How to Make Almost Anything

The Digital Fabrication Revolution

Neil Gershenfeld

A NEW DIGITAL revolution is coming, this time in fabrication. It draws on the same insights that led to the earlier digitizations of communication and computation, but now what is being programmed is the physical world rather than the virtual one. Digital fabrication will allow individuals to design and produce tangible objects on demand, wherever and whenever they need them. Widespread access to these technologies will challenge traditional models of business, aid, and education.

The roots of the revolution date back to 1952, when researchers at the Massachusetts Institute of Technology (MIT) wired an early digital computer to a milling machine, creating the first numerically controlled machine tool. By using a computer program instead of a machinist to turn the screws that moved the metal stock, the researchers were able to produce aircraft components with shapes that were more complex than could be made by hand. From that first revolving end mill, all sorts of cutting tools have been mounted on computer-controlled platforms, including jets of water carrying abrasives that can cut through hard materials, lasers that can quickly carve fine features, and slender electrically charged wires that can make long thin cuts.

Today, numerically controlled machines touch almost every commercial product, whether directly (producing everything from laptop cases to jet engines) or indirectly (producing the tools that

NEIL GERSHENFELD is a Professor at the Massachusetts Institute of Technology and the head of MIT's Center for Bits and Atoms.

mold and stamp mass-produced goods). And yet all these modern descendants of the first numerically controlled machine tool share its original limitation: they can cut, but they cannot reach internal structures. This means, for example, that the axle of a wheel must be manufactured separately from the bearing it passes through.

In the 1980s, however, computer-controlled fabrication processes that added rather than removed material (called additive manufacturing) came on the market. Thanks to 3-D printing, a bearing and an axle could be built by the same machine at the same time. A range of 3-D printing processes are now available, including thermally fusing plastic filaments, using ultraviolet light to cross-link polymer resins, depositing adhesive droplets to bind a powder, cutting and laminating sheets of paper, and shining a laser beam to fuse metal particles. Businesses already use 3-D printers to model products before producing them, a process referred to as rapid prototyping. Companies also rely on the technology to make objects with complex shapes, such as jewelry and medical implants. Research groups have even used 3-D printers to build structures out of cells with the goal of printing living organs.

Additive manufacturing has been widely hailed as a revolution, featured on the cover of publications from *Wired* to *The Economist*. This is, however, a curious sort of revolution, proclaimed more by its observers than its practitioners. In a well-equipped workshop, a 3-D printer might be used for about a quarter of the jobs, with other machines doing the rest. One reason is that the printers are slow, taking hours or even days to make things. Other computer-controlled tools can produce parts faster, or with finer features, or that are larger, lighter, or stronger. Glowing articles about 3-D printers read like the stories in the 1950s that proclaimed that microwave ovens were the future of cooking. Microwaves are convenient, but they don't replace the rest of the kitchen.

The revolution is not additive versus subtractive manufacturing; it is the ability to turn data into things and things into data. That is what is coming; for some perspective, there is a close analogy with the history of computing. The first step in that development was the arrival of large mainframe computers in the 1950s, which only corporations, governments, and elite institutions could afford. Next came the development of minicomputers in the 1960s, led by Digital Equipment Corporation's PDP family of computers, which was based on MIT'S first transistorized computer, the TX-0. These brought down the cost of a computer from hundreds of thousands of dollars to tens of thousands. That was still too much for an individual but was affordable for research groups, university departments, and smaller companies. The people who used these devices developed the applications for just about everything one does now on a computer: sending e-mail, writing in a word processor, playing video games, listening to music. After minicomputers came hobbyist computers. The best known of these, the MITS Altair 8800, was sold in 1975 for about $1,000 assembled or about $400 in kit form. Its capabilities were rudimentary, but it changed the lives of a generation of computing pioneers, who could now own a machine individually. Finally, computing truly turned personal with the appearance of the IBM personal computer in 1981. It was relatively compact, easy to use, useful, and affordable.

> The aim is to not only produce the parts for a drone, for example, but build a complete vehicle that can fly right out of the printer.

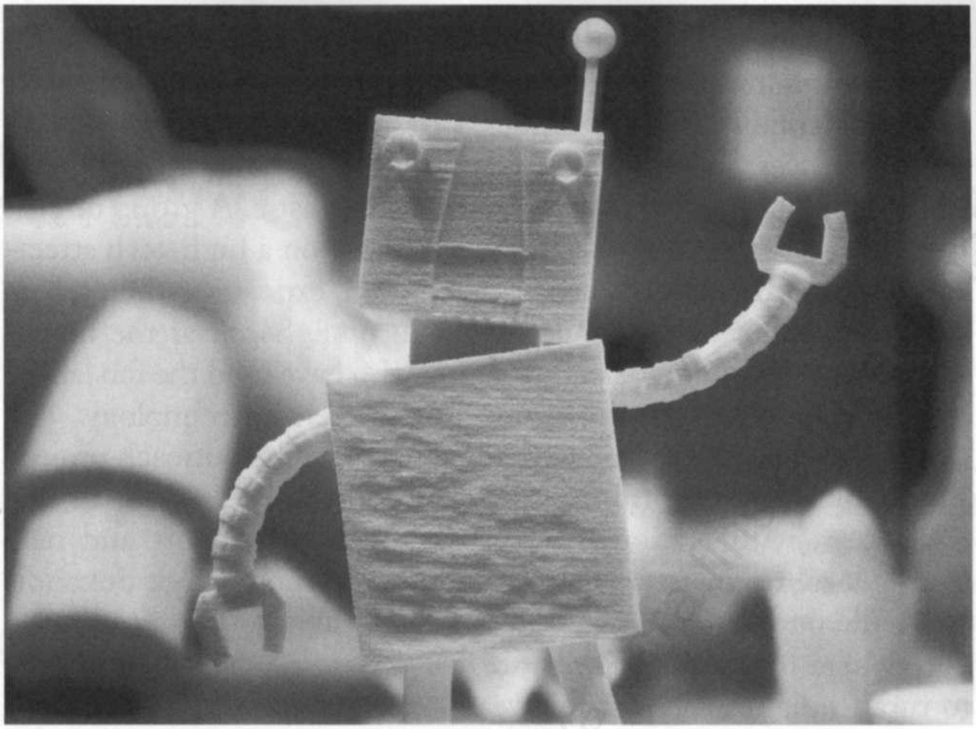
Just as with the old mainframes, only institutions can afford the modern versions of the early bulky and expensive computer-controlled milling devices. In the 1980s, first-generation rapid prototyping systems from companies such as 3D Systems, Stratasys, Epilog Laser, and Universal brought the price of computer-controlled manufacturing systems down from hundreds of thousands of dollars to tens of thousands, making them attractive to research groups. The next-generation digital fabrication products on the market now, such as the RepRap, the MakerBot, the Ultimaker, the PopFab, and the MTM Snap, sell for thousands of dollars assembled or hundreds of dollars as parts. Unlike the digital fabrication tools that came before them, these tools have plans that are typically freely shared, so that those who own the tools (like those who owned the hobbyist computers) can not only use them but also make more of them and modify them. Integrated personal digital fabricators comparable to the personal computer do not yet exist, but they will.

Personal fabrication has been around for years as a science-fiction staple. When the crew of the TV series *Star Trek: The Next Generation* was confronted by a particularly challenging plot development, they could use the onboard replicator to make whatever they needed. Scientists at a number of labs (including mine) are now working on the real thing, developing processes that can place individual atoms and molecules into whatever structure they want. Unlike 3-D printers today, these will be able to build complete functional systems at once, with no need for parts to be assembled. The aim is to not only produce the parts for a drone, for example, but build a complete vehicle that can fly right out of the printer. This goal is still years away, but it is not necessary to wait: most of the computer functions one uses today were invented in the minicomputer era, long before they would flourish in the era of personal computing. Similarly, although today's digital manufacturing machines are still in their infancy, they can already be used to make (almost) anything, anywhere. That changes everything.

THINK GLOBALLY, FABRICATE LOCALLY

I FIRST APPRECIATED the parallel between personal computing and personal fabrication when I taught a class called "How to Make (almost) Anything" at MIT'S Center for Bits and Atoms, which I direct. CBA, which opened in 2001 with funding from the National Science Foundation, was developed to study the boundary between computer science and physical science. It runs a facility that is equipped to make and measure things that are as small as atoms or as large as buildings.

We designed the class to teach a small group of research students how to use CBA'S tools but were overwhelmed by the demand from students who just wanted to make things. Each student later completed a semester-long project to integrate the skills they had learned. One made an alarm clock that the groggy owner would have to wrestle with to prove that he or she was awake. Another made a dress fitted with sensors and motorized spine-like structures that could defend the wearer's personal space. The students were answering a question that I had not asked: What is digital fabrication good for? As it turns out, the "killer app" in digital fabrication, as



FLICKR / MADS BOEDKER

I come in one piece: a printed robot at the Oslo School of Architecture and Design

in computing, is personalization, producing products for a market of one person.

Inspired by the success of that first class, in 2003, CBA began an outreach project with support from the National Science Foundation. Rather than just describe our work, we thought it would be more interesting to provide the tools. We assembled a kit of about $50,000 worth of equipment (including a computer-controlled laser, a 3-D printer, and large and small computer-controlled milling machines) and about $20,000 worth of materials (including components for molding and casting parts and producing electronics). All the tools were connected by custom software. These became known as "fab labs" (for "fabrication labs" or "fabulous labs"). Their cost is comparable to that of a minicomputer, and we have found that they are used in the same way: to develop new uses and new users for the machines.

Starting in December of 2003, a CBA team led by Sherry Lassiter, a colleague of mine, set up the first fab lab at the South End Technology Center, in inner-city Boston. SETC is run by Mel King, an activist who has pioneered the introduction of new technologies to urban communities, from video production to Internet access. For him, digital fabrication machines were a natural next step. For all the differences between the MIT campus and the South End, the responses at both places were equally enthusiastic. A group of girls from the area used the tools in the lab to put on a high-tech street-corner craft sale, simultaneously having fun, expressing themselves, learning technical skills, and earning income. Some of the home-schooled children in the neighborhood who have used the fab lab for hands-on training have since gone on to careers in technology.

The SETC fab lab was all we had planned for the outreach project. But thanks to interest from a Ghanaian community around SETC, in 2004, CBA, with National Science Foundation support and help from a local team, set up a second fab lab in the town of Sekondi-Takoradi, on Ghana's coast. Since then, fab labs have been installed everywhere from South Africa to Norway, from downtown Detroit to rural India. In the past few years, the total number has doubled about every 18 months, with over 100 in operation today and that many more being planned. These labs form part of a larger "maker movement" of high-tech do-it-yourselfers, who are democratizing access to the modern means to make things.

Local demand has pulled fab labs worldwide. Although there is a wide range of sites and funding models, all the labs share the same core capabilities. That allows projects to be shared and people to travel among the labs. Providing Internet access has been a goal of many fab labs. From the Boston lab, a project was started to make antennas, radios, and terminals for wireless networks. The design was refined at a fab lab in Norway, was tested at one in South Africa, was deployed from one in Afghanistan, and is now running on a self-sustaining commercial basis in Kenya. None of these sites had the critical mass of knowledge to design and produce the networks on its own. But by sharing design files and producing the components locally, they could all do so together. The ability to send data across the world and then locally produce products on demand has revolutionary implications for industry.

The first Industrial Revolution can be traced back to 1761, when the Bridgewater Canal opened in Manchester, England. Commissioned by the Duke of Bridgewater to bring coal from his mines in Worsley to Manchester and to ship products made with that coal out to the world, it was the first canal that did not follow an existing waterway. Thanks to the new canal, Manchester boomed. In 1783, the town had one cotton mill; in 1853, it had 108. But the boom was followed by a bust. The canal was rendered obsolete by railroads, then trucks, and finally containerized shipping. Today, industrial production is a race to the bottom, with manufacturers moving to the lowest-cost locations to feed global supply chains.

Now, Manchester has an innovative fab lab that is taking part in a new industrial revolution. A design created there can be sent electronically anywhere in the world for on-demand production, which effectively eliminates the cost of shipping. And unlike the old mills, the means of production can be owned by anyone.

Why might one want to own a digital fabrication machine? Personal fabrication tools have been considered toys, because the incremental cost of mass production will always be lower than for one-off goods. A similar charge was leveled against personal computers. Ken Olsen, founder and CEO of the minicomputer-maker Digital Equipment Corporation, famously said in 1977 that "there is no reason for any individual to have a computer in his home." His company is now defunct. You most likely own a personal computer. It isn't there for inventory and payroll; it is for doing what makes you yourself: listening to music, talking to friends, shopping. Likewise, the goal of personal fabrication is not to make what you can buy in stores but to make what you cannot buy. Consider shopping at iKEA.The furniture giant divines global demand for furniture and then produces and ships items to its big-box stores. For just thousands of dollars, individuals can already purchase the kit for a large-format computer-controlled milling machine that can make all the parts in an IKEA flat-pack box. If having the machine saved just ten IKEA purchases, its expense could be recouped. Even better, each item produced by the machine would be customized to fit the customer's preference. And rather than employing people in remote factories, making furniture this way is a local affair.

The digitization of material is not a new idea. It is four billion years old, going back to the evolutionary age of the ribosome.

This last observation inspired the Fab City project, which is led by Barcelona's chief architect, Vicente Guallart. Barcelona, like the rest of Spain, has a youth unemployment rate of over 50 percent. An entire generation there has few prospects for getting jobs and leaving home. Rather than purchasing products produced far away, the city, with Guallart, is deploying fab labs in every district as part of the civic infrastructure. The goal is for the city to be globally connected for knowledge but self-sufficient for what it consumes.

The digital fabrication tools available today are not in their final form. But rather than wait, programs like Barcelona's are building the capacity to use them as they are being developed.

BITS AND ATOMS

IN COMMON usage, the term "digital fabrication" refers to processes that use the computer-controlled tools that are the descendants of MIT'S 1952 numerically controlled mill. But the "digital" part of those tools resides in the controlling computer; the materials themselves are analog. A deeper meaning of "digital fabrication" is manufacturing processes in which the materials themselves are digital. A number of labs (including mine) are developing digital materials for the future of fabrication.

The distinction is not merely semantic. Telephone calls used to degrade with distance because they were analog: any errors from noise in the system would accumulate. Then, in 1937, the mathematician Claude Shannon wrote what was arguably the best-ever master's thesis, at MIT. In it, he proved that on-off switches could compute any logical function. He applied the idea to telephony in 1938, while working at Bell Labs. He showed that by converting a call to a code of ones and zeros, a message could be sent reliably even in a noisy and imperfect system. The key difference is error correction: if a one becomes a 0.9 or a 1.1, the system can still distinguish it from a zero.

At MIT, Shannon's research had been motivated by the difficulty of working with a giant mechanical analog computer. It used rotating wheels and disks, and its answers got worse the longer it ran. Researchers, including John von Neumann, Jack Cowan, and Samuel Winograd, showed that digitizing data could also apply to computing:

a digital computer that represents information as ones and zeros can be reliable, even if its parts are not. The digitization of data is what made it possible to carry what would once have been called a supercomputer in the smart phone in one's pocket.

These same ideas are now being applied to materials. To understand the difference from the processes used today, compare the performance of a child assembling LEGO pieces to that of a 3-D printer. First, because the LEGO pieces must be aligned to snap together, their ultimate positioning is more accurate than the motor skills of a child would usually allow. By contrast, the 3-D printing process accumulates errors (as anyone who has checked on a 3-D print that has been building for a few hours only to find that it has failed because of imperfect adhesion in the bottom layers can attest). Second, the LEGO pieces themselves define their spacing, allowing a structure to grow to any size. A 3-D printer is limited by the size of the system that positions the print head. Third, LEGO pieces are available in a range of different materials, whereas 3-D printers have a limited ability to use dissimilar materials, because everything must pass through the same printing process. Fourth, a LEGO construction that is no longer needed can be disassembled and the parts reused; when parts from a 3-D printer are no longer needed, they are thrown out. These are exacdy the differences between an analog system (the continuous deposition of the 3-D printer) and a digital one (the LEGO assembly).

The digitization of material is not a new idea. It is four billion years old, going back to the evolutionary age of the ribosome, the protein that makes proteins. Humans are full of molecular machinery, from the motors that move our muscles to the sensors in our eyes. The ribosome builds all that machinery out of a microscopic version of LEGO pieces, amino acids, of which there are 22 different kinds. The sequence for assembling the amino acids is stored in DNA and is sent to the ribosome in another protein called messenger RNA. The code does not just describe the protein to be manufactured; it becomes the new protein.

Labs like mine are now developing 3-D assemblers (rather than printers) that can build structures in the same way as the ribosome. The assemblers will be able to both add and remove parts from a discrete set. One of the assemblers we are developing works with components that are a bit bigger than amino acids, cluster of atoms about ten nanometers long (an amino acid is around one nanometer long). These can have properties that amino acids cannot, such as being good electrical conductors or magnets. The goal is to use the nanoassembler to build nanostructures, such as 3-D integrated circuits. Another assembler we are developing uses parts on the scale of microns to millimeters. We would like this machine to make the electronic circuit boards that the 3-D integrated circuits go on. Yet another assembler we are developing uses parts on the scale of centimeters, to make larger structures, such as aircraft components and even whole aircraft that will be lighter, stronger, and more capable than today's planes—think a jumbo jet that can flap its wings.

A key difference between existing 3-D printers and these assemblers is that the assemblers will be able to create complete functional systems in a single process. They will be able to integrate fixed and moving mechanical structures, sensors and actuators, and electronics. Even more important is what the assemblers don't create: trash. Trash is a concept that applies only to materials that don't contain enough information to be reusable. All the matter on the forest floor is recycled again and again. Likewise, a product assembled from digital materials need not be thrown out when it becomes obsolete. It can simply be disassembled and the parts reconstructed into something new.

The most interesting thing that an assembler can assemble is itself. For now, they are being made out of the same kinds of components as are used in rapid prototyping machines. Eventually, however, the goal is for them to be able to make all their own parts. The motivation is practical. The biggest challenge to building new fab labs around the world has not been generating interest, or teaching people how to use them, or even cost; it has been the logistics. Bureaucracy, incompetent or corrupt border controls, and the inability of supply chains to meet demand have hampered our efforts to ship the machines around the world. When we are ready to ship assemblers, it will be much easier to mail digital material components in bulk and then e-mail the design codes to a fab lab so that one assembler can make another.

Assemblers' being self-replicating is also essential for their scaling. Ribosomes are slow, adding a few amino acids per second. But there are also very many of them, tens of thousands in each of the trillions of cells in the human body, and they can make more of themselves when needed. Likewise, to match the speed of the *Star Trek* replicator, many assemblers must be able to work in parallel.

GRAY GOO

ARE THERE dangers to this sort of technology? In 1986, the engineer Eric Drexler, whose doctoral thesis at MIT was the first in molecular nanotechnology, wrote about what he called "gray goo," a doomsday scenario in which a self-reproducing system multiplies out of control, spreads over the earth, and consumes all its resources. In 2000, Bill Joy, a computing pioneer, wrote in *Wired* magazine about the threat of extremists building self-reproducing weapons of mass destruction. He concluded that there are some areas of research that humans should not pursue. In 2003, a worried Prince Charles asked the Royal Society, the United Kingdom's fellowship of eminent scientists, to assess the risks of nanotechnology and self-replicating systems.

Although alarming, Drexler's scenario does not apply to the self-reproducing assemblers that are now under development: these require an external source of power and the input of nonnatural materials. Although biological warfare is a serious concern, it is not a new one; there has been an arms race in biology going on since the dawn of evolution.

A more immediate threat is that digital fabrication could be used to produce weapons of individual destruction. An amateur gunsmith has already used a 3-D printer to make the lower receiver of a semi-automatic rifle, the AR-15. This heavily regulated part holds the bullets and carries the gun's serial number. A German hacker made 3-D copies of tightly controlled police handcuff keys. Two of my own students, Will Langford and Matt Keeter, made master keys, without access to the originals, for luggage padlocks approved by the U.S. Transportation Security Administration. They x-rayed the locks with a CT scanner in our lab, used the data to build a 3-D computer model of the locks, worked out what the master key was, and then produced working keys with three different processes: numerically controlled milling, 3-D printing, and molding and casting.

These kinds of anecdotes have led to calls to regulate 3-D printers. When I have briefed rooms of intelligence analysts or military leaders on digital fabrication, some of them have invariably concluded that the technology must be restricted. Some have suggested modeling the controls after the ones placed on color laser printers. When that type of printer first appeared, it was used to produce counterfeit currency. Although the fake bills were easily detectable, in the 1990s the U.S. Secret Service convinced laser printer manufacturers to agree to code each device so that it would print tiny yellow dots on every page it printed. The dots are invisible to the naked eye but encode the time, date, and serial number of the printer that printed them. In 2005, the Electronic Frontier Foundation, a group that defends digital rights, decoded and publicized the system. This led to a public outcry over printers invading peoples' privacy, an ongoing practice that was established without public input or apparent checks.

Digital fabrication could be used to produce weapons of individual destruction.

Justified or not, the same approach would not work with 3-D printers. There are only a few manufacturers that make the print engines used in laser printers. So an agreement among them enforced the policy across the industry. There is no corresponding part for 3-D printers. The parts that cannot yet be made by the machine builders themselves, such as computer chips and stepper motors, are commodity items: they are mass-produced and used for many applications, with no central point of control. The parts that are unique to 3-D printing, such as filament feeders and extrusion heads, are not difficult to make. Machines that make machines cannot be regulated in the same way that machines made by a few manufacturers can be.

Even if 3-D printers could be controlled, hurting people is already a well-met market demand. Cheap weapons can be found anywhere in the world. CBA'S experience running fab labs in conflict zones has been that they are used as an alternative to fighting. And although established elites do not see the technology as a threat, its presence can challenge their authority. For example, the fab lab in Jalalabad, Afghanistan, has provided wireless Internet access to a community that can now, for the first time, learn about the rest of the world and extend its own network.

A final concern about digital fabrication relates to the theft of intellectual property. If products are transmitted as designs and produced on demand, what is to prevent those designs from being replicated without permission? That is the dilemma the music and software industries have faced. Their immediate response—introducing technology to restrict copying files—failed. That is because the technology was easily circumvented by those who wanted to cheat and was irritating for everyone else. The solution was to develop app stores that made is easier to buy and sell software and music legally. Files of digital fabrication designs can be sold in the same way, catering to specialized interests that would not support mass manufacturing.

Patent protections on digital fabrication designs can work only if there is some barrier to entry to using the intellectual property and if infringement can be identified. That applies to the products made in expensive integrated circuit foundries, but not to those made in affordable fab labs. Anyone with access to the tools can replicate a design anywhere; it is not feasible to litigate against the whole world. Instead of trying to restrict access, flourishing software businesses have sprung up that freely share their source codes and are compensated for the services they provide. The spread of digital fabrication tools is now leading to a corresponding practice for open-source hardware.

PLANNING INNOVATION

COMMUNITIES SHOULD not fear or ignore digital fabrication. Better ways to build things can help build better communities. A fab lab in Detroit, for example, which is run by the entrepreneur Blair Evans, offers programs for at-risk youth as a social service. It empowers them to design and build things based on their own ideas.

It is possible to tap into the benefits of digital fabrication in several ways. One is top down. In 2005, South Africa launched a national network of fab labs to encourage innovation through its National Advanced Manufacturing Technology Strategy. In the United

States, Representative Bill Foster (D-I11.) proposed legislation, the National Fab Lab Network Act of 2010, to create a national lab linking local fab labs. The existing national laboratory system houses billion-dollar facilities but struggles to directly impact the communities around them. Foster's bill proposes a system that would instead bring the labs to the communities.

Another approach is bottom up. Many of the existing fab lab sites, such as the one in Detroit, began as informal organizations to address unmet local needs. These have joined regional programs. These regional programs, such as the United States Fab Lab Network and FabLab.nl, in Belgium, Luxembourg, and the Netherlands, take on tasks that are too big for an individual lab, such as supporting the launch of new ones. The regional programs, in turn, are linking together through the international Fab Foundation, which will provide support for global challenges, such as sourcing specialized materials around the world.

To keep up with what people are learning in the labs, the fab lab network has launched the Fab Academy. Children working in remote fab labs have progressed so far beyond any local educational opportunities that they would have to travel far away to an advanced institution to continue their studies. To prevent such brain drains, the Fab Academy has linked local labs together into a global campus. Along with access to tools, students who go to these labs are surrounded by peers to learn from and have local mentors to guide them. They participate in interactive global video lectures and share projects and instructional materials online.

The traditional model of advanced education assumes that faculty, books, and labs are scarce and can be accessed by only a few thousand people at a time. In computing terms, MIT can be thought of as a mainframe: students travel there for processing. Recently, there has been an interest in distance learning as an alternative, to be able to handle more students. This approach, however, is like time-sharing on a mainframe, with the distant students like terminals connected to a campus. The Fab Academy is more akin to the Internet, connected locally and managed globally. The combination of digital communications and digital fabrication effectively allows the campus to come to the students, who can share projects that are locally produced on demand.

The U.S. Bureau of Labor Statistics forecasts that in 2020, the United States will have about 9.2 million jobs in the fields of science, technology, engineering, and mathematics. According to data compiled by the National Science Board, the advisory group of the National Science Foundation, college degrees in these fields have not kept pace with college enrollment. And women and minorities remain significandy underrepresented in these fields. Digital fabrication offers a new response to this need, starting at the beginning of the pipeline. Children can come into any of the fab labs and apply the tools to their interests. The Fab Academy seeks to balance the decentralized enthusiasm of the do-it-yourself maker movement and the mentorship that comes from doing it together.

After all, the real strength of a fab lab is not technical; it is social. The innovative people that drive a knowledge economy share a common trait: by definition, they are not good at following rules. To be able to invent, people need to question assumptions. They need to study and work in environments where it is safe to do that. Advanced educational and research institutions have room for only a few thousand of those people each. By bringing welcoming environments to innovators wherever they are, this digital revolution will make it possible to harness a larger fraction of the planet's brainpower.

Digital fabrication consists of much more than 3-D printing. It is an evolving suite of capabilities to turn data into things and things into data. Many years of research remain to complete this vision, but the revolution is already well under way. The collective challenge is to answer the central question it poses: How will we live, learn, work, and play when anyone can make anything, anywhere?

Fonte: Foreign affairs, New York, v. 91, n. 6, p. 43-57, Nov./ Dec. 2012.