Factory @ Home: The Emerging Economy of Personal Fabrication

One of a Series of Occasional Papers in Science and Technology Policy

Hod Lipson and Melba Kurman

Occasional Papers in Science and Technology Policy provides a forum for invited authors to share research and offer thoughts on issues in this field. The Science and Technology Policy Institute developed the series at the request of the Office of Science and Technology Policy, part of the Executive Office of the President.

A Federally Funded Research and Development Center (FFRDC) chartered by Congress in 1991, the Science and Technology Policy Institute provides objective analyses on topics of interest to the Office of Science and Technology Policy and other Federal Government agencies, offices, and councils. The Institute is operated by the Institute for Defense Analyses, and its work for the Office of Science and Technology Policy is funded by the National Science Foundation.

FACTORY@HOME

THE EMERGING ECONOMY OF PERSONAL MANUFACTURING

OVERVIEW AND RECOMMENDATIONS

A report commissioned by the US Office of Science and Technology Policy

December 2010

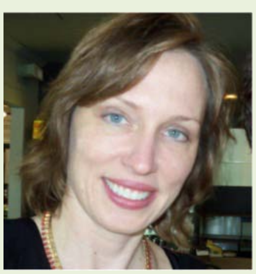
HOD LIPSON, Cornell University

MELBA KURMAN, Triple Helix innovation

(File version PersonalFab46.docx)

About the Authors

Hod Lipson is an Associate Professor of Mechanical & Aerospace Engineering and Computing & Information Science at Cornell University in Ithaca, NY. He directs the Computational Synthesis group, which focuses on novel ways for automatic design, fabrication and adaptation of virtual and physical machines. He co-founded the Fab@home project to develop low cost, open-source 3D printers. He has led work in areas such as evolutionary robotics, multi-material functional rapid prototyping, machine self-replication and programmable self-assembly. Contact Hod at hod.lipson@cornell.edu



Melba Kurman is an analyst and writer with over 15 years of experience in industry product development and university technology transfer. She writes about emerging, game-changing university inventions and university technology transfer strategy and policy. Melba is the president of Triple Helix Innovation, an independent consulting firm dedicated to helping university and industry clients build better technology transfer partnerships. Contact Melba at melbak@triplehelixinnovation.com

EXECUTIVE SUMMARY

This report outlines the emergence of personal manufacturing technologies, describes their potential economic and social benefits, and recommends programs the government should consider to realize this potential.

Personal manufacturing machines, sometimes called "fabbers," are the pint-sized, low-cost descendants of factory-scale, mass manufacturing machines. Personal-scale manufacturing machines use the same fabrication methods as their larger, industrial ancestors, but are smaller, cheaper, and easier to use. Home-scale machines, such as 3D printers, laser cutters, and programmable sewing machines, combined with the right electronic design blueprint, enable people to manufacture functioning products at home, on demand, at the press of a button. In just a few hours, these mini-factory machines can produce a simple object like a toothbrush, or make complex machine components, artisan-style jewelry or household goods. Within a few years, personal manufacturing machines may be sophisticated enough to enable regular people to manufacture complicated objects such as integrated electronic devices.

A number of converging forces are bringing industrial-scale design and manufacturing tools to a tipping point where they will become cheap, reliable, easy, and versatile enough for personal use. The rapid adoption of personal manufacturing technologies is accelerated by low cost machinery, active online user communities, easier-to-use computer aided design (CAD) software, a growing number of online electronic design blueprints, and more easily available raw materials.

Personal manufacturing technologies will profoundly impact how we design, make, transport, and consume physical products. As manufacturing technologies follow the path from factory to home use, like personal computers, "personalized" manufacturing tools will enable consumers, schools and businesses to work and play in new ways. Emerging manufacturing technologies will usher in an industrial "evolution" that combines the best of mass and artisan production models, and has the potential to partially reverse the trend to outsourcing. Personal manufacturing technologies will unleash "long tail" global markets for custom goods, whose sales volumes of will be profitable enough to enable specialists, niche manufacturing, and design companies to make a good living. Underserved communities will be able to design and manufacture their own medical devices, toys, machine parts and other tools locally, using local materials. At school, personal-scale manufacturing tools will empower a new generation of innovators, and spark student interest in science, technology, engineering and math (STEM) education.

Barriers and challenges: A number of barriers stand in the way of mainstream adoption of personal manufacturing technologies that discourage widespread home, school and business use. A chief barrier is the "chicken and egg" paradox, where today's current consumer and education markets for personal fabrication technologies is too small to attract the attention of companies, discouraging company investment in creating products and services, hence failing to attract more consumers. Other barriers are safety concerns, part standardization and version control challenges, intellectual property issues and a lack of appropriate safety and regulatory controls.

Recommendations: Over thirty years ago, our nation led the way in the personal computing revolution. Today, we need to ensure we lead the way in the personal manufacturing revolution. Thoughtful and visionary government investment is needed to ensure that the US remains competitive in an era of personal fabrication and realizes the potential benefits of personal manufacturing technologies.

This report recommends the following actions be taken.

1. Put a personal manufacturing lab in every school
2. Offer teacher education in basic design and manufacturing technologies in relation to STEM education
3. Create high quality, modular curriculum with optional manufacturing components
4. Enhance after school learning to involve design and manufacturing
5. Allocate federal support for pilot MEPs programs to introduce digital manufacturing to regional manufacturing companies
6. Promote published and open hardware standards and specifications
7. Develop standard file formats for electronic blueprints design files
8. Create a database of CAD files used by government agencies
9. Mandate open geometry/source for unclassified government supplies
10. Establish an "Individual Innovation Research Program" for DIY entrepreneurs
11. Give RFP priority to rural manufacturers that use personal manufacturing
12. Establish an IP "Safe Harbor" for aggregators and one-off producers
13. Explore micropatents as a smaller, simpler, and more agile unit of intellectual property
14. Re-visit consumer safety regulations for personally-fabricated products
15. Introduce a more granular definition of a "small" manufacturing business
16. Pass the National Fab Lab Network Act of 2010, HR 6003
17. "Clean company" tax benefits should include efficient manufacturing
18. Offer a tax break for personal manufacturing businesses on raw materials

19. Fund a Department of Education study on personal manufacturing in STEM education
20. Learn more about user-led product design

Acknowledgements

Many thanks are due to many people for helping us assemble this report.

First, the infinitely creative current and former students at the Cornell Computational Synthesis Lab, and in particular those engaged in printing and manufacturing, including, Jeffery Lipton, Evan Malone, Daniel Cohen, and Jonathan Hiller.

The Fab@Home student team who comes up with fresh ideas every day.

To the Fab@School team, including Glen Bull, Peggy Healy Stearns, Laura Smolkin, Robert Berry, Daniel Tillman, William Kjellstrom, and Jack Minsky, who are pioneers of personal fabrication in STEM education.

To Joris Peels and the Materialise staff, who let us see firsthand their facilities and share their insights, as well as suggesting recommendations.

To Robert Schouwenburg and staff at Shapeways, for showing us their facilities and taking the time to talk with us to share valuable insights.

To Adrian Boyer, the pioneer of the open-source 3D printing community, for sharing his thoughts and suggesting recommendations.

To Neil Gershenfeld, founder of the Fab Lab movement and a chief advocate of the value of personal fabrication technologies in education and emerging economies.

To Tom Okite, Fab Lab director in the Kenya Fab Lab, for sharing his wonderful stories and images.

To Rabiah M. Mayas, Science Director, Science Chicago, Museum of Science and Industry, for sharing her thoughts and plans for the Museum Fab Lab.

To Anthony Blumfield, for reading drafts of early manuscripts, and providing invaluable comments and suggestions.

To Zack Schildhorn of Forbes Emerging Tech and Lux Capital for his thoughtful insights.

Table of Contents

INTRODUCTION TO PERSONAL MANUFACTURING

For a few thousand dollars, anyone can buy their own personal-scale manufacturing machine, download electronic blueprints to their home computer, and manufacture unique and complicated objects at home. Personal manufacturing machines, or “fabbers,” are the pint-sized, low-cost descendants of mass manufacturing machines used in factories. Different types of small-scale manufacturing machines such as 3D printers, laser cutters, and programmable sewing machines, combined with an electronic design blueprint, enable people to create a wide range of objects. People that have no special skills or training can “rip, mix and burn” physical objects such as custom machine parts, unique household goods, jewelry, toys, and maybe someday, electronic devices.

Personal manufacturing is where personal computing was in the 1970s, before the advent of home-scale computers and consumer software. Recent rapid technological advances in personal manufacturing technology, combined with shrinking costs of machines, increasingly available design software and raw manufacturing materials, plus most peoples’ tendency to conduct more daily activities online, are tipping personal fabrication from the realm of hobbyists and pioneers to the mainstream. As consumers, businesses, and schools gain access to the same powerful design software and manufacturing tools traditionally available only to large companies and factories, we will witness a cascade of innovation in product design, educational tools, the arts, medical devices, and business models.

A brush made by a 3D printer. The brush was fabricated of two different materials which were printed simultaneously into a single functional object, not assembled later. Image courtesy Objet Inc.

This report provides an overview of today’s emerging personal manufacturing technologies, their societal and economic impact and benefits, their future, and their dangers and challenges. We offer several recommendations to ensure that these emerging technologies fulfill their social, economic, innovative and educational potential.

What is personal-scale manufacturing?

Sophisticated manufacturing technologies are becoming available to regular people. In their 2009 annual report *Innovations That Could Change the Way You Manufacture,* the Society of Manufacturing Engineers (SME) selected personal-scale manufacturing machines as a technology that "could change the way we do manufacturing." Last year, the *Economist* said "home-scale, or personalized manufacturing technologies offer a new approach to designing and making objects that will change the way we design, transport, and consume physical products, unleashing new product ideas, new educational methods and new business models.[1] Recently the *New York Times* ran an article describing the explosive growth of personal manufacturing technologies as a new manufacturing paradigm that "could revamp the economics of manufacturing and revive American industry as creativity and ingenuity replace labor costs as the main concern around a variety of goods."[2]

Personal manufacturing machines use the same manufacturing methods as their larger industrial forbearers to create a mind-boggling variety of goods and products. Most of the products we buy today are mass-produced in factories by machines that use one (or sometimes a combination) of techniques in which a raw material is exposed to machine-based cutting, carving, adding material, burning, reshaping, weaving, or knitting and sewing. A fabber does the same thing as a factory-scale manufacturing machine, but on a smaller scale.

A model train part made on a 3D printer by renowned toy train designer Mark Kendrick. The cow catcher is $22.00 in polished stainless steel. Kendrick sells his custom designs online. Image courtesy Shapeways.

Personal-scale manufacturing tools enable people that have no special training in woodworking, metalsmithing, or embroidery to manufacture their own complex, one-of-a-kind artisan-style objects. A leading example of the power of personal-scale manufacturing technologies is Mark Kendrick. Kendrick designs beautiful custom model train parts. His designs are captured in software blueprints and sold online. Rather than selling his unique model train part designs to large toy companies that would mass produce them, instead, Kendrick targets hobbyist model train enthusiasts that own, or have access to their own small-scale manufacturing machine. Since the cost of manufacturing a custom train part on a small-scale 3D printer is only $25, Kendrick's niche market of loyal consumers can afford to manufacture their own train parts -- no investment in factory-scale production is needed. Imagine if a model train enthusiast purchased Kendrick's electronic blueprint and tried to produce the stainless steel train cowcatcher (shown in the figure) in a factory. The high cost of setting up a factory infrastructure would be well out of the reach of the average consumer. Unless a commercial toymaker was confident Kendrick's custom designs would sell in large numbers, she would probably not invest in the set up costs; the market for custom cowcatchers is too small to warrant the costs of setting up large scale production. Personal-scale manufacturing tools are automated artisans: they combine the power of computer-guided manufacturing machines with the skilled artisan's ability to create custom objects for niche markets. Unlike artisan or large-scale factory production, however, personal manufacturing is a low cost process that doesn't require investment in an assembly line, or a skilled artisan.

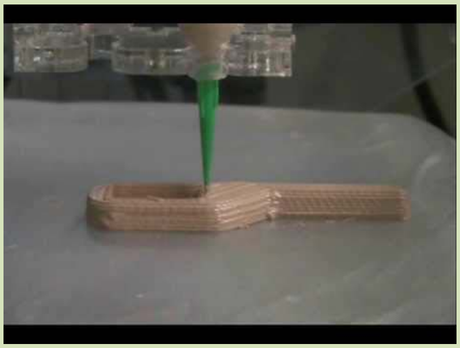
What, exactly, are these radical new manufacturing machines, and how do they work? The most commonly used personal manufacturing machines are 3D printers, desktop routing and milling machines, laser cutters, circuit makers and knitting and sewing machines.

Desktop 3D printers

3D printers are the fastest growing type of personal manufacturing machine, and perhaps the best publicized by the popular press. 3D printers use as an additive process, meaning they make objects by systematically depositing a chosen raw material in layers. Somewhat similar in concept to that of an inkjet printer that orchestrates different colored print cartridges to form an image onto paper, the most common household 3D printing process involves a "print head" that works with any material that can be extruded, or squirted through a nozzle. Another common type of 3D printer uses a laser beam or glue to selectively fuse powdered plastic, metal, or ceramic raw material in layers.

People get excited about 3D printing for several reasons. Thanks to the meticulous layer-by-layer fabrication process, 3D printers are able to combine materials and form shapes that cannot be easily manufactured on traditional manufacturing machines.

3D printers appeal to artists and designers since their unique layer-upon-layer production process enables creative people to precisely fabricate imaginative and unusual objects, according to exact blueprint specifications. 3D printers are clean, meaning since their manufacturing process does not involve cutting, scraping, or burning a raw material, they produce very little manufacturing waste, or un-used by-product. Due to their precision and versatility, 3D printers are already in use in industry for industrial modeling, product or part visualization, and prototyping.



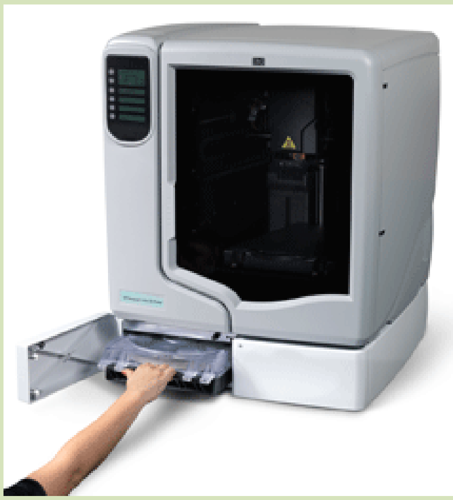
THE 3D PRINTING PROCESS CONSISTS OF A "PRINT HEAD" THAT LIKE AN INKJET PRINTER IN PAPER, DEPOSITS LAYER UP LAYER OF TINY DROPLETS OR STRANDS OF MATERIAL ONTO AN OBJECT UNTIL A THREE-DIMENSIONAL OBJECT IS FORMED. THIS IMAGE FROM THE FAB@HOME PROJECT, DEPICTS THE PRINTING OF A PLASTIC PART FOR A ROBOT'S LEG.

The 3D printing process works as follows. Once the user has selected an electronic design blueprint and loaded up the raw materials into the 3D printer, the machine begins its work. In a process that can take several hours to days, the 3D print head deposits layer upon layer of tiny droplets of raw material to form the object. Depending on the complexity of the design, the machine is able to switch between different print heads to work with multiple materials and form shapes with a number of colors and diverse textures. Eventually, after countless back-and-forth sweeps, a three-dimensional object forms out of raw material.

Consider the formal definition of 3D printing, or "additive manufacturing" as defined by the ASTM International Committee F42 on Additive Manufacturing Technologies[3] as, *"process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies."*

Note the allusion above to medical scanners and video games, which hints at the versatility of 3D printers. Almost any physical object that can be sliced into thin, horizontal cross-sections and represented in an electronic blueprint can be 3D printed. Another characteristic of 3D printers which makes them uniquely versatile is their ability to simultaneously print, into a single object, previously incompatible materials.

When working with raw materials that are chemically incompatible, or that require different manufacturing conditions, traditional manufacturing machines must work on the incompatible materials in separate processes and then assemble them later. Since 3D printers form objects layer by layer, they fuse together multiple materials into a single object at the time or printing. As a result, in a single "print job," a 3D printer can combine materials that have different physical properties to produce, for example, a plastic hair brush with soft-bristles set into hard plastic.



A 3D PRINTER. ABOUT THE SIZE OF A MICROWAVE OVEN, IT FABRICATES COMPLEX OBJECTS BY DEPOSITING MATERIAL LAYER BY LAYER. HERE SHOWN WITH A USER LOADING A MATERIAL CARTRIDGE. IMAGE COURTESY STRATASYS INC.

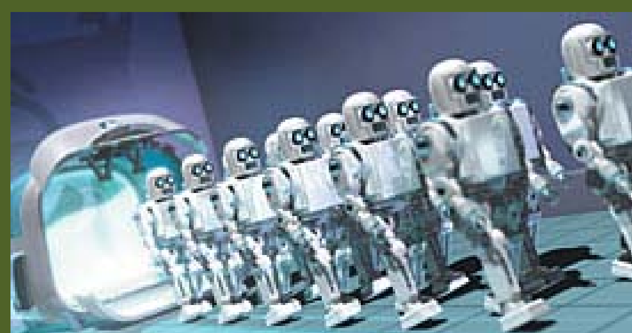
This "co-fabrication" process is not unlike biological growth, where hard and soft tissue is co-fabricated and intertwined in living beings of infinite complexity. Future applications for 3D printing remain as limitless as the human imagination. Someday 3D printers will be able to print complete electronic circuits that come out of the machine already inside their mechanical casing, with no later assembly required. Perhaps not surprisingly, given our love affair with food, a popular application for 3D printers is that of custom food and candy. Since it is meticulous and can combine materials in new ways, a 3D printer can create edible materials and custom confections that rival, or even exceed those made by skilled master bakers.

The most commonly used material in 3D print applications is plastic, but some higher-end machines are able to work with metals and ceramics. As the price of 3D printers shrinks, consumers are experimenting with the fabrication of novel recreational consumer items such as jewelry and toys. In industry, companies print specialized technical parts for high end electronic and medical products that demand custom precision, such as dental crowns and bridges. A vibrant hobbyist 3D printing community continues to attract a growing number of designers, businesses and consumers.

Robots printing robots

Assembling electrical and mechanical parts is a costly and error-prone step in the process of making electronic devices. The Fab@Home team at Cornell is pursuing the holy grail of personal fabrication, the ability to manufacture, on a single 3D printer machine in a single "print job," an object that contains a battery, actuators, sensors, and a physical "body." In other words… a robot. Today's 3D printers are already capable of combining and manufacturing previously incompatible materials, namely simple electrical components and mechanical parts, called electro mechanical devices. Your cell phone or laptop (or Roomba) is made of electrical and mechanical parts that were manufactured on separate, specialized machines and assembled afterwards by yet another machine, or human factory workers.

To the lay person, printing an electro mechanical device on the same machine, at the same time, may not sound that revolutionary. However, when future 3D printers are able to manufacture very sophisticated devices that contain fully formed electronic circuitry, batteries, sensors inside some sort of mechanical "body," we will witness the production of fully formed robots that will not require further assembly. The ability of a 3D printer to print all of a robot's vital parts in one fell swoop, directly from raw materials, would not only save time and effort on assembly. Printing previously incompatible materials into a single object would allow scientists and designers to explore new and more efficient structures for robotic devices.



Perhaps someday the first 3D printed robot will be "born" from a printer, fully complete, with a full functioning electrical "brain" inside of its physical "body." If you consider a 3D printer, plus an electronic blueprint to be a form of robot, (it's a bit of a stretch but who says robots have to be built like humans or R2D2?), then a 3D printer that manufactures a complete robot would qualify as "a robot printing robots." Imagine an assembly line of computer-guided, 3D printers giving "birth" to baby robots that crawl out of the printer and wander off to a nearby nursery where they learn to use their arms and legs according to instructions already hard-wired into their electronic circuitry.

Industrial size 3D printers cost up to half a million dollars, but low end personal-scale 3D printers cost less than $1000. The main disadvantage of 3D printers is the slow speed of their unique layer-upon-layer fabrication process. Even industrial-scale 3D printers are too slow to quickly produce large volumes at the rate needed in mass production environments. As a result, 3D printers remain impractical for the production of anything other than small batches of a kind custom objects, complex product prototypes or objects d'art.

DESKTOP ROUTERS AND MILLING MACHINES

Perhaps less exotic, but more established than 3D printers are desktop-sized numerically controlled (CNC) routing and milling machines. These machines use a physical blade to cut and carve precise designs into a broad range of materials. Under the guidance of an electronic design blueprint, a rotating mill bit, sometimes called a cutter, is spun along by a motor called a router or spindle. As the electronic blueprint guides the cutter along x, y and z coordinates, the cutting tool makes multiple passes over the material to create perfectly carved engravings or shapes.

A COMPUTER NUMERICALLY CONTROLLED (CNC) ROUTING AND MILLING MACHINE STEERS A ROTATING BIT OVER A PIECE OF PLASTER TO CREATE THIS RELIEF DIRECTLY FROM AN ELECTRONIC BLUEPRINT. PICTURE TAKEN AT THE 2010 MAKERFAIRE

CNC routers and milling machines work with a wide variety of materials, from wax to wood to metal to porcelain. CNC routers and milling machines are capable of manufacturing a broad range of everyday objects and parts, ranging from plastic name plates and printed circuit boards, to complex 3D objects such as airplane parts and kitchen utensils.

The upside of desktop routers and milling machines is that they are precise, faster than 3D printers, and work with a larger variety of materials. Since computer-guided CNC routers and milling machines have been in existence in industry for decades, they enjoy a large variety of available tooling, and a broad and experienced user base. Due to their speed and precision, CNC routers and milling machines, even small ones, are ideal for creating large batches of items. However, CNC machines are significantly less versatile than 3D printers in the range of shapes they can create.

Desktop laser cutters and engravers

Affordable laser cutters and engravers bring immense power and versatility to the average consumer, teacher or small business. Like their industrial-strength forbears, laser cutters and engravers use intense, focused beams of light to cut out shapes and engrave images onto a wide variety of materials. Laser machines can produce images, text or designs in an amazing level of detail and precision. Laser cutters are versatile and can cut a range of materials from wood to plastics to leather, and can etch or engrave metals, glass and ceramics. Their versatility, speed and precision make them ideal machines for small businesses to create design prototypes and customized consumer products. Beyond engraving, one of the most common uses of home-scale laser cutters is to precisely cut parts out of a sheet of acrylic or wood. These parts can be assembled by hand into complex, 3D products such as the wooden lantern pictured here.

This lamp was assembled out of flat pieces of wood that were cut by a laser beam according to a custom design with a desktop laser cutter. Picture taken at the 2010 MakerFaire

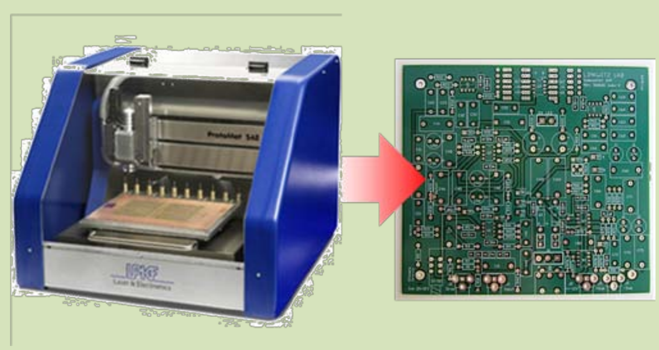
Desktop sewing and embroidering machines

Sewing, knitting and weaving machines have long been in home use. However, automated sewing, knitting and weaving machines have until recently, only been available to industrial textile and clothing manufacturers. Automated, personal-scale embroidery machines are already available in mainstream stores such

This computer-guided home sewing machine can embroider elaborate patterns according to designs from a selection of electronic blueprints. Similar machines can knit, weave and sew clothing according to patterns from a design file. Picture from Singer's web site as JoAnn Fabrics. JoAnn Fabrics customers download a design blueprint for a custom piece of embroidery from the web, save it onto a USB key, and insert the USB key into the store's automated embroidery machine. The machine custom-embroiders their custom pattern on the spot, in the store, while the customer waits. Computer-guided embroidery machines are as skilled as an expert needle worker and can fabricate ornate designs involving several different colors of thread and intricate patterns.

So far, personal-scale knitting and sewing machines continue to be manufactured and sold by large, established companies such as Singer and Brother. Singer's venture into automated, personal-scale sewing machines bills itself as "SINGER® Futura.™ The first sewing and embroidery machine that uses a personal computer to power the embroidery features."[4] Brother's entry into automated home sewing and embroidery is more ambitious. Brother offers five models that all have a USB port so users can import designs from their computer. Their models range in price from an $800 entry-level version to the powerful "Entrepreneur™ PR-650," available only through authorized dealers, which bills itself as "The Next Step In Starting Your Own Embroidery Business." All Brother machines embroider and sew; the two most expensive Entrepreneur resemble medical machines with an attached computer monitor, a white, clinical-looking dashboard with a number of knobs, and gleaming machine parts that hold different colored threads[5].

DESKTOP CIRCUIT MAKERS



PERSONAL CIRCUIT MAKERS FABRICATE MULTILAYER PRINTED CIRCUIT BOARDS ON YOUR DESKTOP, WITHOUT THE TRADITIONAL CHEMICAL-INTENSIVE INDUSTRIAL PROCESSES, EITHER BY MILLING OR SPRAYING CONDUCTIVE TRACES. IMAGE COURTESY LPKF

Circuit boards, also known as printed circuit boards (PCBs) are the heart of almost every laptop, cell phone, iPad, GPS and medical device in use today. Currently, almost all PCBs are manufactured industrially, but at-home manufacture of circuit boards is a rapidly emerging application for hobbyists and electronic designers. The traditional manufacturing of circuit boards is a messy and toxic process, involving strong acids and solvents. Desktop circuit makers offer a clean alternative to traditional chemical-based processes, making them an appropriate tool for the classroom, lab or home.

Personal scale PCB milling machines use one of two processes, a mechanical etching process, or a process in which conductive materials are sprayed onto a base board. The mechanical etching process on a desktop circuit maker involves a rotating milling bit that mechanically etches out the desired circuit design onto a copper circuit board. Both etching and spraying techniques enable users to create multi-layer and finely detailed PCBs.

While small-scale circuit makers are relatively low cost and versatile, they are, like most other personal fabrication technologies, too slow for large batch production. As a result, most users are hobbyists and students. PCB makers are a catalyst for the emergence of an open source hardware movement. A small but enthusiastic user community of hobbyists exchange open source hardware blueprints and are developing an open source hardware license.

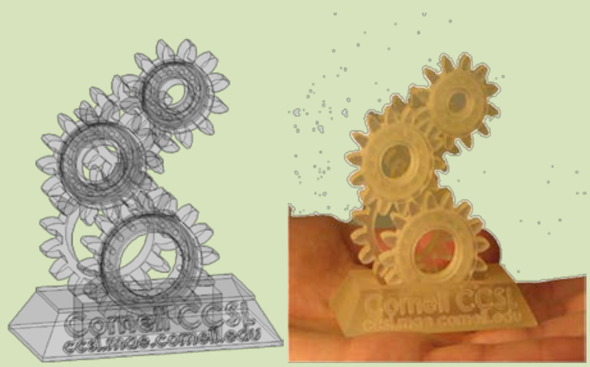
Computer-aided design software (CAD)

Hardware is not useful without software. The adoption of personal-scale manufacturing machines comes hand-in-hand with the emergence of cheaper, and increasingly accessible computer aided design software (CAD). Personal computers offered little appeal to non-expert users before the mainstream introduction of intuitive graphical user interfaces such as Windows, office software, and the web. Similarly, personal-scale manufacturing machines gain greater mainstream appeal as software design tools becoming increasingly accessible to mainstream users.

Industrial designers and engineers have used CAD software for decades. However, CAD software has been slow to reach the consumer market and remains one of the last bastions of software still targeted to, and controlled primarily by high-end industrial users. CAD software is expensive, requires a computer with an excellent monitor and lots of memory, and perhaps most importantly, has a long learning curve that deters casual users. In industry, CAD software long ago replaced drafting tables and paper blueprints. However, due to its cost and complexity, CAD software has remained the tool of trained specialists and professional designers, not home users.

Industrial designers use CAD software mainly to design detailed 3D models or 2D drawings of components or floor plans. Process diagrams are another popular application. Engineers rely heavily on CAD software to draft and analyze the entire engineering process from concept, to layout, to analysis, to defining the best manufacturing methods. While critical to the process of industrial design, these powerful software design tools, thus far, have not been relevant to needs of the average consumer, student or designer.

The same forces that brought us mainstream consumer software, however, are beginning to impact even the world of CAD software, The cost of CAD software is dropping and software companies are working hard to make it more user-friendly. In 2008, Google entered the CAD game with a no-cost version of 3D modeling software called SketchUp. Currently, SketchUp is offered in a "Pro" version that costs about $500 (at the time of this writing), alongside a free version. Rhino offers Windows-based 3D design software from $95 to $1000. http://www.rhino3d.com/ . A company called Silo offers Windows and Mac based design software for $99 and $159. http://www.nevercenter.com/silo/



The personal fabrication process begins with an electronic blueprint (left). The fabber reads the electronic blueprint and follows its instruction to manufacture the final physical object (right) from raw materials. Image courtesy Michael Tolley.

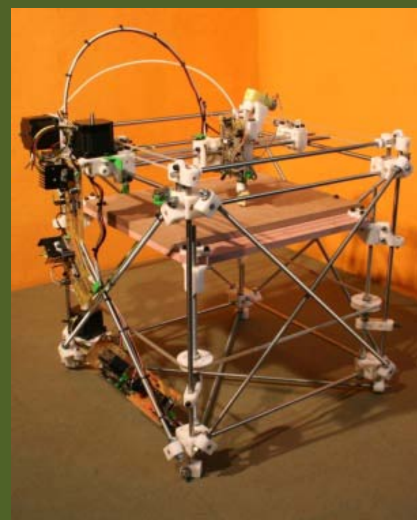
Realistically, though CAD software continues to drop in price and complexity, it's still nowhere near as user-friendly as today's mainstream office applications. Another barrier is that even the low-end CAD software described above was not created with personal fabrication applications in mind. Instead, today's CAD software reflects its industrial legacy and is intended primarily for modeling and visualization applications rather than designing consumer goods and machine parts. Ideally, to accelerate the adoption of CAD software aimed at the personal manufacturing market, design software would need to be easier to use and optimized for the unique constraints and capabilities of the physical manufacturing process.

A foundation on university technologies

Today's lowest cost 3D printers have their roots in university research projects. The two leading consumer-level 3D printer platforms originated from university research labs at Bath University in England, and Cornell University in the United States. The University of Bath's 3D printer is called RepRap and Cornell's is called Fab@Home.

Perhaps because of their university origins, the machine blueprints for both RepRap and Fab@Home are freely available to anyone who wants to build their own machine, or to improve upon the existing designs. Not only do Cornell and the University of Bath openly publish their machine design blueprints, they permit commercial companies to develop and sell their own versions based off of the designs of the original university machines. In contrast, commercial-scale 3D printers are developed commercially and their product designs are proprietary and not shared publicly.

RepRap (short for Replicating Rapid-prototyper). Bath University in England

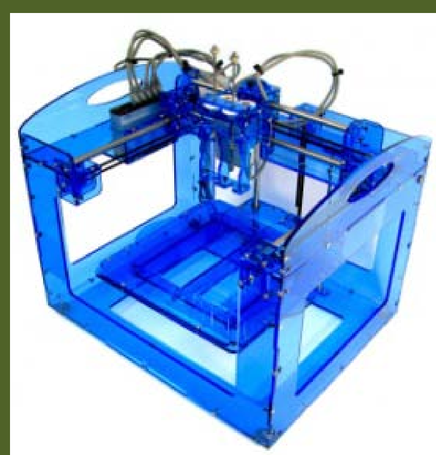


Dr. Adrian Bowyer and his graduate student, Ed Sells, created RepRap in 2004 with the goal of making a low cost 3D printer, but also one that could print its own parts. Darwin, an open-source 3D printer, was made available in 2007. Today a number of commercial kit makers sell versions of the RepRap, including Ponoko in New Zealand, Bits From Bytes (UK), MakerBot (U.S.) and Shapercube (Germany). MakerBot sells their entry level Cupcake machine for about $950[6].

In 2009, Bowyer and team introduced the second-generation RepRap machine, Mendel.

Fab@Home. Cornell University in Ithaca, NY, USA.

Fab@Home is an open source 3D printing platform that was developed at Cornell University. In 2006, graduate student Evan Malone and Professor Hod Lipson created the Fab@Home personal 3D printer. Fab@Home was designed to be versatile and works with almost any material that can be extruded through a plastic syringe and nozzle.



Though more expensive than other entry level 3D printers, Fab@Home can produce objects from a wide range of materials such as silicon, wiring, even food and has a variety of digital manufacturing tools for extruding, cutting, milling and assembling various materials[7]. The parts for Fab@Home, as well as complete machines are sold online by a variety of vendors and hobbyists. The cost of an unassembled machine kit is about $1,600.

MAKERS, DESIGNERS AND AGGREGATORS

"Economically — we are seeing the early beginnings of a powerful Maker innovation ecosystem. New products and services will allow individuals to not only Design it Yourself, but Make it Yourself and Sell it Yourself. For example, Tech Shops are providing access to 21st century machine tools, in the same way that Kinkos gave millions of small and home-based business access to copying, printing, and shipping."

– Thomas Kalil. Remarks on Innovation, Education, and the Maker Movement
New York Hall of Science, September 29, 2010

A growing number of small companies today are basing their business on personal-scale design and manufacturing tools. This section lists leading businesses in the personal fabrication space. The field is rapidly expanding so this list is by no means comprehensive.

MAKERS

A new breed of personal-scale manufacturer is emerging, despite the fact that the majority of personal fabrication technologies are used by individual hobbyists (who are too many to list). Below we provide brief descriptions of leading personal manufacturing companies, sometimes called "makers."

Big Blue Saw. Like eMachineShop, Big Blue Saw offers users its own CAD tools so they can design wood, fabric, metal or plastic parts for prototypes and small project. Their web site describes the process as: 1) Create a design using the Big Blue Saw Designer or your favorite design software. 2) Upload your design to our website to get an instant price quote and to order. 3) We will ship you your custom metal, plastic, wood, or fabric object, typically within 3 business days.

eMachineShop provides provide easy, convenient and low-cost fabrication of custom parts via the web. Customers can design whatever part they need using emachineshop's CAD tools. Once the electronic blueprint is complete, users get an instant quote and can order the part to be made in the material of their choice. Users have ordered toys, car parts, electronic devices, games and more. Industrial machine parts are sold at eMachineshop http://www.emachineshop.com/

Materialise is a Belgium-based company that designs and manufactures high end art, housewares, jewelry and other luxury items in-house. Materialise hires professional designers to create blueprints of stunning usable objects that users purchase from their web site; if customization is desired, customers work with the professional designer to alter basic design parameters such as the size or color of the object.

i.materialise is an experimental spin-off from Materialise. i.materialise is an on-line service that offers 3D printing services of custom designs made by consumers. Consumers first manufacture their own designs using Google Sketchup. They get an account on i.materialise follow a series of simple steps to turn their electronic blueprints into reality using the site's easy pull-down menu selection of surface textures, colors and other design features. After customers select their design, i.materialise manufactures their design using 3D printers.

Print23D – Pennsylvania, US. Print23D offers 3D printing services for Fortune 500 companies to regular people who have CAD designs they'd like to try out. A small print job costs about $50 while a five or six inch square object may cost about $400 to 3D print. Print23D's focus is on industrial and machine parts, not consumers and product designs.

AGGREGATORS

Aggregators are companies that host online catalogs of electronic design blueprints for available products, machine parts and other objects. Like amazon.com or eBay, aggregators offer storefronts for third party merchants such as designers. Some aggregators like shapeways.com also offer fabrication services, while others offer small-scale manufacturing services, while others, such as Ponoko, act as brokers between consumers, designers and makers.

While new aggregators appear every week, two of the pioneering companies are Shapeways and Ponoko.

Ponoko – Location: New Zealand. On Ponoko's web site, consumers, designers, makers and materials suppliers register for accounts and come together online. Consumers can design their own product using Ponoko's starter kit design software and fabricate their chosen product themselves, on their own fabber. Or, consumers can download free and purchasable software design blueprints, and if they don't have access to their own home manufacturing machine, can post a request via an online form to tap into Ponoko's "making hubs" to have a nearby maker nearby do the fabrication. Ponoko's materials suppliers sell paper, fabric, metal, rubber and wood alongside sophisticated hardware components such as accelerometers, sensors, GPS and wireless antennas.

Shapeways – Location: The Netherlands and New York. Shapeways is the leading aggregator with a large online collection of sophisticated designs that range from toys to art to machine parts. Shapeways has a manufacturing space that contains several 3D printers that fabricate customer designs. Products are sold via a number of different storefronts that each feature a different designer. Consumers select a design from a designer who runs their own online storefront or consumers can make their own design using Shapeway's proprietary design tools. Shapeways employees offer user support and design advice, if needed. Consumers and designers interact directly if the user has a special request. The more active designers on Shapeways earn several thousand euro a month from selling their designs.

DESIGNERS

Designers that create objects for personal-scale manufacturing tools run the gamut from established professional design firms to part-time hobbyists. Designers that have access to personal manufacturing technologies can tinker with riskier designs made of unusual materials at a much lower cost than currently possible. While designers create electronic blueprints for all types of personal fabrication technologies (i.e. CNC routers, laser cutters, sewing machines), the majority of designers focus on 3D printed objects. However, the field grows every day, and there are countless talented designers not listed below.

A CUSTOM VASE DESIGNED BY FUNG KWOK PAN OF DWELL ON DESIGN. THIS VASE WAS 3D PRINTED; ITS UNIQUE SHAPE WOULD BE VERY DIFFICULT TO CARVE OR MOLD. INDEPENDENT DESIGNERS CAN SELL UNIQUE DESIGNS SUCH AS THIS ON THEIR WEB SITES AND FILL ORDERS ONLY AS THEY COME IN. PHOTO FROM DWELL ON DESIGN WEB SITE.

Unfold design studios. Location: Belgium. Unfold studios was founded in 2002 by Claire Warnier and Dries Verbruggen. They design and sell a wide variety of contemporary custom-designed and made furniture, household goods and jewelry.

Nervous System. Location: Massachusetts, United States. Nervous System was founded in 2007 by Jessica Rosenkrantz and Jesse Louis-Rosenberg. Nervous System 3D prints computer generated designs to produce affordable art, jewelry, and housewares.

Bathsheba: Location: California, United States. Bathsheba Grossman is one of the world's leading 3D printing designers. She creates sculptures and math models, what she calls " handheld geometry" out of 3D printed metal.

MACHINE BUILDERS

Below are a few small machine builders that focus exclusively on the sale of personal-scale manufacturing machines.

MakerBot: Location: New York, New York. MakerBot makes and sells affordable 3D printers that print plastics. Their leading 3D printer is called CupCake CNC which was has its technological roots in an open source hardware design for a model of 3D printer called RepRap that was invented at the University of Bath. Machine blueprints for CupCake can be freely downloaded. The CupCake is unique in that it can replicate its own parts. Users purchase machine kits online and assemble them at home. It takes two skilled people about two days to assemble a CupCake. MakerBot sales are strong. It began to sell kits in April, 2009. In March, 2010, 11 months later, the company reported it had sold 695 kits**Error! Bookmark not defined.**.

> ***"American culture presents a very low penalty for trying and failing. This may be the last true global competitive advantage we have and putting the maximum range of capabilities in the hands of the average citizen-designer/entrepreneur will help leverage this advantage."***
>
> *– Bruce Kramer, NSF Program director*

Lumenlab Micro CNC. Location: The United Kingdom. LumenLab sells multipurpose machines, meaning their personal-scale machines have the ability to use a number of different toolings, including 3D printing, 3D milling, and precision-engraving. LumenLab's two machine models are the micro v3 that's about 10 by 12 inches in size and costs $1294, and the larger m2 for $1799, which is about 19 inches square.

Bits From Bytes, Ltc. Location: United Kingcom. Bits From Bytes sells kits for 3D printers for home, classroom and small business use. Bits From Bytes was recently acquired by a larger 3D manufacturing machine company called 3D Systems. Bits From Bytes plans to continue to sell their low-end 3D printers. Their BFB300 sells for 2000 euro and can print a number of different materials. Their 3D printers are also based on the RapRap Darwin open source machine created by researchers at Bath University in England. As of March, 2010, Bits from Bytes was shipping about 200 kits a month**Error! Bookmark not defined.**. Each kit costs about $1,100 and is ssembled by its buyer.

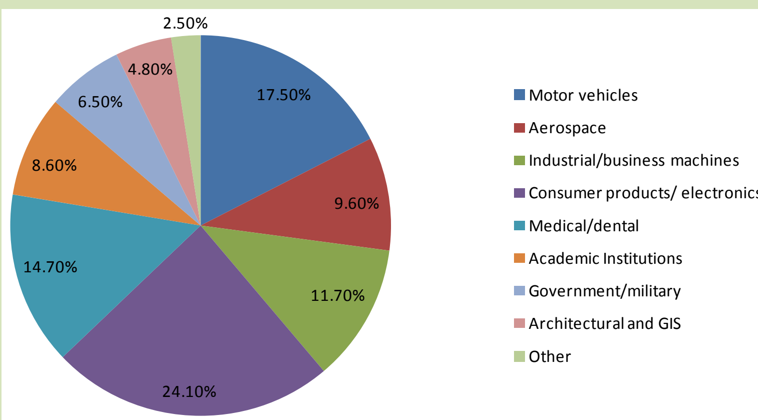
The market

Just as the democratization of information through personal computers was a key advance of the 20th century, the democratization of production through improvements in fabrication technologies will be a pivotal development in the 21st century."

– Simon Bradshaw, Adrian Bowyer and Patrick Haufe

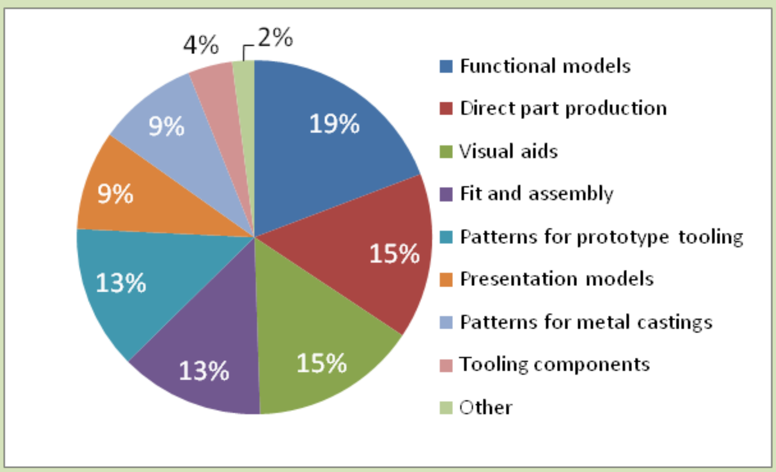
We've covered the emergence of leading personal manufacturing technologies and have provided an overview of their inner workings, but how many consumers, businesses and schools are buying the machines, and what are consumers using the machines for? Unfortunately, hard market data about consumer and industry use of personal manufacturing technologies is scarce. For the consumer market, we have only estimates and anecdotal data about the number of personal manufacturing machines in use today, and what type of objects people like to fabricate. More data exists on industry-scale 3D printers.

The growth of personal manufacturing technologies for everyday consumer use is driven by a small but growing worldwide community of "power users," self-selected, highly skilled enthusiasts. Power users can be tinkerers, innovators, researchers, teachers, business people, manufacturers and hobbyists. Power users tend to congregate online. For example, online communities of personal fabrication enthusiasts mingle on sites such as *Make* magazine's community forum *(Make* is the leading DIY magazine published by O'Reilly Media, Inc.), and swap designs on Google's 3D Warehouse and Shapeway's online marketplace. The size of these user communities is difficult to estimate since the owners of the web sites do not share how many active users they have, nor is it possible to get a count of



Industries that requested commercial 3D printing services. Data source: Wohlers Report, 2010 how many electronic blueprints are being uploaded and downloaded. Currently, there's no market research firm that tracks consumer machine sales, nor the number of installed machines, nor what types of services and products the machines are being used to provide. Like the market for early hobbyist personal computers, the personal manufacturing market is hard to quantify due to the fact that expert users tend to build their own personal manufacturing machines from toolkits or from spare parts they've salvaged from other manufacturing machines.

We have slightly better data about personal manufacturing technologies in the industrial space, but again, it's incomplete for several reasons. Businesses that use small-scale manufacturing machines are under the market research radar for reasons similar to those of consumer hobbyists. In addition, a number of different types of personal manufacturing machines are in use today; while it's likely that many companies use small-scale CNC routing and milling machines, or have a personal-scale laser cutter on site, these machines are unlikely to be counted or identified separately from their larger, industrial-scale counterparts.



THE TYPES OF OBJECTS REQUESTED BY COMPANIES WHO ORDER ITEMS FROM 3D PRINTING SERVICE COMPANIES. DATA SOURCE: WOHLERS REPORT, 2010

The commercial 3D printer space offers the most solid market research data thanks to the meticulous research conducted by Terry Wohlers and compiled in the annual *Wohlers Report,* the leading market research publication for the 3D print industry. The *Wohlers Report* tracks sales, applications and other news of 3D printing service providers and machine makers. According to the *Wohlers Report*, the industries that most commonly request 3D manufacturing services are consumer products/electronics, cars, the medical profession and companies that make industrial and business machines. The 3D printed objects most commonly requested by these industries are functional models, machine parts, visual aids and patterns for prototype tooling. The Wohlers Report data suggests that consumer companies, the auto industry, and specialized parts companies could someday provide a foundation for a new manufacturing ecosystem made up of 3D printing services providers that specialize in rapid prototyping and on-the-fly machine part production services.

Even given the limited data on the 3D printing industry, it's clear that in terms of machine sales, commercial activity and services revenue, the 3D printing marketplace still belongs to industrial-scale, not personal-scale machines. However, Wohlers' market data offers hints that this may be changing. In 2009, the biggest companies that made and sold 3D printers together earned a total of about $312 million in machine sales[9]. Market demand, however, may be shifting towards low-end 3D commercial printers. Last year, revenue across all reporting 3D printer companies indicated that 3D printer sales experienced their first-ever decline, dropping 13% from the year before.[9] In the same timeframe, however, the total *number* of 3D printers sold increased by almost 20%, suggesting that while total sales revenue earned by 3D printer-makers declined, the number of units sold of low-cost 3D printers *increased* significantly. Wohlers' data could suggest that 3D printers are on their way to becoming a commodity item, like laptops and other computing hardware. It's possible that as market demand increases for smaller, cheaper industrial 3D printers and the cost of these printers continues to drop, machine manufacturers will sell higher volumes of lower-cost printers to compensate for shrinking profit margins.

> ***"Our intention is to expand use of 3D printing in current markets, which are manufacturing and education segments. We are exploring how to expand to adjacent markets, such as architecture, which is currently using it in a marginal way. We are trying to understand the needs that customers have, from which we can then define future products.[8]"***
>
> *– Emilio Juarez, HP's worldwide 3D printing manager*
>
> *on HPs recent entry into 3D printing*

Wohlers' revenue data on sales of 3D printers is not the only indicator that commercial 3D printer manufacturers may be eyeing the low-end space. Recently, a leading home-scale 3D printer company, Bits from Bytes, was acquired by 3D Systems, an established industrial 3D printer manufacturer. 3D Systems may have been drawn to the fact that according to the 2010 Wohlers Report, in its first year of tracked commercial sales, Bits from Bytes outsold established industrial 3D printer companies. In its first year of selling 3D printers commercially, Bits From Bytes sold 17% of all 3D printer units worldwide, placing them second in 3D printer shipments. Their first-year sales are even more phenomenal when one considers that Bits from Bytes sells 3D printers primarily to the education and hobbyist markets, and that the 3D printers made and sold by Bits from Bytes have their roots in the open source RepRap project at the University of Bath.

If trends in the industrial markets for 3D printers are any indication, companies that sell large-scale manufacturing machines may soon face the innovator's dilemma. In his hugely influential book the *Innovator's Dilemma*, Clay Christensen describes the cyclical rise and fall of mature, industry-leading companies that at first, enjoy market dominance, and then again and again, fall into sudden obsolescence.[10] The force that pulls powerful, well-managed companies to their knees is not, as typically believed, poor management or brain drain. Instead, powerful market-leading companies falter because they are defeated by the innovator's dilemma: sales of their once cutting-edge, feature-rich, market-leading incumbent product are cannibalized by cheaper simpler products which Christensen calls "disruptive technologies."

A disruptive technology is not the most sophisticated or highest performing technology. Instead, a disruptive technology is a lower-cost product, or commodity product, that has fewer features but is cheap and considered "good enough" by at first, fringe users, and eventually, by mainstream users. The lifecycle of companies felled by the innovator's dilemma is as follows: a tech company painstakingly develops and improves their product according to ongoing feedback from their most lucrative customers. Although the incumbent company does everything right according to conventional business wisdom, its market dominance can't last forever. Eventually, a small company appears on the scene that presents a disruptive technology to the marketplace. The disruptive technology at first, appeals only to smaller customers who can't pay for, or don't need the incumbent company's expensive, feature-rich product.

The underdog business selling their disruptive technology continues to develop its product and eventually moves up market as their low-end technology improves to the point of being "good enough" for mainstream use, yet is significantly cheaper than the incumbent technology. Eventually, the disruptive technology cannibalizes the market from the incumbent technology, putting the putting formerly leading incumbent company out of business. Interestingly, before their demise, incumbent companies facing the innovator's dilemma are fully aware of commodity-level competitors. In Christensen's analysis of the phenomenon of disruptive technologies, the incumbent companies 1) already knew about the technology that eventually undercut them yet 2) chose to not do anything about it due to the small market size of potential customers and fear of cannibalizing sales of the incumbent product. In a sense, incumbent companies could be considered a victim of their own success.

We mention Christensen's work here to call attention to the possibility that personal manufacturing technologies have the potential to disrupt the dominance of their larger, more powerful industrial cousins in the manufacturing machine marketplace. The average selling price of an industrial-scale 3D printer continues to drop. In 2007, the average cost of a commercial-scale 3D printer was $77,000; in 2008, the cost was $70,000 in 2008; in 2009, the average price dropped further, to $52,000[9]. Consider the development of personal-scale manufacturing in the context of the computer chip industry, where as described by Christensen, leading chip companies, based on diligent market research and customer demand, went out of business because they continued to enhance their existing incumbent product line, ignoring smaller, cheaper, lower-end solutions that appealed to niche customers who had less money and simpler needs.

It's still very early in the game to predict whether companies that make expensive, industrial-strength manufacturing machines will face the innovator's dilemma. At this time, large-scale industrial manufacturing machines remain the incumbent technology. Today's personal fabrication technologies cannot offer large scale manufacturers the features and power they need to rapidly fabricate huge volumes of a mass produced product. As a result, most personal manufacturing machines are sold into the hobbyist space, a market that currently is too small to appeal to companies that make and sell large and costly manufacturing machines. However incumbent companies may find that low-cost, personal-scale manufacturing technologies are increasingly capable of taking over tasks that used to be the domain of larger, more expensive machines. Someday, if home-scale manufacturing technologies continue to improve at their current pace, personal fabrication technologies will creep up market, disrupting the dominance of costly, feature-laden, factory-scale manufacturing machines.

REACHING THE TIPPING POINT

> ***"There is no reason anyone would want a computer in their home."***
>
> *–Ken Olson, president, chairman and founder of DEC*

A number of converging forces will promote personal manufacturing from a fringe technology used by pioneers and hobbyists, to an everyday tool for mainstream consumers and businesses. Within a few years, personal manufacturing technologies will be commonplace in small businesses and schools. Within a decade or two, every household and office will own their own machine. Within a generation, you will have a hard time explaining to your grandchildren how you were able to live without your own fabber, when you actually had to buy ready made things online, and wait a long 24 hours before they showed up in your mailbox.

Customization is in and consumers want to be unique: In this era of mass production, today's status symbols are the goods and products that no one else has. Personal fabrication technologies bring one-of-a-kind products into the reach of middle-class budgets. Do you have a unique ringtone that no one else has? Now you can have a unique shoe too.

Rip, mix and burn ... physical objects: "Home creators" make their own movies and custom music playlists.   and the same mentality is motivating people to buy a personal fabrication machine and set up a home manufacturing area in their garage. Today's consumers, particularly young consumers, expect to be able to make their own digital goods and products. Soon they will have the tools to make their own physical goods and products.

Cheap hardware: Personal manufacturing machines grow less expensive every year thanks to cheap hardware components. The lowest cost 3D printers on the consumer market today cost about $1000.

Accessible design software: Computer-aided design (CAD) software has traditionally been expensive and hard to use. As software tools become simpler and powerful enough for sophisticated design tasks, they will appeal to consumers that have no special training. Personal manufacturing machines will develop alongside design software, giving regular people and children access to powerful modeling and prototyping tools.

Electronic blueprints: The greater the number of designs for items to fabricate, the greater the appeal of personal manufacturing technologies. A growing number of web sites called aggregators host online blueprints for consumer goods and industrial machining parts. Some blueprints are created by skilled designers for commercial sale, while other blueprints are created by budding hobbyists and offered online free for purposes of reputation building.

> ***"A convergence of several trends are enabling the "DIY revolution": The growing online learning resources and digitally-facilitated distance collaboration, the increasing affordability of advanced tools and technology, and the expanding reach of online marketplaces to easily buy supplies and sell goods to dispersed set of customers"***
>
> *Zack Schildhorn, contributing editor of Forbes Emerging Tech Report*

Proven ecommerce retail model: Personal manufacturing aggregators, designers and makers do not have to break new ground to conduct their business transactions online. Thanks to well-established online e-commerce sites, consumers are already comfortable buying designs online from merchants they do not know, or see in person. E-commerce tools such as search technologies, product and designer reviews and merchant rankings have also become familiar to most consumers.

Proven ecommerce operational model: Online retailers have already figured out effective operational models to handle the shipping and distribution of objects ordered online. As a result, companies that manufacture and ship custom-manufactured products won't have to repeat the learning curve, nor will they need to convince consumers that their object will arrive unbroken and in good condition.

Social networking in maker communities: Personal manufacturing technologies are accelerated by the online communities of people who create electronic blueprints, those who build and fix machines, and consumers. Similar to the already well-known online community of open source software enthusiasts, communities are a critical part of the personal manufacturing revolution since little formal training and tech support exists. Online colleagues offer one another help, teamwork and encouragement.

Available raw materials: Personal manufacturing tools are of no use without easy available raw materials. Thanks to the advent of the Internet, rapid distribution services such as FedEx, a growing number of high quality, non-toxic plastics and ceramic, and a growing consumer base, home-scale manufacturing materials are becoming easier to locate and buy.

Educators want to serve different learning styles and offer hands-on learning: Personal-scale manufacturing tools serve today's educator's growing application of constructionist educational theory. Mainstream educators know that there is no "one size fits all" when it comes to classroom learning. Personal manufacturing tools offer students and teachers a wide range of pedagogical exercises and teaching aids.

Personal fabrication technologies offer the following advantages:

- **Better prototyping quality.** When a manufacturer has the luxury of running off designs overnight or faster, she can run more iterations of an idea. Manufacturers and designers have a lower cost way to tinker with design variations and make the final prototype is right.
- **Can respond to shorter product life cycles.** Even though improved quality will make a product able to last longer, the ability to iterate and improve upon product designs goes on continuously. Continuous product improvement and development will bring customers back for the latest versions of products.
- **Recyclability.** The combination of improved quality and shorter life cycles creates a conflict in the mind of the customer. He or she doesn't want to throw away a perfectly good product that's only a few months old, but she does want to get the latest version. The answer to this dilemma is to consume the old product in manufacturing the new one. This has been going on for years in the automotive parts industry, where, for example, customers get a discount on brake shoes if they bring in their old ones for remanufacturing.
- **Less waste and cleaner.** Personal fabrication machines, particularly 3D printers, are efficient; therefore they produce very little left-over waste material.
- **Low cost product prototyping and customization.** Since they demand less intensive and set up time compared to industrial manufacturing machines, tinkering and revising a prototype costs less on a personal fabricator.
- **Regional/local/home production – less shipping.** On-site manufacturing of goods means they can be made locally and do not need to be shipped.
- **No inventory – production on demand.** Virtual storefronts and small businesses that custom manufacture and sell products and goods do not need to invest in infrastructure up front; as a result, they can start their business on a small budget and scale up only as product sales grow.
- **Product lifetime saving.** When products are optimized for their target use, they often result in reduced lifetime costs. For example, if a motorcycle is

tailored to the unique size and riding habits of its own, it can be weigh less than a generic motorcycle, and therefore consume less energy over its entire life. [11]

The disadvantages of personal fabrication are as follows:

- **Reliability and quality assurance.** Home-manufactured toys, machine parts and other objects may suffer from a lack of regulatory oversight and quality control.
- **Liability challenges.** If a consumer is harmed by a home-produced object, it's not clear who will assume responsibility: the software designer, the maker, the materials manufacturer, etc.
- **No version control.** Because anything can be made anywhere, it's difficult to track revisions and sources. Software designs for machine parts or medical parts do not have a version control system to ensure that consumers purchase parts that are the correct and most current version.

> ***"A key to the effectiveness is a [personal fabrication lab] is that students don't need to imagine outcomes. When they can see and feel them with their own eyes and hands, their ability to analyze and understand is rapidly accelerated. Couple this with feedback from experienced mentors, and you have an unsurpassed learning model."***
>
> *– Will Ober, Sr. Instructional Designer, K12, Inc Commenting on the value of 3D printers as a STEM instructional tool.*

- **Consumer protection.** Since consumers use personal fabrication technologies at home, consumer protection is difficult to enforce if toxic materials are used or the machine malfunctions and harms somebody.
- **Intellectual property challenges.** IP issues are a leading concern of companies that work with personal fabrication technologies. For example, who would get sued if a consumer printed and sold a Mickey-mouse toy from someone else's downloaded electronic blueprints? The designer, the aggregator, the consumer, or all three?
- **No formal standards.** Each personal fabricator uses its own software and hardware standards, making interoperability and collaborations difficult.
- **No killer app.** Mainstream adoption is stymied by a "chicken and egg" problem similar to the early days of personal computing. Without a mainstream application, consumers will not purchase their own personal fabricator. Without enough of a potential consumer market, companies will not invest in creating software designs, inventing novel and improved raw materials.
- **Not yet cheap enough.** Most small-scale manufacturing machines still cost well over $2000, out of range for most hobbyist budgets.

- **Primitive.** Most machines today can only work with a single material at a time.

As they mature, personal manufacturing machines will have a profound impact on several arenas of our lives. A potentially promising application is as an instructional tool for our nation's faltering science, technology, engineering and math (STEM) education. As the U.S. struggles to maintain its status as a world super-power, there's growing concern that K-12 STEM education in U.S. public schools is failing to excite and prepare today's children to enter engineering, scientific and math-oriented fields. Without enough skilled engineers and scientists, our nation will have a difficult time making the transition from a manufacturing, to an innovation-based economy. Personal manufacturing technologies offer STEM educators the hope that if students are given the opportunity to design and manufacture their own ideas, students can put abstract scientific concepts into practice, hopefully sparking their interest in math and science. For students, these technologies offer a channel to exchange and co-design electronic blueprints with their classmates and schoolchildren in distant countries. Teachers will be able to create their own high quality teaching manipulatives that are directly related to their own unique course curriculum.

Printing food: 3d printers can produce a wide variety of food types from cookies with embedded vertical text to chocolate. Anything that can be squirted can be used as a raw material for the 3d printer. For some, food may be a comfortable and disarming avenue to introduce technology and stem. Image courtesy Fab@Home

Personal manufacturing technologies continue their slow creep into everyday life. The appeal of unexplored avenues of design and creation continue to attract new users, even engineering students who used their lab's 3D printer to become sophisticated bakers. At Cornell, engineering students that had no formal culinary training fabricated a number of custom-designed cakes on their lab's 3D printer. These custom-cakes, when cut open, revealed a letter "C," a feat that even skilled bakers can't achieve since cake batter cannot be manipulated to bake into precise vertically curved shapes. The engineering students designed the electronic blueprints for the special cake, and students from Cornell's hotel school made red and white cake batter and carried it over to the lab. Using the lab's 3D printer, the students printed cake prototype after prototype, until a party-quality cake containing the perfect vertically-aligned "C" inside appeared. Scenarios such as these, where unskilled people are transformed into designers and skilled creators, are happening today in people's homes, kitchens, and businesses.

Hobbyist interest in personal fabrication technologies continues to grow. At the 2010 MakerFaire in Queens, New York, a number of exhibitors demonstrated their personal manufacturing businesses and projects. The Queen of do-it-yourself (DIY), Martha Stewart, was a media sponsor of the event. Not all hobbyists need to invest in their own personal manufacturing machines and equipment. Around the country, buying a membership in a chain of TechShops provides an away-from-home workshop for people who love to make things, somewhat like a fitness center. TechShops lets members exercise their creativity rather than their muscles, providing members access to a wide variety of personal-scale machinery and tools, including milling machines and lathes, welding stations and a CNC plasma cutter, industrial sewing machines, a 4' x 8' ShopBot CNC router, Epilog laser cutters, and a Dimension SST 3-D printer. Currently there are several TechShops in California, Michigan, Oregon and North Carolina. Similar home-away-from-home workshops that provide local hobbyists with access to with personal manufacturing tools are sprouting up in cities around the U.S.

Getting personal: smaller, cheaper, easier and more fun

"Recent developments in producing affordable and hobbyist-friendly printers that can reproduce three-dimensional rather than just flat objects may mean that printing a toast-rack or a comb becomes as easy as printing a birthday card."

– Simon Bradshaw, Adrian Bowyer and Patrick Haufe

An industrial technology becomes "personalized" when it becomes cheap, small, and easy enough for mainstream consumers to use without extensive training. A virtuous cycle ensues as an industrial technology creeps into homes and offices, catalyzing new markets for companies that create applications, thereby attracting yet more consumers, and an even bigger market for applications. When enough applications exist that the formerly industrial technology becomes an affordable and essential tool for everyday use, the technology has become personalized. Probably the best known example of the emergence of a "personal" technology is that of the personal computer. Only a few decades ago, industrial computing was a highly specialized field that involved expensive mainframes the size of a small room doing primarily military and payroll calculations. Today, thanks to rapid, Internet-fueled evolution of online shopping, banking and socializing, the rise of everyday business software, and the advent of digitized media, most people today have a computer in their home. Even non-skilled users conduct a significant amount of their daily activities online.

Converging forces that are "personalizing" manufacturing technologies

	Personal fabricators	Industrial-scale manufacturing machines
Machine size	Fit on a desktop or kitchen table	Are the size of a cargo van or much, much larger
User safety	Use built in filters and sensors to provide non-expert users with safety mechanisms	Require monitoring and careful configuration to ensure they meet OSHA requirements
	Use modular raw ingredients that are packaged to be "plug and play," and do not require processing or special handling.	Need raw material that comes from a number of suppliers and is potentially toxic and requires special handling
	Are precise, therefore create very little left over waste, offering a cleaner and more eco-friendly manufacturing process	Use wasteful, mass production techniques that create large amounts of toxic waste and unusable scrap materials
Cost	Cost about $1000 for the cheapest, low end 3D printers, laser cutters and automated sewing and embroidery machines	Cost up to tens or thousands of dollars for a basic mill or laser cutter; some mass production injection molding machines cost hundreds of thousands of dollars
	Are greener and use less power than their industrial strength counterparts	Consume enormous amounts of power
	Create low-cost prototypes, enabling designers to experiment with different materials and designs at a very low cost	Do not offer cheap prototyping or low-cost, small-scale production of custom objects, since machine set up costs must be amortized by making and selling large volumes
Ease of use	Require very little user training	Require specialized training and certification for machine operators
	Are supported by online communities	Make it costly for regular people to become skilled operators due to proprietary machine technology and costly, required certification
	Benefit from Internet retail and	Rely on massive supply chains and

	online storefronts that sell custom blueprint designs and offer a ready-made marketplace to sell custom objects	large distributors or retail chains
Universality	Run on customizable electronic blueprints that can be downloaded from the Internet from anywhere in the world	Use proprietary, complicated and expensive design software and machine automation
	Can be made from low cost kits by moderately skilled users	Can be purchased only by those who can afford large and costly machines that require a lot of expensive upkeep and maintenance
	Use machine parts are based on open source hardware designs, meaning anybody can use and customize their fabber without worrying about patents or IP issues	Rely on expensive, specialized, patented parts that can't be duplicated and are expensive to purchase .
Software availability	CAD software is growing more sophisticated and easier to use and cheaper	Work only with expensive, proprietary CAD software that requires a lot of user training
	Growing number of design blueprints available online for sale and swap	Electronic blueprints are not freely available for mass produced products and machine parts; many products are protected by copyrights and patents, therefore usable only for a fee

The same forces that transformed information technologies will introduce the descendents of industrial manufacturing technologies and design software into our daily lives. Personalized design and manufacturing machines will be an emancipating technology, creating freedom for people to work and play independently in ways that were previously restricted to an elite few. [12] According to Marshall Burns, previous emancipating technologies in human history were the book (enabled by the invention of the printing press), cars (enabled by new roads and gas stations) and now personal fabrication (enabled by 3D design software). What this random collection of technologies has in common is that they entered the lives of everyday people in a gradual way as the technology dropped in price, became easy to use, and accumulated a critical mass of applications, fellow users, or supportive infrastructure such as roads or high speed Internet. While mainstream adoption of personal manufacturing technologies is a few decades away, the manufacturing industry will experience the same forces that brought us YouTube, laptops, mobile phones and online retailers.

While illuminating, the analogy of personal computing to personal manufacturing is complicated by the fact that the end result of manufacturing, regardless of scale, involves the making of physical objects. While industrial manufacturing technologies and high end design software have started the inevitable series of steps that brought computing from the mainframe to the consumer pocket, the physical world of making and distributing objects will be slower to digitize. If a consumer finds an electronic blueprint online, that's not the end of the transaction. She must procure physical raw materials to manufacture her custom object, and at the end of the process, if she wants to sell her product, tap into a physical distribution channel. In essence, her desired object must be transformed from online bits to physical atoms. Transforming bits to atoms requires additional effort and involves more players. In contrast, music, video, data and information -- the catalysts for the development of user-friendly software that made computers a household item -- stream effortlessly around the Internet.

Personal computers and the Internet cannot yet transport a physical object from one place to the next. Because of the stubborn inability of atoms to morph, at least temporarily, into digital format for distribution, the world of manufacturing, thus far, has resisted personalization. The journey to from industrial to personal technology can be long and complicated, but it will eventually happen, even in the manufacturing space. Consider that in the 1970s, skeptics of personal computing did not envision that mainframe and mini computers, DARPANET, or mobile phones could be used for anything beyond industrial and military applications. However, thanks to Moore's Law, falling hardware costs, and the never-ceasing lure of more and more available services and social opportunities online, computers and cell phones have become commonplace commodity items, affordable to a significant chunk of the world's population. The personalizing process of manufacturing will face its own unique challenges, yet fabbers are taking their first steps towards mainstream consumer use.

THE BEST OF MASS AND ARTISAN PRODUCTION

> ***These new artisans represent the massive innovation potential of a tech-savvy public that can tap into portable, digital designs and the accuracy of computer-controlled fabrication systems to overcome the lack of standardization that handicapped cottage industries of old."***
>
> *– Evan Malone, NextFab Organization and Fab@Home co-founder*

Personal fabrication technologies present an opportunity for our nation to continue to lead the rest of the world in manufacturing, but in a new way. Since personal fabrication technologies remove the barriers of investment in heavy machinery and specialized operator skill, consumers, for the first time since the era of artisan craft production, will lead the design and manufacturing process. Personal fabrication technologies offer us a second chance to create a new retail ecosystem and manufacturing economy in the U.S. so we can continue to lead the rest of the world in product innovation and manufacturing. One hundred and fifty years after the first U.S. industrial revolution, we are at the dawn of a new manufacturing paradigm, an industrial *evolution* that combines the appeal of artisan production with the power, precision, selection, low cost and global markets associated with factory-based mass production.

The first big wave of industrialization in the second half of the 19th century forever changed the U.S. economy and the way companies advertised, made, sold, and shipped products. The 19th century industrial revolution was catalyzed by the convergence of new technologies such as railroads, steam engines, and punch-card programmable weaving machines, and aided by communication technologies such as newspapers, postal mail and the telegraph. As manufacturing became increasingly machine-based, the means of production shifted away from the hands of local artisans and into the hands of wealthy industrialists and factory owners.

> ***Two crucial elements combined to foster the rapid expansion of industrialization: an army of freshly minted entrepreneurs and a stunning array of new technologies that literally changed the face of America.***
>
> *– Maury Klein in The Genesis of Industrial America, 1870 – 1920.*

One hundred and fifty years ago, the then-new manufacturing paradigm introduced factory machines fed by coal and steam that mass-produced large numbers of identical objects 24 hours a day, seven days a week. Former agricultural workers, artisans and immigrants flooded America's growing cities to work in the booming steel, textile, and railroad industries. The cost of steel plummeted. Freshly laid railroad track made it possible to transport goods from coast to coast in a reasonable amount of time so manufacturing companies could set up geographically dispersed but efficient supply chains and distribution networks. By the end of the 19th century, our urban landscape consisted of factories with gigantic smokestacks inside which hundreds of interchangeable workers toiled on assembly lines to turn unwieldy, toxic raw materials into sellable goods. Mass production had become the dominant form of manufacturing in the United States.[13]

Improved channels of communication, powerful new tools of production, innovative technologies and a fast, reliable distribution infrastructure ushered in the 19th century industrial revolution. Today's dawning industrial manufacturing "evolution" will replace trains, steam engines, the telegraphy and factories with electronic design blueprints, online communities and storefronts, and cheap, powerful manufacturing machines small enough for home use.

Comparing the U.S. 19th century industrial revolution to today's personal manufacturing industrial "evolution"

	Industrial revolution	**Personal manufacturing "evolution"**
Communications	Telegraph, telephone, improved commercial printing technologies	Internet, online shopping, online use communities, search and rank algorithms that enable users to find what they're looking for in the chaos, online blueprints
Power	Steam, coal, electricity	Powerful computing technologies bring formerly industrial-scale desig and analytical capabilities to the masses
Machine technology	Steam engines, coal burning machines, looms, automated agricultural technologies Factory-scale machines mass produced standardized objects very quickly	Personal fabrication machines are ready for home use, outside the factory Cheaper and easier CAD software Hardware and electronic component get smaller and cheaper and more powerful
Distribution infrastructure	Rail ways, improved roads, the postal system	The Internet becomes the distribution infrastructure. Fabbers are local so no distribution or inventory is needed
Consumers	Emerging consumer markets eagerly purchased lower-cost mass produced items	Today's consumers want to be uniqu and express themselves with custom objects
Labor	Unskilled labor could assemble objects on an assembly line	Unskilled consumers, like unskilled computer users, can design and operate their own manufacturing machinery

The industrial revolution of the 19th century introduced the notion that the production of physical objects does not take place at home or school. Most of us in the U.S. still view manufacturing through the lens of the first major industrial revolution, as something that happens in factories in far away industrial cities and more frequently, other nations. If one imagines manufacturing in that context, it seems untenable that we would want to bring enormous, polluting, noisy manufacturing machines into our homes, businesses and schools if we can buy perfectly good products and artwork our nearby department store, or if not there, online. The industrial evolution of personal-scale manufacturing will happen because consumers want custom-made, artisan style goods and not just mass produced products. While the big brand names we buy in the store are cheap and plentiful, no consumer gets exactly what she wants: customization is for the rich. The mass manufacturing model that took over in the previous century relies on economies of scale and therefore, cannot cheaply and quickly produce single items, custom items, or small batches of objects in response to customer demand.

> ***"So, a lot is going to depend on people working in 100,000 or more garages, probably with little funding or support ... We're looking specifically for technologies that can be shared and replicated around the world. We're looking for projects that make a real difference and can help us create or cope with the necessary changes. Our goal is to find some of those industrious, ingenious Makers at work in garages everywhere."***
>
> *– Dale Dougherty, publisher of Make Magazine*

Right now, we take for granted that the items we wear, drive, play with and hang on our walls will be made in large quantities in factories we never see, and that we will not get a say in their design. If you look around your home or office, aside from a painting or unique hand-crafted item someone gave to you as a gift, probably most of the objects surrounding you are impersonal and were designed with a careful balance between cost-to-manufacture and projected sales volume in mind. In 20 years, when you look around your home or office, in addition to the usual mass-produced objects, you will see a quirky, one-of-a-kind lampshade, a coffee cup with your dog's face engraved on it, an elaborately embroidered cell phone case that you designed, maybe even a box of chocolates in the shape of your house. Perhaps your shoes will be custom-made to fit exactly your feet, or your toothbrush will have your name engraved into it and fit exactly into your hand the way you like it. Maybe you will have custom-made crowns or a prosthetic limb or hearing aid.

A new consumer experience is already taking place online in a manufacturing consortium housed on a web site called 100KGarages.com. 100KGarages is a partnership between Ponoko, a New Zealand-based aggregator of custom blueprint designs and a North Carolina-based company [ShopBot Tools](), a company that makes and sells both small scale and industrial CNC routing manufacturing machines. 100KGarages.com is an online, decentralized community of consumers, small manufacturers (makers) and designers. Once they register for an account on the 100Kgarages web site, makers (or manufacturers), designers and consumers become part of a sprawling, unregulated, global, virtual design and production ecosystem.

The makers (makers must own a ShopBot to participate on the site) post a profile about their workshop's unique manufacturing capabilities. The designers post their design ideas online in the form of electronic blueprints, or CAD designs. The consumers post descriptions of the objects they would like to have manufactured, including their ideal purchase price, delivery date and product specs. Consumers browse designs online and when they find an object they'd like to have custom-made, the action turns to the online Job Site. On the online Job Site, consumers invite bids and negotiate directly with the maker on project details, design issues, cost and so on. When a deal between a customer and maker is struck, the customer sends payment to the maker for labor and materials, production begins, and the item is shipped to the consumer when finished. Quality control is consumer reviews of their experience with various makers and designers.

A GROWING NUMBER OF INDIVIDUALS AND SMALL BUSINESSES ARE OFFERING ON-DEMAND SMALL-SCALE MANUFACTURING THROUGH WEB SITES SUCH AS 100KGARAGES.COM. IMAGE FROM 100KGARAGES WEB SITE.

Consumers, designers and makers on 100KGarages.com enjoy the benefits of the traditional artisan craft model of production. The consumer controls the product design process and enjoys direct one-on-one interaction with product designers and makers. 100Kgarages customers enjoy affordable customized designs and sometimes, higher quality goods. Yet, consumers on 100KGarages.com enjoy the benefits of mass manufacturing since the goods they buy online are made according to precise software design specifications so each custom product is documented and can be exactly duplicated in the future. Another benefit is that, unlike the network of available makers in traditional artisan production models, the network of designers and makers is global and not constrained by geography. Even many highly skilled artisans can't fabricate the range of shapes, and use novel materials as quickly and precisely as can computer-guided manufacturing machines. Thanks to digitization and computer-guided tooling, machines can quickly create repeatable and precise shapes and curves beyond the capacity of many top-notch craftspeople.

As consumer skill and desire for custom-made products increases, the evolving model of small-scale, decentralized, U.S.-based manufacturing expressed on sites like 100Kgarages.com could help slow down, or even reverse the economically devastating trend towards outsourcing. Yet, while mass manufacturing remains a key part of the foundation of the U.S. economy, the mass production of common goods continues to move to cheaper and less regulated labor markets. Since 2000, a total of 3.2 million – one in six U.S. factory jobs – have moved to cheaper, less regulated labor markets such as China and India.[14] Many of us have either lived in or driven thru shrinking cities such as Detroit or Buffalo that, a few decades ago, used to be thriving manufacturing hubs before U.S. manufacturers closed the local factories and laid off their workers.

Some outsourced jobs will never return. The United States, however, still retains a lot of manufacturing muscle. It has been the world's largest national economy since 1870 and remains the world's largest manufacturer, still representing 19% of the world's manufacturing output which in 2007, was worth about $2.6 trillion.[15] Clearly, despite millions of offshored factory jobs, the U.S. remains a manufacturing powerhouse, but we need to find new manufacturing models in order to keep our lead.

If the rate of technological development of personal fabrication continues at the pace of recent years, consumers and small businesses alike will discover their own local manufacturing solutions and business models that may lessen the appeal of remotely made mass-produced products, machine parts, and offshore prototyping services. Some products, even mass-produced products, are still better made domestically. Products suitable for Far East manufacturing have low to medium technical requirements, require a significant amount of manual labor and are small in size (therefore cheaper to ship). Not all products are cheaper to make offshore, however, nor have low cost producers, thus far, proven to excel at product design and innovation. Offshored goods are burdened by high shipping costs and complex, inflexible remote management challenges. The cost of shipping containers is rising, as eight years ago, the cost to ship a 56 meter container was about $2,000; today the shipping cost for the same container is more than $5,000[9]. Due to the rising cost of shipping, large products such as washers, dryers and refrigerators continue to be manufactured in the U.S.

Personal manufacturing technologies offer cheap prototyping and custom work, which could help reduce some of the costs associated with product development. As personal manufacturing technologies mature, a greater number of products, machine parts and prototypes could be produced locally, on demand, when and where they are needed, virtually eliminating costs of stock and shipping. Perhaps products that are too heavy to ship could be manufactured in pieces, on small-scale machines located domestically. Personal manufacturing technologies offer cleaner production; for example, the 3D printing process produces less waste scrap during the manufacturing process, since the only material used goes directly into the final product. These various advantages need to be further explored to tap into the potential value of personal manufacturing technologies as a medium to encourage novel, small scale domestically-based manufacturing services.

> ***"As with the earlier case of desktop publishing, this democratization of innovation will certainly not lead to the demise of professional industrial design and manufacturing, but it will open up the space of material fabrication and customization to the masses"***
>
> *– Glen Bull,*
> *Curry School of Education, Univ. of VA*

Despite their promise, personal fabrication technologies will supplement, but not replace factory-scale mass manufacturing, especially for large, complex products or for commodity products that consumers have no interest in customizing. In the coming decades, industrial manufacturing and personal manufacturing will co-exist, but address different needs in separate but overlapping ecosystems. As Joel Johnson points out in an article in *Gizmodo* magazine, manufacturing is not a "virtual" but a physical activity, and that a growing community of do-it-yourself (DIY) hobbyists, while intriguing, does not constitutes a "real" industrial revolution.[16] We believe that the future of industrial manufacturing lies between traditional mass manufacturing and the emerging world of custom, personal-scale manufacturing. Personal manufacturing technologies are developing rapidly, but our incumbent mass manufacturing paradigm still offers better economies of scale and established supply chain and distribution infrastructures.

Compare the ongoing (albeit uneasy) co-existence of old school vs. new school in two other industries that were profoundly changed by forces similar to those driving this emerging industrial evolution. Retail, for example, is still dominated by physical stores. According to market research firm Forrester Research, despite their impact on how we shop, e-commerce sales in 2009 represented only 6% of all retail sales in the United States and by 2014, will likely represent 8%.[17] Although rooted in a centuries-old model of retail, bricks and mortar retail is here to stay. Similarly, big screen movies shown at the local cinema have not been replaced by on-demand video or YouTube. Not all businesses, however, have survived the advent of ecommerce and digital media. While movie theaters remain, DVD rental stores and CD music stores are a thing of the past. Similarly, traditional bookstores and libraries have been forced to close down, or have survived by reinventing themselves as social space by adding cafes and childcare services. Despite significant shake-out at the hands of digital media and online retail, at the end of the day, old-school physical stores, booksellers, and Hollywood movies remain in the game. Similarly, in the coming industrial evolution, mass produced commodity goods will remain a critical part of our lives, but like Hollywood movies, will be forced to share the stage with custom-designed, locally-made custom toothbrushes, toys, custom-made prosthetic limbs, product prototypes and machine parts.

THE EMERGING LONG TAIL OF MANUFACTURING

"Transformative change happens when industries democratize, when they're ripped from the sole domain of companies, governments, and other institutions and handed over to regular folks. The Internet democratized publishing, broadcasting, and communications, and the consequence was a massive increase in the range of both participation and participants in everything digital — the long tail of bits. Now the same is happening to manufacturing — the long tail of things."

-- Chris Anderson, The Long Tail

Personal manufacturing will transform the world of physical objects from a mass production-based, bricks and mortar model, to a long tail model made up of infinite shelf space, large numbers of custom products and global niche consumer markets. The concept of the long tail was popularized by *Wired Magazine* editor Chris Anderson, in his bestseller *The Long Tail: Why the Future of Business is Selling Less of More.*[18] As defined by Wikipedia, the long tail

> *"The term has gained popularity in recent times as a retailing concept describing the niche strategy of selling a large number of unique items in relatively small quantities – usually in addition to selling fewer popular items in large quantities. The distribution and inventory costs of businesses successfully applying this strategy allow them to realize significant profit out of selling small volumes of hard-to-find items to many customers instead of only selling large volumes of a reduced number of popular items. The total sales of this large number of "non-hit items" is called the Long Tail."*[19]

A key effect of the long tail of retail, as described by Anderson, is that products that earn little sales revenue can collectively, if enough of these low sellers are offered to the market, make up a revenue stream that rivals or exceeds that of the relatively few bestsellers and blockbusters. In contrast, in the bricks and mortar retail world, products with low sales volumes typically did not make it to the store shelf, since they earned less in sales revenue than the cost of stocking and selling them. In stores with finite shelf space, low volume products, in order to enable the merchant to still turn a profit, were priced much higher than their faster-selling counterparts. As a result, custom products were expensive and despite demand from niche customer markets, a retailer could not stay in business by selling low-cost, unique objects to a scattered global customer base.

A key tenet of the long tail of retail is that the cost of maintaining physical inventory drops dramatically when unsold goods are kept by a decentralized network of online merchants, or stored in an offsite warehouse. Early online retailers hit upon a profitable business model when they realized they no longer needed to pay for physical shelf space, nor base their entire revenue stream on volume sales of a few "greatest hits" types of product lines. By liberating online merchants from the tyranny of physical shelf space, the long tail of product sales allows ecommerce merchants to profitably sell a far broader range of products to a globally distributed customer base.

The long tail effect enables online merchants to profitably sell a broader range of unique products to a global marketplace of potential customers who will purchase enough niche items to keep their sellers and makers afloat financially. Consumers also benefit from the long tail of retail since they gain access to a much larger amount of available inventory that likely costs less. The long tail of retail is aided by Internet search capabilities that help consumers find their desired niche items and esoteric merchants online. Online user reviews and online ranking capabilities provide consumers insight into the value and popularity of online merchants they can't see face to face, or novel products they've never tried before. Imagine applying online retail models to custom manufacturing, where consumers would locate and purchase niche objects from makers and designers all over the globe, no mass produced products need apply.

Today's product design and manufacturing industry resembles the music industry of twenty years ago. Before the long tail effect swept through the music industry, consumers were offered a limited selection of recording artists that were selected for them by professional "hit makers" whose goal was to sell as many albums as possible. For musicians, a professional music career was an all-or-nothing game as niche opportunities yielded very little income and performances in local clubs reached very few potential fans. When the Internet connected non-mainstream musicians to niche consumer markets, suddenly, professional hit-makers were no longer all-powerful deities. The long tail of music enables a broader range of musicians to find fans, sell albums and in general, have a professional presence in the music industry.

Like the pre-long tail music industry, today's product design and manufacturing companies offer consumers a small number of carefully selected, mass-produced "hit products." Companies rely on volume sales of mass produced items in order to make a profit; custom goods are reserved for high end, costly products. Corporations make and sell large volumes of mass-produced items that are acceptable to most people, but (despite diligent market research and market segmentation strategies), delight almost no one. Even if they wanted to, the high cost of product development prevents them from offering highly customized products to small, niche consumer markets.

The long tail effect forever changes an industry when the following conditions are met: there's a large selection of products or items to choose from, sufficient availability of these products, a large number of potential consumers, and low inventory and distribution costs. All of these forces are already in play in the emerging world of personal manufacturing technologies.

- First, thanks to ever-improving design software and creative designers, the number of available electronic blueprints is increasing daily.
- Second, electronic blueprints can be endlessly replicated quickly and easily.
- Third, there's a quickly growing population of people who own their own personal fabrication machines and those who prefer to shop for designs and let someone else handle the manufacturing.
- Finally, since objects are made in small batches as demand dictates, no inventory is necessary for a retailer who sells custom-manufactured, custom-designed products.

While not yet mainstream, the long tail of manufacturing is gradually taking shape on web sites such as thingiverse.com which describes itself as "a place for friends to share digital designs for physical objects" (reminiscent of Napster). A quick browse of thingiverse.com reveals an online flea market of electronic blueprints for objects anyone can make if they have access to a personal fabricator. For example, in the online catalog, a plastic model of the Notre Dame cathedral ("Cathedral Play Set") is offered alongside a Filament Guide Bracket (a part for a 3D printer) and a pair of black plastic nerd glasses. Each design is featured on its own web page, complete with user reviews about the product, information about the designer, license information and pictures of people using or wearing the technology. Enterprising thingiverse.com users, if they see a design they like, can download the electronic blueprint, and further customize it if they want using free software design tools such as Google Sketchup or Blender. If they like, users can discuss their design innovations design online, share tips on the best materials to use and how the product worked once it was finally manufactured at home. Right now, most contributors and consumers on thingiverse.com are students and hobbyists, but the underlying buy/design/sell paradigm could easily scale into industrial manufacturing services

> ***The power of a manufacturing facility contained within a small affordable device is an exciting prospect for industrial design. It changes the very nature of product development as it is done today."***
>
> *– Jason A. Morris, professor at Western Washington University*

such as prototyping, making machine parts, visual aids for product designers, even custom body parts.

Thingiverse.com users are currently cutting-edge, tech-savvy consumers; the products they design are not sold by mainstream companies. Professional designers still dominate mainstream product innovation, thanks to highly-priced design and prototyping equipment, manufacturing machines and the presence of skilled product development support staff. But today's amateur consumer/designers and small businesses could become tomorrow's professional-caliber product innovators. As the long tail lashes through manufacturing technology, personal fabrication technologies will push product design and manufacturing methods onto the same path already traversed by the music and film industries, the mass media and ecommerce retailers. We will see the emergence of long tail manufacturing in niche consumer markets, low cost custom goods, and a level playing field no longer dominated by professional, company-based product designers and large-scale manufacturers.

Shapeways

Shapeways is an aggregator, a web-based clearinghouse where mostly unknown designers sell software designs of unusual and outrageous product. Shapeways sells product designs via a number of online storefronts and 3D blueprint designs for consumers. Consumers browse professionally designed blueprints for custom jewelry, household goods, toys and miniatures.

When consumers purchase a design, much like buying a book online, Shapeways takes care of the manufacturing and shipping of the resulting product. Shapeway's business model rests on the assumption that customers are tired of mass produced products and if given the opportunity, will buy custom-designed products that are made especially for them.

Shapeway's manufacturing facility and distribution center are housed in an industrial park about an hour outside of Amsterdam. Their personal-scale factory is the size of a school gym. Several manufacturing machines toil day and night, painstakingly fabricating custom objects from electronic blueprints which are sorted and placed bins where they're boxed and shipped to customers.

The company employs a few dozen staff members, about half high-skill technicians, software designers and engineers and the other half who post-process the prints and pack items to ship. Shapeways plans to set up relationships with manufacturing companies all over the world so when customers order a design, it can be printed near where they live to save on shipping costs.

Image courtesy Shapeways Inc.

Amazon.com was a pioneering long tail merchant that forever change the face of retail. Perhaps one of today's online aggregators of custom designs and manufacturing services will have a similarly transformative effect on product manufacturing. If you ask Robert Schouwenburg, CTO of Shapeways.com where he envisions his company in ten years, without hesitation, says "we will be the amazon.com of personal manufacturing – a household name." His dream is one step closer to reality as Union Square Ventures and Index Ventures invested $5 million to build the company and moved Shapeway's headquarters from the Netherlands to New York City. Shapeways is an aggregator, a web-based clearinghouse where mostly unknown designers sell product designs of unusual and outrageous goods and products. Consumers purchase a design, much like buying a book online, and Shapeways takes care of the manufacturing and shipping of the resulting product. What makes Shapeways unique from today's online retailers is that it does not sell ready-made mass-produced products; instead it sells custom designs.

Businesses such as Shapeways are liberating product design and manufacturing capabilities from factory assembly lines and professional designers. Shapeways sells its customers any custom product they can find an electronic blueprint for. Up until now, unless you had the money to buy one-of-a-kind custom products such as designer couture or a custom car, most of us have lived with what's available. Shapeways' business model rests on the assumption that customers are tired of mass produced products, and if given the opportunity, will buy custom-designed products that are made especially for them. Like Amazon but different, customers will shop and browse an online catalog of designs, contact the designer to arrange their desired changes and adaptations, place their order on Shapeways' web site, and their design will be manufactured and shipped to them. As business continues to grow, Shapeways plans to set up relationships with manufacturing companies all over the world so customer orders can be manufactured in a regional facility near customers' homes to save on shipping costs, delivery time, and the environment.

In the long tail model of manufacturing, middlemen go away and the line between professional and amateur begins to blur. Personal fabrication technologies, combined with large numbers of electronic blueprints, combined with user-friendly design software will result change product development and manufacturing in the following ways:

Ecosystems of small manufacturers: Online repositories of products and machine parts will be the foundation for a new ecosystem of small machine-part manufacturers and service providers who make custom objects and prototypes to order.

Long tail niche markets: Manufacturers will use personal fabrication technology to create low-cost custom objects, on demand, that sell in small volumes. Due to the low cost of inventory, designers and manufacturers of niche products will still earn a reasonable profit margin.

Economic emergence of underserved communities: When they can design and manufacture items locally, according to their own designs, people in developing nations and underserved communities will overcome limitations in their physical distribution infrastructure. They will be empowered with the tools of design and production to create their own solutions to local needs and problems that are best understood by local people.

A SMALL COMPANY MAKERBOT SELLS A 3D PRINTER CALLED CUPCAKE CNC FOR LESS THAN $950. PHOTO COURTESY OF MAKERBOT.

Consumer-led product design: Product design will shift away from companies and into the hands of consumers. Personal fabrication technologies and accessible design software enable consumers to take the lead in the product design process; consumers will be able to design, modify and make their own products designs just for fun, or for their own personal use (similar to today's active consumers who design their own extreme sporting equipment, custom ringtones and iPod playlists).

Scale up from one: Regular people and small manufacturing companies that lack investment capital will be able to set up low investment, "start small and scale up as it goes" businesses. Thanks to the low-cost Internet virtual storefronts, and the low cost of small-scale manufacturing for prototypes and custom goods, new companies can get started on a shoestring budget, yet sell their wares or services to niche, global marketplaces.

Mass customization and crowdsourcing: Personal manufacturing technologies will extend the concept of mass customization, which today, consists of a retailer offering consumers a few, set choices to alter a core, unchanging product along specific, pre-defined configurations. Another emerging innovation paradigm is that of "crowdsourcing," in which a company or organization asks for help or input from online communities made up of both amateur and professional experts.

Eco-conscious and subsistence-level manufacturing (including space exploration): Consumers and companies will use personal fabrication technologies to re-use locally available scrap or waste material. In the quest for sustainability in space travel, astronauts will take 3D printers into space with them to fabricate parts and supplies on demand.

Less market research, more toolkits: Companies will supplement traditional, formal market research techniques with prototyping toolkits that utilize personal fabrication technologies. Companies will design and equip special prototyping toolkits aimed at specific product development challenges.

Open source hardware: Intellectual property (IP) models and the practice of inventorship will move away from proprietary approaches to more open models, such as open source hardware licenses and crowdsourced problem-solving and product design.

ECOSYSTEMS OF SMALL MANUFACTURERS

"The real end of the rainbow is the creative disruption of the manufacturing value chain. Instead of driving to the hardware store to get a replacement part, you will go to a manufacturer's website and pay a small fee to download that object."

– Cathy Lewis, CEO of DeskTop Factory
a 3D printing seller on eventually entering the home user market

Personal manufacturing technologies are the ideal foundation for an emerging ecosystem of small manufacturers that sell custom-made machine parts to the government or other clients via online procurement catalogs. The long tail of machine parts is already taking shape in all places, an online supplies catalog managed by the Department of Defense (DoD). The U.S. government is one of the world's largest consumers of machine parts and supplies. To make the government procurement process more efficient, the Department of Defense developed Emall, an online repository of approved vendors that sell batteries, aircraft covers, office supplies and packing material to government agencies. Over the years, DoD's Emall has grown from a research and development project to a billion-dollar government enterprise. Today, Emall's product catalog includes over 70 million items from 1,900 individual suppliers.

Imagine a future online long tail government marketplace, similar to Emall combined with 100Kgarages.com, where government procurement officers and other customers would not just procure supplies, but browse electronic blueprints in search of a desired custom part or object. On the supply side, such a site would provide an active and lucrative market for small manufacturers whose business is based on personal-scale manufacturing technology. In this online marketplace, small manufacturers would sell blueprint designs of custom parts and objects they could fabricate for people, on demand. This long tail government manufacturing marketplace would be open to any small manufacturer located in the U.S. Access to the lucrative marketplace of government parts procurement would spur the creation of innumerable small manufacturing firms and would provide our economy with a much-needed boost and create jobs.

A SIGN AT THE MAKERFAIRE IN QUEENS, NY. WILL 3D PRINTING WILL SOMEDAY BE AS ESSENTIAL (OR AS COOL) AS MUSIC, FOOD AND BEER? PHOTO TAKEN AT THE 2010 MAKERFAIRE

Today, a long tail manufacturing marketplace taking place in the commercial sector is exemplified by a company called eMachineShop which provides easy, convenient and low-cost fabrication services of custom parts via its web site. eMachineShop has its own, proprietary design software that customers use to design the part they need so they can submit the blueprint design to eMachineShop for an instant price quote. Once their design is completed, customers can play with alternative options that affect the cost of manufacturing their desired design by getting a smorgasbord of cost estimates based on using different available materials, and adding or subtracting product features. eMachineshop does an active business, as customers design and order toys, electronic devices, games and car parts that are manufactured by eMachineShop and shipped to customers' homes.

Long tail niche markets

Personal manufacturing is ideal for letting consumers run wild with their desires. Personal manufacturing technologies make it possible for consumers to design, manufacture, or just purchase unusual or hard-to-find items for a reasonable price. Consumers of niche goods can live anywhere in the world, providing their favored merchants a much larger online customer base compared to bricks and mortar boutique stores.

Manufacturers will use personal fabrication technology to create low-cost custom objects, on demand, that sell with a reasonable profit margin; as a result, companies will be able to run a profitable business by selling small volumes of custom objects to niche consumer markets. Small manufacturing companies, unlike their bricks and mortar counterparts, will enjoy low overhead costs, no retail shelf space, and no elaborate and expensive distribution and storage operation. Similar to the world of rare book sellers or specialized web-based retailers, manufacturing companies and designers will unearth profitable niches by selling custom products, on demand, to customers from all over the world.

Economic emergence of underserved communities

People in developing nations and underserved communities will tap into the power of personal-scale design and manufacturing technologies to overcome limitations in their physical distribution infrastructure. In a humanitarian context, personal-scale manufacturing could alleviate the lack of medical supplies to underserved areas. As it becomes cheaper to design and manufacture custom prosthetic parts locally, low-income patients will enjoy higher quality, better fitting artificial limbs. Dental manufacturing companies are already making custom crowns for local dentists.

A student works in a Fab Lab in Kenya. Picture courtesy of Tom Okite

Since personally manufactured products can be locally produced, people in remote areas can order a design online and have it made locally. Lower distribution costs and local production make it possible for firms to still earn a profit selling to remote and underserved areas. Eco-conscious and subsistence-level consumers and companies will use personal fabrication technologies to re-use locally available scrap or waste material which would save money on potentially high materials costs.

CONSUMER LED PRODUCT DESIGN

Personal manufacturing technologies will exert a democratizing effect on the process of innovative product development. As consumers, most of us are used to the idea that companies design and make products for us; to express our appreciation, we vote with our dollars. Well-designed, well-marketed products that fill a need sell well (similar to top 40 music hits), and products for which the company guessed wrong don't sell so well. In the traditional manufacturing product design process, manufacturers develop a prototype based on research data about consumer preferences, test the prototype with customers, find flaws, and then continue to develop and fix the product. Traditional product development is a cumbersome, iterative back-and-forth between manufacturers and consumers as consumers know what they want, but their task of defining and articulating it to the manufacturer involves many steps and middlemen.

> ***"Manufacturers ... are increasingly shifting away from product design and focusing on producing product designs first developed and tested by user innovation communities."***
>
> *– Eric Von Hippel in Democratizing Innovation*

Pre-long tail companies follow an elaborate, expensive, centrally-controlled product research and design process, yet common sense and our own experience tell us that we as users have a pretty good idea of what we would like the product to do. Eric Von Hippel describes user-centered innovation as the converse of the traditional top-down product design and product manufacturing model in which companies conduct market research in order to design products and goods based on what they think users will buy.[20] In addition to market research, for over a hundred years, manufacturers have harvested user-developed innovations ("home-builts") by converting them into a more robust and reliable form when preparing them for sale on the commercial market. Personal fabrication technologies will allow companies and consumers to take "home builts" to a new, and more sophisticated level.

As the long tail effect of personal manufacturing technologies cracks open the product design process, we will witness a growing amount of consumer-led product development and modification across a wide range of industries that manufacture physical objects, similar to the already mainstream open source software model. Already across diverse industries such as printed circuit CAD software, surgical equipment, sporting equipment and pipe hanger hardware, up to a third of product users reported designing, modifying and developing their products themselves to suit their needs. [21]

Wise companies will learn from their customers. Products designed by consumers may be more profitable than products conceived and designed using traditional market research and in-house engineering departments.[22] A major research study at 3M Corporation indicates that consumer-designed product improvements were more novel than the incremental product improvements dreamed up by in-house design teams and market researchers[22]. In the same study, researchers predicted that new products created by passionate leading-edge consumers would end up with higher market share, and be more likely to evolve into an entirely new product lines that would earn an estimated five times as much as products dreamed up using traditional methods[22]. In the same way that amateur bloggers have an uncanny ability to spot trends before professional journalists, consumers have the ability to design products with higher commercial potential.

Mass customization and crowdsourcing

Consumers with highly specialized needs (e.g. the extreme athletes, pipe hangers or surgeons described earlier) are not the only ones who want to design their own products. Thanks to constantly improving software tools and the variety of design options offered by the long tentacles of Internet retail, less demanding consumers are also beginning to discover the joys of making products that satisfy their unique tastes and needs. Mass customization is a half step towards true custom manufacturing since it offers the consumer a few, set choices about a core, unchanging product along specific, pre-defined configurations. Mass customization for regular consumers is taking place today as companies like Timbuk2 and most famously, Nike and Dell offer consumers the ability to design their own bag, shoes or computer.

A similar concept called "crowdsourcing" describes a new problem solving paradigm in which a company or organization asks for help or input from online communities of amateur and professional experts.[23] Crowdsourcing, like user led innovation communities, blurs and narrows the gap between professional problem solvers and designers and regular consumers. Crowdsourcing is already used by a number of Fortune 500 companies to solve product design problems. Astronomy researchers collect valuable data on celestial activities from a worldwide community of hobbyist astronomers. Consumers know what works best in everyday products and given their own manufacturing tools, can prototype it. Future consumer goods companies will follow the lead of the open source software communities and learn to tap into the power of crowdsourcing to design and improve their products. Companies that ignore their customers' talent for designing and making profitable, innovative products will lumber their way to obsolescence.

LESS MARKET RESEARCH, MORE PROTOTYPING TOOLKITS

To develop new product prototypes, future companies will supplement market research with design toolkits based on personal manufacturing technologies. Company-issued design toolkits consisting of customizable electronic blueprints and on-the-spot manufacturing tools would enable consumers to do their own product prototyping and customization, providing companies with a powerful alternative to market research. Company-issued prototyping toolkits would provide a natural test platform for consumers to create or modify a product they need that's compatible with the company's existing product line. A toolkit based on personal fabrication technology would permit users to prototype and test various design solutions in a controlled design and fabrication space, and provide them with immediate feedback on what their design is going to look like in the physical world. A well-designed prototyping toolkit would enable a company to peer into the heart of customer preferences. If companies issued toolkits in exchange for product discounts or prizes in product design contests, they could harvest customer ingenuity in a systematic, mostly orderly fashion.

> ***"Companies have abandoned their efforts to understand exactly what products their customers want and have instead, equipped them with tools to design and develop their own products, ranging from minor modifications to major new innovations."***
> *– Stefan Thomke and Eric von Hippel , Harvard Business Review*

Several studies of the probability of success for new products, both consumer and industrial, show that despite the type of product, only about one quarter of newly introduced products survive their introduction to the commercial marketplace.[24] Today, good companies keep their fingers to the pulse of their users' desires using market research, but even precise and diligent market research may not give companies an accurate picture of consumer needs. Most new products will fail shortly after they reach the market mostly because manufacturers failed to understand what users needed. Traditional businesses and market departments spend a lot of time and money figuring out how to group their customers into meaningful customer segments but they frequently guess wrong. Market research is a guessing game. Surveys and focus groups may ask the wrong questions or overlook critical questions altogether, leading companies to create the wrong features, or worse, to make the wrong cost-based product compromises, such as cutting the wrong features.

Why not give customers their own set of tools and ask them to design the product they would prefer to buy? Which approach would tell you more about what your customers want? The casual swapping and evaluation and refinement of product designs between consumers, designers and makers on thingiverse.com or formal corporate market research techniques? Research indicates that consumers are better at designing profitable products.[25]

Prototyping toolkits differ from traditional market research in that rather than asking individual users what they want, toolkits allow users to design the product they would prefer. An effective toolkit

- Helps customers run experiments through computer simulations and rapid prototyping
- Uses design language that consumers are already familiar with
- Contains standard design components and modules so customers can create complex and interesting design rapidly and are freed of time-consuming set up and troubleshooting procedures
- Contains detailed information about the company's internal production processes so users can create designs that are realistically producible.[26]

In the future of long tail manufacturing, toolkits would offer small businesses a niche service specialty. Small businesses could help larger companies develop and maintain their toolkit-based product development ecosystem. A new type of innovation service provider could play a leading role in the front lines of toolkit programs for product design and manufacturing companies, creating and issuing targeted toolkits based on personal fabrication technologies, providing customer support, collecting kit feedback and organizing and making sense of user design prototypes and suggestions. Expert consumers could make a living as free-lance product designers by charging the creation of high quality prototypes.

The semiconductor industry has been giving its customers do-it-yourself kits for years so customers can design their own custom chips. The software industry has also been a long-time beneficiary of volunteer communities of beta testers of soon-to-be launched products. Yet, most manufacturing and product design companies have been reluctant to offer their users toolkits, in part, due to internal myopia, but also in response to legitimate concerns about complication imposed by applying wild and wooly user-designed innovation to routine company product development processes. Typically, large companies are slow to change internal research and development processes but the potential rewards of toolkit-based, user led design could outweigh the high cost of developing products that no one wants to by. Toolkits enable a company to collect a direct physical manifestation of what their customers want that's not tainted by clumsy market segmentation, internal company politics or received wisdom.

Scale up from one

The "scale up from one" aspect of personal manufacturing democratizes the world of manufacturing and retail by lowering the barriers to entry. Launching a new product today requires its maker to start large: industrial-scale manufacturing machines are not designed to make only one item at a time. Today's would-be entrepreneurs must invest in factory machine time, procure large amounts of material to make a large number of products to tap into economies of scale, and pay for retail shelf space.

The long tail effect in any industry is activated in part, by the democratizing of tools of production. Personal-scale manufacturing machines will lower the cost and risk of introducing a novel product to the marketplace by enabling small manufacturers to make one product at a time in response to customer demand, and scale up production as the product sells. If a manufacturer can make and sell an untested product in small volumes to see how the market responds, she assumes less financial risk since she doesn't have to invest in the machinery and large volumes associated with today's manufacturing environments. In comparison, launching a new product into the marketplace in today's mass manufacturing paradigm is expensive and risky since it's not possible to start small and test the waters of market demand in small steps.

Future entrepreneurs will be able to experiment with new products and new business models with almost no upfront financial investment. Entrepreneurs with ideas for new businesses will be able to prove their idea to investors, or if they're lucky, will be liberated from having to seek investors or take loans. People can keep their day jobs as they explore the market potential for a novel product they dreamed up in their garage. People living in subsistence economies and small companies are spared the financial risk of investing in costly machinery, expert technical help, and shelf space they may never use. In developing nations, people without access to capital will be able to start manufacturing at local fabrication centers without needing unrealistically large amounts of capital to pay for infrastructure that may never be used.

ECO-CONSCIOUS, SUBSISTENCE-LEVEL AND SPACE EXPLORATION

Personal fabrication is cleaner and more versatile than mass manufacturing. Not only can objects be made locally using available scrap or waste materials. With local, on-site production, long-distance shipping of the completed item is no longer necessary. Products and parts can be made only when they're needed, saving on storage space and the costs of maintaining un-used goods and products.

> ***Machines that can create spare parts and useful products in a spacecraft or a planetary surface are integral to sustaining a long-term presence in space."***
>
> *– NASA, in Technology Frontiers: Breakthrough Technologies for Space Exploration*

NASA is exploring the role of 3D printers as an integral tool for space exploration missions. Small-scale manufacturing machinery offers astronauts the ability to fabricate vital parts and supplies on demand so they don't need to wait for critical replacement parts to arrive from Earth. In space exploration, outpost build-up and maintenance, space and weight are in short supply. Transporting heavy machinery back and forth from Earth is not an option. Space exploration missions need manufacturing machines that can print their own replacement parts (such as 3D printers) and are versatile enough to use a wide variety of materials available on site. Further work needs to be done, but personal fabrication technologies, particularly 3D printers, are a promising new manufacturing paradigm for those living at the subsistence level off of locally available resources and technologies.

OPEN SOURCE HARDWARE

> ***"Back in the early days of the web, every document had at the bottom "Copyright 1997. Do not distribute." Now every document has at the bottom "Copyright 2007. Click here to send to your friend". So there is already a big revolution in how we view intellectual property."***
>
> *– Hal Varian, Day of the number cruncher*

Open source hardware is a growing movement in the personal fabrication community. If an inventor chooses to open source her hardware design, she makes publicly available all the schematics, detailed description of needed parts and software, drawings and "board" files – basically all the information anybody would need to identically re-create the product or object. Once a design blueprint is open sourced, a company or individual will have a hard time trying to claim private ownership of the design since detailed information about for that object will begin to appear in the USPTO's prior art search, making it impossible for a company, university or individual to claim ownership of open sourced designs.

The open source hardware movement is led by a non-profit coalition called Creative Commons http://creativecommons.org/ and a working group made up of personal manufacturing companies, hobbyists, lawyers and academics. Efforts are underway to draft the first-ever open source hardware license that's modeled on successful open source software licenses.[27] Open source hardware is just one example of the way the long tail of manufacturing will change the way patents and other intellectual property is handled by inventors and manufacturers.

Today, alternative IP models for personal fabrication technologies are in their infancy, and much more development of alternative IP models is needed in order to find the right balance between openness and commercial profitability. Products and objects fabricated from electronic blueprints will raise an additional challenge to intellectual property issues since there are two components that could be considered intellectual property: the electronic blueprints and the resulting physical object. As software designs proliferate and anybody with a machine can make anything, IP concerns threaten to block the free flow of new design ideas. Our patent system will be challenged by the deluge of legal questions generated when regular people get a hold of powerful design and manufacturing tools.

Personal manufacturing in STEM education

> ***"Students will launch rockets, construct miniature windmills, and get their hands dirty. They'll have the chance to build and create — and maybe destroy just a little bit — to see the promise of being the makers of things, and not just the consumers of things."***
>
> *– President Obama, November 2009*
>
> *in a speech to launch the Educate to Innovate campaign and National Lab Day*

Most parents, educators and policy makers agree that the U.S. needs to improve its science and technology education to ensure the next generation workforce remains competitive in a global, high tech economy. In a recent report, the President's Council of Advisors on Science and Technology (PCAST) offered a comprehensive analysis of science, technology, engineering and math (STEM) education in the United States. Their findings confirmed that the U.S. is now at risk of falling behind other nations if it fails to improve STEM education at the elementary and high school levels.[29] On tests of science and math proficiency, a number of international comparisons indicate that U.S. public school students continue to drop lower and lower in worldwide rankings as they progress from 4th grad to 12th grade. There is a large interest and achievement

Designed by Simcha Davis, this laser-cut wooden moose head jewelry holder can be ordered in two sizes, 13 inches across and 18 inches across. The moosehead is made in the Fabratory, a teaching space that offers skill based workshops in basic computer literacy, graphic design, industrial design, and 3D modeling[28]. Photo from thingiverse.com web site gap in STEM-oriented fields and classrooms among African Americans, Hispanics, Native Americans and women. More than half of the science and engineering graduate students in U.S. universities are from outside the U.S.[30]

The Report concludes that in order for the U.S. to remain a global leader, we must increase the effectiveness of STEM education at the K-12 levels. Most notably, the PCAST report highlights that if we are to move our students from the middle to the top of the pack in science, math and engineering, our public schools must emphasis subject *proficiency* but equally as important, must provide *inspiration.* A number of recommendations in the Report dovetail with the educational value of personal-scale design and manufacturing tools.

Fabrication as an educational medium

Personal fabrication technologies provide a powerful educational tool that puts students into the driver's seat in the design and engineering process, a "soup to nuts" learning experience that reinforces a number of the abstract concepts students learn in STEM classrooms. Computer design software, combined with low-cost, small scale manufacturing technologies, when integrated into science and technology classes, help educators craft physical models that help demonstrate abstract educational concepts. By removing the barriers of specialized resources and skill that currently prevent many ideas from being realized, personal fabrication technologies will excite and empower a new generation of inventors.

> ***Young students typically have not had the opportunity to see their concepts make the trip from beginning conceptual idea to a final physical form, components of the engineering design process. The advent of personal fabrication can allow students this opportunity for the first time, facilitating the incorporation of "children's engineering" into K-12 education.***
>
> *– Glen Bull, Professor of Education, University of Virginia*

Personal fabrication technologies catalyze STEM education in the following ways.

Prepare students for more advanced STEM concepts by teaching basic, hands-on skills. Students working with personal fabrication technologies must learn basic programming skills and basic design concepts. In the process, they will gain a basic understanding of how computers and machines work together and gain exposure to basic physical principles.

Prepare students to solve problems independently. Since personal fabrication technologies create visible, usable objects, students see immediately if their problem-solving strategies are not working out. Since each problem is unique, students must think outside the box and experiment with several solutions until they find the right one.

Prepare students for deeper understanding. As opposed to solving abstract, theoretical problems in the classroom, physically manufacturing an object requires students to apply the theoretical concepts they've learned so far, reinforcing existing STEM lessons by pushing students towards deeper understanding. Solving problems in a physical medium supplements abstract lessons students learn from textbooks and the classroom.

Inspire creativity in designing and problem solving. Personal fabrication technologies are like a mini-factory on the spot. They provide students, particularly at risk students who don't like school, the pleasure of designing something of their own vision and then turning it into a real, usable object.

Inspire students to see the value of science and engineering in their own lives. Students, armed with their own design and production tools, will be able to identify an engineering problem in their own life and create a custom, functioning solution they can hold in their hand.

EDUCATIONAL MODELS DEMONSTRATE THE VERSATILITY OF 3D PRINTERS AS AN INSTRUCTION TOOL. SHOWN IS A 3D PRINTED REPRODUCTION OF CUNEIFORM TABLET (CIRCA 1000 BC). SAME TEXTURE, WEIGHT, AND COLOR AS ORIGINAL. IMAGE COURTESY DAVID I OWEN, CORNELL UNIVERSITY.

Inspire a playful and iterative approach to problem solving. Many great scientists emphasize that solving problems is a form of adult play and curiosity is the bedrock of innovation. If students are given powerful tools to tinker with, they enjoy enter open-ended, playful exploration when they create blueprints, test prototypes, and identify and correct design problems, all key skills in a STEM-oriented career.

Inspire STEM student and teachers to transcend low-level factual recall in favor of constructionist learning. Many science classes today rely on low-level factual recall rather than teaching students to solve complex problems, work in teams and interpret and communicate complex scientific information. Personal manufacturing technologies push students and teachers into the realm of the applied, where rote learning must be set aside in favor of hands-on problem solving, teamwork and creative thinking.

Inspire eco-friendly thinking. Personal fabrication tools are ideal for re-using waste and scrap materials. Students can see, first hand, the value of transforming unwanted material into something usable, a key concept for next-generation scientists, manufacturers, designers and consumers.

Inspire teachers to create engaging and creative teaching aids. Personal fabrication dramatically expands the repertoire of the possible classroom teaching tools that teachers can create. Personal fabrication technologies do not require a long learning curve to master, so they lend themselves nicely to hands-on classroom activities that primary school teachers rely on to transmit complex knowledge to their students.

Inspire teachers to enjoy STEM education. Many primary school teachers do not feel confident while teaching abstract STEM concepts, yet are gifted communicators and translators of complex subjects. Design and manufacturing tools enable teachers to offer their students tangible, physical objects that demonstrate abstract and complicated STEM concepts. Confident, engaged STEM teachers are critical. Teacher engagement is a strong predictor of student engagement; the more engaged the teacher in teaching STEM concepts, the more enthusiastic the students.

Personal fabrication as a constructionist foundation

"In a very real sense post-digital literacy now includes 3D machining and microcontroller programming. I've even been taking my twins, now 6, in to use MIT's workshops; they talk about going to MIT to make things they think of rather than going to a toy store to buy what someone else has designed."

– Neil Gershenfeld on personal fabrication

Personal fabrication technologies provide a constructionist foundation to STEM education by providing a medium in which abstract problems are translated into the tangible world in a classroom setting. Constructionist learning is based on the idea that learning is an active process that works best when students are exposed to experiences, hands on projects and even failure so they can discover, first hand, underlying principles, concepts and facts. Based on the work of Jean Piaget, constructionist learning theory views the teacher as an essential facilitator and guide for their student's voyage of discovery.

Mainstream acceptance of constructionist learning theory was accelerated by Seymour Papert, a visionary MIT professor of math, computer science and education.

Papert was an early proponent of the value of computers and multimedia as educational tools. Personal-scale manufacturing and software design tools did not exist while Papert was formulating his theories, yet he would likely embrace them as a valuable pedagogical tool. Students given access to design and fabrication tools are transformed from passive consumers of knowledge to active problem solvers, designers and producers. The gratification of designing and making a real physical object that solves a problem, or is a work of art, makes it possible for a student to own and experience the entire design cycle from conceptualization to physical realization. Finally, like computers and multimedia tools, personal fabrication technologies can be adapted to a broad range of learning styles and types of projects. For visually impaired and learning impaired students, physical models alleviate learning disparities associated with educational tools that rely on visual information or spatial reasoning.

Traditional STEM education has focused on teaching abstract concepts first, then later continuing to practical application and testing of the concept, an approach that introduces hands on learning dead last in the process. While a theory-first approach works well for many students, it's not productive for students who prefer to learn using a trial and error approach, or who learn applications first and then work backwards, later, to the underlying theory. STEM educators recognize this challenge and initiatives such as NSF's Discovery Research K-12 Program have made significant progress in creating instructional material that includes elements of active problem solving in the learning process. Often, however, even active problem solving exercises must be solved in the abstract, meaning the testing, fixing and validation process remains untested and intangible. In addition, the design challenge is often removed from daily life of the child. For example, while valuable, a science and engineering problem-solving exercise that assigns students to devise a device to prevent the next Gulf Oil spill may not appeal to otherwise gifted students. Some may not be able to drawn to solving a problem whose urgency is so distant to their daily lives. Others may feel the lesson is irrelevant since student solutions will never be tested or put to use. Traditional conceptual learning, even creative problem solving, may inadvertently act as a barrier to gifted students who would otherwise be attracted to the rich intellectual world of science and engineering. STEM education as it stands today, may put non-traditional learners at risk of turning away from further STEM education and potential career opportunities.

Fab@School laboratory

Glen Bull from the Curry School of Education at the University of Virginia is developing a pilot program to develop a K-12 STEM curriculum based on Fab@home's 3D printing technologies. Glen Bull will head the project which was funded by a grant from the MacArthur Digital Media and Learning Competition. Hod Lipson from Cornell University will provide the technical expertise on the Fab@home 3D printers.

The Fab@School laboratory will introduce students to the excitement and power of digital fabrication to learn engineering and other STEM skills by designing and making their own solutions and products. The Fab@School laboratory aims to make digital fabrication practical and scalable in elementary and middle school classrooms. Fab@School will encourage students to experiment, design, and create with an emergent technology that has implications for the workforce of the future.

The Fab@School laboratory will adapt the open-source 3D printer, Fab@Home (http://fabathome.org), developed by Lipson and students at Cornell and modify it for school use. The infrastructure that Bull and Lipson aim to develop will include 3D printing hardware, design software and design blueprints of educational materials, an accompanying STEM curriculum, and an online collaborative space where students can interact with one another. As curriculum materials develop, Bull and colleagues will align material with school standards.

Activity will take place under the umbrella of a lab called "The Children's Engineering Institute" managed by Bull. University of Virginia education students will develop a STEM teaching curriculum based on 3D printers as a teaching tool for a pilot group of elementary classrooms.   To make learnings from the Fab@School laboratory available to the rest of the world, an online fabrication library will be sponsored by a non-profit educational association (www.aace.org/site) to support a growing global partnership of STEM teachers and students which includes the US, United Kingdom, China, India, and Indonesia.

In the U.S., pioneering STEM educators in high schools, technical colleges and universities have integrated personal fabrication technologies into their science and engineering curriculums. Leading examples include:

Stanford University: professor Paulo Blikstein teaches a hands-on course to prepare education students to integrate personal fabrication technologies into their future classrooms. Students use prototyping machines (such as laser cutters and 3D printers) to design and create toys, games and other learning tools ("artifacts") for children. Stanford students graduate from Blikstein's class knowing how to use computers and personal fabrication technologies to design and create classroom learning kits and educational tools.

PERSONAL FABRICATION TECHNOLOGIES IN THE CLASSROOM APPEAL TO A BROAD RANGE OF STUDENT INTERESTS AND LEARNING STYLES. THIS 3RD GRADER IS EXAMINING THE TOOLING MECHANISM OF A FAB@HOME 3D PRINTER AS IT CREATES A PLASTIC TOY. PHOTO TAKEN AT THE 2010 MAKERFAIRE

MIT: Students in a course called "How to make (almost) anything" apply personal fabrication technologies to solve real world problems. Taught by a leader in the field of personal fabrication, Neal Gershenfeld, students in the class range from engineers to artists to art historians. Over the course of a semester, students learn to use CAD software, work with a circuit board, and use a number of personal fabrication machines.   The final semester project is each students' designed and fabricated solution to a real world problem.

Cornell University: At Cornell, the Fab@Home project is both the name of a 3D printer model, as well as an ongoing initiative aimed at STEM educators. Developed by Professor Hod Lipson and postdoctoral student Evan Malone, the Fab@home 3D printer offers open-sourced design blueprints for the printer, so anybody who is interested can download the design files, make their own Fab@Home, or improve upon its existing design. Fab@home works with a number of kid-friendly materials, including Play-Doh, cookie dough, and chocolate, as well as polymers and metals. Technical development and support for Fab@home is provided by students and open source volunteers. A second major STEM initiative under the Fab@home umbrella is 3dprintables.org, a web site exchange of no-cost 3D electronic blueprints for educational tools and classroom models intended for use in K-12 STEM education. K-12 students upload electronic blueprints onto the site for objects such as printable models of the molecular structure of a particular element, or the physical manifestation of a mathematical equation. Other students browse and download the collection of designs and print their selected object on their local Fab@home 3D printer. A growing collection of online electronic blueprints for a wide range of 3D printable items are available at 3Dprintables.org.

The University of Virginia and Cornell: In conjunction with Cornell, the Curry School of Education at the University of Virginia was awarded a grant from the MacArthur Digital Media and Learning Competition to develop a STEM curriculum based on Fab@home's 3D printing technologies. Glen Bull, a professor of instructional technology founded the Fab@School initiative. Bull's goal was to teach future STEM educators to integrate 3D printers into their instructional materials to help them explain mathematical and scientific principles used in engineering. Curriculum development will take place under the umbrella of a lab called "The Children's Engineering Institute" managed by Bull. University of Virginia education students will develop the Fab@school STEM teaching curriculum for a pilot group of elementary classrooms. At the National Technology Summit in DC, Karen Cator, Director of the U.S. Office for Educational Technology described the Fab@School initiative as "fantastic."

A printable anatomical model of the human heart whose electronic blueprint is downloadable from 3Dprintables.org at no cost. Image from 3Dprintables.org

Lorain County Community College (LCCC): LCCC is a leading personal manufacturing educator. Their Fab Lab is open to students and the general public. Students can take a one-credit course on Introduction to Personal Fabrication or can enroll in a non-credit workshop. The Fab Lab has personal-scale vinyl cutter, table-top milling machine and a laser cutter that can engrave text, graphics, and photographs onto a wide variety of materials (wood, acrylic, marble, mat board, leather, glass, and more).

Defense Advanced Research Projects Agency (DARPA): DARPA launched a Manufacturing Experimentation and Outreach (MENTOR) initiative to deploy digital manufacturing equipment, including 3D printers, in public high schools throughout the country. STEM high school students will compete as teams to design and build cyber-electro-mechanical systems using personal manufacturing tools. These students will learn the introductory concepts they will need to someday build sophisticated robots and small unmanned aircraft. The program is intended to encourage students to study STEM subjects in college. DARPA will expand the program to over 1000 high schools over the next three years.

University of Washington: The University of Washington's Open3DP (Open 3D printing) project is a website hosted by the Solheim Rapid Prototyping Laboratory in the Mechanical Engineering Department. Its purpose is to disseminate information and foster a community of people interested in an open sharing of 3D printing information. The Solheim Lab is directed by Mark Ganter and Duane Storti.

Fab Labs

It would be impossible to describe the past and future of personal manufacturing technologies without mentioning the pioneering work of Neal Gershenfeld at MIT's Center for Bits and Atoms. Gershenfeld is the vision behind the creation of Fab Labs, personal fabrication centers around the world that provide people in low-income neighborhoods and developing countries with personal fabrication machines that were once only available to industrial manufacturers. There are now 40 Fab Labs in almost every continent including Afghanistan, Kenya, Norway, Peru and the United States. Fab Labs typically have some kind of combination of personal fabrication technologies such as laser cutters, 3D printers, circuit makers.

Fab Labs share core capabilities, so that people and projects can be shared across them. This currently includes:

- A computer-controlled lasercutter, for press-fit assembly of 3D structures from 2D parts
- A larger (4'x8') numerically-controlled milling machine, for making furniture- (and house-) sized parts
- A signcutter, to produce printing masks, flexible circuits, and antennas
- A precision (micron resolution) milling machine to make three-dimensional molds and surface-mount circuit boards
- Programming tools for low-cost high-speed embedded processors

In Fab Labs, local users download electronic blueprints or design their own objects to fabricate complex and everyday objects they need in their daily lives. In India, school children fabricated timing devices to improve the performance of diesel engines and sensing devices to test for spoiled milk. In Norway, reindeer herders manufactured special tracking devices to attach to reindeer collars that would make them easier to locate after the long winter. Projects being developed and produced in fab labs include solar and wind-powered turbines, thin-client computers and wireless data networks, analytical instrumentation for agriculture and healthcare, custom housing, and rapid-prototyping of rapid-prototyping machines.

In the future, Gershenfeld's envisions people in developing nations downloading electronic blueprints to make things they need such as active electronics, bicycles, chemical sensors, radios, robots, and maybe someday prosthetic limbs. Students in the Fab Lab at the Loraine County Community College in Ohio manufactured a boat that works well enough to hold a person afloat.

Photo taken at the 2010 Fab Lab Conference in Amsterdam.

HARNESSING THE EDUCATIONAL POTENTIAL OF PERSONAL FABRICATION

"Technology has been the "next big thing" in education for the past 50 years – first with television, videotapes, computers, the internet, and mobile phones. Countless conferences, books, national plans, and international initiatives have promised better student performance, motivating courses, better teacher training, lower costs, or more equity. Why hasn't technology in education lived up to its hype?"

– Stanford professor Paulo Blikstein

If STEM educators intend to mine the promise offered by emerging personal manufacturing as a teaching tool, they need to actively ensure that personal fabrication technologies don't fall prey to the same bureaucratic traps that still stymie the use of computers in public K-12 schools. The best way to ensure that personal manufacturing technologies reach their full potential in the classroom as a tool to promote STEM education is to learn from the lesson of the personal computer. Schools and policy makers must commit to providing adequate funding for machine hardware, software, curriculum development and teacher training.

Over the years, countless reports and publications have offered recommendations to overcome the obstacles that limit the value of computer-based instructional technology in STEM education. Computer-based instruction has faltered in U.S. public schools for several reasons.

- A fragmented educational software market discourages would-be software companies from entering the space, resulting in little competition, therefore technology-based teaching tools of poor quality.
- Software vendors are turned off by the slow pace of the school procurement process and the school systems' lack of money to spend on support and upgrades.[31]
- Computer-based instructional materials are frequently incompatible with those of other systems, which discourages educators from investing in educational software due to the risk of getting "locked in" to a single vendor.
- Instructional resources on the Internet tend to be disorganized, of varying quality and fragmented.

- Many schools still lack high speed Internet access and can afford only a few computers that are locked away in a "computer lab;" on average, public schools spend only an average of $10 per student on computing technology[31].
- With the increasing emphasis on assessment, emphasis on computer-literacy has been sidelined as teachers are under tremendous pressure to drill students on reading, math and other basic skills. Computer-based instruction, as well as basic computer skills, have become a luxury that many students, teachers and schools don't have the time or support to afford.
- Teachers who cannot afford to own a computer in their own homes will not be proficient users of computers in their school. Until teachers are offered adequate training or are given their own home computer, they won't feel comfortable embracing computer-based instruction in their classrooms.

FOR MATH EDUCATORS, THESE FIGURES REPRESENT MATHEMATICAL EQUATIONS. THEIR BLUEPRINTS ARE DOWNLOADED. STUDENTS WHO CREATE NEW MODELS CAN UPLOAD THOSE TO ADD TO THE COLLECTION. PHOTO FROM 3DPRINTABLES.ORG

These insights and suggestions are also relevant to emerging personal fabrication technologies. To ensure that personal fabrication technologies avoid the fate of personal computers in our public school system, the following five fronts need to be successfully addressed. (More detailed recommendations are outlined in the Recommendations section of this paper.)

HARDWARE

Without a sufficient number of personal manufacturing machines per school, students will have to wait too long to use them and both students and teachers will quickly lose interest. It won't be easy or inexpensive to equip public schools with a sufficient number of personal manufacturing tools. The U.S. public school system is vast, with about 3.2 million K-12 teachers in a total of 98,000 schools. In addition, personal fabricators are an emerging technology and their hardware changes rapidly, making it difficult for school systems to keep up with rapid technological development. Currently, an entry level 3D printer costs about $1000 per machine, and laser cutters and mills cost a few thousand apiece. Clearly, for less affluent school districts, replacing a dozen or two personal fabrication technologies every 2-3 years is likely to be out of reach financially.

SOFTWARE

Electronic blueprint designs are actually the easiest factor to successfully address. Thanks to the growing number of free electronic blueprints on sites such as 3dprintables.org and thingiverse and others, teachers and students will have no problem finding interesting designs to fabricate. Design software, however, with the exception of Google Sketchup and Shapeways, still costs money. The cost of design software should continue to drop. At least two companies at the time of this report writing, Rhino and Silo, offer entry-level educational packages for about $100.

Museum of Science in Chicago

The Museum of Science in Chicago hosts 1.5 million visitors every year who view 14 acres of exhibition space. Their mission is to inspire and motivate children to achieve their full potential in the fields of science, technology, engineering and medicine. The Museum's Center for the Advancement of Science Education develops and runs student learning labs, after-school science clubs, teen volunteer programs, teacher development classes and community outreach.

The Museum set up a Fab Lab in 2007 as part of the curriculum for the Science Minors Program, a 10-week educational outreach program aimed at local teens. The Science Minors program is aimed at kids between the ages of 14-17 to help them develop job skills and increase their knowledge of science and science careers. Students in the program attend ten weekly Saturday training sessions after which they were allowed hands-on access to the Fab Lab. Despite dedicated full-time staff, the Fab Labs attracted about 35 dedicated students who learned how to use design software to manufacture items on the lab's 3D printer, ShopBot, 3D milling machine and vinyl cutter. The Museum Fab Lab is about the size of 2.5 large classrooms with twelve computer workstations.

The Museum recently decided to increase its commitment to the Fab Lab in order to reach more kids and science teachers. The Museum's Center for the Advancement of Science Education will develop a personal fabrication curriculum to teach students and teachers how to use the personal fabrication technologies and design software. In the coming months, the Museum will hire a full time Fab Lab manager and outreach champion. K-12 public school science teachers will be a primary target for the new Fab Lab curriculum to promote the use of personal fabrication technologies in science education.

Courseware and curriculum

Integrated, modular and relevant courseware and curriculum will emerge as perhaps the biggest ongoing challenge if schools are to integrate personal manufacturing technologies into their STEM courses. First, instructional software packages that teach students to work with personal fabrication technologies should be operable on both Windows and Macintosh computers. Second, courseware must be modular so teachers can re-arrange instructional tools to suit their own lesson plans and style of teaching. Finally, courseware that addresses different functions (e.g. keeps track student's progress thru exercises or tests, gives the student feedback on their proposed design, etc.) must work together with complementary courseware from other vendors. It's critical that software vendors are encouraged to use common technical standards to enable their software and machines to work together with that from other companies.

Teacher Training

Without prepared and engaged teachers, there will be no engaged students. Teachers are a critical factor in introducing personal manufacturing technologies to STEM students. All K-12 STEM teachers should be comfortable with the basics aspects of the personal fabrication process: finding and downloading software design blueprints, doing minor customization of software designs, and setting up the fabrication machine and materials. Next generation educators, college students, should study personal fabrication technology in university cousework for education majors. Teachers already in the workforce should attend a 3-day, paid annual intensive summer workshop. Practicing teachers do not have time to tinker with new technologies on their own or to attend after-work, unpaid educational workshops.

Student support

Most school districts already have supplementary programs in place for STEM students. School districts should add a personal fabrication component to their existing after school and weekend STEM programs. High schools should offer their students course credit if they take courses to master personal manufacturing and design tools at their nearby community college or university.

BARRIERS AND CHALLENGES: WHAT STANDS IN OUR WAY?

Despite their great promise, a number of barriers stand in the way of mainstream adoption of personal manufacturing technologies that could discourage widespread home, school and business use. This section briefly describes challenges that need to be addressed, such as safety concerns, part standardization and version control challenges, intellectual property issues and creating appropriate regulatory controls.

THE "CHICKEN AND THE EGG" PARADOX

Personal fabrication technologies are poised to enter the mainstream, yet are stymied by a "chicken and egg" paradox. The chicken and egg paradox is similar to the early days of computing when pioneers and hobbyists created their own software applications and could only exchange email with other hobbyists. Right now, most consumers, schools and businesses do not own personal manufacturing machines, and perhaps as a result, are not able to integrate them into their daily lives. Due to low market demand, software companies have not yet invested heavily in the consumer-oriented product design software market. Although online repositories of electronic blueprints continue to multiply in size, few designers are yet making a living off of selling their designs. Without a large enough market for their custom-manufacturing services, few small-scale manufacturers earn enough from personal manufacturing services to attract the attention of investors.

The stand-off continues as stakeholders eye one another and wait for somebody to invest in either low cost consumer design software, local manufacturing services, cheaper and better machines and so on, hence the chicken and egg paradox. The chicken and egg paradox is not insurmountable. Promising signs such as a recent $5 million dollar investment in Shapeways and the acquisition of 3D printer manufacturer Bits From Bytes indicate that the market for consumer-scale personal fabrication technologies is growing.

CONSUMER SAFETY AND QUALITY CONTROL

In the early days of the U.S. industrial revolution, factory workers were regularly accidentally injured or killed by dangerous machinery and toxic materials. Unregulated sweatshops were the norm until labor unions forced the passage of federal regulations eventually forced companies to adopt machine safety standards and ban or at least warn workers about hazardous materials. Unlike other personal technologies, a personal computer or cell phone, a personal fabrication machine can physically harm its user since its use involves potentially hazardous materials and sharp parts or lasers.

In addition to hazardous production environments, once regular people and small businesses gain access to their own powerful design and manufacturing tools, they will be able to make any object they desire, including object that are dangerous, counterfeited or shoddy. Poorly made or inaccurate machine parts pose a potential safety risk for their buyers. Faulty, low quality medical equipment or toxic toys are also a potential risk. Finally, highly skilled designers and tinkerers will be able to make powerful weaponry once they have access to tools that used to be limited to carefully selected manufacturing companies. Once electronic blueprint designs for hand grenades and guns are available, it won't be long until enterprising users or terrorists start to manufacture their own.

3D PRINTED HANDGUN, WITH INSERTED METAL BARREL. CAN PERSONAL FABRICATORS BE USED MALICIOUSLY? WHO'S RESPONSIBLE? IMAGE FROM SUPERDUKE FORUM WEB SITE[32]

Finally, liability issues need to be addressed. If a person makes and gives her friend a custom-designed object that later harms someone, who is liable? The designer of the electronic blueprints? The person who actually manufactured the object? The company that made and sold the personal fabrication machine? Or whoever provided the material for the object? Since the players in the personal fabrication ecosystem tend to be a decentralized web of loosely connected individuals and small companies, it's difficult to pin down who's accountable for a shoddy or harmful product.

HARDWARE-RELATED CHALLENGES

Like any early-stage technology, personal manufacturing have their technical challenges. Since personal fabrication machines represent a broad variety of manufacturing technology and tooling, it's impossible to do justice here to the myriad technical limitations peculiar to each machine. Laser cutters, for example, regardless of their size, have different technical shortcomings than, for example, 3D printers. Technical challenges shared by all varieties of personal-scale manufacturing machines are listed below.

- Compared to their factory counterparts, personal-scale manufacturing machines take much longer to produce an identical object.
- DIY hobbyist kits are the predominant source for people to procure personal-scale manufacturing machines today. As a result, there's as significant amount of undocumented variation in machines which makes version control and standardization difficult, even in models purchased from the same company.
- Factories enjoy elaborate, global supply chains that bring together needed raw materials. Personal manufacturers would not have access to the same networks, nor would they purchase enough materials to enjoy economies of scale.
- Factory manufacturing machines are run by skilled and certified operators. However, many hobbyists and early adopters lack the technical training required to do high-level troubleshooting or repairs of their own machines.

Hardware and software standards

There are three key factors for innovation: Common technical standards, collaboration, and customization. First, it is critical that there be standard ways for exchanging technical information between members of each economic system and across economic systems. Second, more open collaboration between economic system members, and at times even among competitors. Third, the primacy of the individual as the driver and user of scientific discoveries is paramount."

– Global Innovation Outlook, 2004 IBM study on innovation.

The emerging market for makers of personal fabrication machines is fragmented and decentralized. Equally fragmented is the marketplace for electronic blueprint designs. Standards, or a lack thereof, are another major barrier facing machine makers, software designers and consumers. Machine parts for personal-scale manufacturing machines are not registered in an official, centralized parts registry. As a result, similar to the early days of the automobile, it's difficult to buy standard replacements parts for a 3D printer or home-scale laser cutter.

If a sizeable small-scale manufacturing ecosystem is to emerge, interoperability issues must be addressed. Standard, interoperable machine parts and software design files need to be defined. Electronic blueprints designs exist in a broad range of different file formats including some that may not be compatible with a particular type of personal fabrication machine. Not only are machines and blueprints non-standardized. The world of computer-aided design software lacks a Microsoft or

Apple. A large number of CAD software companies offer design software that relies on a variety of proprietary file formats.

Version control

Due to the hobbyist culture underlying emerging personal design and manufacturing technologies, version control remains an unresolved challenge for both software and hardware. In the software industry, companies keep tight control over each version they release. When consumers purchase a software application or device, the first thing they do is to check the software version numbers that their intended purchase is compatible with. The market for personal fabrication, both hardware and software, is not nearly as organized.

Like personal computing in the pre-Altair days, the world of personal fabrication technology and accompanying software have a long way to go before a novice consumer can confidently purchase accessories in Best Buy or RadioShack.

IP issues

> ***As 3D printing proliferates, individuals will look to solve problems by designing and creating their own solutions. In producing those solutions, it is quite possible that they will unwittingly incorporate elements protected by patent… Sharing designs on the Internet amplifies the problem.***
>
> *– Michael Weinberg, Writing on IP issues in 3D printing*[33]

Intellectual property issues are a leading concern of businesses in the personal manufacturing space. Aggregators are concerned about being held liable for contributory intellectual property infringement since their web sites serve as storefronts and repositories for illegal copies of patented or copyrighted designs. Designers worry that their custom designed objects will be too easy to copy, or that lesser designers will sell counterfeit, black market blueprints under their more famous brand name. Consumers and businesses worry that they may unintentionally purchase a shoddy, counterfeit blueprint or invest a significant amount of money buying a product or machine part that later turns out to be in violation of another company's patent. Makers run the risk of creating an object or product that unwittingly infringes someone else's patent or copyright. Unlike European countries, the U.S. does not exempt non-commercial home use.

In our long tail world of media and information, files containing digital music, content, video, artwork, and data are easily copied. As a result, chasing down copyright violators of digital works has become as unproductive as chasing after a cloud of gnats. Preventing copyright and patent violations in the world of electronic blueprints and small-scale manufacturing machines will be equally challenging. The personal fabrication process spans both the digital and physical worlds and involves two components that involve intellectual property issues: the electronic blueprints and the resulting physical object. While one can protect a digital blueprint using digital rights management, this approach offers only a partial solution, since once the electronic blueprint is put to work fabricating physical objects, it can be used to produce as many objects as the maker wants to make. The resulting physical objects, unlike a music file, cannot be digitally signed.

Even if someone were to legally purchase an electronic blueprint, additional intellectual property issues could arise depending on what the buyer does with the object he or she creates from the blueprint. If a user buys a legal copy of a blueprint, makes a tiny modification and then re-sells huge quantities of that object, is that a violation of copyright law? Or, if a user buys a blueprint and uses the resulting object in a novel way, does that qualify the object for a brand new patent? The production of replacement parts for commercially produced, patented product on personal fabrication machines offers another potentially troublesome IP-related grey area. Today's large companies suffer from counterfeiting, piracy and patent disputes, but the big difference with personal fabrication technologies is that they put the power of production into the hands of millions of unregulated consumers. Anybody with the right software and machine can 3D scan an existing product or download a proprietary blueprint and make as many copies of copyrighted and patented physical objects as they desire.

Another troublesome complication is what sort of IP protection would be appropriate for personal manufacturing technologies: copyrights, patents,, or a blend of both? A related question is how U.S. federal law and business models will address home-based, non-commercial reproduction of commercial product and machine parts. The scope of copyright and patent protection must be addressed. For example, if an electronic blueprint is copyright protected, it's not yet clear whether that copyright protection extends to the resulting physical product. The ability of personal fabrication technologies, particularly 3D printers, to manufacture items out of a broad range of material will also likely trigger new IP disputes about what constitutes a "novel" object or product.

So far, companies have not had much success preventing widespread copying of digital media such as commercial software, music and videos. Personal fabrication technologies will likely offer yet another battlefield over control of IP rights. Our nation's IP policies and practices are already under scrutiny as the U.S. patent office wrestles with a backlog of several years' worth of patent applications and our nation's universities struggle to find new models to commercialize federally funded university research. To anticipate the IP implications of this emerging paradigm, courts, businesses and policy makers will need to coordinate with stakeholders to create forward-thinking legal guidance. An example of pioneering work on re-thinking traditional IP models for personal fabrication is that of the non-profit think tank Creative Commons, whose goal is to "increase the amount of creativity (cultural, educational, and scientific content) in "the commons" — the body of work that is available to the public for free and legal sharing, use, repurposing, and remixing." Attorneys at the Creative Commons are working with the personal fabrication community to sketch out an equivalent open source licensing infrastructure for hardware based on the success of open source software licensing models.

A deeper investigation of intellectual property issues in the dawn of a new industrial revolution is beyond the scope of this paper. However, given our nation's reliance on innovation as the engine of economic development, we need IP policy that helps, not hinders technology-based economic vitality. If addressed fairly and promptly, the emergence of mainstream digital personal fabrication technologies could actually emerge as a welcome inflection point. The fact that the personal fabrication process spans both the digital and creative worlds of copyright as well as the physical world of patents will force us to re-examine antiquated intellectual property laws and policies. The unique blend of the digital and physical represented by personal fabrication will propel technology transfer and IP law forward, into more flexible paradigms appropriate for today's decentralized, digitally based, networked world.

EDUCATION CHALLENGES

The challenges facing the widespread adoption of personal manufacturing technologies in K-12 STEM education mirror the challenges faced by other computer-based educational technologies. Many U.S. public schools have already failed to make computer literacy and software instructional tools a core part of their curriculum, yet personal fabrication machines require a solid network infrastructure and an attached computer. In addition, they introduce a new dimension, that of the physical machinery of the manufacturing process. The challenges facing the uptake of personal fabrication technologies as a valuable STEM teaching aid involve hardware and software infrastructure, teacher readiness, available courseware and curriculum, and sources to promote student involvement.

- Teachers and students need high speed internet access to find software design blueprints and to read online user help communities. However, many public schools in the U.S. still lack high speed Internet access.
- Personal fabrication technologies must be attached to a computer. Some schools cannot afford additional computers and the few they have for other purposes

remain locked away in a “computer lab.” If public schools are already struggling to keep up with the pace of change in the world of computing, they will need significant support to handle new costs and complications associated with personal fabrication technologies.

- Educational software never found its feet in the classroom largely due to a highly fragmented market of proprietary software products. The marketplace for personal fabrication education software is almost non-existent at this time. Now would be the right time for the government could step in at this early stage and mandate that software aimed at U.S. public school STEM education adhere to public open standards in order to be interoperable with rival products. A more vibrant software market of higher quality educational software designed to teach personal fabrication technologies would make schools more likely to invest.
- The web is rich and growing repository of electronic blueprints, user communities and other sorts of educational materials. However, most STEM teachers do not have time to sift through the riches and cobble together coherent lesson plans. Some resources need to be aimed at simply organizing and packaging what’s already available on various web sites.
- As schools are increasingly pressured to prove their worth with high test scores, schools, teachers and students have less time to focus on novel and emerging technologies such as personal fabrication machines. While learning basic critical skills such as reading, math and other core topics is critical, somehow room and resources must be found for playful and open-ended exploration of emerging technologies.
- Teachers without ready access to a personal manufacturing machine will not be able to teach these technologies to their students. Until teachers are offered adequate training or are given regular hands-on practice using personal manufacturing design and manufacturing tools, they won’t feel comfortable embracing these tools in their STEM classrooms.

BUSINESS MODEL CHALLENGES

> ***“A company has to decide precisely what it is willing to offer the marketplace in terms of product configurability. If this is left entirely to the imagination of the customer, chaos ensues.”***
>
> *– author David Gardner about mass customization*

nal fabrication technologies open up new business models, some we can’t even imagine right now. However, not all custom manufacturing is profitable and the majority of today’s personal fabrication makers do not make a substantial profit from their efforts.   What factors would stand in the way of profitability for a small manufacturing business that makes custom objects for one or few customers?   If the profit margin from the manufacture of custom objects is high enough, a business can stay afloat. However, when the economies of scale of mass production are removed, custom manufacturers will have to earn enough to compensate for the hidden costs of artisan-scale production.

New business models based on personal-scale manufacturing technologies will have to content with the following challenges:

- A requested custom object may be design-wise, too far outside the manufacturer's area of specialization.   If a small manufacturer invests in a substantial learning curve, new materials and machine configuration, he would have to charge a high prices for the custom goods he produces. If the price is too high, consumers will switch back to mass produced objects or find a custom manufacturer who's cheaper.
- When the customer receives her completed custom product, it may not be what she had in mind. The product may not be worthwhile without an accompanying ecosystem or support infrastructure. The product's performance may offer unwanted surprises.
- If a custom product turns out poorly or hurts somebody, it reflects badly on the manufacturer. Legally, the manufacturer may be at risk.
- If a customer knowingly or unknowingly copies a copyrighted or patented design, the manufacturer is unwittingly participating in an violation of intellectual property. Most small-scale manufacturers do not have the skill, time nor resources to do a comprehensive patent search before creating custom products.
- Unintentional IP violations since manufacturer likely won't have the resources of expertise to do a patent search before making a single, custom product

Some of these challenges could be alleviated if small-scale manufacturing companies formed a manufacturing collective to share costs and resources. Manufacturing co-ops could form around a particular industry or product (say a particular Boeing jet). Each participating manufacturer would have a few personal-scale manufacturing machines in their shop and would specialize in their particular part. However, challenges are inherent in this sort of product development model as well. In a product that consists of parts from a thousand small contributors, if one part malfunctions, it's difficult to pin responsibility.

Recommendations for Government Investment

Thoughtful and visionary government investment is needed to ensure we establish the U.S. as the world leader in personal fabrication technologies. Over thirty years ago, our nation led the way in the personal computing revolution that firmly established the U.S. as the world epicenter of software companies and innovation, creating a host of educational benefits, a vibrant economy, and billions of dollars of wealth. Appropriate government policies will nourish the potential of personal, digital manufacturing technologies to create domestic jobs, new businesses, and to promote STEM education.

This report recommends the following actions be taken.

STEM Education

"[Personal Fabrication] is a way of changing how students look at the world around them. Envisioning the world in 3-D and being able to fabricate it and actually manipulate it allows even very young students to think at very different levels. The increase in questioning skills and scientific thinking and mathematical analysis is simply amazing to watch [...] providing JUST the kind of support needed to once again put America's students back in the top of the world's thinkers in these areas!"

– Paula White, Teacher, Charlottesville VA

The federal government needs to invest in placing personal fabrication technologies into public schools and training teachers how to use them. To excel in the field of digital fabrication, students will need early access to personal fabrication tools and opportunities to practice using them on a nearly daily basis. Teachers need support and incentive to go thru the learning curve needed to integrate the power of classroom-based manufacturing into their educational curriculums. High quality, integrated yet modular course curriculums need to be developed and software vendors need incentives to make their products interoperable with those of other companies.

Federal support for STEM education flows through several channels. The following recommendations highlight specific initiatives already in place where personal fabrication technologies could be added onto existing program infrastructure.

PUT A DIGITAL FABRICATION LAB IN EVERY SCHOOL

"There's nothing like building one of these machines, and subsequently building things made from its products, to inculcate a strong feeling for - and practical knowledge of - mechanical, electronic, and software engineering. For the first three-quarters of the 20th century, there was a very widespread hobbyist culture in both the US and Europe, with people making radio sets, models, items of carpentry, and so on. As we have become more efficient at making such items centrally by mass production, this culture has attenuated, with a corresponding attenuation in general technical skill in the population at large. Government encouragement of personal fabrication may well reverse that trend, creating - as a by-product - a correspondingly larger pool of skilled personnel for industry."

– Adrian Bowyer, University of Bath, UK

DARPA's MENTOR program will deploy 3D printers in a thousand high schools. DARPA's initiative is a great first step but remain thousands more schools and public school STEM educators who will remain untouched. DARPA should approach the MENTOR program as a scalable pilot and if results are positive, target funding to scale up the MENTOR program to include every public school by 2015.

Companies that make personal fabrication machines should be given tax incentives to donate machines to schools. For example, Makerbot, in a "back to school giveaway," is giving 10 teachers each a MakerBot Cupcake CNC Deluxe Kit with standard MK4 Extruder and a bonus Heated Build Platform kit. MakerBot is not receiving a tax break, but if such a thing existed, they could be a good candidate.

Another jumpstart to adoption of personal manufacturing technologies could be for the government to create a five-year pilot personal fabrication program in the top 100 public high schools that focus primarily on STEM subjects such as Stuyvesant high School and the Illinois Mathematics and Science Academy. Each high school could receive funding to equip a Fab Lab and to hire a resident expert to instruct teachers and students on the use of the fabrication technologies. Teachers and students would be encouraged to find ways to integrate the technologies into their STEM projects and course curriculums. At the end of five years, if deemed successful, the best programs would be scaled up and extended to other U.S. public high schools.

Offer teacher education in fabrication technologies and relation to STEM education

Teachers also need support. The government should consider adding a personal manufacturing component to the Math and Science Partnerships program. Such a component could improve teacher content knowledge of basic personal fabrication technologies and how to integrate them into their STEM curriculum. Decision-makers should consider connecting with UTeach program administrators to raise the visibility of personal fabrication technologies as a pedagogical tool for future STEM educators. An overview on personal-scale design and fabrication could become part of UTeach's classroom preparation.

At the university level, funding should be allotted for an NSF RFP to university education departments to develop undergraduate and graduate-level teacher training courses to prepare students to be STEM educators. There should be more funding and support for personal fabrication projects on the National Lab Day website. Scientists, professionals, engineers and manufacturing companies could reach out to enterprising STEM K-12 teachers on this site to share expertise and to work together to find ways to integrate technology into the STEM curriculum.

Enhance after school learning to involve manufacturing rather than consumption

STEM education does not stop after school. Personal fabrication technologies lend themselves well to fun and creative activities that could take place outside the classrooms. A number of after-school activities already exist, that could integrate design software and personal fabrication technologies into their offerings.

- Add a Fab Lab initiative to existing Century Community Learning Centers (CCLC) so students from at-risk backgrounds can get first-hand exposure to personal fabrication technologies.
- Fund a personal fabrication channel in the Informal Science Education Program to create programming to raise the visibility of the wonders of the design and manufacturing capabilities.
- Fund the purchase of personal fabrication technology and design software for after school programs such as Project Exploration and Expanding your Horizons.
- Add a personal manufacturing track or prize to existing STEM contests such as the Digital Media and Learning Competition, the Intel Science Talent Search, thte International Science and Engineering Fair, the FIRST Robotics competition, as well as many local and regional math and engineering competitions.

Create high quality, modular curriculum with an optional manufacturing component

U.S. public schools are receiving increasing amounts of financial investment from the federal government. Personal fabrication technologies should be considered in plans and programs aimed at improving STEM education.

- Set aside grant money through the Investing in Innovation Fund to fund qualified individuals and businesses to develop deeply digital STEM courseware and curriculum on personal-scale design and manufacturing tools.
- Add a personal fabrication component to NSF's Discovery Research K-12 portfolio of instructional materials.
- For grant applicants for Race to the Top funding, offer extra points if their proposal involves the use of personal fabrication technologies as a core component of STEM courses.
- Fund open source initiatives to develop web repositories of software design blueprints and instructional materials similar to Cornell's 3dprintables.org
- Put together a plan to ensure that any courseware that's developed must adhere to selected common technical standards to ensure interoperability. A standards-based curriculum would create a more vibrant software ecosystem that would attract more companies and raise the quality of educational software available.

Community outreach

Allocate federal support for pilot MEPs programs

Regional Manufacturing Extension Partnerships (MEPs) are a federally sponsored channel to disseminate innovation manufacturing techniques to small, regional manufacturing companies. MEPs were set up in 1989 by the National Institute of Standards and Technology (NIST) to help local manufacturing companies adopt modern manufacturing technologies by providing them expert assistance and education. The MEP program is modeled on agricultural extension programs. Typical assistance provided to small manufacturers are "off-the-shelf" solutions to technical problems such as helping a plant install a CAD/CAM system or educating them about available new lower cost, higher performance materials. Most MEPs offer business, marketing, and other "softer" types of assistance.[34]

The MEPs program could be a natural channel to introduce regional manufacturing companies to personal manufacturing technologies and business strategies. The government could select several regions to host a series of hands-on, professionally staffed workshop where companies could tinker with new tools and machines.

Local manufacturers, since they know their regions better than anyone else, would likely come up with innovative new manufacturing business models when given free rein to explore personal manufacturing technology. Despite the importance of small manufacturing firms to the United States economy, federal support for manufacturing extension activities has shrunk steadily from $138.4 million in 1995 to $106.6 million in recent years to only $90 million in FY 2008—well under $7 annually per manufacturing worker.[35] MEP funding is shrinking, yet regional manufacturers have never needed assistance and education more than now.

TECHNICAL STANDARDS

PROMOTE PUBLISHED AND OPEN HARDWARE STANDARDS AND SPECIFICATIONS

Today's lack of hardware standards inhibit the growth of this field and may make it more difficult for businesses to invest in this emerging market. To create a vibrant ecosystem, companies that make 3D printers and other personal fabrication technologies must be incented to converge around core, published technical standards and specifications. A number of large and small companies are introducing their own version of small-scale 3D printers. HP and Xerox are investing in 3D printing research and technology development. A risk of proprietary standards is that the companies that gain the largest market share will enjoy a "black box" monopoly, driving up the cost of parts, training and credentialing, maybe gaining control of design file formats.

Open hardware specs that any company can build parts around would ensure a level playing field to spark the growth of new hardware companies. In addition, open and standard hardware specs will make it easier for software companies who make engineering design software for this emerging medium to write to a number of different hardware platforms.

DEVELOP STANDARD FILE FORMATS FOR BLUEPRINT DESIGN FILES

Software companies need standard file formats also. Right now, there are no agreed upon file formats for electronic blueprint designs. A few decades ago, Internet usage exploded thanks to non-proprietary software standards and standard protocols such as the Linux/Apache/MySQL/php web serving platform that revolutionized the web by offering web developers low cost development tools and transparent APIs.

Computer-aided design software will similarly flourish if common software standards are observed. If a single software design company gains a monopoly because of the predominance of their proprietary blueprint file format, poor people and hobbyists will not have access to low cost design tools. If personal fabrication machines work with only a few, commercial file formats, only professional or affluent designers will have access to the design space.

Create a database of CAD files used by government agencies

> ***"With its purchasing power the government can mandate that they need the CAD data for any and all parts they order. From a Boeing aircraft part to a tape measure. This will enable interoperability, hacking by troops, allow the government to easily source replacement parts and cheaper components. There will be no place for the rip off artists to hide. No more "let's put a different label on these glasses and triple the price"... The government will source it from the cheapest supplier. The cost savings will be enormous."***
>
> *– Joris Peels, i.Materialise*

Government agencies should place CAD files and fabrication blueprints of the machine parts that the U.S. government procures from various vendors into an online database. Small, domestic manufacturers should be given access to this database (subject to classified access when appropriate). When the government issues an RFP on future contracts, small manufacturers could bid to fabricate the desired part. This would increase the competition amongst parts vendors and will encourage the growth of small, domestic manufacturing companies that can serve the government. An online database of CAD files would also incent manufacturers to develop part add-on, extensions, replacements, and improvements.

Grants & funding

Establish an "Individual Innovation Research Program" for very small manufacturing businesses and DIY entrepreneurs

In addition to SBIR funding, the government should institute an additional "Individual Innovation Research Program" that offers SBIR-like funding opportunities for individuals and small domestic companies (fewer than 25 employees) whose businesses are exploring cutting-edge small-scale, regional, product design and manufacturing methods. Small businesses are an increasingly critical source of product and process innovation. In addition, small businesses are regional, meaning they create jobs close to home. Their expertise is "sticky," in that it's difficult to outsource.

If small businesses are supported in their utilization of personal design and manufacturing tools to accelerate their product innovation efforts, that will help improve their effectiveness and could help retain small scale manufacturing in the U.S.

GIVE RFP PRIORITY TO RURAL MANUFACTURERS THAT USE PERSONAL MANUFACTURING

> ***"Widespread adoption of RepRap [a type of 3D printer] would reduce transportation. Most consumer items undergo many separate journeys between the production of their raw materials and their final arrival at a person's home. But if people were to begin making things by downloading designs from the web to their own rapid prototyping machine, then just raw material would have to be transported."***
>
> *– Adrian Bowyer, creator of the RepRap project, University of Bath, UK*

Rural small-scale manufacturing companies should receive extra assistance and higher priority when competing for federal funding awards. Personal fabrication technologies are a good fit for rural manufacturing companies since the technologies make it possible to design and manufacture sophisticated, custom products and objects close to home. Rural manufacturing companies typically serve economically-challenged regions, both as consumers and as employers. Rural manufacturers who can fabricate medical devices and supplies should be eligible for additional government subsidies or receive a tax break.

IP POLICIES

ESTABLISH AN IP "SAFE HARBOR" FOR AGGREGATORS AND ONE-OFF PRODUCERS

The leading concern amongst companies in the personal fabrication space is that of intellectual property complications. Small scale digital fabrication, like digital music and media, shatters existing models of intellectual property management based on patents and copyrights. IP laws need to adapt to new retail models, new product design models and new personal fabrication technical capabilities. Right now, companies who host blueprint designs and those who manufacture custom objects for consumers are at risk of being penalized for violating copyright if they unknowingly make an illegal copy of a copyrighted or patented object.

The regulatory framework around ownership of small scale, digital manufacturing needs to be updated. U.S. patent and copyright law is too rigid. Anyone working with personal manufacturing will need a good faith "safe harbor" from IP prosecution. Prototypes should be usable under a fair use clause. More leeway needs to be given for private or home use of objects, similar to the IP exemption already used in Europe. Further exploration of the economic feasibility of running a business selling open source hardware devices is required.

MICRO PATENTS – A SMALLER, SIMPLER, AND MORE AGILE UNIT OF INTELLECTUAL PROPERTY

A good intellectual-property foundation is key to a prosperous innovation economy, but the current intellectual property "unit" for technical innovation - a utility patent - may be too complex, costly, and slow for individual inventors and small businesses. Micro-patents, an alternative intellectual property unit, should be considered for the emerging economic landscape of rapid, individually-driven small inventions that will likely typify this new economy. In the world of small-scale, on demand custom manufacturing, micro-patents could offer lone inventors and small businesses simple, agile and cost-effective intellectual property protection they need to get their idea off the ground. In the same way that micro-loans give low-income individuals the opportunity to found a small business, micro-patents could level the playing patent playing field between large and small businesses.

Here's how micro-patents would work. An inventor would submit, for a few hundred dollars, a document describing their invention to a centralized government micro-patent repository. The document would be time-stamped and immediately publically released, without having to be subject to the traditional tests of novelty, utility and non-obviousness. The inventor's micro-patent application would claim very few fields of use, perhaps there could even be a mandatory limit on scope to qualify as a micro-patent, such that it must have been implemented and used in practice at the time the application if filed. By filing this document, the inventor would immediately be granted an implicit, short-term (say 5 year) exclusive right to her new disclosed idea in a that narrow field of invention, as long as the idea was not already disclosed publically earlier. Only in the case of alleged infringement, would intellectual property experts, lawyers, and the judicial system be brought to bear on the case with the all the costs, time, and complexities involved.

Utility patents, conceived more than a century ago, are designed for and used mostly by large corporations, who can spend tens of thousands of dollars on preparing applications, seeing them through the lengthy review process, and then defending and enforcing them for their 17-year-long lifetime. In return for this protection, patent holders agree to disclose all the information they have about their invention, so that it can be used by others after the patent expires, almost two decades later, but still much better than an indefinite trade secret. Most corporations do not rely on just one patent, but develop an arsenal of patents to completely fence off an area of innovation and prevent competitors from entering.

While useful for corporations, most individual inventors and small businesses miss out on the benefits of the patent system for several reasons.

- they cannot afford to spend the tens of thousands of dollars on preparing, defending, and enforcing patents
- they do not need the same level of protection - they may not be trying to fence off an entire field, nor are they looking for two decades of protection
- they cannot wait two or three years for their patent to be reviewed and approved. They need something simple, quick, and cheap.

Today, the primary alternative to patents that's available to individual inventors is that of the "trade secret." However, trade secrets work against the original intent of our nation's patent process and may discourage industry-wide innovation due to their indefinite lifespan. Few of the issued U.S. patents are ever licensed or tested in court. Therefore, micro-patents would shift the costs burden of IP protection to those rare cases where a company wants to invest in broad patent protection, implying a huge cost saving to the system. For decentralized, rapidly developing fields such as personal fabrication, micro-patents would be a simpler, more agile, shorter term and cheaper alternative to today's utility patents.

Some argue that the advent of micro patents will lead to fragmentation of the intellectual property space, causing a gridlock in innovation. Note however that this fragmentation will be limited by the relatively short time span that a micro-patent would hold, its relatively narrow scope of use, and the requirement that it is used in practice. Micro-patents may thus unleash innovation that would otherwise be kept trade secret, much in the same way that standard utility patents are designed to. These pros and cons need to be evaluated and discussed carefully.

Regulatory

Re-visit consumer safety regulations for personally-fabricated products

New regulatory frameworks are needed to protect consumers in the emerging era of small-scale, digital personal manufacturing. Consumer safety regulations are based on a model of mass production in which the FDA (or other regulatory agency) has the centralized power and control to oversee the design of new products. Centralized control, however, goes away when manufacturing and product design take place in the hands of regular people. The beauty of personal scale digital manufacturing is that consumers have access to powerful design and manufacturing tools previously in the hands of a few. However, this same power opens up new concerns about consumer safety in connection with self- designed products that may malfunction, be toxic, or be counterfeit.

Introduce a more granular definition of a "small" manufacturing business

Personal scale manufacturing companies, unlike old-school "small" manufacturing companies, typically hire far fewer than 500 employees, currently the formal definition of what qualifies as a small business. A more granular definition of small business needs to be defined by the U.S. Small Business Administration. 500 employees is much too large of a number of employees to accurately reflect the growing number of 5, 10, and 20 person manufacturing companies in today's small-scale world of personalized manufacturing. A more granular definition would give emerging and innovative businesses a better shot at SBIR awards. For example, a 20 person small businesses cannot compete with a 490 person small business in RFPs and other competitive bids.

Small businesses should be classified in sub-groups, starting with less than 20, 21-50, 50-100 and so on. Government set-asides for very small businesses would level the playing field to lower the barrier to entry to bright and hard-working small business owners who are seeking government support.

Pass the National Fab Lab Network Act of 2010, HR 6003

Current legislation before Congress aims to "To provide for the establishment of the National Fab Lab Network (NFLN) to build out a network of community based, networked Fabrication Laboratories across the United States to foster a new generation with scientific and engineering skills and to provide a workforce capable of producing world class individualized and traditional manufactured goods." More specifically, the Act wants to establish one Fab Lab per every 700,000 individuals in the United States in the first ten years of its operation.

Fueled by Neal Gershenfeld's tireless efforts to promote Fab Labs as a tool for education and community development, the Fab Lab Network Act would establish a new kind of national infrastructure to take advantage of leading edge digital fabrication technologies to secure the United States' leading position in science and manufacturing. The Act proposes to establish a non-profit entity that would manage a national network of fabrication laboratories and coordinate activities between them. The new non-profit entity, the NFLN, would be the first point of contact for anyone wishing to create a new Fab Lab, set standards for Fab Labs and judge whether requestors are able to meet them, help Fab Labs find sponsors and machines and promote the idea of personal fabrication to the public.

TAX CREDITS

"CLEAN COMPANY" TAX BENEFITS

"One of the potential advantages of home fabbing is the massive reduction in goods transport that would be consequent on people's making lots of stuff for themselves, with all the greenhouse gas savings that that implies. Well, for energy itself we now have feed-in tariff laws, which oblige utilities to pay a fixed price for home-generated green electricity. This costs government nothing, as the utilities pass the charges on to their other customers. Dirty energy users are paying a premium, which is then used to reward clean generators. By analogy, one can imagine changes in, say, sales tax laws that would increase the cost of finished goods, but reduce that of raw materials used by personal fabricators. This would be revenue-neutral for government, but would encourage the use of the technology with

consequent transport savings."

– Adrian Bowyer, University of Bath, UK

Companies that use personal manufacturing technologies deserve competitive advantage for their eco-friendliness. Personal manufacturing keeps production regional, but also is less polluting than traditional mass manufacturing methods. Personal-scale manufacturing technologies offer a more precise form of manufacturing that leaves less toxic waste and manufacturing scrap by product. As a result, personal fabrication technologies provide a natural vehicle with which to experiment with local, recycled, or novel materials.

More research is needed to pinpoint the optimal criteria for "clean company" tax advantages. Examples of possible criteria would be to offer advantages to manufacturing companies that:

- Use a certain percentage of raw material from their local region
- Use a certain percentage of raw manufacturing materials are of re-used waste materials
- Produce few than a certain number of tons of waste per year
- Emit a certain amount of exhaust into the air or nearby groundwater

Tax-free raw materials for personal manufacturing businesses

Related to the tax benefits of being a "clean company," companies and individuals who primarily use personal-scale manufacturing technologies should not pay taxes when they procure the raw materials they use for production. If companies who are already eco-friendly in their manufacturing practices are able to procure the raw materials at a lower cost, they can pass along the cost savings to their customers in the form of lower prices. Lower cost, clean, domestically produced goods will be better able to compete on price against mass produced goods imported from highly polluting and unregulated offshored factories.

FURTHER EXPLORATION AND RESEARCH

ENCOURAGE AN NSF/DOED STUDY ON PERSONAL DIGITAL MANUFACTURING AS A TOOL IN STEM EDUCATION

Federal grant money should be made available to gain insight into the value of hands-on, small scale product design and manufacturing tools in the science and engineering classroom. Much study has already been done on the impact of hands-on learning in STEM education. Personal computing and educational software in STEM education are also similarly well-explored. However, spotty anecdotal data about the benefit of personal, digital manufacturing technologies in STEM education is not enough -- a more rigorous approach is needed. There is currently no data on the impact (on students and teachers both) of making hands-on personal, digital design and manufacturing technologies a core part of K-12 STEM education.

A federal funding agency should initiate a call for controlled, longitudinal studies that track the development and retention of students in engineering education between two control groups: students with regular hands-on access to digital design and manufacturing technologies as a core part of their educational curriculum vs. students without access to digital manufacturing technologies. The study should explore key questions such as

- whether students whose STEM coursework involved designing and making their own models performed better on standard scholastic tests
- whether K-12 students were more inclined to view an engineering and science career more positively if their curriculum involved personal digital manufacturing technologies
- what percentages of target vs control each group selected a science or engineering major upon graduation from high school
- whether retention rates amongst girls and minority students improved if personal fabrication technologies were part of their STEM classroom curriculum.

Similarly, K-12 STEM teachers should be studied in the same manner.

LEARN MORE ABOUT USER LED PRODUCT DESIGN

Personal manufacturing technologies provide the perfect platform for user-led innovation and formal product development toolkits. However, little is known about the challenges and benefits of user led innovation on small scale and large scale manufacturing, our economy, and environment, particularly in the context of formal company-issued produce development toolkits. Users that come up with significant improvements to products have not been factored into our understanding of how the product innovation process works. Public policies should be reviewed in a new context in which small-scale, decentralized personal digital manufacturing. More exploration is need to answer questions of the impact on businesses if regular people are able to design and make their own products. For example, what will happen to large companies that rely on the sale of low margin, mass produced goods to make a profit? If consumers get hooked on designing and producing things themselves, how will that impact federal safety regulations and the environment? More targeted questions also demand exploration. For example, large corporations are given R&D subsidies and tax credits when they invest in product innovation. However, it would be useful to explore the value and impact of giving similar tax breaks to small companies and individuals also who invest time and resources in product innovation.

CONCLUSION

Personal-scale manufacturing machines use the same fabrication methods as their larger, industrial ancestors, but are smaller, cheaper, and easier to use. Home-scale machines, such as 3D printers, laser cutters, and programmable sewing machines, combined with the right electronic design blueprint, enable people to manufacture functioning products at home, on demand, at the press of a button. These technologies make manufacturing accessible to everyone; for the first time, designing and making custom objects is cheap, easy, and fun. Recent rapid technological advances in design software and personal manufacturing machines, combined with shrinking costs of machines and materials, increasingly active and helpful online user communities, plus most peoples' tendency to conduct more and more daily activities online, will tip personal fabrication from the realm of hobbyists and pioneers to the mainstream.

Personal manufacturing technologies will profoundly impact how we design, make, transport, and consume physical products. As manufacturing technologies follow the path from factory to home use, like personal computers, "personalized" manufacturing tools will enable consumers, schools and businesses to work and play in new ways. Emerging manufacturing technologies will usher in an industrial "evolution" that combines the best of mass and artisan production models, and has the potential to partially reverse the trend to outsourcing. Personal manufacturing technologies will unleash "long tail" global markets for custom goods, whose sales volumes of will be profitable enough to enable specialists, niche manufacturing, and design companies to make a good living. Underserved communities will be able to design and manufacture their own medical devices, toys, machine parts and other tools locally, using local materials. At school, personal-scale manufacturing tools will empower a new generation of innovators, and spark student interest in science, technology, engineering and math (STEM) education.

Like computing, transportation and communication, shrinking manufacturing tools represent a strategic infrastructure technology that has the potential to catalyze innovation in many other fields and industries. These technologies remove the barriers of investment in heavy machinery and specialized operator skill, so consumers, for the first time since the era of artisan craft production, will lead the design and manufacturing process. We have the opportunity to create a new retail ecosystem and manufacturing economy in the U.S. so we can continue to lead the rest of the world in product innovation and manufacturing. New business models will become possible, such as small-scale, regional manufacturing hubs, mom and pop shops that create niche products for a global market, custom and on-demand manufacturing, and toolkit-based industrial product design and development.

Despite their great promise, successful adoption of personal manufacturing technologies is not assured. A number of barriers stand in the way that discourage widespread home, school and business use such as safety concerns, part standardization and version control challenges, intellectual property issues and creating appropriate regulatory controls. Thoughtful and visionary government investment is needed to ensure we establish the U.S. as the world leader in personal fabrication technologies. Appropriate government policies will nourish the potential of these technologies to promote STEM education, create new industries and innovation-based domestic jobs, provide a new design space to foster invention, and spark the formation of new businesses.

BIBLIOGRAPHY

[1] No author given. "A Factory on your desk." Case history in *The Economist print edition*, Sep 3rd, 2009.

[2] Vance, Ashlee. "3-D Printing Spurs a Manufacturing Revolution." *New York Times,* September 13, 2010. Available online at http://www.nytimes.com/2010/09/14/technology/14print.html

[3] ASTM F2792-10 Standard Terminology for Additive Manufacturing Technologies

[4] Image and information from Singer's web site at http://www.singerco.com/futura

[5] Information and image from Brother's web site at http://www.brother-usa.com/HomeSewing/ProductList.aspx?cat=embroidery&WT.svl=EmbroideryTopNav

[6] CNC Cupcake price quote from the MakerBot store's web site in November, 2010. Up-to-date additional information is available at http://store.makerbot.com

[7] http://fabathome.org

[8] Upfront.eZine's interview with Emilio Juarez. All About HP's Strategy for 3D printing." Posted May 25, 2010 at http://www.upfrontezine.com/2010/upf-647.htm

[9] Terry Wohlers. *Additive manufacturing state of the industry annual progress report.* Fort Collins, CO: Wohlers Associates, Inc., 2010.

[10] Christensen, C. M. *The Innovator's Dilemma*. Cambridge, MA: Harvard Business School Press, 1997.

[11] No author given. "ATKINS project: a low-carbon manufacturing solution." Loughborough University New and Events page, January, 2009. Available at http://www.lboro.ac.uk/service/publicity/news-releases/2009/03_ATKINS.html

[12] Burns M. "The Freedom to Create." *Technology Management* 1 (1995).

[13] Maury Klein. *The Genesis of Industrial America, 1870 – 1920.* Cambridge, MA: Cambridge University Press. 2007.

[14] No author given. "Factory jobs: 3 million lost since 2000". *USATODAY.com.* April 20, 2007.

[15] Chart, Natasha. "G-20 Manufacturing: A look at the numbers." Blog post, October 19, 2009. Available at http://www.ourfuture.org/blog-entry/2009104319/g20-manufacturing-output-capita .

[16] Johnson, Joel. *Gizmodo* magazine. Available online at http://gizmodo.com/5457461/atoms-are-not-bits-wired-is-not-a-business-magazine#comments

[17] Forrester Research. Report on US online retail sales. More information available at http://techcrunch.com/2010/03/08/forrester-forecast-online-retail-sales-will-grow-to-250-billion-by-2014/

[18] Chris Anderson. *The Long Tail.* New York: Hyperion. 2006.

[19] http://en.wikipedia.7val.com/wiki/Long_Tail

[20] Von Hippel, Eric. *Democratizing Innovation.* Cambridge, MA: The MIT Press, 2005.

[21] Herstatt, C., and E. von Hippel. "From Experience: Developing New Product Concepts via the Lead User Method." *Journal of Product Innovation Management* 9 (1992): 213-222.

[22] Lilien, G. L., P. D. Morrison, K. Searls, M. Sonnack, and E. von Hippel. "Performance Assessment of the Lead User Idea-Generation Process for New Product Development." *Management Science* 48 (2002): 1042–1059.

[23] Howe, Jeff. "The Rise of Crowdsourcing." *Wired,* June, 2006. Available online at http://www.wired.com/wired/archive/14.06/crowds.html.

[24] Henkel, J. and von Hippel, E. "Welfare implications of user innovation." *Journal of Technology Transfer*, 30 (2005): 73-88.

[25] Lilien, G. L., P. D. Morrison, K. Searls, M. Sonnack, and E. von Hippel. "Performance Assessment of the Lead User Idea-Generation Process for New Product Development." *Management Science* 48 (2002): 1042–1059.

[26] Thomke, Stefan and von Hippel, Eric. "Customers as Innovators. A New Way to Create Value." *Harvard Business Review*. April 2002: 2-10.

[27] Volume 1.1 of the Open Source Hardware Draft Statement of Principles and Definition. Available online at http://freedomdefined.org/OSHW_draft

[28] AS220 Youth's Fabratory. Information and images from thingiverse.com web site at http://www.thingiverse.com/thefabratory

[29] President's Council of Advisors on Science and Technology. "Prepare and inspire: K-12 education in science, technology, engineering, and math (STEM) for America's future." Report to the President. September, 2010.

[30] National Science Board. "Science and Engineering Indicators: 2010." Arlington, VA: National Science Foundation. 2010. Available online at http://www.nsf.gov/statistics/seind10/start.html

[31] Kalil, Thomas. "An information commons for e-learning: Designing a digital opportunity investment trust." *Spectrum Series* Working Paper 2 (2002). New America Foundation, Washington, DC.

[32] Information from the superduke forum at http://www.superduke.net

[33] Weinberg, Michael. "3D printing: It will be awesome if they don't screw it up." From Public Knowledge blog. Posted November 10, 2010.

[34] Jarmin, Ronald S. "Evaluating the impact of manufacturing extension on productivity growth." *Journal of Policy Analysis and Management 18 (*1999): 99-119.

[35] Helper, Susan and Janet Kiel. "Developing supplier capabilities: Market and non-market approaches." *Industry & Innovation* 11 (2004): 89-107.