Participatory Material Culture
Environmental Scan

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DESKTOP PROTOTYPING

Desktop prototyping is the process of creating and testing a working model of a desired system using tools that can be purchased, maintained, and operated on the scale of a small business or even an individual. The process is similar to desktop publishing, the creation of printed materials on a personal computer, in that desktop prototyping fills a niche for hobbyists or small businesses that do not have the resources or need to hire a specialized design firm or to build a traditional manufacturing plant. In recent years, several new tools have become available at the desktop scale, including 3D printers, numerous sensor packages, and relatively cheap and easy to use logic packages. This report details the current state of the desktop prototyping market, observes some opportunities for further growth, and identifies some challenges from traditional manufacturing and production concerns.

Before delving into the specifics of desktop prototyping in 2012, let us first consider why the space exists at all, some of the tradeoffs between desktop and traditional methods, and some of the alternatives to desktop prototyping. Desktop prototyping allows for prototyping without the capital expense associated with traditional factory-scale manufacturing equipment, and without the same training, professional standards, and expertise of a fab. It also allows individuals more control over design. Furthermore, desktop prototyping equipment can be used for production at small scales. Individual parts may be more expensive, slower, and even lower quality than when scaled to a traditional manufacturing environment using traditional materials, but the overall production run can in some circumstances be less expensive or may have other benefits, such as being more customizable, or being scheduled on demand, which minimizes warehousing costs.

ALTERNATIVES TO DESKTOP PROTOTYPING

There are four basic alternatives to desktop prototyping: industrial prototyping, virtual prototyping, hand-crafted prototyping, and no prototyping. Industrial prototyping involves prototyping directly on the full-scale industrial manufacturing equipment. This tends to be most cost-effective for large runs of a product, and often involves custom tools that, while individually expensive, shave pennies or seconds from the manufacturing process. These savings accrue to repay the capital invested to build the factory line. It is only available to designers who have access to such equipment, which represents a large capital investment. In a typical injection moulding process, industrial prototyping would involve the creation of a mould and a short run of parts that could then be quality tested to ensure that expected tolerances have been met. Because moulds are expensive to create relative to the parts that come out of them, moulding is cost-effective only when its cost of creation can be amortized over a relatively large production run. It does not make economic sense to prototype a part before there is some assurance of a market to defray the setup cost. Each extra round of prototyping would therefore be very costly, multiplying the length of the amortizing run. It rarely makes sense to experiment freely using industrial tools, which usually have to be run steadily in production mode to amortize their own capital costs. Industrial prototyping is generally reserved for fine-tuning an already solid design.

Virtual prototyping uses computer simulation to investigate the expected performance of a design. Perhaps the most prominent site for virtual prototyping is in aerodynamic design. Most aircraft are now constructed from material parts only after they have been virtually constructed in a computer and run through a sophisticated set of simulations that incorporate every bolt and
rivet in the airframe and model the material stresses they would encounter under various simulated flight conditions. Computer simulation on the scale of a jetliner is extraordinarily costly, but has now surpassed scale models in wind tunnels for accuracy, and this can ultimately shorten the design cycle. In addition, of course, the cost of simulation is reflected in the price of a jetliner. Small scale designers rarely have access to either the computing power or the sophisticated simulation software necessary to prototype to the exacting standards of the airline industry, but in many cases such detail is not necessary anyhow. It is worth noting that very few software packages allow for virtual prototyping with material properties, and those that do cost tens of thousands of dollars and require significant training. They are not meant for hobbyists or for desktop prototypers.

Hand-crafted prototyping involves the careful construction (using hand tools) of a model object that is ultimately intended to be produced using automatic industrial techniques. For example, the design for a plastic toy might first be modelled in clay, or a circuit plan may be constructed on a bread board for testing before it is sent to be milled and mounted on a printed circuit board. Hand-crafting is sometimes contrasted with computer-aided desktop prototyping because the tools are under manual control and are therefore subject to a different set of skills and constraints. However, as computer controls find their way into more desktop tools, this distinction may disappear or appear as more of a continuum between manual and automated tool control.

The final alternative to desktop prototyping is no prototyping. Variations on well-understood processes may sometimes be adopted immediately, without the need for a separate testing phase. Architects working on single-family dwellings, for example, may be satisfied with a sketch or a CAD drawing of a planned alteration to a standard design. (Arguably, even a sketch may be seen as a version of ‘virtual prototyping’. The point here is merely to recognize that occasionally there is no explicitly recognized prototyping phase.) In general, forgoing prototyping is possible only when the production process itself is relatively flexible, as in the case of home construction. The workers are relatively autonomous, can make decisions about how to execute various parts of a plan, and can halt work and ask for guidance if confused. The situation I am describing is one of incomplete specification and design-while-constructing. The same conditions often apply at the individual scale, for hand-crafted goods. Rather than completely specifying a plan, a crafter relies on highly tuned intuition and skilled action to produce an object that satisfies the incompletely described need. In industrial processes, this kind of freedom is not possible. The machines do not have the right kind of intelligence built into them, and CAD/CAM software is not structured to accept incomplete specifications.

Given that desktop prototyping exists within the context of a constantly changing set of tradeoffs and alternatives, it can be difficult to predict the opportunities and challenges that face companies trying to enter the space. The first step is to decide what counts as a desktop prototyping tool. In our view, desktop prototyping includes tools on a cost scale an order of magnitude smaller than traditional manufacturing and such tools typically will not require as much specialized training to operate. These are both moving targets, since traditional manufacturing is not a stagnant field. In general, the price for a particular set of capabilities falls as time passes and technology develops. Likewise, the capabilities that are available for a given price increase as time passes. At the same time, the software interfaces designed for consumers and ‘prosumers’ tends to deemphasize specialized skills—an aim greatly aided by the increasing ubiquity of general computing skills.
PARAMETERS OF THE ENVIRONMENTAL SCAN

This environmental scan provides a snapshot of desktop fabrication technologies in 2012. The report focuses on two streams of emerging technologies: (1) additive manufacturing, or “3D printing”, and (2) sensor/controller/actuator toolkits, or “control systems”. Both technologies have existed for decades, but have only recently attained “desktop” status in virtue of increasing public availability, falling capital and supply costs, and the wider availability of enabling technologies like easy-to-use programming languages. The intention is not to ignore well-established desktop prototypers like milling and sewing machines. Rather, the hope is that the attention surrounding emerging technologies will help to underline the opportunities that desktop prototyping affords. Moreover, because these technologies are still emerging, there is ample opportunity to intervene and shape their trajectories, for example to encourage the development of accessible tools. In this report we attend roughly to developments in the $100-$10000 range for 2012 equipment, $10000-$100000 for horizon equipment. Similarly, we attend to parts in the $1-$100 range for 2012 products, and $100-$1000 for future/planned products.

The remainder of this environmental scan is devoted to exploring the economic, technological, political and legal, social, and environmental contexts for desktop prototyping in 2012.

3D PRINTING HISTORY AND MARKET LANDSCAPE

Modern CNC (computer numerical control) systems combine CAD (computer-aided design) and CAM (computer-aided manufacturing) systems into a highly integrated, automated production process. The first numerically controlled machine tools, built in the 1940s, were based on existing manufacturing equipment but were modified to include motors that moved the tool controls through a predetermined path programmed onto a magnetic tape. Subsequent decades saw significant improvements to virtually every aspect of the manufacturing process, including the servomotors that control the movement of the tool head, the software drivers that translate a 3D plan of an object into motion controls, the capabilities of the machine tools themselves, and the design software that produced the 3D plan.

By the 1960s, large industry began making use of computerized ‘rapid prototyping’ tools. Rapid prototypers fabricated prototypes of products or parts for the purpose of testing prior to the tooling required for mass production. Rapid prototyping makes sense when the potential benefits, such as a shorter time to prototype and a lower cost to produce a failed prototype, outweigh the costs, which include the capital investment for the prototyping equipment — often several hundred thousand dollars — and the risk of creating a prototype that does not perfectly represent the finished manufactured product. Mass production techniques such as molding and casting are expensive in both time and materials, often counted in weeks and thousands of dollars. They require the creation of a form before a prototype can be produced. If the prototype is deemed a failure, the entire process of designing and constructing a form has to be repeated — and the initial form discarded. Subtractive processes of manufacturing do not require the construction of an expensive and time-consuming form, but they are expensive in raw materials: the basic mode of operation is to begin with a block of material and then use various tool heads to drill or cut away unwanted material, leaving only the finished product behind. The unwanted material is essentially waste—at best, it must be reprocessed before it can be used.

By contrast to these techniques, additive manufacturing requires neither a form nor a significant amount of excess material. The basic process is to ‘layerize’ a digital model into horizontal layers and build the object up with each new layer resting atop the previous, like the
contours of a terrain model. A typical prototype can be 3D printed in a matter of hours for a cost measured in tens or hundreds of dollars. In addition, prices for high-quality 3D printers have themselves fallen to the tens of thousands of dollars, making in-house fabrication feasible and attractive for industrial designers, research labs, architectural firms, and small-run manufacturers.

Small-run manufacturers occupy a particularly interesting space in the 3D printing landscape. Several such manufacturers present highly customizable customer experience via online design and order systems. These online services can be seen as the modern equivalent of mail-away photographic developing. Shapeways, for example, asks users to create a 3D model separately, then upload the result and select materials from those available. Shapeways then prints the result and ships it to the client. Ponoko, a longtime lasercutting fab, has also added 3D printing to its menu, and companies like Autodesk are beginning to enter the consumer-facing 3D market. Office supply giant Staples recently announced an in-store 3D printing option within some copy centres in Europe. Despite these moves toward consumer-facing 3D printing, the companies providing 3D equipment to small and large industry have yet to fully engage the consumer market for 3D printers and associated software.

Despite the measured pace of industrial players, a plethora of inexpensive 3D printers are currently on the market, and many individuals have constructed their own DIY CNC machines, enabled and encouraged by “advancements in personal computers and programmable microprocessors, as well as the increasing availability of mechanical components such as stepper motors (often recovered from discarded consumer electronics such as inkjet printers and scanners)” (Ratto and Ree, 3). RepRap (for ‘replicating rapid prototyper’) is a UK-based academic project committed to developing a self-replicating 3D printer. RepRap is open-source, which means that it is, in principle, available to anyone. At present, the assembly of a RepRap presents significant technical and logistical challenge “requiring local sourcing of often elusive hardware, extensive wiring and soldering of electronic components” in addition to a relatively sophisticated working knowledge of software code (Ratto and Ree, 3). One offshoot of the RepRap hardware design is MakerBot Industries, which aims to commercialize 3D printing, at least within the DIY or Maker community. MakerBot sells its printers fully assembled, or as a kit ready for assembly.

Although it is possible to identify market leaders, like MakerBot and UP!, the market is extremely volatile at the bottom. Because RepRap is open, the cost of parts is falling, and the requisite skills are available to hobbyists as well as professional engineers, it is relatively easy to enter the consumer/hobbyist 3D market. Internet-based crowd funding schemes (kickstarter, indiegogo) have made startup funds more accessible, removing yet another barrier to entry. Despite this, there are signs that the market could eventually consolidate. MakerBot’s most recent model is ‘partially closed,’ meaning that they no longer openly share all of their designs. At the same time, larger industrial players are moving increasingly aggressively to establish a foothold in consumer-facing 3D printing. HP, for example, has teamed with Stratasys to brand a line of 3D printers priced around $20,000. At the same time, Autodesk, the makers of AutoCAD, the industry standard CAD package, have released the 123D line of software packages. One of these, 123D catch, allows users to easily create a 3D model by photographing an object. This is a dramatic change in the level of technical skill required to create a 3D plan—albeit, in the 3D equivalent of photocopying.

Another distinguishing feature of the 3D printing ecosystem is the growth of online libraries and support communities that help to flatten the learning curve for new entrants to 3D printing practice. Thingiverse, a website maintained by MakerBot Industries, makers of one of
the most popular hobbyist 3D printers, is a repository for 3D designs made available to the public for free by their designers. The plans shared on Thingiverse raise questions about the limitations of the standard file format (see Political: Standards), responsibility for dangerous designs (Legal: Liability), and intellectual property (Legal: Intellectual Property), among others. For the moment, however, let us focus on the economic implications of such shared libraries. First, it lowers the barriers to entry into 3D printing practice. Second, it enables people to easily share, improve, and discuss designs. Third, it has the potential to remove or lower the economic incentive to design 3D objects because it is too easy to copy existing objects and too costly for most small businesses to chase intellectual property thieves.

Because so many entry level 3D printers are based on RepRap, there is the appearance the 3D printing is a single, coordinated technology, with market differentiation around build size, speed, and resolution. In fact, however, 3D printing, or additive manufacturing, is the general term for any technology that forms base materials into a desired shape by an additive process. It stands in contrast to traditional subtractive manufacturing technologies including milling and routing, which create waste material; and form manufacturing, which requires a mould into which liquified base material is injected and set. Additive manufacturing also differs from additive craft technologies, like throwing clay or blowing glass, which are typically not automated.

3D printing encompasses a number of technologies which fulfill the ideal of additive manufacturing in different ways and to different degrees. We may suppose that the ultimate goal of additive manufacture is to be able to specify the exact placement of every last atom in the final product and to be capable of placing any element beside any other, within the limits of physics. Put another way, 3D printing aims toward the Star Trek ‘replicators’ that can produce nearly anything imaginable, at will. Current 3D printers do not come close to satisfying this goal. But 3D printing does allow for the automatic and on-demand creation of shapes that would be impossible to replicate with standard manufacturing techniques and which would require exquisite skill to replicate by craft. For example, 3D printing allows for large undercuts, enclosed areas, and internal moving parts, three general features that subtractive manufacturing cannot accomplish directly.

At the same time, 3D printing allows a level of customization that is difficult to achieve in traditional manufacturing. There, the need to scale production to cost-effective levels militates against customization. With 3D printing, the scaling limit is on the design side, not the production side. The printer itself is indifferent to the design it prints; it can print a left-handed object as easily as a right.

Following is a sampling of currently available 3D printers. The list is not exhaustive, but it is representative of the range of prices and technical capabilities at the lower end. Prices range from $520 to $3299, and in general a higher price buys higher performance along one of two fundamental dimensions: build envelope or resolution. Build envelope is the size of the largest object that can be printed as a single piece. Most entry-level 3D printers are limited to printing pieces that would fit inside a breadbox. Resolution has two elements: the smallest features the printer can produce, and the quality of those features. The usual proxies for measuring these are nozzle size and layer thickness. Layers as thin as 0.05mm begin to be smooth to both touch and appearance, similar to a 600 dpi digital image. Layers thicker than 0.1mm feel ridged to the touch and may need sanding or chemical finishing to achieve the desired level of smoothness. Less expensive, lower quality 3D printers produce objects with pronounced ridges, and objects can appear “pixelated”, like a low resolution image. Most entry level 3D printers print in plastic.
But there are printers that print in wood, metal, ceramic, glass, concrete, and silicon. Some can print multiple materials in a single object, usually by employing multiple print heads. Other printers in development aim to print in “digital” materials that mix primary materials together and extrude them from a single print head. This would enable designers to specify desired material properties like strength and flexibility. At present, however, most entry-level 3D printers are limited to printing in one or two kinds of plastic at resolutions that are generally unsatisfying for an end product.

### 3D PRINTERS

**RepRap Mendel**  
$520 (parts)  
200 x 200 x 140 mm  
0.300 mm  
Fused deposition modelling with PLA, HDPE, ABS & more. Uses ø 3 mm filament at 15.0 cm³ per hour

**Printrbot**  
$999 (assembled)  
200 x 200 x 200 mm  
0.200 mm  
Fused deposition modelling with PLA/ABS

**UP! Plus+ v 1.2**  
$1549  
140 x 140 x 135 mm  
0.150 mm  
Fused deposition modelling with ABS

**LulzBot AO-101**  
$1700  
200 x 190 x 100 mm  
0.075 mm  
ABS/PLA filament extrusion, FAST: 200mm/s

**Makerbot Replicator 2**  
$2199  
285 x 153 x 155 mm  
0.100 mm  
ABS/PLA

**MiiCraft**  
$2,299  
28 x 43 x 178 mm  
0.050 mm  
Stereolithography

**B9 Creator**  
$2,375 (kit), $3,375 (assembled)  
76 x 100 x 200 mm  
0.100 mm  
Stereolithography

**Form 1 from Formlabs**  
$3299
In 2010, Moilanen and Vadén completed one of the first major surveys of 3D printing users. They found respondents through Twitter, listservs, blogs, and promotions by three of the major printing services (Shapeways, Ponoko, and Fabbaloo). It is hard to know how representative this sampling is, but it does give some insight into the 3D printing community. The survey had 358 respondents, predominantly male, highly educated, and from Europe or North America. These results are typical of earlier surveys of open source (software) hackers. Participants said they used 3D printing predominantly for creating functional models, artistic items, spare parts to devices, for research/educational purposes, and (to a slightly lesser extent) for direct part production. Nearly a quarter of all respondents had used RepRap printers. Almost as many had used Makerbots. Objet, ZCorp, 3D Systems, Stratasys, EOS, Dimension, Ultimaker, and BitsfromBytes we also well represented. A few respondents mentioned printers that are just entering the market, like Botmill and Printrobot. Most print in PLA, ABS, or other polymer, though some respondents had tried metal, wood, cement, silicon, or other materials.

To predict where consumer 3D printing may be heading, we can look at 3D printers an order of magnitude more expensive. These are also the printers that are used by print-to-order fabs like Shapeways and Ponoko.

**Stratasys Objet 30 pro**

- **$40,000**
- **294 x 192 x 148 mm**
- **0.028 mm**
- **Build resolution:** X-axis: 600 dpi; Y-axis: 600 dpi; Z-axis: 900 dpi, with proprietary materials, including clear, high temperature, and polypropylene-like “DurusWhite” for snap-fit.

**Fortus 900**

- **$250,000**
- **914 x 610 x 914 mm**
- **0.178 mm**
- **Materials:** ABS-ESD7 for static dissipation; ABSi for translucence; ABS-M30 for great tensile, impact and flexural strength and environmental stability; ABS-M30i for biocompatibility; PC for superior mechanical properties and heat resistance; PC-ABS for the highest impact strength, plus the mechanical properties and heat resistance of PC and the surface appeal of ABS; PC-ISO for biocompatibility and superior strength; PPSF for highest heat and chemical resistance; ULTEM 9085 for best mix of mechanical, chemical and thermal properties (from http://www.stratasys.com/3d-printers/production-series/fortus-900mc).

It is tempting to apply “Moore’s Law”-style reasoning to 3D printing, and assume that there is an innate doubling rate of, say, two years. If this were so, then we would expect that in two years, we could buy a printer with a particular set of capabilities for half the price we can

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today. By the same reasoning, a given amount of money will buy a printer with twice the capability if we just wait for two years. But there are serious challenges to be met before this could happen. For one thing, many high-precision 3D printers use stereolithography, while Makerbot Replicator uses filament extrusion. There is no guarantee that the precision of extruders can be improved to reach desired levels, or that materials like metal, wood, and glass can be adapted to extrusion. Likewise, there is no guarantee that stereolithographic hardware will scale well to a small desktop form factor, or follow the same doubling rate. For the present, however, it seems clear that 3D printers have a lot of space for improvement, lots of innovators working on the problem, and lots of past successes that suggest future improvement is likely.

**CONTROL SYSTEMS HISTORY AND MARKET LANDSCAPE**

The second stream of emerging technologies is in sensor/logic/actuator systems, or “control systems” for short. Mechanical feedback control systems have been in use since antiquity, one of the earliest being a float valve to maintain water levels similar to the one found in modern toilet tanks. The device comprises a float and a valve stop arranged so that when the water level rises above a certain limit, the float pulls the valve free, allowing water to flow out, lowering the water level, lowering the float, and closing the valve. Electronic control systems (the subject of this report) operate on similar principles as mechanical ones, except that the relevant quantities are electrical rather than mechanical. A prototypical electronic control system comprises sensors that detect or measure physical properties and turn them into electrical signals that can be manipulated by logic components before being transformed again into mechanical output by an actuator. A home heating system, for example, comprises a temperature sensor, the very simple “logic” of a setpoint thermostat, and a solenoid actuator to operate the furnace.

The predominant feature of the control systems market is that all of the components are susceptible to exponential rates of improvement, which over the past century has turned the entire field into a commodity market. Electronic components are fabricated and sold in batches of millions, and the price per part is typically measured in pennies. Capabilities are likewise improving exponentially. For example, the computational power of integrated circuits continues to increase according to Moore’s Law, which can be paraphrased as: the number of operations per second available per dollar doubles every eighteen months. The practical consequence is that, as of 2012, the typical smartphone has more computational power than the typical desktop computer a decade earlier—and has more computational power than a supercomputer a few decades earlier than that. Put bluntly, computations are cheap, and computation is being embedded in evermore consumer goods. This is true not only for computation, but also communication. An increasing number of devices are capable of connecting to the Internet, for example. And although the general public still finds the idea of an internet-connected refrigerator to be more of a curiosity than a desirable feature, one might have said the same thing about thermostats, televisions, and even phones not long ago.

Since the middle of the last century, electronic components have been available to consumers in small batches, initially by mail-order and at hobby stores like Radio Shack. Over time, an increasing number of components, integrated circuits, sensors, and actuators have become available, and most of these have eventually fallen in price to pennies per part. Individuals could learn to build circuits by purchasing kits or reading instructions published in magazines or by joining groups of like-minded hardware hackers in a neighborhood garage. With the rise of the Internet, many of these instructions—and the groups publishing them—went
online. Internet commerce has slowly driven brick-and-mortar shops like Radio Shack out of business, but new online stores like Adafruit have replaced them.

Constructing a controller can involve hardware and software design. Hardware sensors, logic chips, and actuators have to be connected together, usually in conjunction with a power supply and various other simple components, like resistors, capacitors, inductors, transistors, and so on. Complex integrated circuits are themselves made up of these simpler components, packaged together on a chip. Hardware design can be complex: different components may require different levels of voltage and current, and these are governed by selecting appropriate accompanying resistors, capacitors, and inductors. Components are sold with data sheets specifying their tolerances, requirements, and often example circuits, all of which make it easier for designers to put together a working circuit. This process can be significantly simplified if all of the components adhere to a single standard. This is precisely what controller kits aim to provide: a set of components that can be easily assembled and run without the danger of overheating, and which, moreover, correspond to functional behaviors. The Arduino standard, for example, includes a controller chip with a specific physical footprint of input-output pins. Additional functional components, called “shields”, can be plugged directly onto the controller. Shields receive power from the controller and are constructed within safety parameters of the input-output pins. A shield might contain a sensor or an actuator, and shields can be stacked up to create complex controllers.

This is not the whole story, however, as the controller chip still has to be told how to interpret sensor inputs, how to manipulate those signals, and what values to output to actuators. That is, they have to be programmed. Arduino makes this easy too. The Arduino controller board includes a USB connection for easy hookup to a standard computer, and the programming environment is available for free download from the Arduino website. Programming is a process of translating a desired set of behaviors into a code that can be understood by a computer. This is a complex task, but recent decades have seen dramatic improvements to programming interfaces. Arduino uses a language very similar to C++, one of the most common programming languages. Virtually everyone who has taken a formal programming class could immediately begin programming for Arduino. That said, programming is not a universal skill; it takes serious dedication to master. Most newcomers to Arduino and other controller platforms do not attempt to learn from scratch. Instead, they download code shared online and adapt it to their particular purposes. Together with active and extensive online discussion communities, online libraries of code help to flatten the barriers to entry. Programmers can easily find projects involving features they want to explore, and in cases where shared code is well-commented, it is easy to modify such projects to do new things. Because many people are likely to be interested in the same problems, and many of them will participate in online discussions and code libraries, packages like Arduino benefit from “Linus’s Law”: “Given enough eyeballs, all bugs are shallow” (Raymond 2000). The law is named for the creator of Linux, and describes the way the Linux community self-organizes to solve problems. Basically, by opening up the platform, people with the right combination of skills and interests can find problems that they can solve, and people without that combination of skills and interests will nevertheless benefit, because the solutions are openly shared.

Following is a sampling of controller kits. Like the sampling of 3D printers, it is not exhaustive, but is intended to give a representative picture of the controller market.
CONTROLLER KITS

Arduino
$40 for kit, $8 for parts
Software: free and open
Library: open.
Limitations/Extensions: shields are open hardware, or available for purchase.

Raspberry Pi
$25
Software: free and open.
Library: open, especially if you count Linux libraries
Limitations/Extensions: Mostly software

Lego Mindstorms NXT 2.0
$350
Software: proprietary. There are a few open alternatives.
Library: open, hosted by Lego.
Limitations/Extensions: Mostly robotics

Littlebits
Kits start at $90
Software: N/A
Library: open, hosted by Littlebits.
Limitations/Extensions: No software, just simple inputs connected to outputs.

PIC Microcontroller
$10
Software: Instruction set, serial programming.
Library: no unified community, but lots of stuff online.
Limitations/Extensions: there is no standard development environment or board for the PIC. Steep learning curve.\(^2\)

A huge variety of sensors and actuators are now available at low cost. For prices ranging from pennies to a few dollars, hobbyists can purchase sensors to detect or measure temperature, pressure, brightness, duration, sound, or motion. Controllers can be fitted with cameras, microphones, buttons and switches, as well as receivers for standards like Near Field Communication (NFC), Global Positioning System (GPS), Radio Frequency IDentification (RFID), or for communication standards like USB, WiFi, Bluetooth, or Ethernet. They can also actuate motors, lights, relays, speakers, screens, and other displays. It seems likely that controllers will become even more ubiquitous in years to come.

\(^2\) Data compiled from manufacturer websites: arduino.cc, raspberrypi.org, mindstorms.lego.com, littlebits.cc, and microchipdirect.com. For additional information, see sketchinginhardware.com, a compilation of information about a variety of toolkits created by Camille Moussette.
SOCIO-ECONOMIC CONTEXT—CHANGING LANDSCAPES OF MANUFACTURING, CONSUMERS, LABOR, AND SOCIAL MOVEMENTS

3D printers, controller kits, and other technologies have the potential to transform the landscapes of manufacturing, consumers, labor, and social movements. As individualized, high-quality 3D printing becomes economical, demand for bespoke items may increase, and demand for mass-produced items may fall, shifting the limiting component of price from labor to shipping. Consumers may become “co-producers”, taking on some of the design work. At the same time, manufacturing may shift to prefer workers with digital rather than manual skills. And depending on their other aims, social movements may adopt or spurn particular desktop prototyping tools, impacting its general acceptance.

MANUFACTURING

Desktop prototypers like 3D printers enable manufacturers to engage in “rapid prototyping”, a design process in which a product goes through many short design iterations before being released to market. Rapid prototyping is desirable because it allows more opportunities for designers, customers, and manufacturers to interact with versions of the product, which often results in a better product. For most products, the limiting factor on the number of such iterations is total time to market. Since 3D printed prototypes shorten the production leg to hours or days instead of weeks, many more iterations fit into a given time to market. Alternatively, a product designed with a particular number of iterations of 3D printed prototypes could reach the market considerably sooner than a competitor attempting the same number of iterations of traditional prototyping tools.

Although industrial 3D printers are currently used primarily for prototyping, as quality improves there is a growing potential to use them for the production of finished products, as the success of services like Shapeways and Ponoko attests. Widely available 3D printing has the potential to decisively shift the balance of factors that go into deciding where to manufacture a product, such as political stability, cost and supply of raw materials, cost and availability of quality labor, and cost to ship to the consumer. For example, rather than shipping a finished product across borders or across a country, a design can be transferred electronically and then printed using raw materials sourced locally or shipped efficiently in relatively large quantities from a distant source. This has the potential to avoid tariffs and other entry regulations and minimize material shipping costs.

Some US technology pundits have suggested that 3D printing is the key to bringing manufacturing back to that country from China and other markets that compete on labor cost and supply. Others envision a future in which small print shops dot the countryside, taking in raw materials and emitting completed products for local shipment (one imagines visiting a showroom of products, trying them out, and then ordering them to be printed onsite and delivered next day). Still others imagine that manufacturing jobs will ultimately disappear as a distinct labor category, to be replaced by ever-present desktop fabrication. In just the way that desktop publishing is ubiquitously available, desktop fabrication could soon be ubiquitous. The fabrication industry faces the same kind of disruption as publication has undergone in the last fifty years.

CONSUMERS

Feeding into these possible changes in the geography of manufacturing are changes in the consumer landscape. Consumers increasingly seek individualized experiences and products. Von Hippel identifies a gap that exists in many product categories between individual needs and
objects capable of being mass produced (2005). This gap leaves space for several alternatives to mass production, including bespoke or custom crafted items; consumer oriented but producer driven customization, for example menus of options that allow consumers to choose the combination of features that best suits their needs; and consumer driven customization (see Mowatt 2005). The latter may include so-called “prosumer” design, which puts the consumer at the center of innovation (Ritzer and Jurgenson 2010, Tapscott 2008); lead user innovation, in which mass produced consumer products are modified after purchase through tinkering or hacking—such activities are sometimes welcomed by manufacturers, but not always; and mass customization, which allows some parts of a product to be individually designed and then created using rapid prototyping equipment to make the finished product (e.g., insignias, engraving, embroidery, and, increasingly, structural pieces).

All of these models seek to incorporate some amount of customization into the production process, and all follow a recognizable economic model. But one other feature of do-it-yourself consumers is worth emphasizing: most report being driven not by financial motives but by other, less intangible benefits: learning, having a creative outlet, and being a part of a community (see Kuznetov and Paulos 2010). These characteristics of DIY-ers suggest several possible interpretations. It may be the case that a relatively fixed and small population care about these benefits enough to invest the time and effort necessary to use 3D printers and controller kits, thereby forever relegating such activities to hobbyists. On the other hand, it may be that most people care about these intangible benefits, and would delight in making their own goods if the barriers to entry were low enough. It may well be the case that a mixture of mass production, prosumer goods, and mass customization is best to suit the wide range of consumer desires and skills.

**LABOR**

Should manufacturing shift toward desktop fabrication, it could have a disruptive effect on the labor market. Discussions of labor disruption are often framed in terms of “deskilling”, in which skilled labor is replaced by a combination of automation and unskilled labor. A more useful conception is one of skill reallocation. This is because “reallocation” is a more accurate description of labor disruption. Deskilling describes a shift from a process requiring rare skills to one requiring only ubiquitous skills. (Similarly, unskilled labor is not really lacking in skills, it is simply limited to skills that are ubiquitous among humans, and therefore easily replaced.) A shift toward desktop prototyping (or desktop manufacturing) requires a reallocation of skills, some of which are more ubiquitous, others less so. For example, in 3D printing, the rare skill to craft a material object is replaced by the (relatively) ubiquitous skill of using a desktop computer. But at the same time, the skill of sketching a design on paper is replaced by the rarer facility with CAD design, programming languages, and databases. Similarly, “while it is true that actually executing a 3D print turns much of the in-situ effort of materialization over to a machine, the machine itself is the manifestation of knowledge, skills, and labor involved in its design, manufacture, and maintenance” (Ratto and Ree 2010, 18). That is, tools dissolve and replace certain kinds of effort, as long as they run smoothly. When they stop working, specialized work is required to return it to an unproblematic state (cf. Knorr-Cetina).

**ENTREPRENEURSHIP**

Another possible consequence of the increased availability of desktop prototyping equipment is that it may unlock latent entrepreneurship (see Ratto and Ree 2010). Bringing an idea to market requires research, funding, prototyping, manufacturing, marketing, and distribution. Access to open libraries of objects and programs, internet based crowd funding,
desktop 3D printers and inexpensive controller kits, services like Shapeways, and the easy creation of sales websites can all speed this process along, making entrepreneurship a much more attractive venture for anyone with the requisite skills and ambition.

SOCIAL MOVEMENTS

Desktop prototyping tools like 3D printers and controller kits have been adopted wholeheartedly by DIY and Maker movements, which encourages individuals to modify and customize their material surroundings and to create new technological solutions for problems they identify. Prototyping tools have been similarly popular within the Open Hardware movement, where kits like RepRap and Arduino are seen as democratizing, putting means of production into the hands of anyone who wants it. (In fact, such tools still require significant technical skill and access to specialized equipment. This may be one reason 3D printers are used mostly by well-educated, well-to-do Western men, and not, say, sub-Saharan Africans.) It seems likely that particular prototyping tools will be accepted or spurned by other social movements as well. For example, 3D printing could be adopted by those who favor local production, but spurned by those who oppose plastic. Recyclers may be drawn to projects like Filabot (mentioned earlier) or to renewable plant-based plastics like PLA. The hacker edge of the self-quantification movement has already adopted tools like Arduino for its data collection experiments. Likewise, the DIY science movement prefers inexpensive and open tools like RepRap and Arduino. More radical associations exist: one group of researchers is working on developing a 3D printer that will produce meat out of undifferentiated cells, potentially providing consumers with guilt-free meat (Geere 2012). Another group of researchers are designing a 3D printable gun that would escape any attempt to regulate firearms (see section on regulation in political and legal context for more on this topic). There is no certainty that any of these existing associations will last, or that forward-looking research projects will succeed, but it is always a possibility that a tool of production may become associated with the objects it creates, and so valorized or condemned as a consequence. This can have a dramatic impact on the general acceptance and adoption of these tools.

TECHNOLOGICAL CONTEXT—POSSIBILITY AND STANDARDS

TECHNOLOGICAL POSSIBILITIES

In the last section, I highlighted some of the economic differences desktop prototyping makes: it allows a lower entry point for certain kinds of product design, and it allows for people with different skill levels to compete on more equal footing. This could make it possible to unleash latent entrepreneurship within a population, assuming appropriate policies and infrastructure are in place to nurture potentially disruptive industries. Entrepreneurs without access to the technical knowledge of traditional prototyping techniques can nevertheless produce working prototypes and improve their designs until they are suitable for production. When used to create end products directly, 3D printers and inexpensive controller kits allow for the creation of sophisticated custom products that can be produced in small batches. Indeed, if desktop fabrication becomes popular, some small enterprises may steer clear of the mass production route altogether, preferring instead to produce small, custom batches of their product near each customer base. But in addition to making certain technological possibilities more economical, desktop prototyping tools can also make certain products technologically possible. That is,
desktop prototypers like 3D printers are capable of producing certain items that cannot be manufactured by traditional means.

3D printers can produce objects with complex interior spaces, moving internal parts, and large overhangs, all of which are difficult or impossible to create using traditional manufacturing techniques. In general, additional complexity requires additional time to produce, interior spaces or moving parts have to be produced separately and pieced together, and large overhangs are out of reach of machine tools, requiring human intervention to reorient a part. In addition, a highly complex geometric shape is no more difficult or time-consuming to produce than a homogeneous solid—once a 3D plan is available. Furthermore, 3D printers are equally economical when every part is different as when every part is the same. All of these characteristics have the potential to disrupt current manufacturing.

Manufacturers of 3D printers are aware of this disparity in technological possibility, and many produce objects that purport to demonstrate the sorts of objects 3D printing makes possible. For example, Shapeways user Virtox has shared “Gyro The Cube”, an object that demonstrates the capacity of 3D printers to easily create highly complex objects with moving parts, fine detail, and hollowed parts (see Waldo 2012 for additional examples). Some of the practical applications are clear: 3D printing can be used to create art or fashion with complex geometric designs, it can easily create fine detail that would otherwise require skilled manual approach or very expensive automated equipment, and it can replicate objects that might otherwise be one-off craft productions. But it is not yet clear what the “killer app” will be for 3D printing. Perhaps for this reason, some 3D printer manufacturers emphasize the ways that 3D printing can fit into and enhance the current manufacturing paradigm. The Objet 30pro, for example, comes with a sample design of an adjustable wrench. It prints in one piece, and when support material is cleaned off, works smoothly. But this is a wrench that uses $17 worth of resin to produce a plastic wrench. The value of such an object is in the speed of its production as a prototype (under two hours versus weeks for the cast alternative), not in its material properties or thrift. The rhetorical value of such an object is diminished for members of the lay public, who often think such creations are “neat,” but not groundbreaking. After all, adjustable wrenches can be (and are) regularly mass produced, and are readily available at any hardware store.

REPLACEMENT PARTS

One potential difference-maker for desktop prototyping tools is in home-brew replacement parts. Rather than searching out rare or discontinued parts at hardware stores, junk shops, or online, people with CAD skills could design replacements or those with access to 3D scanners could scan their broken parts. The resulting parts could then be 3D printed. Moreover, these individuals could share their designs online, opening them up to those without the requisite technical skills to design or scan a part. It is possible that some manufacturers will begin to share designs for replacement parts that are often broken or lost (though see the discussion of intellectual property for more about this). One imagines a booming industry for replacement connectors for IKEA-style furniture. The success of such endeavors depends critically upon the quality of the printed product. Load bearing metal brackets might not be replaceable by plastic printed parts. But knobs or pieces that were plastic to begin with seem like reasonable targets for replacement or repair by currently available 3D printers.

RESTRICTED OR CONTROLLED ITEMS

Widespread availability of desktop prototyping tools could also have a disruptive effect on current modes of restricting or controlling access to certain devices, including dangerous items like firearms. Desktop prototyping equipment is increasingly capable of achieving very
precise tolerances in terms of material purity, physical dimensions, and complex details. Because the Internet makes it relatively easy to share designs, access to desktop prototyping equipment amounts to access to the means of producing objects that were previously de facto restricted. Often, the means of production are out of reach because of cost, complexity, or legal controls on manufacturing equipment. General purpose, but highly capable desktop prototyping equipment can bring such objects within reach of many more people (see also the discussion of regulation for more on this).

STANDARDS

Because desktop prototyping typically involves several pieces of equipment that must be in some kind of agreement, standards are a crucial part of the success of any new element. Different elements of desktop prototyping are at different stages of development with respect to standards. Desktop 3D printing, for example, exists in the context of large-scale manufacturing, which has decades of experience with CAD/CAM standards. For this reason, most 3D printers draw from or conform to established industry standards. Despite the existence of dozens of 3D printer companies, there is a single de facto 3D file standard, STL. By contrast, sensor/logic/actuator packages exist within a sea of existing hardware specifications and programming languages. Arduino, for example, is based on the Wiring hardware project, which is itself modelled after the Processing programming language project. But Arduino code runs only on Arduino, Raspberry Pi uses a different language, Lego mindstorms still another, and so on. Some of these standards are rapidly changing, while others seem relatively stable.

In considering standards, four factors are of central importance.

1. Degree of technology independence. For example, STL files for 3D printing are essentially hardware agnostic. They specify the shape of the surface of a 3D object, which 3D printer drivers can interpret in whatever way works best for its particular technology. Likewise, high level programming languages like python or C++ are relatively hardware independent. But variants like Arduino are hardware specific.

2. Simplicity. In general, standards have to be easy to implement and understand within the context in which they will be used. Arduino is based on C++, which is actually a relatively complex language, but given the context of a user base that probably already knows C++, Arduino becomes dead simple. Likewise, 3D standards like OBJ and PLY (described below) derive from existing industry practices like 3D animation and scanning, and so have a relatively broad existing user base.

3. Scalability. Programming formats should work well for both simple and complex programs. 3D files should scale well with different object sizes and with different resolutions.

4. Compatibility. It should be relatively painless to import a project designed with an older standard into the new standard. Likewise, it should be relatively easy to extend a current standard to take advantage of developing capabilities. Given that 3D printer designers aim to increase resolution, print in multiple colors, and print in multiple materials, it would be wise for the file format to accommodate such changes.

With these considerations in mind, let us briefly consider some of the existing standards within 3D printing and controllers.

3D PRINTING STANDARDS

The typical 3D printing process has four basic steps. First, designers use a CAD program to create a digital representation of a 3D object. Second, they export this design for use with a 3D printer, often in STL format, which approximates the surface contour as triangles of a specified resolution. Third, they import the design into the 3D printer software, which orients the object
and layerizes the result based on the layer thickness the printer will support and specifies the tool path and material output for the printer. Depending on the printing technology, the software may also add support material beneath overhanging features, optimize the material density based on user-specified settings, toggle between hollow or solid objects, and so on. Fourth, and finally, the CAM software drives the printer operation itself. Several file formats are used in this process, often a different one for each step. Each CAD program has its own internal file format and each 3D printer driver has its own format. At present, nearly every 3D program is compatible with the STL file format, which is the de facto standard for additive manufacturing.

STL, originally for STereoLithography, was developed by 3D Systems. The name refers to the printing technique of using a computer-controlled moving laser beam to create a 3D object by building up layers of laser-hardened photosensitive resin. Because several other technologies exist, and STL is used with all of them, the format is sometimes referred to as “Standard Tessellation Language.” STL files specify the triangulated surface geometry of an object using the unit normal and vertices for each triangle. The file does not include color or texture information, nor does it specify material types or desired material properties, although it should be noted that some companies have extended the STL format to include some of this additional information. For example, SolidWorks uses the normal to indicate shading information, VisCAM and SolidView add color information for each triangle, and Materialise Magics specifies the color for the entire object in the file header. These are, however, divergent standards and are not cross-compatible.

### OTHER FILE FORMATS

OBJ, or Wavefront object file format, was developed by Wavefront technologies for its animation visualizer package. It represents the 3D geometry of an object according to the location of each vertex, defines faces, normals, and textures.

PLY, or polygon file format, was designed to store data from 3D scanners. It describes a single object as a list of polygons, and can store data on color and transparency, surface normals, textures, and even data confidence.

AMF, or additive manufacturing file format, is an open standard that essentially extends STL to include color, material, lattices, and constellations of objects. The format was developed by the American Society for Testing and Materials, or ASTM, an international standards organization.

### HARDWARE

Although there are many 3D printing technologies, almost all of the low-cost 3D printers use a single technology: fused deposition modelling. In a typical application, a reel of thermoplastic filament supplies an extrusion nozzle, which melts the filament and extrudes beads that stick to previous layers of material and which harden almost immediately. The position of the nozzle is controlled by computer numerically controlled servos and stepper motors. One of the earliest hobby 3D printers was the open RepRap, or replicating rapid prototyper, which uses a variant of fused deposition modelling called fused filament fabrication. What this means is that there is a de facto standard for both material (in the form of filament) and CAM drivers, and both standards were developed and are maintained by RepRap and the hodgepodge of other 3D printer manufacturers who have adapted RepRap’s basic design.

There is no reason to think that this coalition will last, however, and there are some signs that it is already fading: the two printers with the most press coverage in 2012 were the Replicator 2, which appears to extend RepRap technology but is not open, and Formlab’s Form 1, which uses stereolithography instead of fused filament fabrication. Both represent significant
divergences from the RepRap standard, and neither project is open, meaning that other 3D printer manufacturers cannot adopt their designs. A final note about the filament standard: though simple, the standard 1.8mm and 3mm diameter plastic filament has spawned its own market for innovation. The first RepRap printers used filament made from Acrylonitrile Butadiene Styrene, or ABS, the plastic used in Lego blocks. Soon, some printers switched to Polylactic Acid, or PLA, which contains renewable plant-based materials. Others are working to create filament incorporating metals, ceramics, or other materials. For example, Laywoo-D3 is a wood-based filament. Still others are working on devices that grind up plastic to make filament suitable for 3D printing. Tyler McNaney, for example, has used crowd funding to develop “Filabot”, a desktop grinder that takes in milk jugs, soda bottles—and disused 3D printed objects—and extrudes spools of plastic filament that can be used for 3D printers (see filabot.com).

**CONTROLLER STANDARDS**

Every controller package conforms to or defines a set of hardware and software standards. Basic chips like 555 timers have standard footprints, pinouts, and voltage and current ranges. Programmable ICs, including Arduino’s 8-bit Atmel AVR and 32-bit Atmel ARM processors, as well as Raspberry Pi’s Broadcom BCM2835, on up to the Intel Core i7 in a typical laptop computer, also conform to physical standards, but just as importantly, the machine code for such chips constrain and define what can be done using them. One of the major differentiators in hardware is openness. Arduino is completely open: it is based on Atmel’s open hardware processors, the AVR and ARM, and the board layout and footprint are also open, so anyone with the capability to make a board can make an Arduino. Raspberry Pi uses a proprietary processor, but uses industry standard I/O standards like USB and HDMI.

As was mentioned earlier, the programming environments for logic have become considerably more friendly in recent years. Just a decade ago, it was common to have to learn machine code and program the low-level functions of a chip. Today, most chips come in a package with a high-level language interpreter and compiler that easily allow for higher level functionality, libraries, and easy debugging. Arduino, for example, uses a variant of the common programming language C++ within a Processing-based environment. Raspberry Pi uses a modified Linux environment. The degree of openness of hardware and software standards seems to have some correlation with the size of the online communities associated with each device. The idea seems to be that any individual can choose her point of entry into the controller. She can buy a kit readymade, download a readymade program, and run it. She can write her own programs. She can assemble her own hardware. With the right tools, she could even fabricate her own Atmel chip.

There is a sense in which desktop prototyping tools are universal: anyone could own them, anyone could use them. But this is a conceptual possibility only, not a practicable one. Prototyping tools require expertise that is hard-earned—enough so that only hobbyists, affluent people with lots of spare time, and professionals can afford the time. And the tools are not easy to use. They require mathematical and logical skills that are not universal. To return to the division of skills into algorithmic, ubiquitous human, and rare human, the move to desktop prototyping and manufacturing is a coupling of algorithmic with rare human skills at a new scale.
POLITICAL AND LEGAL CONTEXT—PROTECTION, LIABILITY, INTELLECTUAL PROPERTY, AND POLICIES

In this section, we consider more closely some of the political and legal issues surrounding desktop prototyping. These include consumer protection and liability, regulation and intellectual property, infrastructure, and citizen empowerment. It is worth emphasizing that although this report has focused primarily on emerging desktop prototyping tools like 3D printers and controller kits, these tools are intended to stand in for the entire category of tools. It would be reasonable to expect, therefore, that a well-developed set of policies and case-law dealing with older desktop prototyping tools would merely require adjustment before being applicable to the emerging technologies that have been central to this report. This is to some degree true, but as we will see in this section, the political and legal context in North America has yet to adequately adjust to the challenges posed by technologies of the Internet, like filesharing and digital piracy, and these challenges are only exacerbated by prototyping tools like 3D printers that can “pirate” physical goods as well as media.

CONSUMER PROTECTION AND LIABILITY

For goods produced in a traditional manufacturing setting, there are well-established policies and laws to address concerns about consumer protection and liability, and desktop prototyping tools often fall within those bounds. In such cases, prototypers pose no special concerns. However, not all prototypers fit neatly within existing boundaries. First, many desktop prototypers are (or are based upon) “open hardware” projects where anyone can contribute. Should unpaid contributors be held liable for mismatches between expected and actual performance? Can the creators of a general-purpose technology be held responsible for the objects produced using it? Who is legally or ethically responsible for preventing the creation and dissemination of harmful, faulty, dangerous, or illegal plans or objects? Who is responsible when someone is hurt by a 3D printed object—designer, manufacturer, or 3D printer manufacturer? Who, if anyone, is responsible for testing crowd-sourced plans? So far, 3D printing and other desktop prototyping tools exist mostly in two contexts: traditional manufacturing, where there are existing precedents to help settle these questions, and hobbyist-scale making for personal use, where such questions do not arise. But as desktop manufacturing expands, governments will have to take action to ensure that consumers are protected and that legal responsibility falls on the right parties.

A related consideration is that, in most of the world, traditional large-scale manufacturing requires extensive environmental impact reporting before new facilities can be constructed. Desktop prototyping equipment does not. This raises serious environmental concerns about power use, noise, and chemical/waste disposal for cottage industry prototypers. This is not a wholly new concern: craftspersons and mechanics in many municipalities must apply for permits before opening a business, and workers are responsible for safely handling and disposing of the materials of their trade. But as 3D printing and other prototyping technologies grow in popularity, lawmakers should be aware that they are coming, and should be prepared to understand the tradeoffs between encouraging entrepreneurship and maintaining environmentally safe neighborhoods.

REGULATION

In 2012, Cody Wilson founded Defense Distributed with the aim of developing a shareable design for a 3D printed gun. Guns are a fractious issue, but they can serve to illustrate
a wider point about the capabilities of desktop prototypers and the difficulty in regulating their use. Wilson is not the first to attempt to 3D print gun parts (see, e.g., Walton 2012 for some earlier ventures), but his attempt may be the most prominent so far. Wilson is leveraging the power of the internet to crowd fund his enterprise, spread his message, and (ultimately) to share the resulting design. His aim is to create a gun that cannot be effectively regulated, and he seems to be succeeding. Simply put, four ingredients go into a working gun: the plan for the gun, the material the gun will be made from, the printer that shapes the material according to the plan, and the gunpowder that propels the bullets. In principle, any of these could be regulated, but it is not clear how to actually implement such laws. Wilson’s project has inspired at least one lawmaker to suggest legislation that would ban the printing of 3D printed gun components on the basis that such weapons would be undetectable by metal detectors or X-Ray machines (Greenberg 2013), but it is not clear how to prevent people from printing out gun parts. 3D printer companies are worried about being associated with guns and other illicit objects, and have taken action to impede activists like Wilson. Stratasys confiscated one of its machines that it had leased to Wilson after learning about his plans. Thingiverse has also removed gun designs from its website. But both actions are arbitrary and after-the-fact. It seems implausible to make illegal gun shapes (many items have barrel shapes or trigger mechanisms, for example). Recent experience with pirated media files shows that it is effectively impossible to stop file transfers without disrupting legitimate Internet activities. And 3D printers are general-purpose machines with many legitimate uses—it would be an overreaction to ban them because they might be used to produce illicit materials. It seems more plausible to regulate gunpowder (a substance that can currently be purchased at many hardware stores throughout the United States), but this sidesteps the issue of regulating desktop prototypers and the objects that come out of them. So far, the alternatives seem to be: abandon regulation, find a non-3D printed component to regulate, or create a patchwork of regulations that would impede legitimate uses of prototypers and whose effectiveness is questionable.

INTELLECTUAL PROPERTY: COPYRIGHT AND PATENT LAW

As the music industry has learned, it is difficult to enforce copyright law when the means of production and dissemination of a protected good are distributed. 3D printing promises to distribute the means of production for just about anything to just about anyone. Over the next few years, legal precedents will likely be set that could shape the development of 3D printing technology for decades to come.

Some industries do just fine without copyright protection. Food recipes, for example, enjoy no such protection. Major conglomerates (and individuals) maintain “secret” recipes, but in the days of chemical analysis this secrecy is chancy at best. Despite a lack of legal protection and a lack of any really useful secrecy, the food industry maintains a high level of creativity. This seems to be in part because of what cannot be, or at least is not, captured in recipes, secret or not: execution. Recipes are rather dull things, stripped of the complex decision making that goes into executing them. But 3D printers largely automate the execution of a plan, and reproduce it perfectly. This is one of the risks widespread access to prototyping equipment poses for intellectual property owners. Once a design secret is out, it can’t be hushed up.

The protection of intellectual property relies on a number of factors, including copyright law and keeping execution details tacit or secret. 3D scanning and printing has the potential to disrupt the current balance of these factors, at least in certain regimes of shape, size, and complexity of objects. To put it another way, prior to desktop CNC manufacturing technologies, a highly complex design was by itself a barrier to copying. The advent and increasing availability
of desktop CNC diminishes this ‘natural’ protection (see Weinberg 2010 and Bradshaw, Brower, and Haufe 2010).

The digital nature of the designs and ubiquitous access to the Internet exacerbate the problem. As Weinberg points out, “it is unlikely that a single object produced for home use would attract the attention of a patent holder. But, if the history of the Internet up to this point has taught us anything, it is that people like to share. Individuals who successfully design products that solve real world problems will share their designs online. Other people with similar problems will use (and even remix and improve) those designs. Very successful designs that happen to infringe on patents are the most likely to be targeted by patent holders” (Weinberg 2010, 5).

For these reasons, desktop fabrication occasions a revision of copyright and patent law. Below are four likely targets for legislative and judicial action (see Weinberg 2010 for much more on this). First, let me briefly distinguish between copyright and patent law.

<table>
<thead>
<tr>
<th>Copyright</th>
<th>Patent</th>
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<tbody>
<tr>
<td>Artistic, creative works</td>
<td>Useful articles</td>
</tr>
<tr>
<td>Automatic upon fixation</td>
<td>Must be applied for</td>
</tr>
<tr>
<td>Does not have to be new</td>
<td>Must be new</td>
</tr>
<tr>
<td>Life of author plus 70 years</td>
<td>20 years</td>
</tr>
<tr>
<td>Assumes damages from infringement</td>
<td>Must prove damages</td>
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</tbody>
</table>

(Adapted from Weisberg 2013, 2.)

1. Contributory infringement. Since most infringers will be individuals, they will be hard to find and harder to prosecute. Therefore, patent holders may seek redress through “contributory infringers”: those who share plans or scans. The precedent in copyrighted media suggests that patent holders may target particular file types, sharing sites, or 3D printer manufacturers themselves. But because 3D printers are capable of substantial non-infringing uses, targeting printers themselves probably will not work (see Weinberg 2010, 13). And because filetypes like STL are used in industry, they also seem like unlikely targets. Sharing sites, on the other hand, may well become targets, and the items on display at Thingiverse may eventually join pirated music and movies.

2. Replacement parts. Replacement parts for unpatented portions of an object are not currently protected. However, manufacturers of such parts often have the pragmatic protection that those parts are difficult to produce. If 3D printers make it easy for individuals to produce their own replacement parts, those manufacturers may seek to expand patent law.

3. Severability. Intellectual property owners may attempt to eliminate the severability clause distinguishing the elements of an object that are subject to patent and those subject to copyright. Functional elements are subject to patent, artistic elements are subject to copyright. Eliminating the distinction could allow companies to copyright functional elements of objects. This would have two immediate effects: first, copyright applies automatically upon fixation of the work, so there would be no need to apply for protection. Second, protection would expand from 20 years to the life of the author plus 70 years. Both of these changes have the potential to stifle innovation. The same would be true if some aspects of patent law were extended to
copyrighted objects: patent law has no exception for fair use, which could impede attempts to “mix” hardware designs.

4. Copyright design files. Designers may seek to copyright the STL file that specifies an object. Although this may seem to follow automatically (since copyright automatically applies at the moment of fixation), in fact (as Weinberg points out) copyright law is written in such a way as to prevent a designer from exerting undue control over virtual versions of an object. The relevant statute is 17 U.S.C. § 101, and it states that “the design of a useful article...shall be considered [a work eligible for copyright protection] only if, and only to the extent that, such design incorporates pictorial, graphic, or sculptural features that can be identified separately from, and are capable of existing independently of, the utilitarian aspects of the article” (qtd. in Weinberg 2013, 14). This distinction recognizes that while the expression of an idea is protected by copyright, the idea being conveyed by a plan is not.

INFRASTRUCTURE

Governments friendly to desktop prototyping can encourage its development by developing careful regulations to help consumers and producers of 3D printed objects navigate the legal and practical hurdles that accompany the practice. But they can also encourage desktop prototyping in four other ways. First, governments can support reliable and ubiquitous digital networks to support collaborative work and the transfer of designs. Second, they can invest in the physical infrastructure necessary for shipping materials and goods. Third, they can support large-scale research laboratories devoted to advanced or distributed manufacturing (see, e.g., http://www.manufacturing.gov/nnmi_pilot_institute.html). Fourth and finally, governments can encourage its citizens to train in the skills they will need to compete in advanced or distributed manufacturing. Curricula can incorporate design skills and digital literacy. Retraining programs can help people working in craft or hand traditions to navigate and use network forums, online communities, and fabrication technologies.

SKILLS AND EDUCATION

Literacy in 3D methods and controller kits includes: creating and editing models, circuit plans, and programs; reading, editing, and converting these digital plans; managing databases of design files; analysing models for ‘printability’ on particular prototypers or analysing programs for performance on particular hardware; and fluency in aspects of the digital economy such as funding, communities, and distribution. Those who actually own prototyping equipment (rather than hire the work out to an establishment like Shapeways) will also need the physical skills to maintain equipment, assemble parts, and package them for physical transport.

CITIZEN EMPOWERMENT

A final implication of desktop prototyping for politics and law is that it can be seen as a route to citizen empowerment. Desktop fabrication connects individuals to making and to other makers. To play on Marx’s terminology, it literally puts the means of production back into the hands of the proletariat. This empowers individuals to design technologies that serve them, rather than having to adapt to what is available for sale. Individuals can create custom tools for specific tasks. They can extend or connect disparate forms, systems, structures (for example, by 3D printing an adapter that connects two products made by different companies). Desktop prototypers can help individuals express their aesthetic taste, individuality, or affiliations. And of course, prototyping can be fun (list adapted from Ratto and Ree 2010).
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