Maker Education: A Historical Perspective

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Abstract

The advent of affordable fabrication technologies such as 3D desktop printers and programmable microcontrollers (such as the Arduino microcontroller) have fueled a maker movement. The American Association of Engineering Education (ASEE 2016) described the maker movement as a growing community of creative individuals spanning a broad range of skills and technical backgrounds. A maker is someone who has a do-it-yourself mindset and might identify as an engineer, designer, tinkerer, artist, or another creative identity. Makerspaces are physical locations equipped to facilitate the growth of the maker movement and have garnered attention from the educational community (Peppler, Halverson, and Kafai 2016).

The current maker movement can be traced to the founding of *Make* magazine in 2005. The publisher, Dale Daugherty, subsequently organized Maker Faires to celebrate maker culture. Just as in a previous generation Computer Faires gave birth to the personal computing movement, Maker Faires have provided makers with a venue to share maker techniques and showcase their work. The first makerspaces were established during this era. These facilities for making were established in community spaces, libraries, and schools.

Makerspaces introduce the technological tools used to design and build physical objects; use of the tools creates experiences that contribute to understanding of how objects work (National Academy of Sciences, Engineering, and Medicine 2018). The prevalence of makerspaces in schools has given rise to maker

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education. The maker pedagogy employs making as a framework for learning. The availability of makerspaces in schools has encouraged teachers to explore instructional strategies that incorporate making in some form.

Maker education, in contrast to many pedagogical methods that originated in academic settings, began as a grassroots movement. However, the pedagogy of maker education has connections to longstanding areas of academic research, such as project-based and problemme-based learning, contextualized learning, and design thinking. It also has specific connections to areas of engineering education that include mechanical engineering, electrical engineering, and computer science. From that perspective, the roots of maker education can be traced to the origins of these disciplines.

Keywords: Maker; Making; Maker education; Invention

1 Making in the mechanical age

Almost everything in today's world that is manmade is manufactured. Manufacturing refers to production of products in large quantities by machinery. Manufacturing in its present form is relatively recent and plays a significant role in the current standard of living. Manufacturing entails production of goods in a factory, typically through processes that involve some degree of automation. Automated production of goods yields significantly greater productivity than the methods that preceded it.

Automated production involves three components: (1) a power source, (2) a mechanism, and (3) a control system. The first industrial revolution was powered by steam. The textile industry was transformed when weaving was mechanized when in 1788 Edmund Cartwright developed the steam-powered loom and built the first steam-driven textile mill in England with James Watt. At the beginning of the eighteenth century, the Jacquard loom added a control system in the form of punched cards laced together in a sequence that automated control of the pattern woven into the cloth. In this system a steam engine provided the power source, the loom provided the mechanism that wove the cloth, and the series of punched cards provided the control system.

Mechanized weaving systems led to establishment of the modern factory system. Mechanization of weaving made cloth available in greater abundance than before, with significant economic benefits. At the beginning of the seventeenth century, a suit of clothes could cost the equivalent of a year's salary for an average worker. Prices steadily dropped after introduction of mechanized weaving (Plaza 2013). One consequence was wider availability of rags and used clothing for paper making, which in turn reduced printing costs and made books more readily available.

The three elements of the mechanized loom can be found in today's automated factories. A robotic arm, for example, consists of (1) a power source in the form of electric motors, (2) a mechanism in the form of mechanical manipulators, and (3) a control system in the form of programmable microcontrollers. The path from the Jacquard loom to microcontrollers can be measured in three stages that occurred over the course of the nineteenth and twentieth centuries. These include development of *electromechanical control systems* in the nineteenth century, development of *electronic control systems* in the first half of the twentieth century, and development of *programmable microcontrollers* in the second half of the twentieth century.

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2 Making in the electromechanical age

Although steam gave rise to the first industrial revolution, it had a distinct disadvantage as a power source. The cost and complexity of steam engines made it necessary to power an entire factory from a single power source. Shafts ran from a steam engine at one end of the factory to the other end. Leather belts connected the shafts to machines throughout the factory. A belt might connect the rotating shaft to a lathe, while a second belt might connect the shaft to a drill press, and so forth. This constrained the way in which factories could be structured and organized.

The advent of electrical power transformed factories. The origins of this development can be dated to the invention of the battery by Volta in 1800. Invention of the battery led to discovery of electromagnetism. An electrical current traveling through a wire creates a magnetic field around the wire. Coiling the wire concentrates the magnetic field, creating a more powerful device: the electromagnet. The availability of a power source in the form of an electrical battery gave rise to two great networks in the nineteenth century: the telegraph network and the telephone network. Many of the technologies invented during development of these networks influenced the development of the first commercial electrical network by Edison in lower Manhattan at the end of the nineteenth century.

The battery and electromagnetism made the telegraph network possible. An electromagnet at one end of a telegraph line could be activated by closing a switch (in the form of telegraph key) at the other end of the line to complete an electrical circuit. The electromagnet, in turn, attracted an iron bar, creating a clicking sound that was interpreted as a telegraph signal (i.e., Morse code).

This capability was well understood and used by dozens of inventors to create the precursor of the telegraph network. However, the batteries available in the nineteenth century could only send a telegraph signal a limited distance. This constraint was resolved in an ingenious way by using a relay. This capability enabled Morse to develop the first commercial telegraph network.

The relay was a crucial element in development of the world's first electromechanical control system. This development indirectly made the maker movement possible nearly two centuries later. The telegraph relay enabled replication and propagation of the telegraph signal using the electromechanical technologies of the nineteenth century. The telegraph relay consisted of an electromagnet in a primary circuit on one side and a switch in a secondary circuit on the other side of the relay. Closing the telegraph key created an electromagnetic field at the end of the primary circuit. The electromagnet in the primary circuit closed the switch in the secondary circuit, retransmitting the telegraph signal. The telegraph signal could be transmitted an indefinite distance by chaining a series of relays together in this fashion. Ten years after Morse transmitted the message, "What hath God wrought!" from Baltimore to Washington, DC, more than ten thousand miles of telegraph lines created an extensive network (Samuel Morse Papers, Library of Congress).

The telegraph system made the modern weather service possible. It influenced the outcome of the American Civil War. It transformed Wall Street through use of the telegraphic stock ticker and gave rise to the modern financial system driven by rapid transmission of information. It made newspaper wire services possible and led to creation of a national news service. The descendants of the telegraph relay gave rise to the Programmable Logic Controllers (PLCs) used in today's automated factories.

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3 Invention through emulation

The most important consequence of these and other inventions is that they served as incubators for a series of subsequent inventions. The telegraph served as an incubator that enabled a generation of inventors to learn about electricity and magnetism. Bell's attempts to create a 'harmonic telegraph' contributed to development of the telephone. Edison was a telegrapher and earned his first fortune by inventing a stock ticker that recorded telegraphically communicated stock prices. This invention enabled him to establish Edison Laboratories, popularly known as the Idea Factory.

These inventions collectively led to a significant increase in economic prosperity. The nineteenth century was an era of technological change unprecedented before or since (Hindle 1983; Smil 2005). At the beginning of the nineteenth century the United States was a rural, agricultural nation with living conditions that did not differ greatly from medieval times. By the beginning of the twentieth century, the nation led the world in manufacturing productivity.

Brooke Hindle, past director of the National Museum of American History, refers to this period as an 'American Industrial Revolution'. During his time as director of the museum, Hindle studied the factors underlying this transformation. He summarized his conclusions in a book, *Invention and Emulation*. His goals were to understand the inventiveness and creativity at the centre of mechanical technology:

> This is an essay on mechanical technology. The thinking presented here is a product of several years of study and contemplation of the ways of technology, sharpened by my experiences in the National Museum of American History, of the Smithsonian Institution. A debt more difficult to specify is to the pervasive sense within the museum of the inner nature of the technological enterprise and of material culture. This emphasizes the conviction that surviving artifacts, drawings, and photographs provide an entry to the understanding of technology not attainable from the written record alone.
>
> (Hindle 1983:3)

Hindle ascribed much of the mechanical creativity and inventiveness that occurred to a commonplace familiarity with machines. He notes that Americans – particularly farmers – lived daily with machines: the seed drill, the turpentine and whiskey stills, the gristmills and sawmills, and the clock. Mechanics and artisans worked daily with gears and gear trains, cams, ratchets, escapements, bearings, cylinders, pistons, valves, and cocks – the basic elements of which the new machinery was constructed.

Beyond this pervasive familiarity with mechanical machinery, Hindle ascribed much of the creative impetus to the method by which mechanical knowledge was transferred from one generation to the next. A machine tools apprentice in the nineteenth century learned by copying the best models. A journeyman was expected to use a master work as a starting point of reference and extend it, improving upon the original. This type of emulation led to new inventions like the telegraph, which remixed and combined a number of elements to create new innovations. Morse's collaborator, Alfred Vail, was a machinist, and drew upon this background as he refined Morse's prototype to make it commercially viable.

Hindle believed that a special mode of thinking was required to foster expertise with machines. He cited Benjamin Franklin's recommendation that educators should provide

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drawings of ‘ancient and modern machines’ as models to be copied. Hindle found Franklin’s prescription to be ‘a marvelously precise description of the process of emulation’ (Hindle 1983:13). Hindle concluded that emulation was so central to the process of invention during the American Industrial Revolution that he incorporated the term into the title of his book, *Invention and Emulation*.

4 Making in the electronic age

This emulation method of invention ushered in a new era at the beginning of the twentieth century. Just as the electromechanical age began with Volta’s invention of the electrical battery in 1800, the electronic age began with invention of the vacuum tube amplifier in the early twentieth century. Bell Telephone purchased the patent rights to the vacuum tube invented by Lee de Forest and used it to create an amplifier that made coast-to-coast phone calls possible. In 1915 Alexander Graham Bell made the first transcontinental call from New York City to his former assistant, Thomas Watson, in San Francisco.

The electronic amplifier made commercial radio possible. Station KDKA in Pittsburg made the first commercial radio broadcast in 1920. The amplifier also made the electrically amplified speaker possible and gave rise to the electrical guitar. Two engineers, Kellogg and Rice, invented the dynamic loudspeaker used in most speakers today. The Radio Corporation of America (RCA) began selling Radiola radio receivers with electronically amplified loudspeakers in 1926. By the end of the decade, nearly half of all Americans owned radios (US Census Bureau 1933:414).

The ubiquity of radios expanded the number of citizens who explored invention through emulation. The careers of many scientists of that era were sparked by construction of a crystal radio set. Sherry Turkle, a social scientist who teaches at MIT, found this theme to be common among scientists and engineers: ‘From my very first days at the Massachusetts Institute of Technology, I found a passion for objects everywhere. I had students and colleagues who spoke about how they were drawn into science by the mesmerizing power of a crystal radio …’ (Turkle 2008).

5 Making in the computer age

The vacuum tube, and its successor, the transistor, made the electronic computer feasible and led to invention of solid state integrated circuits. The computer served as a new object for inventors to emulate. Turkle wrote,

> I came to MIT in the early days of the computer culture. My students were beginning to talk about how they identified with their computers, how they experienced these machines as extensions of themselves. For some, computers were ‘objects to think with’ for thinking about larger questions, questions about determinism and free will, mind and mechanism.
>
> (Turkle 2008)

Seymour Papert, a student of Piaget and co-founder of the MIT Artificial Intelligence Laboratory, developed an educational philosophy for use of computers as educational objects grounded in the tradition of invention through emulation. Papert believed that rather than using computers solely for test taking and drills, students should use them as a tool for

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design and creativity (Papert 1991). Papert's work was influenced by his experience as a child on a farm in South Africa, where he employed gears as a mechanism for processing mathematical concepts such as ratios. Based on this experience, he advocated for provision of 'objects to think with'. This thinking led to an extension of Piaget's constructivist theory of learning, which Papert termed 'constructionism'.

Papert anticipated today's makerspaces, noting that

> in the real world computers are used in many different ways. Some are programmed to fly airplanes with electromechanical actuators and to read altitudes and airspeeds with electronic sensing devices. Some computers are programmed to control lathes and milling machines in industrial plants.
>
> (Papert and Solomon 1971:3)

In light of such applications, Papert asked,

> Why then should computers in schools be confined to computing the sum of the squares of the first twenty odd numbers and similar so-called 'problem-solving' uses? Why not use them to produce some action? … Concepts from computational sciences have deeply affected thinking in biology, psychology and even the philosophy of mathematics. Machines from its engineering branches are changing our way of life. How strange, then, that 'computers in education' should so often reduce to 'using bright new objects to teach the same old stuff in thinly disguised versions of the same old way'.
>
> (Papert and Solomon 1971:1–2)

In 1966 Seymour Papert developed a computing language for children known as Logo. The philosophy underlying Logo was influenced by a list processing language (LISP) used in the Artificial Intelligence Laboratory that Papert directed. In today's world of maker culture, the ability to interact with the outside world (i.e., the Internet of Things) is desirable for encouragement of children's ability to invent and create, working with hardware and software. Logo incorporated these capabilities from the beginning, initially through development of the floor turtle (designed by Wally Feurzieg) and later through the widely used Mindstorms robotics system. Today Mitch Resnick, the LEGO Papert Professor of Learning Research at MIT, directs the development of Scratch, a successor to Logo. In the tradition of Logo, Scratch supports rich interactions with the physical world and physical objects.

6 Making today

Microcomputers made possible machines like 3D printers that can make physical objects. In the twentieth century computers were used to create digital copies of physical objects like books, music, x-rays, and blueprints. In the twenty-first century converting digital patterns in the computer back into physical objects is now possible. This most recent wave of innovations is once again transforming society and the way that humans interact with the world. The maker movement made possible by the current age of making also has extended the pedagogy of invention through emulation.

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Many of these fabrication technologies had previously been used in industry. However, advances in microcomputing and digital electronics have made them available at a fraction of their previous costs.

Another MIT professor, Neil Gershenfeld, foresaw the potential for personal fabrication. In 2001, at the beginning of the new century, he secured a National Science Foundation grant to establish the Center for Bits and Atoms. He subsequently published a book, *The Coming Revolution on Your Desktop – from Personal Computers to Personal Fabrication* (Gershenfeld 2005), predicting that in the future the equivalent of a desktop factory would enable consumers to design and produce anything in their homes. To put this idea to the test, he also developed a course at MIT titled 'How to Make Almost Anything'. In the course, MIT students learned to use digital fabrication tools such as 3D printers, laser cutters, and milling machines that could be employed for personal manufacturing. Fabrication Laboratories (Fab Labs) for the general public followed. One of the first was established in Providence, Rhode Island, in 2009. Since that time hundreds of Fab Labs have been established around the world that serve as communities of making in a digital world (Blikstein and Krannich 2013)

In the past 15 years, digital fabrication technologies have become accessible to a broader audience, including K–12 school teachers. Schools are integrating digital fabrication technologies into educational programmes as these tools become more affordable (PCAST 2010). Many educational technologists and educational associations advocate use of digital fabrication technologies in K–12 schools (Bell et al. 2010; Berry et al. 2010; Blikstein and Krannich 2013; Iversen, Smith, Blikstein, Katterfeldt, and Read 2015; Slykhuis et al. 2015; Smith 2013). Digital fabrication may expand possibilities for engaging students in creative, problem-solving, and critical thinking environments and afford students the ability to create, invent, and engage in the engineering design process (Bull, Standish, Johnson, and Haj-Hariri 2016). Thus, digital fabrication and Fab Labs have provided a new approach to integrating engineering design into K–12 curriculum. This area of educational research is still relatively new, but several studies report positive learning outcomes from students using digital fabrication (Corum and Garofalo 2018; Smith 2013; Tillman, Zhang, An, Boren, and Paez-Paez 2015).

Fab Labs in their original form were less expensive than a multi-million dollar factory, but still exceeded the resources of any one individual. The cost of a fully equipped Fab Lab could exceed $100,000 or more.

Dale Daugherty founded *Make Magazine* in 2005 and organized the first Maker Faire shortly afterward. Maker Faires provided a venue where inventors and makers could gather and share their creations with the world. Makerspaces provided sites in communities in which like-minded individuals could gather and invent year round. Makerspaces today can be found in public libraries, schools, museums, universities, non-profits, and community-owned spaces. Fab Labs as conceived by Neil Gershenfeld (2005) provided a level of standardization across fabrication labs. In contrast, makerspaces have proven to be more varied. Some include the higher end fabrication equipment, such as digital milling machines found in Fab Labs, while others consist of collections of more accessible equipment that could be used by almost anyone after a quick orientation.

The educational research community has begun to explore the role of makerspaces in K–12 schools. A recent literature review summarizes characteristics of school makerspaces and their current status (Papavlasopoulou, Giannakos, and Jaccheri 2017). First, learning goals that have been associated with makerspaces include development of students' computational

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thinking capabilities, computer programming skills, science content knowledge, mathematical content knowledge, engineering skills, and technological content knowledge. Second, makerspace technologies widely used in school settings include the Arduino programmable microcontroller, the Raspberry Pi computing platform, and the Scratch programming language. Third, at the present time, experimental research has not yet been conducted that demonstrates the efficacy of makerspaces in achieving the learning goals described above. Some initial exploratory studies provide evidence of promise, but the authors report that further scholarly work will be required before any reliable conclusions can be drawn.

Sheridan et al. (2014) assert that makerspaces have the potential to transform learning through integration of multiple disciplines. They explain, ‘This blending of traditional and digital skills, arts and engineering creates a learning environment in which there are multiple entry points to participation and leads to innovative combinations, juxtapositions, and uses of disciplinary knowledge’ (p. 526). Evidence supports the notion that makerspaces can provide a fun and engaging space for education under the right conditions (Blackley et al. 2018; Chu, Angello, Saenz, and Quek 2017; Chu, Quek, Bhangaonkar, Ging, and Sridharamurthy 2015).

Several authors provide guidance for supporting and facilitating use of school makerspaces (Brown 2015; Chu et al. 2017; Smith 2013). Brown concludes that makerspaces require some form of curriculum to be productive, ‘What seems to be missing at the moment is a curriculum that organizes the 3D printing activities in a manner that helps teachers and instructors design and facilitate structured learning events’ (p. 24). Smith (2013; 2015) recommends use of a semi-structured framework within makerspaces to ensure meaningful learning experiences. Chu et al. (2017) offers a more specific framework. This three-phase model includes exposure, engagement and experimentation, and evaluation and extension. The authors state that ‘a *makerspace approach* sees makers situated in groups of peers and mentored by pre-service teachers to produce a designated artifact’ (p. 19). Their pedagogy includes organizing into groups, mentoring students, constraining the number of resources available through kits, and making explicit connections to science, mathematics, engineering, and technology. While there are differing perspectives on effective pedagogical strategies, there is general agreement that provision of some scaffolding is more productive than random tinkering.

7 Conclusion

From one perspective, the maker movement in its current form dates to the establishment of *Make Magazine* in 2005. However, from another perspective, the maker movement builds upon a tradition that can be traced to the founding of America. Roger Sherman, a curator at the National Museum of American History, commented, ‘There was a feeling that this was a new country. Our governmental system was a new one. We were open to new ideas. The process of innovation and invention was encouraged and supported’. He noted that one goal of the maker movement and contemporary making is to foster a similar sense of creativity, imagination, and innovation (Hoffman and Bull 2016). In a similar vein, Hindle asked,

> Incredibly, the newborn United States was more successful than any other nation in assuming the attitude of mind required and in transferring any desired technology. How could that possibly be? How could a thinly dispersed people, 90 percent of them engaged in agricultural pursuits, a people whose economy was still colonial and commercial, take over the most advanced technology in the world? More amazing still,

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> how could the custodians of an empty continent, far distant from the economic power centers of Europe and from its busy workshops and rising factories, move on to take leadership in one line after another of mechanization and innovation?
>
> (Hindle 1983:3)

Hindle's conclusion was that enthusiasm for mechanization and invention was incorporated at an early stage into the vision of the nation. Based on his research as director of the National Museum of American History, Hindle believed that 'invention through emulation' was the chief pedagogical mechanism responsible for this success:

> Emulation represented an effort to equal or surpass the work of others; it was more a striving for quality and recognition than a marketplace competition and seems to have emerged from the manner of instruction and improvement in the arts and crafts. There the striving was frequently spurred by contests and by constant measurement against the best models. The apprentice learned by copying the work of the master, but the journeyman had to go beyond copying. In order to become a master himself, he had to produce his own 'masterpiece'.
>
> (Hindle 1983:13)

In some disciplines this strategy is still employed as a central pedagogical method. For example, in the machine tools programme at Midlands Technical College in Columbia, SC, students still spend the first year recapitulating all of the industrial methods of the nineteenth and twentieth centuries prior to learning digital manufacturing technologies in the second year of the programme.

Viewed from a historical perspective, what are the implications for maker education today? There are several conclusions that can be drawn.

1. The origins of making began with the industrial revolution. Making did not begin with 3D printing. It was an integral element of the United States from its inception. Making can be viewed as the story of a nation told through the lens of invention.

2. Invention through emulation was a key pedagogical method historically. Invention through emulation has been an important aspect of maker education historically. Much of the success that the country experienced during its transformation from an agricultural nation to an industrial economy can be attributed to this method.

3. Invention through emulation is relevant today. Invention through emulation is relevant to maker education today. It is important to provide students with models that they can emulate. Through invention and emulation, students can learn history, science, mathematics, and engineering and can be inspired to be creative.

4. Historic inventions offer useful models for emulation. Historical inventions offer an effective source of models for acquisition of foundational maker knowledge. The simplicity and transparency of these original inventions make them accessible to novices.

5. Each discipline has a structure. Viewed from a broad perspective, making is not simply disconnected bits and pieces of technology. There is a framework that encompasses each discipline: mechanical engineering, electrical engineering, and computer science. In maker education, scaffolding is crucial for students' success. The framework developed over time for each discipline provides a guide to maker technologies and the associated fields of engineering represented.

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Contemporary research suggests that scaffolding and structure over an extended period of time is required for makerspaces to be effective learning environments. The historical record agrees. If Hindle was correct that invention through emulation is a cornerstone that led to establishment of the nation in its current form, then from a historical perspective it follows that this same method may be an effective strategy for encouraging and fostering the work of young makers today. The goal is not for makers today simply to replicate prior work but to encourage the creation of their own inventions in the same manner as makers historically.

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