

Papert, S. (1993). *The children's machine: Rethinking school in the age of the computer*. New York, NY: Basic Books.

Pellegrini, A. D. (2009). *The role of play in human development*. New York, NY: Oxford University Press.

Perkins, D., Tishman, S., Ritchhart, R., Donis, K., & Andrade, A. (2000). Intelligence in the wild: A dispositional view of intellectual traits. *Educational Psychology Review*, *12*(3), 269–293. doi: 10.1023/a:1009031605464.

Petrich, M., Wilkinson, K., & Bevan, B. (2013). It looks like fun, but are they learning? In Honey, M., & Kanter, D. E. (Eds.), *Design. Make. Play. Growing the next generation of STEM innovators* (pp. 50–70). New York, NY: Routledge.

Piaget, J. (1945). *Play, dreams, and imitation in childhood*. New York, NY: WW Norton.

Piaget, J. (1950). *The psychology of intelligence*. New York, NY: Harcourt Brace.

Quinn, H., & Bell, P. (2013). How designing, making, and playing relate to the learning goals of K-12 science education. In Honey, M., & Kanter, D. (Eds.), *Design. Make. Play: Growing the next generation of STEM innovators* (pp. 17–33). New York, NY: Routledge.

Resnick, M., Berg, R., & Eisenberg, M. (2000). Beyond black boxes: Bringing transparency and aesthetics back to scientific investigation. *Journal of the Learning Sciences*, *9*(1), 7–30.

Resnick, M., & Rosenbaum, E. (2013). Designing for tinkerability. In Honey, M., & Kanter, D. (Eds.), *Design. Make. Play: Growing the next generation of STEM innovators* (pp. 163–181). New York, NY: Routledge.

Resnick, M., & Silverman, B. (2005). Some reflections on designing construction kits for kids. *Proceedings of Interaction Design and Children Conference*, Boulder, CO.

Ryan, R. M., & Deci, E. L. (2000). Intrinsic and extrinsic motivations: Classic definitions and new directions. *Contemporary Educational Psychology*, *25*(1), 54–67.

Scardamalia, M., & Bereiter, C. (2006). Knowledge building: Theory, pedagogy, and technology. In Sawyer, R. K. (Ed.), *The Cambridge Handbook of the Learning Sciences* (pp. 97–115). New York, NY: Cambridge University Press.

Sheridan, K. M., Halverson, E. R., Litts, B. K., Brahms, L., Jacobs-Priebe, L., & Owens, T . (2014). Learning in the making: A comparative case study of three makerspaces. *Harvard Educational Review*, *84*(4), 505–531.

Soep, E. (2014). *Participatory politics: Next-generation tactics to remake public spheres*. Cambridge, MA: MIT Press.

Tai, R. H., Liu, C. Q., Maltese, A. V., & Fan, X. (2006). Planning early for careers in science. *Science*, *312*(5777), 1143–1144.

Vansteenkiste, M., Simons, J., Lens, W., Sheldon, K. M., & Deci, E. L. (2004). Motivating learning, performance, and persistence: the synergistic effects of intrinsic goal contents and autonomy-supportive contexts. *Journal of Personality and Social Psychology*, *87*(2), 246.

Vossoughi, S., Escudé, M., Kong, F., & Hooper, P. (2013). Tinkering, learning & equity in the after-school setting. Paper presented at FabLearn, Stanford, CA. Retrieved from http://fablearn.stanford.edu/2013/papers/.

Vygotsky, L. S. (1978). *Mind in society*. Cambridge, MA: Harvard University Press.