To appear in: **Blikstein, P. (2013). Digital Fabrication and 'Making' in Education: The Democratization of Invention. In J. Walter-Herrmann & C. Büching (Eds.),** ***FabLabs: Of Machines, Makers and Inventors.*** **Bielefeld: Transcript Publishers.**

Digital Fabrication and 'Making' in Education: The Democratization of Invention

Paulo Blikstein (paulob@stanford.edu)

Assistant Professor, Graduate School of Education, Stanford University

1. The Democratization of Invention

1.1 Digital Fabrication: Logo for Atoms

A quote often attributed to Seymour Papert states that if a teacher from the 16th century would time-travel to the present, he or she would have no problem entering a school and teaching a class. Historical documents from that time show that he could not be more accurate. The Treviso Arithmetic, from 1478, teaches students how to do multiplication and division using 'exactly' the same paper-based algorithms we use today. Several descriptions of 16th century schools and their curricula look strikingly similar to today's mathematics classes, such as a well-known school in Florence run by Master Francesco Ghaligai in 1519 which had a "…heavy emphasis on memorization and procedures" and a curriculum comprised of units on "multiplication, practice in the use of algorithms, division, fractions, and the rule of three" (Swetz & Smith, 1987).

A thriving 15th century Venice saw the appearance of the Treviso Arithmetic in a time of great need for a new type of mathematics. The Indo-Arabic system was proving itself to be faster and more practical than the abacus, and soon Venetians realized that it was also easier to learn. All the pieces were falling into place: a new set of societal needs, new technologies, new ways of using knowledge, and the recognition that a task previously monopolized by experts was potentially accessible to the masses ('restructurations,' Wilensky & Papert, 2010).

Every few decades or centuries, a new set of skills and intellectual activities become crucial for work, conviviality, and citizenship—often democratizing tasks and skills previously only accessible to experts. Fast forward to the early seventies: computer programming was becoming one of those new activities (Papert, 1991). But computers in those years were large, expensive, awkward machines, and the idea of using them as a medium for personal expression and learning was inconceivable—in the same way that the abacus establishment derided the Treviso techniques. The educational establishment put down the idea of programming as a fundamental pedagogical goal: it was too difficult for children to learn, and unlikely to improve learning in math and science.

However, since the seventies, researchers have been hard at work creating tools to make programming easier to learn. Programming tools such as Scratch (Resnick et al., 2009) and NetLogo (Wilensky, 1999) have achieved unprecedented popularity and made coding accessible to millions of students and teachers. The world caught up with the idea that not only computational media could be a vehicle for powerful ideas in mathematics, engineering, and science—an important new kind of literacy—but it was an approachable activity in schools.

Digital fabrication and 'making' could be a new and major chapter in this process of bringing powerful ideas, literacies, and expressive tools to children. Today, the range of accepted disciplinary knowledge has expanded to include not only programming, but also engineering and design (Astrachan, Hambrusch, Peckham, & Settle, 2009; Yasar & Landau, 2003). In addition, there are calls everywhere for educational approaches that foster creativity and inventiveness.

The analogy with the development of Logo is clear: simultaneously, digital fabrication technology became better and more accessible, and the intellectual activities enabled by the new technology became more valued and important. What Logo did for geometry and programming – bringing complex mathematics within the reach of schoolchildren – fabrication labs can do for design and engineering. Digital fabrication is Logo for atoms.

In this chapter, I will first briefly review the history of engineering education to show the rise and fall then rise again of the making and building as curricular foci. I then discuss the theoretical underpinnings of project-based, student-centered, constructionist learning, showing that much of what digital fabrication labs can enact was already predicted and advocated in the theories and writings of John Dewey, Seymour Papert, and Paulo Freire. The following section approaches the educational benefits of digital fabrication and how it could be a unique tool in the hands of progressive educators. In the final part of the chapter I present not only four prototypical episodes that exemplify the advantages and perils of FabLabs in schools, but also some guidelines for the design of learning environments incorporating these types of technologies.

1.2 Technological Knowledge: From Skills to Literacy

In 1999, the National Research Council issued a landmark report stating that technology was changing too fast for the 'skill-based' approach to be effective and instead called for a 'fluency' approach. They suggested technological education to include the development of adaptive, foundational skills in technology and computation, in particular "[intellectual] capabilities [to] empower people to manipulate the medium to their advantage and to handle unintended and unexpected problems when they arise" (National Research Council, 1999).

The same concerns were echoed in the later report, "Technically Speaking: Why All Americans Need to Know More About Technology," which confirmed the demise of the "computer skills" approach and recognized that decades had been lost teaching dated skills to millions of students. It called for a move from ‘computer skills’ towards ‘computational fluency’ or ‘literacy’ (diSessa, 2000) and broadening technological literacy to include basic engineering knowledge, and the nature and limitations of the engineering design process (National Research Council, 2002).

The report also introduced an important distinction, which resonated with the concerns of educational theorists such as Seymour Papert and Andrea diSessa: the recognition of a difference between ‘technological literacy’ (a general set of skills and intellectual dispositions for all citizens) and ‘technical competence’ (in-depth knowledge that professional engineers and scientists need to know to perform their work). The distinction identifies fluency with technology as no longer a vocational skill or a way to train future science, technology, engineering and mathematics (STEM) workers, but knowledge valuable for every citizen. Since the publication of the 2002 “Technically Speaking” report, several other developments in research, technology and policy have further supported this need: the acceleration of technological innovation, further automation of routine jobs (Levy & Murnane, 2004), ubiquity of open-source hardware and software, and the development of low-cost digital fabrication tools (Gershenfeld, 2007). These national reports and societal developments are noteworthy because they signal the mainstream acceptance of Papert’s once controversial vision. Taken together, the once dismissed idea of children programming computers was not only embraced, but developed into a much larger vision of students participating in sophisticated activities that were previously restricted to specialized professionals, such as robotics, environmental sensing, data analysis, advanced science, and engineering design.

1.3 The Demise of the Shop Class and the Rise of the Digital Fabrication Lab

Notwithstanding the natural content overlaps amongst science and engineering disciplines, they are fundamentally different. While a scientific investigation is typically concerned with finding the one law to explain many natural phenomena, a technological investigation typically finds many solutions for the same problem (Atkin, 1990). A typical school science lab is designed for rigorous, disciplined, and scripted experiences in which students are guided towards the re-discovery of a unifying principle. School science labs are architected to facilitate and optimize such a process—but would those spaces be appropriate for engineering and design?

Despite engineers’ dependence on basic scientific knowledge to do their work, their epistemology even precedes science; humans have been creating tools and altering their environment much before the inception of the scientific method. In fact, engineers’ ‘ethos’ as inventors and tinkerers, in both K-12 and college education, survived up to the fifties and sixties, after which there was a significant push towards analysis and mathematics, and away from traditional “shop work,” (Grinter, 1955), which was overwhelmingly present in curricula during the first half of the 20th century (Dym, 1999). The ‘professional engineer’ of the first half of the 20th century was replaced by the ‘scientific engineer’ of the second half (Tryggvason & Apelian, 2006), mostly motivated by the end of the abundant Apollo-era funding—less expensive theoretical classes prevailed over engineering labs or design work (Feisel & Rosa, 2005). Over time, this resulted in the removal of the engineering design experience from not only college curriculum, but also from K-12 education. Shop class became “vocational education” for those who supposedly could not handle 'serious' math or science.

Two independent processes started to reverse this trend. First, around the eighties, faculty and employers started to feel that the design-deprived engineering graduates were not well prepared do to any real engineering design work, which had started to become more important (Sheppard & Jenison, 1997). Second, in the early 2000s, prototyping equipment, such as laser cutters and 3D printers, dramatically dropped in price, and Open Source hardware further popularized these technologies. Suddenly, corporate product development moved towards a "studio" model in which groups of engineers and industrial designers could create prototypes in days instead of months: consequently the nature of product engineering was radically transformed. Gershenfeld and colleagues (Gershenfeld, 2007; Mikhak et al., 2002) at MIT were the first to package such equipment in a standardized low-cost lab and deploy it in both community centers and universities around the globe: the FabLab was born. Gershenfeld's network of FabLabs quickly spread in all five continents, and spurred a vibrant global movement. Four years later, in 2005, the MAKE Magazine, a monthly publication dedicated to DIY enthusiasts and tinkerers was created, and soon after the Maker Faire, a large science and engineering fair in California, launched with great success.

2. Dewey, Papert, and Freire: Theoretical Pillars for Digital Fabrication and 'Making' in Education

Toward the end of the 2000s, researchers and educators started to consider the use of digital fabrication in education. In 2008 Stanford University launched the FabLab@School project, and started building FabLabs in K-12 schools around the world. In 2009 the MC2STEM High School in Ohio (USA) opened its first digital fabrication lab. In 2011 the Maker Media launched the MakerSpace project with DARPA funding. In 2011 and 2012 alone countless museums, schools, community centers, and libraries announced plans to build digital fabrication and 'making' facilities—it became mainstream. Despite this resurgence of fabrication labs and "making" in formal and informal settings, the ideas behind this movement are at least a century old. Digital fabrication and "making" are based on three theoretical and pedagogical pillars: experiential education, constructionism, and critical pedagogy.

Since Rousseau's invention of childhood (Rousseau, 1961), progressive education theorists have been questioning the prevalent assumptions of their time regarding the project of education, and have been prescribing more experiential, student-centered approaches. The idea that education should be more experiential and connected to real-world objects is originally attributed to John Dewey but also to many other scholars and innovators (Dewey, 1902; Freudenthal, 1973; Fröbel & Hailmann, 1901; Montessori, 1964, 1965; von Glasersfeld, 1984).

Critical pedagogy scholars (Freire, 1974; Illich, 1970), Freire in particular, criticized school's "banking education" approach and the decontextualization of curriculum. Freire introduced the idea of culturally meaningful curriculum construction, in which designers get inspiration from the local culture toward creating "generative themes" with members of these cultures. Freire was also an advocate for education as a form of empowerment, and argued that learners should go from the "consciousness of the real" to the "consciousness of the possible" as they perceive the "viable new alternatives" beyond "limiting-situations" (Freire, 1974). Therefore, students' projects should be deeply connected with meaningful problems, either at a personal or community level, and designing solutions to those problems would become both educational and empowering (Blikstein, 2008; Cavallo, 2000).

Seymour Papert shares Paulo Freire's enthusiasm for unleashing the latent learning potential of students by providing environments in which their passions and interests thrive. A mathematician by training, who then worked with Jean Piaget for many years, Papert pioneered the use of digital technologies in education. Yet Papert's reasons for advocating the use of computers in education are far from technocentric (Papert, 1987)—some of his motivations are very similar to Freire's. Papert's Constructionism builds upon Piaget's Constructivism and claims that the construction of knowledge happens remarkably well when students build, make, and publicly share objects. His theory is at the very core of what "making" and digital fabrication mean for education, and underlie what many enthusiasts of the "maker movement" propose—even if many are not aware of it. Papert's words describe precisely the relationship between making and learning: "Construction that takes place 'in the head' often happens especially felicitously when it is supported by construction of a more public sort "in the world" – a sand castle or a cake, a Lego house or a corporation, a computer program, a poem, or a theory of the universe. Part of what I mean by 'in the world' is that the product can be shown, discussed, examined, probed, and admired [...] It attaches special importance to the role of constructions in the world as a support for those in the head, thereby becoming less of a purely mentalist doctrine." (Papert, 1980, p. 142).

Papert advocates technology in schools not as a way to optimize traditional education, but rather as an emancipatory tool that puts the most powerful construction materials in the hands of children—again, another idea that inspired the resurgence of the 'maker' sensibilities. These protean machines which would enable students to design, engineer, and construct would cater to many forms of working, expressing, and building. This chameleonesque adaptivity, which is embedded in technology, permits the acknowledgement and embracing of different learning styles and epistemologies, engendering a convivial environment in which students can concretize their ideas and projects with intense personal engagement. In a typical Constructionist learning environment, there is rarely a fixed curriculum. Children use technology to build projects, and teachers act as facilitators of the process.

The Logo programming language was the first attempt in education to demonstrate that the computer is not only an information and communication device, but also an expressive tool for construction and self-expression. In the early nineties, Papert, Mitchel Resnick and Fred Martin extended the powerful ideas of Logo to the physical world by making robotics accessible to children through the Lego Mindstorms kit and the Cricket (Martin, 1994; Martin & Resnick, 1993), and together with collaborators did extensive work on robotics and 'making' workshops using microcontrollers and sensors (Resnick, Berg, & Eisenberg, 2000). Sipitakiat and Blikstein extended this work to developing countries and low-income communities by working with low-cost hardware as well as repurposed materials (Blikstein, 2008; Sipitakiat, 2000; Sipitakiat, Blikstein, & Cavallo, 2002, 2004). More recently, new developments are putting cutting-edge hardware and software in the hands of children to conduct advanced scientific explorations (Blikstein, 2010; Blikstein, Fuhrmann, Greene, & Salehi, 2012), create interactive textiles (Buechley, 2006; Buechley & Eisenberg, 2008; Buechley, Eisenberg, Catchen, & Crockett, 2008), build electronic jewelry (Perner-Wilson, Buechley, & Satomi, 2011; Sylvan, 2005), design participatory simulations and games (Wilensky & Stroup, 1999), program videogames (Millner & Resnick, 2005), design virtual robotic systems (Berland, 2008; Berland & Wilensky, 2006), create sophisticated 3D worlds and games through programming (Cooper, Dann, & Pausch, 2000), build new types of cybernetic creatures (Raffle, Parkes, & Ishii, 2004; Schweikardt & Gross, 2006) and explore environmental science and geographical information systems (Edelson, 2000).

These toolkits and technologies prepared the ground for the popularity of the 'maker' movement and digital fabrication. They showed that it was possible to engage children in complex uses of technology, that those same children could actively construct with technology rather than just consume technological products. They revealed how the ideas and intellectual passions of children could be powerful and generative, and that the perceived difficulties of many of those tasks were due to deficient design rather than learners' cognitive deficiencies. Rather than random developments, these new technologies, materials, and toolkits were deeply influenced by the theoretical constructs put forth by Dewey, Papert, and Freire, around constructive uses of technology, culturally-aware education, experiential learning, and interest-driven curricula.

3. Why Do We Need Digital Fabrication Labs in Schools?

The plethora of constructionist toolkits created and deployed in the 2000s, with improved and friendlier designs, coincided with the development of the FabLab concept by Neil Gershelfeld at MIT and the popularity of the Maker Faire—the perfect storm was in place. At that time, after having conducted tens of robotics and 'invention' workshops in schools, I was disappointed by the fact that students did not have a place to continue and deepen their projects—and projects would die after the workshop or the final expo. Schools manifest how they value a particular activity by building a space for it. If sports are important, schools build a gym and a basketball court. If music education is in demand, schools set up music rooms. Only then can likeminded students gather together, hang out, do projects, talk about them, and create a productive subculture in schools. Unfortunately, I realized that there was no such space for engineering and invention. Even when schools had robotics labs, they were highly gender-biased and not inviting for most students. Robotics labs and science labs were not disruptive spaces anymore. Therefore in 2008 I started to work with schools around the world to establish digital fabrication labs—the FabLab@School project was born.

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.

Both programming and educational robotics enhanced an existing activity with a powerful new expressive medium. Logo programming reinvented differential geometry by adding computer algorithms to children's everyday bodily movements – forward, turn right, turn left. Robotics kits added computational behaviors to familiar materials – crafts, Legos, wheels – and behaviors – "light up if dark," "bounce off the walls," "follow the dark line." Each one of them made possible for new forms of expressiveness by adding a carefully designed technological layer to everyday, familiar materials and practices.

Digital fabrication is a new chapter in this story. Especially in low-income schools, students would often tell me that they used to 'make' and build things with their parents and friends, and often had jobs in garages, construction companies, or carpentry shops. However that experience was disconnected from their school life, since they did not see a link between the intellectual work in the classroom and the manual labor in the wood shop. Because of bias inherit within the educational system their own forms of engineering and tinkering, stripped down of any form of mathematical of scientific content, were looked down upon by society and by themselves.

Enhancing existing practices and expertise. One of the first and most striking results of the initial workshops in digital fabrication is that students reported have gained a new appreciation for the 'manual' labor they used to do, and also for the occupation of their parents. In the lab, students had to first design their creations on a computer, often after several types of measurements and calculations. However, they were still constructing, building, and using their hands, but all the work was permeated with two socially valued practices: computation and mathematics. Again, the familiar practices of building and making were augmented with computational tools, which generated not only more refined and sophisticated projects, but also empowerment and increased self-esteem. This proved to be a crucial Freirean principle for the design of digital fabrication experiences. By building onto students' familiar practices and adding a layer of expressive technologies, a digital fabrication lab, which merges computation, tinkering and engineering, has the potential to augment rather than replace familiar and powerful practices that students already possess, therefore they can recognize their own previous expertise in what they accomplish in the lab, rather than acquiring a new identity altogether.

Accelerate invention and design cycles. An additional benefit of digital fabrication is that it accelerates the processes of ideation and invention. It eliminates manual dexterity as the "middleman" in transforming an idea into a product, so students can focus their attention on improving the design rather than taking care of mundane issues with the materials—and many more cycles of redesign are possible in the same time interval. Moreover, as I consistently observed, the fact that the products generated in the laser cutter and the 3D printer were aesthetically pleasing had a strong impact in students' self-esteem—instead of taking home asymmetric and fragile cardboard prototypes, they were building functional 3D objects with a near-professional finish—it wasn't 'school stuff,' it was the 'real thing.'

Long term projects and deep collaboration. We also observed that the establishment of this new space in schools allowed students to engage in intellectual activities and practices that would not be possible anywhere else, and experience new ways of work and novel levels of team collaboration. A real engineering project takes several cycles of design and redesign. It does not fit the one-size-fits all 50-minute format. The digital fabrication lab provided a 'safe space' for long-term projects, which in turn enabled students to face (alone or in groups) a new and intense experience: failure. Learning how to manage failure—something rarely taught in schools—ended up being another crucial educational benefits of the lab work. As we will see in many of the vignettes, through several cycles of failure and redesign, students not only achieved incredibly original and complex designs, but also became more persistent, learned to work in heterogeneous teams, and became better at managing intellectual diversity.

4. Four Vignettes and Many Lessons About Digital Fabrication in Education

In the following four vignettes, I will discuss positive and negative scenarios of the implementation of digital fabrication in education based on the categories I just described. I will exemplify some of the learning outcomes, and offer recommendations for the design and management of such spaces. Each vignette will illustrate one or two important principles, and in particular I will discuss (a) the dangers of trivialization, (b) the potential for deep engagement in projects of unprecedented complexity, (c) the power of interdisciplinary work; (d) Contextualized learning in STEM, and (e) intellectualization and re-evaluation of familiar practices.

4.1. The 'Keychain Syndrome', or the Temptations of Trivialization

For the first digital fabrication workshops we held in 2009, I designed introductory activities to get students acquainted with the machines: semi-structured short projects such as creating a keychain, a nametag, or an acrylic sign for a sports team. On a technical level these projects required students to learn how to cut and engrave using the laser cutter, use vector drawing software to create and combine geometric shapes, and import/manipulate bitmapped images from the web.

I assumed that by asking them to create highly-personal objects, such as keychains and nametags, students would get excited about the technologies not only because they would create objects for everyday use, but they would 'decorate' their rooms, school materials, and clothes with them, attracting the attention of family members and other students in the school. They would feel proud of their creations and associate their newly acquired engineering skill to the production of socially valued artifacts.

Students engaged with enthusiasm in the creation of their keychains. The plan worked. For the second session, they came back even more excited about their objects – parents, friends, even teachers wanted an acrylic keychain. Students lined up by the laser cutter to make more keychains. Excitement was in the air. Digital fabrication was succeeding, and students – both girls and boys – were very excited about "making stuff."

By the third session, my team had decided that it was time to move on to new activities – in particular, I wanted to introduce robotics and electronics. I rounded up students at the beginning of the session and ran a short robotics tutorial, teaching them how to hook up sensors and motors, and write simple programs. At the end of the workshop, some students came to talk to me and asked permission to use the laser cutter for some new keychains. I postponed robotics for another day. By the fourth session, I knew something was wrong. The workshop became a keychain factory, and students would not engage in anything else. The plan worked too well – it backfired. Students found an activity that was personally meaningful, produced professional looking products that were admired and envied, and used a high-tech device. However, as much as it was a very effective solution to engage them in digital fabrication, it offered a too big reward for a relatively small effort, to produce an object that did not include any computation or complex constructive challenges. Ironically, it is as if students had discovered exactly what manufacturing is about – mass-producing with little effort – and were making the best of it. Students "cracked" digital fabrication and were using the lab as a fabrication facility, rather than a place for invention.

The following dialogue, which took place several days into the workshop, illustrates the seductions of the "keychain syndrome":

> Facilitator: What would you do if you had a laser cutter at home?
>
> Megan: I would make keychains.
>
> Nancy: Yeah, and sell 'em.
>
> Facilitator: Keychains? What kind?
>
> Megan: Like, these (she takes out a collection of keychains that she had recently printed)
>
> Facilitator: Anything else?
>
> Megan: No, just keychains.

But there was a more systemic issue at play – "friends and family" were focusing on the only values that they know, not coincidentally values which schools have traditionally focused on: valuing 'product' over 'process.' In that sense, digital fabrication is a type of Trojan horse: it introduces in schools a "genre" of tools that have the very special property of easily generating aesthetically pleasing, almost magical products. Therefore, for the student-creator, there is a conflicting incentive: (i) obfuscate the simplicity of the process ("I used this laser cutter machine, it's science fiction, it's really complicated"), and enhance the value of the product to others, or (ii) make the process transparent ("I used the laser cutter, it's actually not so hard to do keychains, the machine did most of the work!"), and reveal the triviality of the product.

For the educational designer and facilitator, it is fundamental to understand this incentive system to avoid this potentially harmful aspect of this 'genre' of machines. The feedback loop that the first incentive (obfuscating the simplicity of production) generates is that students get engrossed in the production of the same type of simple products. In the case of the second incentive, students are led to "un-trivialize" the product given the new level of product complexity that digital fabrication enables them to achieve. In the first case, despite appearances, we 'schoolify' and trivialize the lab, in the second, we make it a place for excellence and inquiry. The solution, however, is not inconsequential – while the product-over-process conundrum does not resolve itself, there will always be an incentive for simple, well-polished products, as opposed to messy, complex, and potentially 'ugly' projects. Unless educational designers unveil the real incentive systems at play in the classroom, teachers who reward students based on quick completion times, quality of solution, and efficiency, might actually be fostering classrooms in which students rarely venture outside of what they already know (Abrahamson, Blikstein, & Wilensky, 2007).

The "keychain syndrome," therefore, revealed two of the crucial elements of learning environments based on digital fabrication. First, the equipment is capable of easily generating aesthetically attractive objects and products. Second, this generates an incentive system in which there is a disproportionate payoff in staying a 'local minimum' where the projects are very simple but at the same time very admired by external observers. Settling for simple projects is a temptation that educators have to avoid at all cost. The non-triviality of navigating these new incentive systems was one of the important lessons learned in these early workshops.

4.2. The Upside-down Roller Coaster, or the Power of Despair

Before coming to one of the digital fabrication workshops, John, Tyler, and Bob found themselves brainstorming about what to build. One of their oddest ideas was to build a roller coaster in their backyard. After the first few days of the workshop they decided to tackle it—but clearly more as a playful thing do to, without much hope of actually building it. Their first step was to scale down the project from a backyard to a 'tabletop' rollercoaster. They then imagined that the process would be quite straightforward: designing the tracks on a vector-drawing software, "printing" using the laser cutter, and assembling everything.

When they started the design, the first problem came about: how to make curved tracks with uniform width? They realized that they could not just use any type of lines to curve the track, as an uneven track would cause the car to get stuck. Their first challenge was to solve a geometrical puzzle: Should they make tracks using the freehand tool? Bezier curves? Other kinds of curves? Should they create two perfect arcs? Should the arcs have the same radii?

In such an environment, there are no right answers, so these debates take a long time. After a day of discussions and experimentation, they ended up using arcs to create the smoothest possible curve while retaining the width of the track, and printed them out on the laser cutter. However, they realized that they had another problem in hands: the sharpness of the turns, which would make the car "lose most of its speed." After much bending and warping of the track, they eventually decided to scrap this design and start from scratch. Tyler worked on the new design, now with much wider turns, which seemed to work better (see Figure 1).

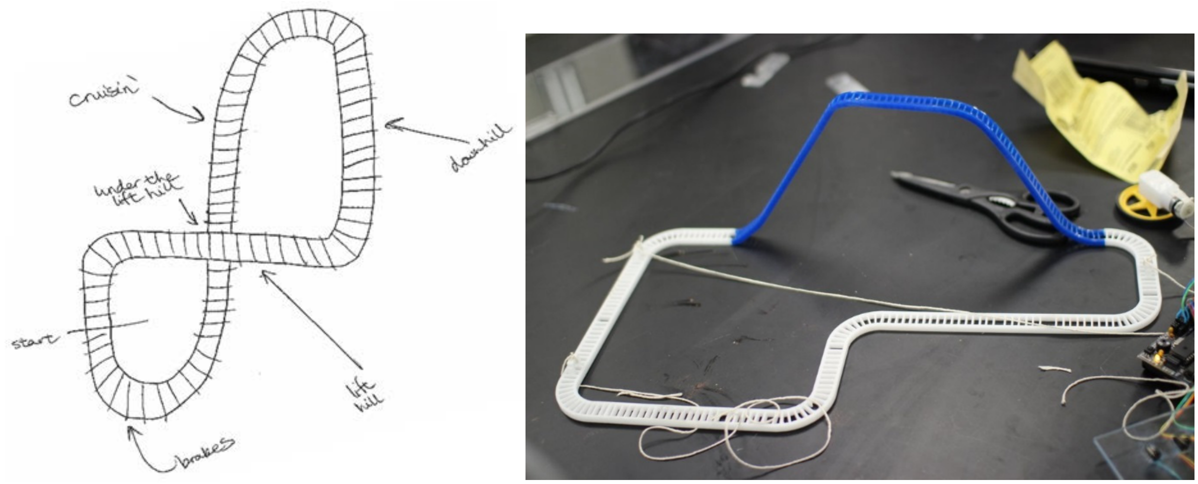

Figure 1. The initial plan for the rollercoaster track (left), and the second design (right)

Another problem that presented itself was the car. Several ideas were proposed for its design. Initially students were considering a normal rollercoaster car that would just roll on top of the track. They tried several designs, with and without wheels, but soon realized that friction was again making the car lose speed. After much brainstorming, they came up with a new idea: a hanging car under the track, which would have much less contact area and thus minimize friction. The group then designed the hanging car and printed it on the 3D printer. However, another problem arose: students realized they would have to suspend the track so that the car would not touch the table, and could not think of a reasonable way to accomplish it and maintain balance. They went back to the car-on-top idea, now with a better design for the wheels. After a day of hard work, they thought they had the final design, and printed everything. The first test was a disaster: the car did not have enough power to make it around the entire track. The original idea was to rig a device to bring the car to the top of the big hill, and let gravity do the rest. Students attempted several methods to bring the car to the top of the hill, from using magnets to attempt to pull the car up the track, to using a string towrope to pull it up the hill. After hours of failed experiments, they came to an even more devastating realization. Gravity would not provide enough energy to make the car go around the entire track—too much momentum was lost in turns and due to friction, and the plastic car was too light to accumulate enough potential energy. They gave up on gravity, and started considering other options. Their next idea was to rig a sail up on the car and use a battery-powered propeller to provide wind. But they again ran into problems, first with attaching the sail, then with the issue that the force applied to the sail pushed the nose of the car down without moving it. They realized this was due to one of two elements: either the fact that they were using a central wheel system, thus not providing stability in the front or back, or that the wheel system was not providing enough grip, thus the car was not stable enough. Students threw the design out the window, and one team member gave up on the project.

At this point, the rest of the team was desperate, asking everyone in the lab for ideas and help. They had spent almost two weeks on the project and nothing seemed to work – frustration was in the air. Some facilitators volunteered to help and come up with new ideas, and when just about everything seemed to be a failure, one revolutionary idea emerged: instead of having the car go around the track, why not make the track go around the car? The main problems arose from the fact that it was too difficult to power a tiny car without any motors, since the car was too small for that. So what about turning the problem on its head, and move the track instead? The suggested a design would treat the track as a puppet, with strings attached to each of its corners, and motors pulling them up and down – then they could easily use gravity again. Students took on the challenge, printed another track, created an acrylic frame, attached motors and programmed the GoGo Board (Sipitakiat et al., 2004), and in a few hours had a working prototype (Figure 2.)

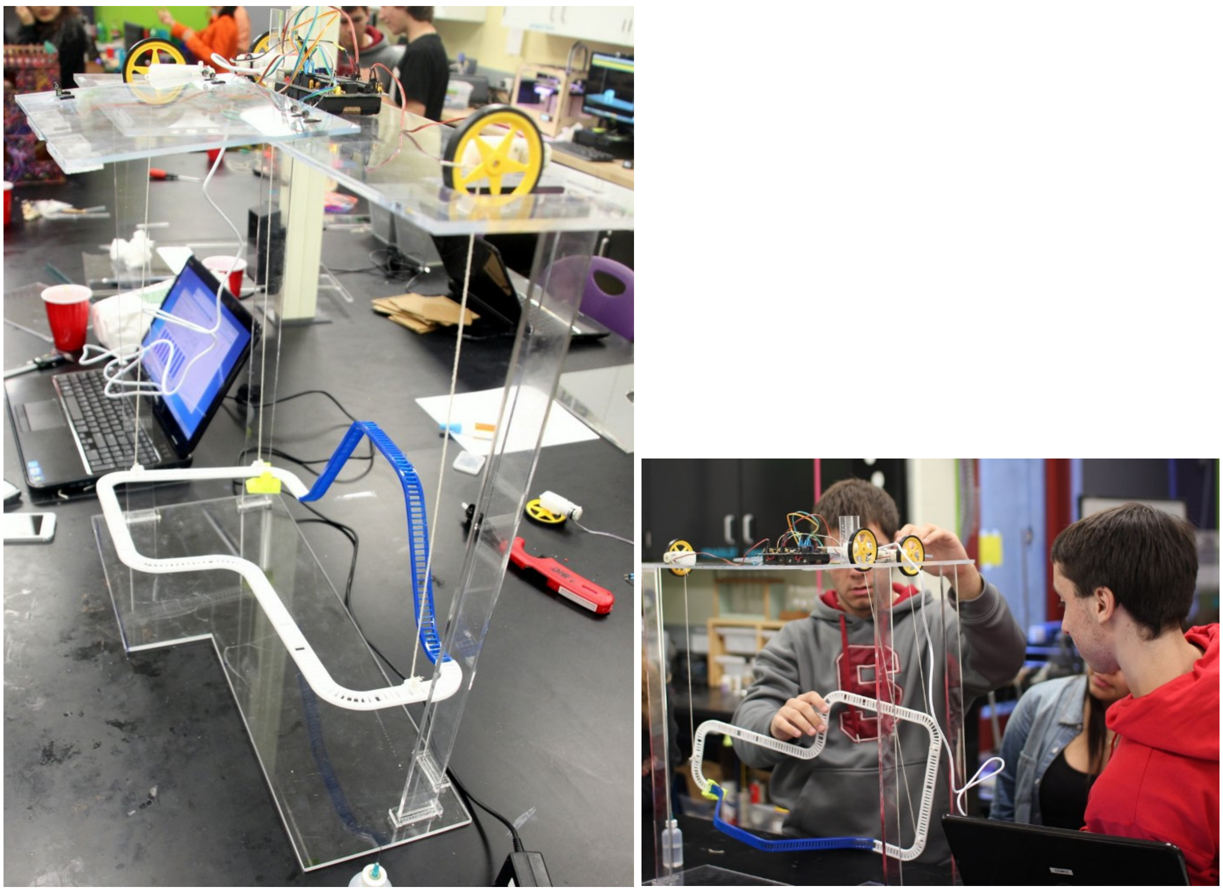

Figure 2. The upside-down rollercoaster

This episode illustrates the working dynamics in a digital fabrication lab or 'maker space' along many dimensions. First, it promoted contextualized encounter with scientific knowledge and lexicon. During the two weeks of the project, students struggled with several physics problems, some of which they knew about but had never seen in real life. Their dialogue, which initially was about the "losing speed," became increasingly complex, rigorous, and compliant with the lexicon of physics: for example, "speed" became "momentum," and the generic statement that the car was "losing speed" was later decoupled into friction, number of turns, angle of turns, and lack of initial potential energy. They also identified several causes for friction, and discussed ways to minimize it by reducing the surface area, the friction coefficient, or making the car hang from the track. Physics, engineering, and problem solving were organically connected a part of a seamless process, which is what happens when professional engineers work on projects.

Second, the space was flexible with students' contrasting attitudes towards failure. The narrative of this episode is as baffling and meandering as the project development was. There were no easy answers for the problems that students were facing. The group went through a complex process, filled with frustration, failure, but also exhilarating success in the end. While Tyler, Bob, and John worked together for almost the entire program, they had very different styles in going about their projects. As a team, Tyler's optimism in the face of adversity worked as a great balance to John's aptitude for ideating. While John often drove the start of projects, it was Tyler who would use the inevitable failures to advance their goal. Tyler would often tell John "Things never work the first time, and that's okay." Almost every day they hit a fundamental problem with their design, and consistently came up with means to work through it. While Tyler took the constant setbacks in stride, accepting them as part of the engineering process, John considered them instead as embarrassing failures. Despite these differences, the team showed remarkable perseverance throughout in the project, and was able to use their different approaches to failure as a feature of their collective strategy of problem solving, rather than a difficulty. These students were able to experience realistic engineering design because they had the space and time to fail and try again, and a strong motivation to pursue their own idea. In short-term projects, scripted construction challenges, or time-constrained competitions, the class dynamics would have been radically different, and students would never have been able to experience these dramatic levels of failure and reward. Ultimately, their deep sense of achievement was a consequence of their visceral involvement in the construction of the rollercoaster, and the originality of their design was only possible because of the technical and emotional support that they had in order to withstand extended frustration, shake it up, and go back to the drawing board.

4.3. The Most Math I Have Ever Learned in a History Class," or the Power of Interdisciplinary Projects

Digital fabrication is typically associated with the learning and practice of STEM disciplines. Laser cutters and 3D printer are "hard sciences" territory, and supposedly math and science teachers should be the ones primarily involved. In one of the projects in the Lincoln school, however, we had an unlikely scenario: Mary, a history teacher with many years of experience, wanted to bring her four 8th grade classes to the lab. She was not a typical early adopter of a digital prototyping lab – in one of our surveys, she rated herself at the bottom of the scale in knowledge about robotics, mechanical engineering, and computer programming. But Mary was not concerned in training future STEM workers. Her main goal fell within the disciplinary boundaries of History: she wanted her students to learn about great female characters in American history by building historical monuments for them, using 3D printing and laser cutting.

Mary's project illustrates two aspects of the implementation of digital fabrication in classrooms. First, I will show how she prepared herself for, and structured the activity. Second, I will narrate how a complex and productive "division of labor" emerged from the project as a result of the interactions between the technical lab teacher and Mary.

She had gone through the digital fabrication training workshop and had basic understanding of how most of the equipment worked. Initially, she was not comfortable using the laser cutter by herself, though. However, we had set up the lab with a full time technical lab person that could help teachers and students to operate and learn the machines. Thus Mary did not feel she had to master all the tools before starting to work with her students, or that she would be alone with the students exploring all of the unfamiliar territory of the lab.

Even though Mary was not well versed in programming or engineering, she was comfortable using unfamiliar technologies in her classroom. Part of her method was to experiment with the technology 'as a learner' before even starting working with students. Therefore, two days before the start of the digital fabrication activity, she created her own historical monument using the digital fabrication equipment. She went through the entire process herself and understood the challenges and difficulties in building it. Thus when she started working with students, she not only felt more comfortable facilitating the activity, but could also predict bottlenecks and difficulties. She became aware of how much technical expertise was needed to facilitate the project, and realized that the help of the lab's technical coordinator, David, would be crucial. As the activity unfolded, Mary's role evolved to be a project manager, and David's to be a design helper and an equipment operator. Mary set class goals, checked in on the groups, volunteered to laser cut pieces for them in her spare time, and kept track of time. David would sit by the laser cutter most of the time, not interfering with the girls' designs, and acting mostly as a facilitator and consultant. His help was instrumental in moving many groups forward. When the students had a very difficult technical challenge to solve, David had the ability to envision how the entire system should work and give life-saving suggestions. Most students did not have the ability to look at their work as a system, but on interactions between one or two parts at most. David would guide them throughout the process, not taking over or undermining their ideas, but co-designing. The work dynamics that Mary and David put in place was different from a traditional classroom, of course, but it was also a departure from many technology-based after school programs where there is no space for a person with Mary's profile.

In a robotics workshop, each group has its own equipment and work autonomously. In a digital fabrication environment, however, the work is centralized in just one or two machines. The question, then, is deciding on the side of efficiency (one specialist operating the machine for everyone), or equity (everyone operating the machine). In Mary and David's model, the workflow was faster, but there was doubt if the girls were actually learning while watching David work through problems, or if they were simply relieved to have something done for them, and if they could come up with elegant solutions without him.

This assembly-line division of labor made it possible for students to get their parts cut in 50-minute periods. However, there were unintended consequences to this scheme. Some students may have prematurely aborted design elements that they deemed too difficult to do on their own, given the time constraint. In addition, the amount of experience Mary's students had with fabrication varied from group to group. It seemed like there was a place for every student on the spectrum to fit in. Some groups required more technical (and mathematical) help than others, but the students all seemed to be in charge of the creative part of their designs. However, it was unclear whether David was being helpful by doing some of the more complex calculations for the students or simply passing the information along to the students. At this point the aim was efficiency; and it could have undermined students' willingness to persist through difficult problems.

Mary also made changes to her own activity design. Instead of a completely open-ended project, she introduced some structure: the wooden base of the historical monuments would be standardized (a 15x15 square grid with a 3/16":1 ft scale, see Figure 3, left).

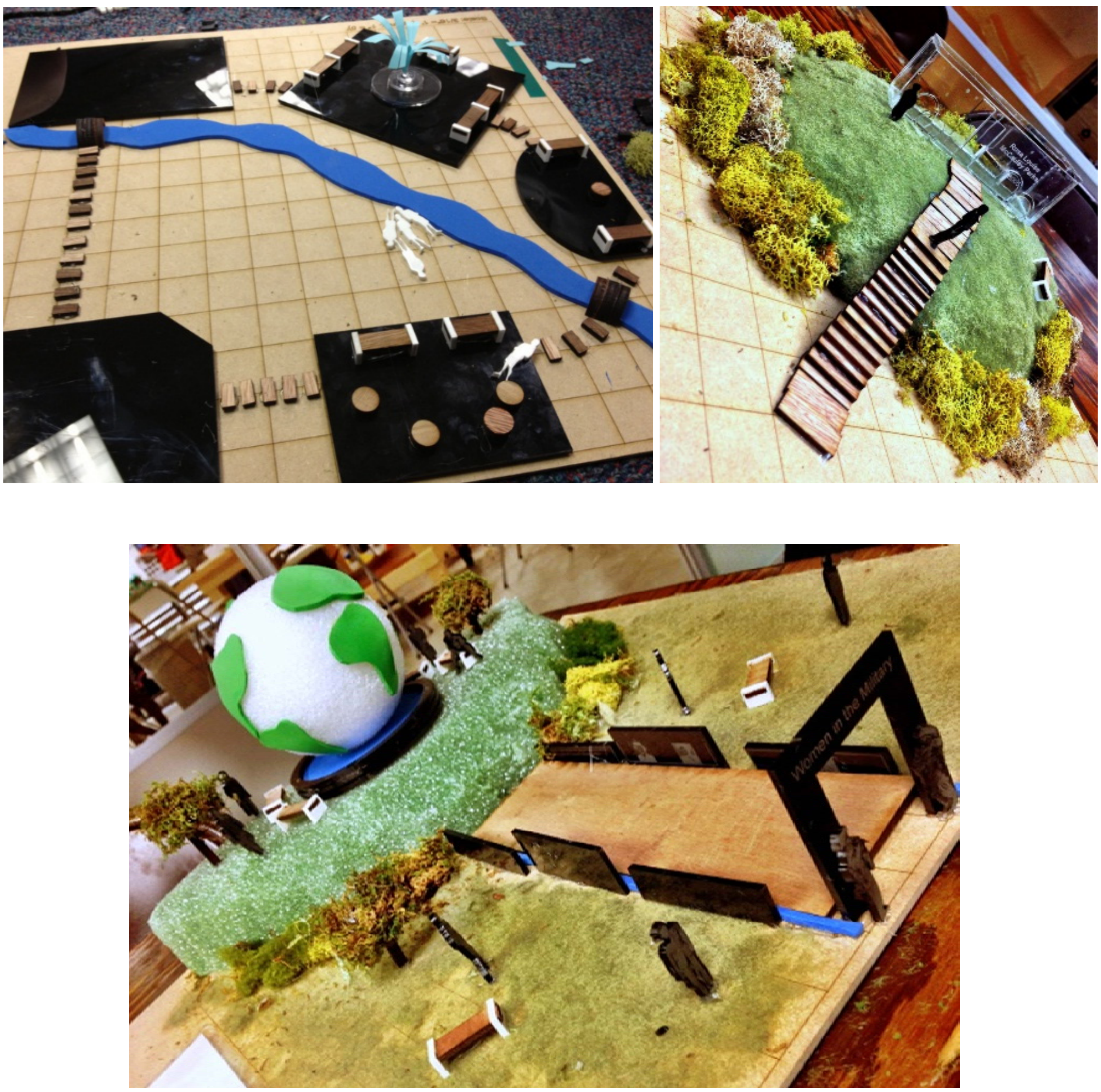

Figure 3. One in-progress project with the grid clearly visible (left), and some of the projects done by students (right, bottom)

Mary's activity design, which was intended to give students a safe starting point for their projects, had an unexpected consequence as well. The activity, which was originally a history project, suddenly became a sophisticated mathematics project. When Mary standardized the base and assigned strict dimensions to it, she foregrounded one aspect of the activity that would have been overlooked by many students: measurement. All of a sudden, the objects had to fit the base and their relative sizes had to be exact. Students did not want to have a park bench be the same size as a person, and they knew they could not tinker with the dimensions of objects after the fact. In the post-interviews, students were very surprised with how much math they had to learn and use to accomplish the history project.

The History Monuments project unwittingly illustrated some additional principles of digital fabrication in schools. First, digital fabrication introduces a new type of 'workflow.' Differently from a science lab or a robotics workshop, in which each group works autonomously with one kit, in a FabLab there is just one laser cutter. This generates pressure for productivity and division of labor that could be either productive or disempowering. In Mary's case, the scheme was mostly productive in which it enabled students to focus on the creative part of the project, not having to deal with the specifics of the software and the laser cutter. In fact, the division of labor was also a crucial enabler for the project to happen within the four 50-minute time slots that she had. However, we also observed that this scheme could easily turn into a disempowering arrangement when students realize that they are too dependent on the facilitators and cannot create the more complex designs by themselves—all the hard work is done by eager facilitators racing against the school bell.

Second, the environment was conducive to unlikely interdisciplinary projects**:** The making of a physical project will always entail some engineering work. Despite the fact that students were working on a history-themed project, they ended up having to explore multiple topics in mathematics such as measurement, scale, and proportion, both in two and three dimensions. In the same way that the rollercoaster students encountered physics in authentic ways, the 'Monuments' students were seeing mathematics everywhere in their projects.

4.4. The Robotic Flute Player, or the Demise of Constant Airflow

Max, a high school student in Moscow, was not an engineering type. He was passionate about music—Bach in particular. In one of our first meetings, he told the facilitators his childhood dream was to build a robot that could play Bach—thus his interest in digital fabrication, although he had no idea where to start. After a week, he had learned how to laser cut, program, control motors and sensors, and had an incredible prototype of the flute. It was not yet good enough for him. The workshop was over, but now finishing the flute was his personal project, so he kept coming to the lab for two months, several times a week. In the end, he built a flute with 12 servomotors (Figure 4), a highly complex control mechanism, and was able to play some simple Bach melodies by programming the microcontroller board. He took this project to the National Science Exhibition, a very competitive event in Russia with hundreds of students from all over the country, and won 3rd place. It seems like a success, but the competition was not the most important part of the story.

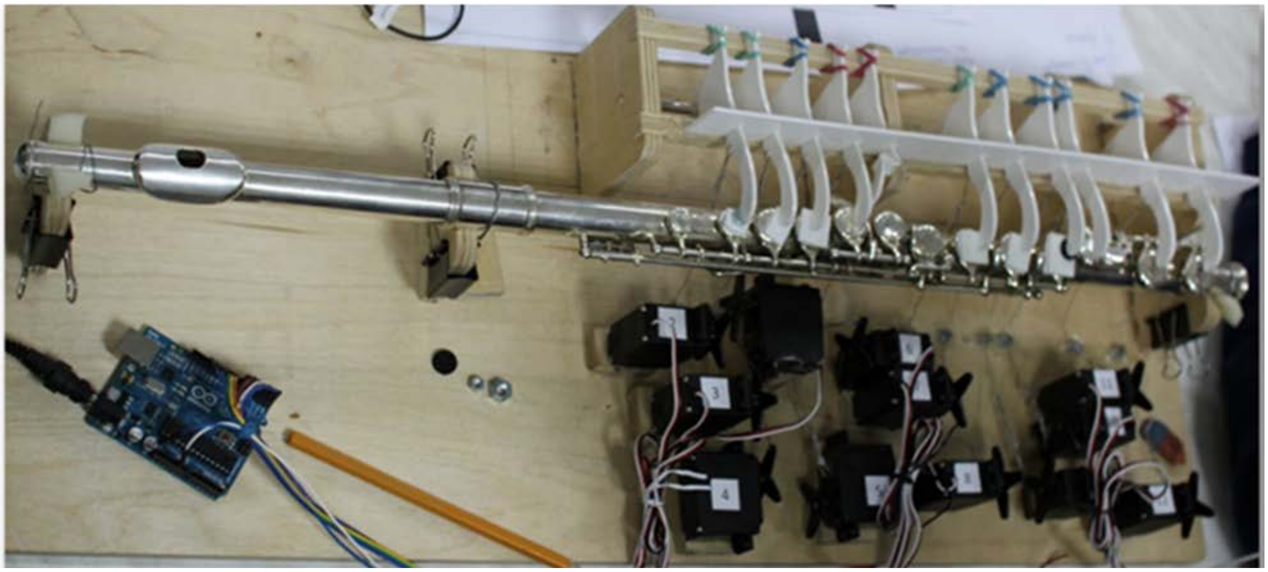

Figure 4. The robotic flute.

Apart from controlling the robotic "fingers," Max also wanted a machine to blow air into the flute. For several weeks, he tried many solutions—foleys, pumps, vacuum cleaners, and even complex piping systems. After countless experiments and redesigns, he finally found a way to blow a consistent amount of air at just the right angle to produce sound. He decided to use an inverted vacuum cleaner with a series of polymer-cast pipes which he made himself. Max turned the system on, started the servo motor system, and waited for the contraption to play Bach—when something remarkable happened. Even though the system was working as planned, it did not sound like a Bach piece. Something was off: the movements were correct, the air was flowing steadily, but it was not what he expected. After much reflection with the facilitators, Max finally understood the problem. No human flute player would have a steady flow of air – regulating the airflow is exactly the craft of musicians, who interpret the melody in their own way, emphasizing and highlighting different parts. Bach pieces sound weird when played by a robot because there is no interpretation, just an automatic execution with constant airflow.

Max was disappointed but also extremely happy, too – by building a robotic flute, he had learned a lot about engineering, but the main lesson was about music interpretation, and the true craft of a musician. His episode illustrates, again, the integrated nature of projects in the lab, where there is no real boundary between disciplines. But even more importantly, it shows a crucial component of the lab's success: attracting students who would not traditionally see themselves as engineers or scientists. Since the lab was architected (and advertised) as a place for invention—and not for "building robots" or making lights blink—even students like Max felt compelled to try something. His contribution, as a musician/engineer, made the environment more diverse and intellectually rich, attracted even more students, and infused unexpected ideas into other students' work.

5. Digital Fabrication and 'Making:' the Ultimate Construction Kit

In this chapter, I first told the story of the rise and fall then rise again of the making and building in education, discussed the theoretical underpinnings of project-based, student-centered learning, and presented the work of John Dewey, Seymour Papert, and Paulo Freire. I discussed how digital fabrication brings unique tools to progressive educators, and presented four prototypical episodes that exemplify the advantages and perils of FabLabs in schools. These examples highlight five important design principles:

(a) **The "Keychain Syndrome:"** since digital fabrication machines might generate aesthetically-pleasing products with little effort, educators should shy away from quick demonstration projects and push students towards more complex endeavors;

(b) **The power of despair and visceral involvement:** FabLabs provide an environment for unprecedented visceral design experiences, multiple cycles of design, and new levels for both frustration and excitement, which students normally do not experience in their normal school experience;

(c) **Powerful interdisciplinary projects:** the artificial boundaries between disciplines are completely reconfigured in the lab. History and mathematics become closely related, and so do music and robotics, and this richness results in a more diverse and accepting intellectual environment;

(d) **Contextualized learning in STEM:** students have the opportunity to come across several concepts in engineering and science in a highly meaningful, engaging, and contextualized fashion. Abstract ideas such as friction and momentum become meaningful and concrete when they are needed to accomplish a task within a project; math becomes a necessity in a history project.

(e) **Intellectualization and re-evaluation of familiar practices, rather than the replacement of existing ones (Blikstein, 2008):** Students bring their own familiar practices to the lab (craft, construction, carpentry), and those practices get augmented using socially-valued tools such as computational and mathematics. The malleability of the equipment and the pedagogical space in the lab makes the augmentation and embracement of such practices feasible, generating an environment that values multiple ways of working.

Despite the potential of digital fabrication labs and 'making' in education, educators and scholars must remember that, as Seymour Papert would say, the real power of any technology is not in the technique itself or in the allure it generates, but in the new ways of personal expression it enables, the new forms of human interaction it facilitates, and the powerful ideas it makes accessible to children.

6. References

Abrahamson, D., Blikstein, P., & Wilensky, U. (2007). *Classroom model, model classroom: computer-supported methodology for investigating collaborative-learning pedagogy*. Paper presented at the Proceedings of the 8th International Conference on Computer Supported Collaborative Learning, NJ: Rutgers University.

Astrachan, O., Hambrusch, S., Peckham, J., & Settle, A. (2009). *The present and future of computational thinking*. Paper presented at the Proceedings of the 40th ACM technical symposium on Computer science education, Chattanooga, TN, USA.

Atkin, J. (1990). Teach science for science's sake: For Global Competitiveness, try technology. *Education Week, 10,* 32.

Berland, M. (2008). *VBOT: Motivating Computational and Complex Systems Fluencies with Constructionist Virtual/Physical Robotics.* PhD., Northwestern University, Evanston.

Berland, M., & Wilensky, U. (2006). *Constructionist collaborative engineering: Results from an implementation of PVBOT.* Paper presented at the Annual meeting of the American Educational Research Association, San Francisco, CA.

Blikstein, P. (2008). Travels in Troy with Freire: Technology as an Agent for Emancipation. In P. Noguera & C. A. Torres (Eds.), *Social Justice Education for Teachers: Paulo Freire and the possible dream* (pp. 205-244). Rotterdam, Netherlands: Sense.

Blikstein, P. (2010). *Connecting the science classroom and tangible interfaces: the bifocal modeling framework*. Paper presented at the Proceedings of the 9th International Conference of the Learning Sciences - Volume 2, Chicago, Illinois.

Blikstein, P., Fuhrmann, T., Greene, D., & Salehi, S. (2012). *Bifocal modeling: mixing real and virtual labs for advanced science learning*. Paper presented at the Proceedings of the 11th International Conference on Interaction Design and Children, Bremen, Germany.

Buechley, L. (2006). *A Construction Kit for Electronic Textiles.* Paper presented at the IEEE International Symposium on Wearable Computers (ISWC), Montreux, Switzerland.

Buechley, L., & Eisenberg, M. (2008). The LilyPad Arduino: toward wearable engineering for everyone. *IEEE Pervasive Computing, 7*(2), 12-15.

Buechley, L., Eisenberg, M., Catchen, J., & Crockett, A. (2008). *The LilyPad Arduino: using computational textiles to investigate engagement, aesthetics, and diversity in computer science education*.

Cavallo, D. (2000). Emergent Design and learning environments: Building on indigenous knowledge. *IBM System Journal, 39*(3&4), 768-781.

Cooper, S., Dann, W., & Pausch, R. (2000). *Alice: a 3-D tool for introductory programming concepts.* Paper presented at the Journal of Computing Sciences in Colleges.

Dewey, J. (1902). *The Child and Curriculum*. Chicago, IL: University of Chicago Press.

diSessa, A. A. (2000). *Changing minds: computers, learning, and literacy*. Cambridge, MA: MIT Press.

Dym, C. L. (1999). Learning Engineering: Design, Languages, and Experiences. *Journal of Engineering*

Education, 145-148.
Edelson, D. (2000). My World GIS. Evanston, IL: PASCO Scientific.
Feisel, L. D., & Rosa, A. J. (2005). The Role of the Laboratory in Undergraduate Engineering Education. *Journal of Engineering Education, 94*(1), 121-130.
Freire, P. (1974). *Pedagogy of the oppressed*. New York,: Seabury Press.
Freudenthal, H. (1973). *Mathematics as an educational task*. Dordrecht,: Reidel.
Fröbel, F., & Hailmann, W. N. (1901). *The education of man*. New York: D. Appleton.
Gershenfeld, N. (2007). *Fab: the coming revolution on your desktop--from personal computers to personal fabrication*: Basic Books (AZ).
Grinter, L. E. (1955). Report on Evaluation of Engineering Education. Washington, DC: ASEE.
Illich, I. (1970). *Deschooling society*. New York: Harper & Row.
Levy, F., & Murnane, R. J. (2004). *The new division of labor: How computers are creating the next job market*: Princeton University Press.
Martin, F. (1994). *Circuits to Control: Learning Engineering by Designing LEGO Robots.* MIT, Cambridge, MA.
Martin, F., & Resnick, M. (1993). Lego/Logo and electronic bricks: Creating a scienceland for children. In D. L. Ferguson (Ed.), *Advanced educational technologies for mathematics and science*. Berlin, Heidelberg: Springer-Verlag.
Mikhak, B., Lyon, C., Gorton, T., Gershenfeld, N., McEnnis, C., & Taylor, J. (2002). Fab Lab: An Alternative Model of ICT for Development."development by design"(dyd02). *Bangalore: ThinkCycle*.
Millner, A., & Resnick, M. (2005). *Tools for Creating Custom Physical Computer Interfaces.* Paper presented at the 4th International Conference for Interaction Desing for Children, Boulder, CO.
Montessori, M. (1964). *The advanced Montessori method*. Cambridge, Mass.,: R. Bentley.
Montessori, M. (1965). *Spontaneous activity in education*. New York,: Schocken Books.
National Research Council. (1999). *Being Fluent with Information Technology*: The National Academies Press.
National Research Council. (2002). *Technically Speaking: Why All Americans Need to Know More About Technology*: The National Academies Press.
Papert, S. (1980). *Mindstorms : children, computers, and powerful ideas*. New York: Basic Books.
Papert, S. (1987). Computer Criticism vs. Technocentric Thinking. *Educational Researcher, 16*(1).
Papert, S. (1991). Situating Constructionism. In S. Papert & I. Harel (Eds.), *Constructionism*. Cambridge, MA: MIT Press.
Perner-Wilson, H., Buechley, L., & Satomi, M. (2011). *Handcrafting textile interfaces from a kit-of-no-parts.* Paper presented at the Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction.
Raffle, H. S., Parkes, A. J., & Ishii, H. (2004). *Topobo: a constructive assembly system with kinetic memory.* Paper presented at the Proceedings of the SIGCHI conference on Human factors in computing systems.
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., Maloney, J., Monroy-Hernández, A., Rusk, N., Eastmond, E., Brennan, K., . . . Silverman, B. (2009). Scratch: programming for all. *Communications of the ACM, 52*(11), 60-67.
Rousseau, J.-J. (1961). *Emile*. New York: Dutton.
Schweikardt, E., & Gross, M. D. (2006). *roBlocks: a robotic construction kit for mathematics and science education*. Paper presented at the Proceedings of the 8th international conference on Multimodal interfaces, Banff, Alberta, Canada.
Sheppard, S., & Jenison, R. (1997). Examples of Freshman Design Education. *International Journal of Engineering Education, 13*(4), 248-261.
Sipitakiat, A. (2000). *Digital Technology for Conviviality: making the most of learners' energy and imagination.* MSc. thesis, Massachusetts Institute of Technology, Cambridge.
Sipitakiat, A., Blikstein, P., & Cavallo, D. P. (2002). *The GoGo Board: Moving towards highly available computational tools in learning environments.* Paper presented at the Interactive Computer Aided Learning International Workshop, Villach, Austria.
Sipitakiat, A., Blikstein, P., & Cavallo, D. P. (2004). *GoGo Board: Augmenting Programmable Bricks for Economically Challenged Audiences.* Paper presented at the International Conference of the Learning Sciences, Los Angeles, USA.
Swetz, F., & Smith, D. (1987). *Capitalism and arithmetic: The new math of the 15th century*: Open Court.
Sylvan, E. (2005). *Integrating Aesthetic, Engineering, and Scientific Understanding in a Hands-on Design Activity.* Paper presented at the Interaction Design for Children, Boulder, CO.
Tryggvason, G., & Apelian, D. (2006). Re-engineering engineering education for the challenges of the 21 st century. *JOM, 58*(10), 14-17.
von Glasersfeld, E. (1984). An Introduction to Radical Constructivism. In P. Watzlawick (Ed.), *The Invented Reality*. New York: Norton.
Wilensky, U. (1999). NetLogo. Evanston, IL: Center for Connected Learning and Computer-Based Modeling. http://ccl.northwestern.edu/netlogo. Retrieved from http://ccl.northwestern.edu/netlogo
Wilensky, U., & Papert, S. (2010). *Restructurations: Reformulating knowledge disciplines through new representational forms.* Paper presented at the Constructionism 2010, Paris, France.
Wilensky, U., & Stroup, W. (1999). *Learning Through Participatory Simulations: Network-Based Design for Systems Learning in Classrooms.* Paper presented at the Computer Supported Collaborative Learning Conference, Stanford University, California.
Yasar, O., & Landau, R. H. (2003). Elements of computational science and engineering education. *SIAM review*, 787-805.