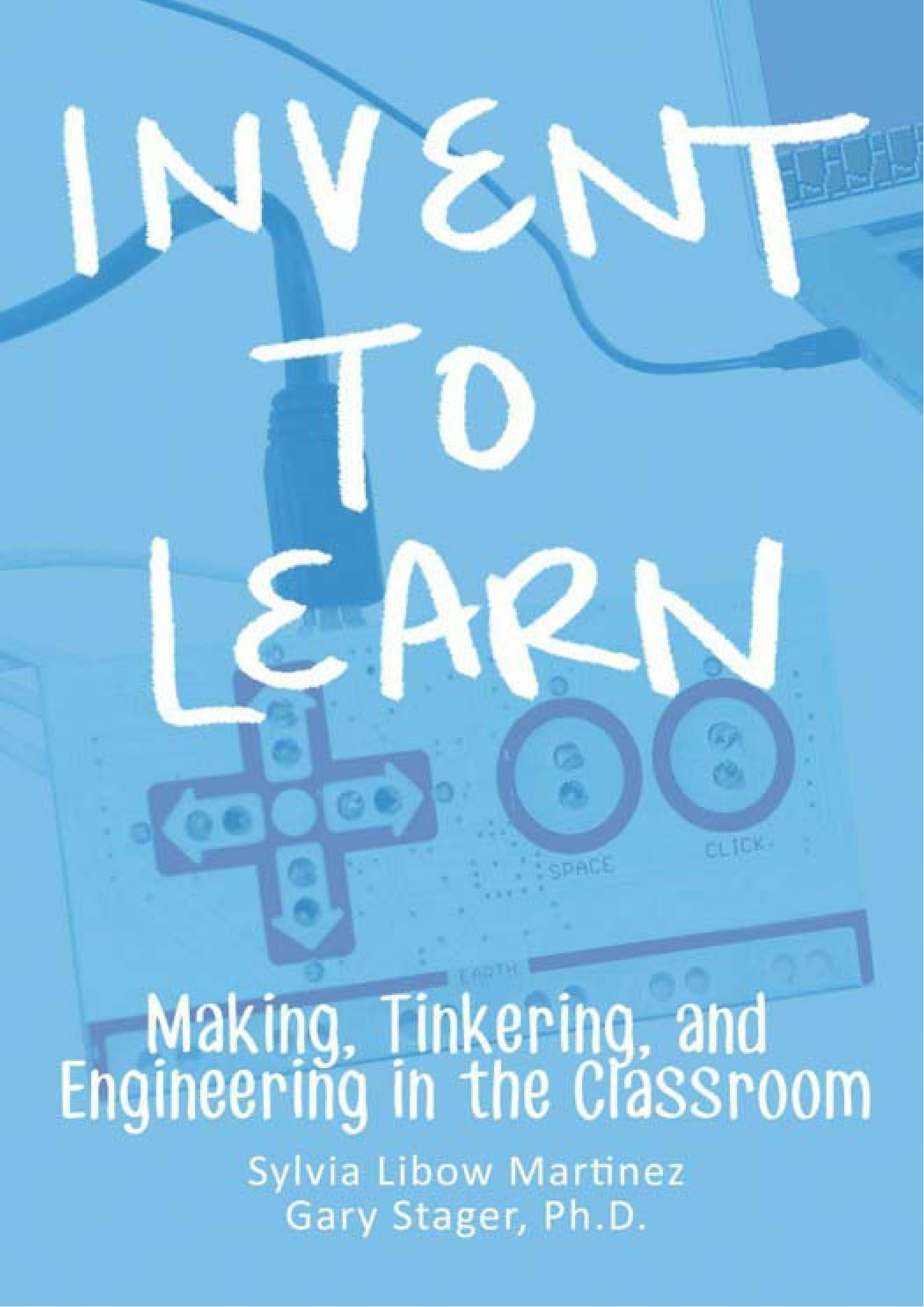

INVENT TO LEARN

Making, Tinkering, and Engineering in the Classroom

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Chapter 1 – An Insanely Brief and Incomplete History of Making

I do not think there is any thrill that can go through the human heart like that felt by the inventor as he sees some creation of the brain unfolding to success. Such emotions make a man forget food, sleep, friends, love, everything.
— Nikola Tesla

Making things and then making those things better is at the core of humanity. Ever since early man started his first fire or clubbed his first seal, humans have been tinkerers. Farming, designing weapons for hunting, and building shelter were early forms of engineering. Tinkering was a way of controlling the environment and a vehicle for intellectual development. Throughout history, art and science, craft and engineering, analytic thinking, and personal expression have coexisted in communities, industry, culture, commerce, academia, and in the heads of creative people. Throughout history there has been an acceptance of the intuitive sense that peak learning results from direct experience.

If you are an educator who creates opportunities for making and inventing in your school or classroom, know that you are in good company. These are indeed exciting times to learn by doing. There have never been more fascinating or powerful materials available for personal expression and knowledge construction. Who knows? The maker movement may represent our best hope for reigniting progressive education. As you embark on a personal adventure to bring making, tinkering, and engineering into your classroom, know that you are not alone. You stand on the shoulders of giants and there is a rapidly growing community of makers available to help.

A KINDA SORTA HISTORY LESSON

Leonardo da Vinci (1452–1519) was the quintessential Renaissance man. He was a creative inventor, artist, sculptor, architect, engineer, musician, mathematician, and anatomist who dabbled brilliantly in a dozen other fields. Ushering in the Scientific Renaissance, da Vinci used his powers of observation, rather than the prevailing medieval practice of using the Bible and classical Greek writings, as the basis for science. Many of his inventions were ahead of their time and some of his important scientific discoveries were lost to history, but one can confidently say that Leonardo da Vinci was a maker – perhaps the greatest maker of all time.

Unsung Heroes

Philosopher Jean-Jacques Rousseau (1712–1778) made waves when he published *Emîle, or On Education,* a book that celebrated the natural abilities of the child and the importance of allowing children to develop freely in nature. He believed that individuals were blessed with innate goodness and competence and has been called “the inventor of childhood.” At a time when education for children was characterized by memorization and beatings, Rousseau’s philosophy was extraordinary.

Johann Pestalozzi (1746–1827) was inspired by Rousseau and believed that learning was natural and resulted from a balance between heart, head, and hand. Pestalozzi believed in nurturing children, and put this theory into action by rescuing orphans abandoned in the aftermath of Napoleon's armies. Like Piaget more than a century later, Pestalozzi thought that learning resulted from the learner's first-hand experiences and self-activity. Pestalozzi's theories also portend Piagetian stage development by recognizing that learning occurs from the concrete to abstract, known to unknown, and simple to the complex. He favored things and deeds over words. He believed that there was much to learn from nature, play, and observing the world.

Pestalozzi was a huge influence on one of his students, Friedrich Froebel (1782–1852), who built upon Pestalozzi's ideas in the design of kindergarten, the first formalized educational institution for young children. In naming his system of schooling "a children's garden," Froebel gave great consideration to what children could learn by interacting with the natural world. Planting seeds, observing their growth, caring for the resulting plants, and harvesting the resulting crops provided a rich laboratory for a young child. Froebel also created provocative objects that could be used in multiple ways through play and experimentation called "gifts," followed by more guided material-based activities called "occupations." You might think of the Froebel gifts as the first educational toys. In fact, the Milton Bradley Company was one of the largest manufacturers of Froebel's gifts as kindergartens spread across the globe and parents wanted their children to learn from the Froebel gifts at home. Froebel's aesthetic sense also inspired generations of architects and artists, including Frank Lloyd Wright, whose own son attended an early kindergarten, and perhaps not too coincidentally, invented "Lincoln Logs" as an adult.

Italian medical doctor, Maria Montessori (1870–1952), embraced many of Froebel's ideas, notably the deliberate use of materials for learning specific concepts in creating her approach to educating poor preschoolers.

PIAGET

Swiss psychologist and epistemologist Jean Piaget (1896–1980) formalized and confirmed many of the ideas of John Dewey, Montessori, Froebel, and Pestalozzi with his theories of constructivism and stage development. Piaget advanced the idea of genetic epistemology in *To Understand is to Invent*, which advocated the "…use of active methods which give broad scope to the spontaneous research of the child or adolescent and requires that every new truth to be learned, be rediscovered, or at least reconstructed by the student and not simply imported to him." (Piaget, 1976) This theory of learning came to be known as *constructivism*. The learner constructs knowledge inside their head based on experience. Knowledge does not result from receipt of information transmitted by someone else without the learner undergoing an internal process of sense making.

Piaget also called for interdisciplinary learning and made a plea for schools to create polymaths. Such educational experiences by teachers would aid students in the construction of meaning.

> What is needed at both the university and secondary level are teachers who indeed know their subject but who approach it from a constantly interdisciplinary point of

> view – i.e., knowing how to give general significance to the structures they use and to reintegrate them into overall systems embracing the other disciplines with the spirit of epistemology to be able to make their students constantly aware of the relations between their special province and the sciences as a whole. Such men are rare today. (Piaget, 1976)

Learning by making, tinkering, and engineering is consistent with Piagetian theories. "Students who are thus reputedly poor in mathematics show an entirely different attitude when the problem comes from a concrete situation and is related to other interests." (Piaget, 1976) In the following passage, he rejects the popular notion that some or most students are no good at math, but the larger point refers to learning in any discipline.

> Every normal student is capable of good mathematical reasoning if attention is directed to activities of his interest, and if by this method the emotional inhibitions that too often give him a feeling of inferiority in lessons in this area are removed. In most mathematical lessons the whole difference lies in the fact that the student is asked to accept from outside an already entirely organized intellectual discipline which he may or may not understand. (Piaget, 1976)

Piaget reminds teachers not to present students with pre-organized vocabulary and concepts, but rather provide students with a learning environment grounded in action.

> Abstraction is only a sort of trickery and deflection of the mind if it doesn't constitute the crowning stage of a series of previously concrete actions. The real cause of failure in formal education is therefore essentially the fact that one begins with language instead of beginning with real and material action. (Piaget, 1976)

Piaget's colleague, Seymour Papert, would later frame the educational establishment's favoring of the former approach over the latter as a battle between instructionism and constructionism.

John Dewey and the Progressive Era

John Dewey (1859–1952) rejected the mechanistic ideals and highly regimented factory schooling that resulted from the industrial revolution. He viewed the process of education as continuous growth across a lifetime, resulting from personal motivation and resistant to external forces or what would later become known as behaviorism. Dewey wrote extensively about the critical role community, democracy, and experience play in shaping the educational process. He advocated for students to be actively engaged in authentic interdisciplinary projects connected to the real world. In Dewey's view, education should prepare children to solve problems in a methodical fashion resulting from careful observation and previous experience. Dewey said that schools should be concerned with the intellectual, social, physical, and emotional needs of each person while subordinating the standards of adults to the needs of children. The iterative design methodology that characterizes modern making may be found in the words of John Dewey.

> It is part of the educator's responsibility to see equally to two things: First, that the problem grows out of the conditions of the experience being had in the present, and that it is within the range of the capacity of students; and, secondly, that it is such

> that it arouses in the learner an active quest for information and for production of new ideas. The new facts and new ideas thus obtained become the ground for further experiences in which new problems are presented. The process is a continuous spiral. (Dewey, 1938)

Amateur crafts, like sewing, weaving, carpentry, woodworking – even farming, hunting, and fishing – have been necessities and avocations for millennia. Hobbyists have always embraced art, music, and dance. Since the 17 century, "gentleman amateurs" dabbled in science and made important contributions to knowledge of the natural world. Amateur science among the general populace is more recent, but no less robust. *Popular Science* began publishing in 1872, *Popular Mechanics* in 1902, and *Boy's Life* in 1911. Authors like Jules Verne and H.G. Wells published popular books of science fiction around this time. These publications, among others, brought the innovations of the industrial revolution to amateurs. Progressive era exploration of the world, oceans, heavens, and machinery generated great interest in home-based tinkering, experimentation, and invention. Dewey not only wrote articles for *Popular Science* magazine, but was also heavily influenced by the relatively new evolutionary theories of Charles Darwin. As in today's maker movement, connections between ideas, people, and disciplines are complex and abundant.

Today, computers, microcontrollers, sophisticated software, and the Internet are allowing amateurs to collaborate with each other and professional scientists in significant ways. Norm Stanley began a speech to the First Annual Citizen Science Conference in June 2002 by saying:

> Science, as we know it today, would not be what it is without the contributions of amateurs. In fact I think it not too brash a statement to assert that basic science and what we know as the scientific method was largely developed by amateurs. From alchemists in search of the philosophers' stone to monks investigating nature in pea gardens to the gentlemen amateurs of the 17th century on, they were developing the experimental/observational/hypothetical approach of modern science. True, with the passage of time the role of the amateur, working independently, has diminished as experimental techniques became highly sophisticated and string and sealing wax no longer sufficed for doing cutting-edge science. Despite vicissitudes, amateur or recreational science remains healthy today, as witness the present gathering. (Stanley, 2002)

Amateur astronomy has been popular since the invention of the telescope. Chemistry sets captured the imagination of children for 200 years from the late 18 century until the late 20century when ninnies suddenly determined that fire, chemistry, and fun were just too dangerous for young people.

One of the most popular purveyors of chemistry sets during the 20 century was A.C. Gilbert (1891–1984), a medical doctor, Olympic medalist, inventor, and master salesman. Gilbert pioneered the modern construction kit when he invented Erector Sets in 1911. The Erector Set was set apart from other kits by the inclusion of a motor that allowed the construction of moving models. Aggressive marketing to boys and a sales pitch to adults promised that playing with Erector Sets would reduce the "problems with boys" plaguing society. This claim proved so convincing that Gilbert convinced the United States government to withdraw their plans to ban toy production during World War I. This earned Gilbert the nickname, “the man who saved Christmas.” (Watson, 2002)

In addition to Erector Sets, Gilbert published his own magazines touting the virtues of his products, which included other building materials, chemistry sets, microscopes, magic tricks and model trains. Gilbert was even a hundred years ahead of the current badge craze being hyped as today’s educational revolution.

> Gilbert touted the Erector as a “real engineering” toy and created the “Gilbert Institute of Erector Engineering.” A boy could “win degrees, honors, a handsome diploma, valuable prizes and a salary through free membership” in the Institute. Diplomas for First Degree, Second Degree and Third Degree Engineers were awarded with a gold “E.M.E” fraternity pin for the third degree Master Engineer. Gilbert even offered to write a reference for the winner to any business house stating this accomplishment. (Hill, n.d.)

Tinker Toys, Meccano, Lincoln Logs, LEGO, and other construction kits would follow Erector. All of these toys could be used to construct fanciful models of things, but not the things themselves. The game-changing “toys” available to today’s girls and boys are capable of making real things.

All Aboard!

In the late 1950s, The Tech Modern Railroad Club (TMRC) at the Massachusetts Institute of Technology was filled with makers who, according to journalist Steven Levy, became self-proclaimed “hackers.” These hackers not only spurred generations of remarkable innovation in computer hardware and software development, but were an early maker community.

Members of the TMRC fell into two groups based on interest and aptitude. The “knife-and-paintbrush” contingent loved trains. They read railroading magazines, arranged club rail trips, and worked on improving the TMRC’s large train layout. The Signals and Power (S&P) subcommittee was largely concerned with what went on underneath the train layout, in other words, how the trains operated. Each group reflected a particular style and shared a meticulous attention to detail. Yet they represented two synchronistic systems – the art and science of model railroading. These distinct groups reflect common preferences and learning styles found in classrooms today.

The increasing complexity of track switching and the simultaneous control of several trains required the S&P committee to find novel ways to repurpose telephone equipment. The late-night obsessions of the TMRC also coincided with a chance to use MIT’s gigantic computer systems during the hours they were idle. Learning to control the computer and get it to do things it was not intended to do enhanced the model railroading and vice versa. The “Midnight Requisitioning Committee” would scrounge for electronics parts that could be used to “hack” the large computer or their toy trains. Quickly the boundaries between the two pursuits blurred.

Hack had long been a term of art at MIT used to describe the elaborate pranks for which the institute’s students had gained infamy. Now those who achieved feats of control over a system, “…imbued with innovation, style, and technical virtuosity,” were prestigiously referred to as hacks and their perpetrators, hackers. (Levy, 2010)

In 1959, MIT borrowed a TX-0 computer that no longer required programming by handing over punch cards to the computer room operator. Terminals with a keyboard, called

Flexowriters, could be typed on and generate a paper tape that could be fed directly into the TX-0. Instead of waiting hours for the results of your computer program to be handed to you, the result could be experienced immediately. This immediacy made it possible for the first time to modify a program while sitting at the computer. (Levy, 2010) This new level of interactivity raised the roof on "personal" computing and sent the passion of the TMRC members skyrocketing through the stratosphere. The hackers would do anything necessary to learn more and increase access to "the machine." It would not be long before their programs made music, played games, and performed computational tricks never before imagined on what were enormous multimillion dollar accounting machines.

> Hackers believe that essential lessons can be learned about the systems – about the world – from taking things apart, seeing how they work, and using this knowledge to create new and even more interesting things. (Levy, 2010)

Outsiders in their own institution, the hackers formed a computer culture unique to its surroundings, complete with its own values, heroes, legends, and goals. Quickly a "Hacker Ethic" emerged that challenged seemingly arbitrary rules and artificially scarce computing resources. It included the following principles:

- "Access to computers – and anything that might teach you something about the way the world works – should be unlimited and total. Always yield to the Hands-On Imperative!
- Mistrust Authority – Promote Decentralization.
- Hackers should be judged by their hacking, not bogus criteria such as degrees, age, race, or position.
- You can create art and beauty on a computer.
- Computers can change your life for the better." (Levy, 2010)

Such values are noble, creative and egalitarian – nothing like the way in which the media portrays hackers. Fifty years later, the motto of the maker movement, "If you can't open it, you don't own it," and the emphasis on learning by doing resonates with the Hacker Ethic dating back to MIT a half century ago.

SEYMOUR PAPERT: FATHER OF THE MAKER MOVEMENT

Mathematician, computer scientist, artificial intelligence pioneer, psychologist, educator, inventor, epistemologist, activist, and author Seymour Papert was born in 1928 in South Africa. His father was an entomologist who frequently moved the family around South Africa. Papert tells the story of playing with automobile gears beginning at the age of two and attributes much of his thinking about thinking to those experiences. His tale is one of learning through tinkering.

> I became adept at turning wheels in my head and at making chains of cause and effect: "This one turns this way so that must turn that way so..." I found particular pleasure in such systems as the differential gear, which does not follow a simple linear chain of causality since the motion in the transmission shaft can be distributed in many different ways to the two wheels depending on what resistance they encounter. I remember quite vividly my excitement at discovering that a system

> could be lawful and completely comprehensible without being rigidly deterministic… Anything is easy if you can assimilate it to your collection of models. If you can't, anything can be painfully difficult. What an individual can learn, and how he learns it, depends on what models he has available. (Papert, 1980)

Papert takes great pains to declare that one particular experience, no matter how rich, might not have the same effect on other learners. To Papert, "the most powerful idea of all is the idea of powerful ideas." (Papert, 1980) His life's work has been creating tools, theories, and coercion-free learning environments that inspire children to construct powerful ideas through firsthand experience.

> A modern-day Montessori might propose, if convinced by my story, to create a gear set for children. Thus every child might have the experience I had. But to hope for this would be to miss the essence of the story. I fell in love with the gears. This is something that cannot be reduced to purely "cognitive" terms. Something very personal happened, and one cannot assume that it would be repeated for other children in exactly the same form. My thesis could be summarized as: What the gears cannot do the computer might. (Papert, 1980)

When Piaget sought a greater understanding of how children construct mathematical knowledge in the late 1950s, he hired a mathematician, Papert. Years earlier, Papert had to sneak out of South Africa, where he was labeled as a dissident prohibited from international travel due to his anti-Apartheid activities. From his days as a child, the insanity of Apartheid caused Papert to become fascinated by the nature of thinking, an interest that suited his collaboration with Piaget, whose life's work was as an epistemologist

Following several years of work with Jean Piaget, Papert was invited by Marvin Minsky to join the MIT faculty. It was during his first day at MIT that Papert began tinkering with computers, and over the next few years he and Minsky collaborated on pioneering work in the field of artificial intelligence. In 1968, Papert's interest in learning, mathematics, and computing led to the invention of the Logo programming language along with Cynthia Solomon, Wally Feurzig, and others. At a time when few adults had ever seen a computer, Papert sought to make them for children. He not only advocated that children should use computers, but that they should make things with them via programming. Logo was developed as a language for making things and for learning powerful ideas while making things. To this day, versions of Logo, including Scratch, remain the most popular programming environments for children.

> The computer is the Proteus of machines. Its essence is its universality, its power to simulate. Because it can take on a thousand forms and can serve a thousand functions, it can appeal to a thousand tastes. (Papert, 1980)

It did not take long for Papert to turn his sights on the troublesome nature of schooling. In *Teaching Children Thinking*, a paper originally written in 1968, Seymour Papert makes an audacious claim:

> The phrase, "technology and education" usually means inventing new gadgets to teach the same old stuff in a thinly disguised version of the same old way. Moreover, if the gadgets are computers, the same old teaching becomes incredibly more expensive and biased towards its dumbest parts, namely the kind of rote learning in which measurable results can be obtained by treating the children like

> pigeons in a Skinner box. (Papert, 1972a)

His words seem revolutionary for 1968, but sadly remain as a perceptive critique of schooling today. The maker movement represents a bright spot in a world that too often uses computers biased towards the least empowering aspects of formal education.

Four decades ago, Papert questioned why computers were being used by schools in such unimaginative ways. His words might be used today to question why the institutionalized "educational technology" community appears so ignorant of the affordances created by the maker movement.

> 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? There is no better reason than the intellectual timidity of the computers-in-education community, which seems remarkably reluctant to use the computers for any purpose that fails to look very much like something that has been taught in schools for the past centuries. (Papert & Solomon, 1971)

In a stunning 1971 paper, *Twenty Things to Do with a Computer*, Seymour Papert and Logo co-creator Cynthia Solomon proposed educative computer-based projects for kids. They included composing music, controlling puppets, programming, movie making, mathematical modeling, and a host of other projects that schools should aspire to more than 40 years later. Papert and Solomon also made the case for 1:1 computing and stressed the three game changers discussed later in this book.

> The school computer should have a large number of output ports to allow the computer to switch lights on and off, start tape recorders, actuate slide projectors and start and stop all manner of little machines. There should also be input ports to allow signals to be sent to the computer.
>
> In our image of a school computation laboratory, an important role is played by numerous "controller ports" which allow any student to plug any device into the computer… The laboratory will have a supply of motors, solenoids, relays, sense devices of various kids, etc. Using them, the students will be able to invent and build an endless variety of cybernetic systems. (Papert & Solomon, 1971)

Computer game design was viewed as a way of learning powerful mathematical concepts, even in 1970. Papert's 1972 paper, *Teaching Children to be Mathematicians vs. Teaching About Mathematics,* (Papert, 1972b) continued the progressive tradition of advocating for children to have real experiences rather than be taught subjects. Throughout his career, Papert viewed the activities and values now embraced by the maker movement as consistent with progressive ideals of education.

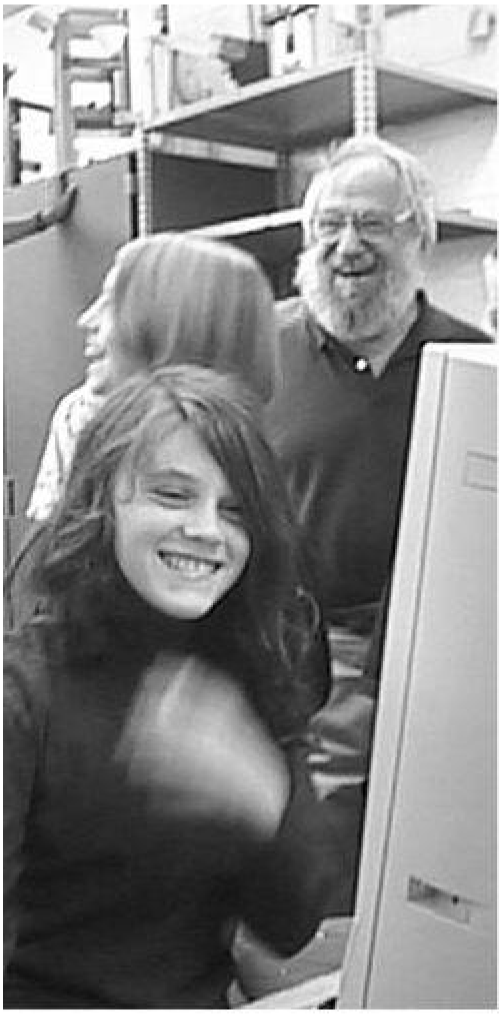
> It is 100 years since John Dewey began arguing for the kind of change that would move schools away from authoritarian classrooms with abstract notions to environments in which learning is achieved through experimentation, practice and exposure to the real world. I, for one, believe the computer makes Dewey's vision far more accessible epistemologically. It also makes it politically more likely to happen, for where Dewey had nothing but philosophical arguments, the present day movement for change has an army of agents. The ultimate pressure for the change

> will be child power. (Papert, 1996)

In conversation over the years, Papert frequently argued that the technology of a previous era allowed the ideas of Dewey to take root in humanities subjects, but had little impact on allowing children to experience powerful ideas of mathematics and science. As a result, the teaching of science and math remained just as impersonal and didactic as it had for centuries, ultimately reintroducing coercion into otherwise progressive schools. Papert attributed much of that failure to what he called “idea aversion,” (Papert, 2000) and to a lesser extent, the absence of computational technology that would afford opportunities for learners to have direct firsthand experience with what are now commonly referred to as the STEM subjects.

> I think that the great thinkers about education – the Deweys and the Piagets and the Montessoris and the Vygotskys – they all see the same fault in our education system. I think the differences between them are absolutely minor compared with the situation of sticking with the system as it is. But although they had the right idea, like Leonardo da Vinci and his airplane, they didn’t have the infrastructure to be able to implement it. So, are we going to continue using the new technology to implement what was only there because there wasn’t the technology? (Papert, 2006)

Despite school’s resistance to change, Papert had great confidence in teachers’ ability to increase their personal fluency so that “…powerful advanced ideas can become elementary without losing their power.” (Papert, 1998)



Seymour Papert delights in a kid's computer programming

Papert developed the theory of constructionism and wrote three profound books about learning with computers, *Mindstorms, The Children's Machine,* and *The Connected Family*. Each book was intended for a different audience: academics, educators, and parents respectively. The message of learning by actively constructing knowledge through the act of making something shareable is consistent across all three books, whether he was talking about programming, robotics, or media making.

In addition to his work as an educator and evangelist for educational computing, school reform, and constructionism, Papert spent nearly 40 years creating new "objects to think with" and computationally rich materials. He and his colleagues developed countless dialects of Logo, the first programmable robotics construction kits with LEGO. Papert was a major force behind 1:1 computing in Maine and the creation of the One Laptop Per Child initiative creating a low-cost laptop for children in the developing world.

During Papert's last institutional research project he created an alternative learning environment entirely designed to support constructionism inside a prison for teens. It was during this project that constructionism was expanded to include a wider variety of non-computational materials, often in concert with computers to create hand-crafted classical guitars, ultra-light airplanes, films, telescopes, photography, animal habitats, publications, and more. The continuum of low- and high-tech materials allowed for learning through the construction of shareable artifacts not normally associated with school.

PROGRESSIVE EDUCATION STAGES A COMEBACK

For a brief period during the 1960s and '70s, progressive education reemerged in the United States and other industrialized economies. The Sputnik crisis spurred investment in hands-on science programs, mathematics manipulatives were in vogue, and school arts programs bloomed. Society's attention to matters of civil rights, democracy, war, and peace led to attempts at less coercive schooling and a greater emphasis on individuality within a democratic context. Summerhill and The British Infant School movement inspired open education, classroom centers, and project-based learning across the globe. Herbert Kohl, Jonathan Kozol, John Holt, Ivan Illich, Jerome Bruner, Lillian Weber, and Vito Perrone enjoyed the greatest influence on classroom practice since John Dewey.

As in the previous period of progressivism, efforts were made to change curricular content, combine subjects, reconfigure class organization and age segregation, create authentic learning experiences connected to the world outside of the school, reject behaviorism, and resist external assessment.

Howard Gardner's 1983 introduction of the theory of multiple intelligences recognized what good teachers had known for ages: intelligence comes in many forms and humans learn differently. Hands-on learning through the sort of rich projects advocated by makers offers flexible opportunities for students to learn in their personal style or styles. Classroom projects that welcome various problem-solving strategies provide fertile ground for the expression of multiple intelligences. (Gardner, 1983) (Shearer, 2009)

The Reggio Emilia Approach

In the early 1960s, the Italian city of Reggio Emilia decided to rebuild its community still ravaged by World War II by investing heavily in the education of its very youngest citizens. The system of municipal infant and toddler centers and preschools created by Loris Malaguzzi and his colleagues were built upon the philosophies of Dewey, Piaget, Vygotsky and others who placed the child at the center of the learning process. The Reggio Emilia Approach is highly sensitive to local culture and community, and respects the rights, needs, talent, and questions of children. Educational activities emerge from the interests of children, and the environment is "the third teacher," after the parent and teacher. A wide variety of materials are used for knowledge construction and to express understanding through the "hundred languages of children." In the classrooms, atelier (studio), and community of Reggio Emilia you will find the tiniest toddlers using real tools in pursuit of authentic problem solving. The primary role of the teacher in a Reggio-inspired setting is as a researcher charged with understanding the thinking of each child and preparing the environment for that child's natural intellectual growth. There may be no more consistent model of learning through making, tinkering, and engineering than found in the work of our Italian colleagues. Carlina Rinaldi, the president of Reggio Children, offers a glimpse into the Reggio Approach's thoughtful reinvention of school:

> The word, 'project' evokes the idea of a dynamic process, an itinerary. It is sensitive to the rhythms of communication and incorporates the significance and time of children's investigation and research. The duration of a project can be short, medium or long, continuous or discontinuous, with pauses, suspensions and restarts.

> The term, 'curriculum' (along with the corresponding terms 'curriculum planning' or 'lesson planning') is unsuitable for representing the complex and multiple strategies that are necessary for sustaining children's knowledge-building processes. (Rinaldi, 2006)

We are blessed with 50 years' worth of wisdom, research, and documentation from the Reggio Emilia Approach. This may represent the world's most mature model of sustained constructionism and progressive education. The lessons of Reggio Emilia have profound implications for every level of education, not just preschool. While the subtlety, beauty, and wisdom of the approach could and should be studied for a lifetime, we suggest that readers of this book pursue the Reggio Emilia resources listed later in this text.

MAKING MAKES A COMEBACK

Computer Hobbyists

The invention of the microcomputer led to an explosion of interest in hobbyist computing from the mid-1970s through the mid-1980s. It was these hobbyists and their social clubs, such as Silicon Valley's Homebrew Computer Club, that led to the invention and popularity of personal computing. Steve Jobs and Steve Wozniak, founders of Apple Computer, were members of the Homebrew Computer Club. Other clubs existed around the world for the purpose of sharing knowledge, parts, and circuits with other enthusiasts. Periodicals from that period, including: *Byte, Creative Computing, Compute, Dr. Dobb's Journal* (still in print), and *Logo Exchange* spread the joy of computer programming to hundreds of thousands of hobbyists around the world. The hobbyists planted the seeds for the explosive growth of Silicon Valley.

The Capital of Making

In 1985, Nicholas Negroponte, along with Jerome Wiesner, Seymour Papert, and Marvin Minsky, created the MIT Media Lab. Negroponte imagined a convergence of technology, multimedia communication, and design. In the original proposal for the Lab, Negroponte drew a sketch of how the computer, broadcast and motion picture, and publishing industries had an area of intersection in a Venn diagram representing their narrow common interests. A second sketch showed how those three industries would soon be indistinguishable from one another, a prediction that quickly became reality. Negroponte said that at the Media Lab, "…new theories of signals, symbols and systems will emerge from the merger of engineering, social science and the arts." (Brand, 1988) The Media Lab embraced polymaths and became a grand center for tinkering across the lines of traditional disciplines. The Media Lab reinvented university research and development while inspiring competitors around the world to create their own media labs.

The Media Lab's playful spirit of learning by doing made it the birthplace of many of the ideas and materials embraced by the modern maker movement. The MIT Media Lab has a special knack for taking complex, expensive, and foreboding technology and making it accessible to laypeople, even children. Programmable LEGO robotics sets, Scratch, and MaKey MaKey are but three of the Lab's inventions popular in classrooms and kids' bedrooms around the world. One Media Lab invention is the invention of other labs for invention – the FabLab. Graduates of the Media Lab are inventing new products and companies that are fueling the maker movement. The maker family tree has a deep set of roots at MIT and another in Silicon Valley.

Fab

In his 2005 book, *Fab: The Coming Revolution on Your Desktop – from Personal Computers to Personal Fabrication*, MIT Professor Neil Gershenfeld described the next technological revolution as one in which users would make the tools they need to solve their own problems. Gershenfield predicted that for the cost of your school's first computer, you would soon have a Fabrication Lab or fab lab – a mini high-tech factory – capable of making things designed on a computer. In the near future, such factories may fit on your desktop. Gershenfeld tells readers that Seymour Papert was the first to blur "…the distinction between toys and tools for invention, culminating in the integration of play and work in the technology for personal fabrication." Gershenfeld also mentions how Papert always believed that children should invent, as well as use, technology. The longstanding obstacles to children constructing their own computers was a "thorn in our flesh," said Papert. (Gershenfeld, 2007)

Gershenfeld's MIT course, "How to Make Almost Anything," became enormously popular among students across a wide spectrum of academic disciplines. When art, science, engineering, computer science, and crafting meet whimsy, a new era of personal empowerment emerges. You could design a bicycle in the shape of Matisse's *Blue Nude Number Two* and then email it to your sister in Australia. ("Scientific American Frontiers: You Can Make it On Your Own," 2003) Gershenfeld was surprised to learn that students with "skills best suited for arts and crafts" were able to create complete functioning systems. He was also surprised to see that these inventions were not only highly personal, but executed by students working alone, when in a corporate context such products would be the work of teams. Personal ownership of an idea can lead learners to exceed all expectations. (See "Stager's Hypothesis" later in this book.)

In *Fab*, Gershenfeld describes a collaborative culture that emerged during classes in his own "FabLab." His depiction is not dissimilar from what we find in K–12 maker classrooms. In just a few sentences, Gershenfeld addresses collaboration, design, teaching, learning, and curriculum in makerspaces.

> The final surprise was how these students learned to do what they did: the class turned out to be something of an intellectual pyramid scheme. Just as a typical working engineer would not have the design and manufacturing skills to personally produce one of these projects, no single curriculum or teacher could cover the needs of such a heterogeneous group of people and machines. Instead, the learning process was driven by the demand for, rather than supply of, knowledge. Once students mastered a new capability, such as waterjet cutting or microcontroller programming, they had a near-evangelical interest in showing others how to use it. As students needed new skills for their projects they would learn them from their peers and then in turn pass them on. Along the way, they would leave behind extensive tutorial material that they assembled as they worked. This phase might last a month or so, after which they were so busy using the tools that they couldn't be bothered to document anything, but by then others had taken their place. This process can be thought of as a "just-in-time" educational model, teaching on demand, rather than the more traditional "just-in-case" model that covers a

> curriculum fixed in advance in the hopes that it will include something that will later be useful.

Students will learn, they will invent, they will teach, they will collaborate, and they will share knowledge when it best suits their needs, interests, and style. The maker culture gets smarter when it buzzes with activity. Paradoxically, it may be an absence of the external pressures of schooling – assessment, curriculum, lecture, and demands for note-taking that leads to the greatest achievement.

Gershenfeld's work teaches us that everyday objects can have intelligent features built in and fab labs may be created in developing communities. Such fab labs allow locals to meet specific needs by shaping low-cost digital technology. Different communities have unique requirements that now could be satisfied by technology they invent and fabricate for themselves.

Moi?

You may be asking, "All that tinkering and high-tech wizardry may be fine for MIT professors and students, but what does it have to do with my school?"

The most obvious implication is for the ways computers are used in school. Making and personal fabrication are a clear departure from the status quo. Instead of training another generation to perfect secretarial skills via word processor instruction or drilling basic skills, computers can and will be used to shape the world of the student. Policy shifts are already afoot in the U.K. where in 2012, the government announced that they were scrapping the national ICT curriculum because, in the words of the British Secretary of State, "It is harmful and dull." (Barnett, 2012) The government proposes to replace the emphasis on information literacy and productivity applications – things quickly learned naturally – with computer science.

Although much work needs to be done to define what K–12 computer science means and how teacher preparation needs to change, such curricular shifts will likely spread worldwide.

Many educators, beginning in the 1960s with Seymour Papert, Alan Kay, and Cynthia Solomon, recognized that computers could be powerful knowledge incubators where formal ideas could be concretized through computer programming and debugging. Educators who were focused on outcomes or who were unfamiliar with the sorts of sophisticated thinking their students were experiencing were quick to question the value of programming in school. Others dismissed it as "only for some children." Today, the personal fabrication and physical computing revolution allows the very same intellectual experiences to result in tangible products more likely to be admired by adults. Just as Logo programming gained respect when it teamed with LEGO bricks to propel robotics into the classroom 25 years ago, new construction toolkits breathe life into exciting project-based learning.

Schools should seize any opportunity for students to learn and express their knowledge in new and exciting ways. Classrooms need to reflect the world their kids live in and leverage new tools to amplify human capacity.

Fab Labs Go to School

As early as 2003, Mike Eisenberg of the University of Colorado Boulder began to publish articles and papers about the potential for new computationally enhanced materials and personal fabrication to support constructivist learning in K–12 schools.

> Why should educational technologists be interested in these devices? Briefly, the answer is that these new technologies can vastly extend and reinvigorate the best traditions of student-driven design and construction. (Eisenberg & Buechley, 2008)

In 2008, Paulo Blikstein of Stanford University started working with K–12 schools to create digital fabrication labs called the FabLab@Schools project. As part of FabLab@School, he built the first fabrication lab in a School of Education in the U.S. and began teaching the first course (outside of the MIT Media Lab) for graduate students and teachers to design new projects for K–12 education using a fab lab or makerspace. Blikstein says,

> I realized that digital fabrication had the potential to be the ultimate construction kit, a disruptive place in schools where students could safely make, build, and share their creations. I designed those spaces to be inviting and gender-neutral, in order to attract both the high-end engineering types, but also students who just wanted to try a project with technology, or enhance something that they were already doing with digital fabrication. (Blikstein, 2013)

In 2011, Blikstein hosted the first FabLab@School conference at Stanford, drawing K–12 educators from around the world who then became the leaders of many “first ever” makerspaces in their own schools.

TODAY

June 2012 saw two national magazines, *Wired* and *Make*, feature cover stories on summer technology projects for kids and parents. Newsstands across the U.S. alerted laypeople to the tinkering revolution and new opportunities for intergenerational learning. Articles about personal fabrication could be found in specialized magazines and newspapers for the past few years, but now children are being placed in the center of the revolution.

Since Gershenfeld published *Fab*, the availability and mainstream popularity of personal fabrication has skyrocketed. Three forces have made his predictions accessible and affordable: physical computing with Arduino and other microcontrollers, low-cost 3D printers and cutters, and programming. Each of these innovations has profound implications for classroom practice and school reform. A growing library of accessible print materials, countless websites, social networks where makers share ideas, and Maker Faires around the world support these game changers.

The quarterly magazine *Make* is the Gutenberg Bible of the burgeoning “maker” community. Dale Dougherty (*Make’s* founder and publisher) and Mark Frauenfelder (editor-in-chief) first noticed the growing energy and participation at the intersection of craft, engineering, computer science, and whimsy. Think of *Make* as a combination of *Popular Mechanics* meets computer science and fabrication. Its pages delight readers with projects featuring programming, robotics, amateur space exploration, backyard ballistics, cigar box guitars, and old VCRs turned into automatic cat feeders. The magazine celebrates and inspires ingenuity, innovation, and creativity, as should your school. No school library is complete without a subscription.

When soldering, prototyping, programming, and inventing return to the lives of children, remarkable projects result. Arduino is a low-cost (approx. $25–$30) open source programmable micro-controller that allows you to build robots and "intelligent" machines of varying sophistication out of broken toys, electronic parts, and increasingly sophisticated sensors. Arduino continuously adds functionality, as its price remains constant or even goes down. Arduino is the standard robotics controller used by hobbyists and industry alike. It belongs in the toolbox of school children.

Arduino variants like the "Lilypad" expand the student toolbox to e-textiles – computers you can wear. The Lilypad Arduino includes buttons, sensors, lights, and sound elements that become part of garments and "soft sculptures" when circuits are sewn with conductive thread. Now your school T-shirt can feature a dancing light pattern, or directional signals may illuminate the back of a kid's sweatshirt while they ride their bike. Code libraries for Arduino are freely shared online, allowing learners to download a program similar to their needs and then modifying it to their personal specifications. Reading and "remixing" another person's computer program is a sophisticated form of literacy students need today.

3D printers and precision cutters are breaking the $1,000 barrier. These desktop machines allow a user to design an object on a computer with increasingly simple software and then print or cut the actual object. Kids view the ability to print their own toys, tools, and models with a sort of blasé attitude described by Alan Kay's adage that, "Technology is anything that wasn't there when you were born."

The Spring 2012 Bay Area Maker Faire, organized by *Make* magazine, attracted over 100,000 children and adults who came together for a weekend of tinkering, crafting, inventing, showing-off, learning, and making together. In addition to the fall New York City and spring San Mateo fairs, local communities around the world are encouraged to make their own Mini-Maker Faires. Maker Faires, like the hackerspaces, fab labs, and tech shops popping up all over the world, are remarkably rich learning environments where novices learn alongside experts. These communal learning spaces have access to equipment that an individual or school may not yet be able to own. Schools would be wise to create similar learning environments. Already, a growing number of schools have their own fab labs or are hosting their own Maker Days.

There is a growing body of literature to inspire a teacher or parent interested in making with children. In addition to *Make* magazine, there is *Howtoons*, *50 Dangerous Things (You Should Let Your Children Do)*, *Made by Hand: Searching for Meaning in a Throwaway World*, *Unbored*, and the *Geek Dad/Geek Mom* series' of books. Books such as *62 Projects to Make with a Dead Computer (and Other Discarded Electronics)* combine this generation's passion for environmentalism with electronics, science, engineering, and arts and crafts. Websites like *Makezine* and *Instructables* feature countless project ideas and tutorials. "Sylvia's Super Awesome Maker Show" is a series of Web videos by an elementary school student who shares her love and knowledge of making and fabrication with learners of all ages. There are millions of Scratch projects designed and programmed by children and shared online. Online communities are the new guilds, where access to expertise, mentors, and affinity groups are a mouse click away.

One might even consider the popularity of reality television as a manifestation of our desire to make things and have authentic learning experiences with experts. If you want to learn to build a shed, dance the Paso Doblé, bake a soufflé, or be a drunken loser, there is an expert you can apprentice with, if only through a screen. The primal human need to be creative is bursting out in thousands of ways across the culture. At the same time, too many schools are stifling individuality and personal expression.

The maker community is bringing time-honored forms of craft and handiwork back into the lives of children. You may knit an intelligent scarf, recycle a pile of junk into an underwater robot, or build a remarkable cardboard arcade, like Caine, a 9-year-old kid in Los Angeles, did. In 1988, Seymour Papert wrote about the computer as material with which you can make things and other powerful ideas. Nearly a decade earlier, Papert described the computer as mud pie. At last, this vision of computing being as handy as a pencil or paper mâché is becoming a reality.

The maker ethos values learning through direct experience and the intellectual and social benefits that accrue from creating something shareable. Not only are there a plethora of exciting high-tech materials available for childhood knowledge construction, but the growing popularity of making things has led to many "low-tech" innovations to spice up hands-on learning. Makedo is a series of reusable connectors and hinges for turning cardboard packaging materials into elaborate structures and play objects. Sugru is a space-age material that allows you to make a shape or stick two objects together as you might do with clay, but within 24 hours it air sets as rubber. Best of all, the plethora of new materials lets children build actual things, not just models of things.

Kids have always made things – tree houses, skateboards, soapbox cars, doll houses, forts, and igloos. They have learned socially through collaborative play and construction by putting on shows, experimenting with roles, and performing magic tricks. The major difference today is computation. As Brian Silverman says, "A little bit of programming goes a long way. It is like a jet assist" in solving problems or building exciting things. (Silverman & Kay, 2013)

Empowerment

In the late 1960s, Seymour Papert began asking, "Does the computer program the child or the child program the computer?" The growing list of creative technology accessible to children represents the closest realization of the goal of empowering the human in this cybernetic relationship. Beyond fluency, personal fabrication, programming, and physical computing shift the emphasis from passive consumption to active creation and invention.

Personal fabrication is more than inventing alarm clocks that run away and hide when you press the snooze button; it is revolutionizing every field dependent on design. Gone are the days of tedious calculation, speculation, sketches, or cardboard models. Now you can make the actual thing you are trying to test. Best of all, gone are the days of helplessness, dependency, and consumption. Making lets you take control of your life, be more active, and be responsible for your own learning.

A Rainbow in the Clouds

Kid makers possess a skill set and self-efficacy that will serve them well in school, as long as they are engaged in interesting activities worthy of their capacity for intensity. Despite the swirling politics and external pressures on schools, the maker movement may offer teachers cause for optimism. The stuff of making is super cool and gives those teachers so inclined another chance to reanimate progressive education. If your administrator likes to buy shiny new things, then there are plenty of things to buy that actually amplify the potential of children.

Silicon Valley billionaires are endorsing the non-profit, Code.org, which advocates for kids to learn computer programming. The Association for Computing Machinery is advocating for computer science to be a curriculum staple from kindergarten to twelfth grade and the brand new Next Generation Science Standards by the National Academies of Science makes explicit calls for meaningful assessment, interdisciplinary knowledge, inquiry, and engineering.

> In the future, science assessments will not assess students' understanding of core ideas separately from their abilities to use the practices of science and engineering. They will be assessed together, showing that students not only "know" science concepts; but also that they can use their understanding to investigate the natural world through the practices of science inquiry, or solve meaningful problems through the practices of engineering design. ("Next Generation Science Standards," 2013)

None of the experiences advocated in this book or the materials that enable them are inconsistent with the imaginations of children or with the types of learning experiences society has long valued. Making is a stance that puts the learner at the center of the educational process and creates opportunities that students may never have encountered themselves. Makers are confident, competent, curious citizens in a new world of possibility.

This book is intended to be aspirational. Like Papert, we believe in kid power and know that teachers hold the key to liberating the learner. The values, tools, and activities of the maker movement enrich and accelerate that process.