THE FUTURE OF OPEN FABRICATION

INSTITUTE FOR THE FUTURE

Technology Horizons Program

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about the ...

TECHNOLOGY HORIZONS PROGRAM

The Technology Horizons Program combines a deep understanding of technology and societal forces to identify and evaluate discontinuities and innovations in the next three to ten years. Our approach to technology forecasting is unique—we put people at the center of our forecasts. Understanding humans as consumers, workers, householders, and community members allows IFTF to help companies look beyond technical feasibility to identify the value in new technologies, forecast adoption and diffusion patterns, and discover new market opportunities and threats.

INSTITUTE FOR THE FUTURE

The Institute for the Future is an independent, nonprofit strategic research group with more than 40 years of forecasting experience. The core of our work is identifying emerging trends and discontinuities that will transform global society and the global marketplace. We provide our members with insights into business strategy, design process, innovation, and social dilemmas. Our research spans a broad territory of deeply transformative trends, from health and health care to technology, the workplace, and human identity. The Institute for the Future is located in Palo Alto, California.

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INTRODUCTION

When tracking technological innovation, pay attention not so much to what is new as to what is ready to take off, as IFTF Distinguished Fellow Bob Johansen likes to say. By that measure, we're officially entering the decade when 3D printing—think printing *objects*—fulfills the promise that makers, programmers, and geeks have been forecasting for the last 20 years. 3D printing is slowly but surely moving beyond the realm of high-end design and factory shops, and entering the consciousness of technology lead-users—those in cities around the world who are most likely to adopt new tools, start new businesses, and champion new movements.

Three years ago, IFTF published a forecast on *The Future of Making*, which looked at the future of the DIY movement. We highlighted the democratization of access to new tools and open-source everything (along with eco-motivation and a quest for authenticity) as key drivers of the future of making. Today, in *The Future of Open Fabrication*, we take a deeper dive into the tools, processes, and manufacturing landscapes that are transforming how we reshape our material world. In the coming decade, we'll manipulate the atoms of stuff—plastic, metal, concrete, glass, even biological matter—using many of the same tools, business models, and inspirations as the last decade applied to bits of information. Some of us will do it ourselves, while millions more will outsource it to a local shop or a factory in China. But no matter where it happens, new manufacturing tools in the hands of a wider variety of people will challenge the basic assumptions of industrial production, retail, and consumption. Welcome to the future of open fabrication.

Start with our introduction to the emerging world of open fabrication for a look at the big shifts under way in manufacturing. Dip into Foundations, where we lay out the building blocks of open fabrication, from mesh-merging software and 3D scanning to biological feedstocks and printable electronics. Open Fabrication Communities takes you into the world of the MakerBot, the first affordable 3D printer aimed at the nonindustrial market, and then out again to China's shanzhai manufacturers, whose small-batch open networks give us clues about what the future of 3D printing might look like. Or go straight to our forecasts to see what the next decade could hold—and what it might mean for you and your organization.

1 THE EMERGING WORLD OF OPEN FABRICATION

Accelerating the flow of things

Ten years ago, the Internet was still mostly a medium for text and images. While interactivity was becoming more commonplace, audio and video content were just beginning to trickle. Yet today, rich multimedia content dominates the commerce and infrastructure of the Web. By one estimate, Netflix streaming video alone consumes 20% of U.S. Internet bandwidth during primetime evening viewing hours.

Today, it's equally hard to imagine the Web as a future medium for sharing not just digital media, but also digital things. Digital things are data packages that describe the shape, material composition, and fabrication of objects. Industrial manufacturers have worked this way for decades, using computer-aided design (CAD) to transmit new ideas from drawing board to factory. But today, online repositories such as Thingiverse—where people openly share and invite others to build on their designs—are unlocking the innovative potential of a grassroots community of tinkerers and designers to create and share digital plans for real objects.

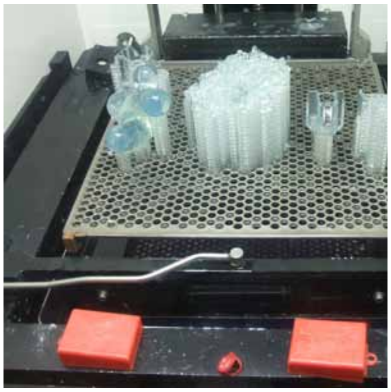
These communal repositories coupled with cheap CAD software and a new breed of desktop 3D printers—which can "print," or layer up, designs in a variety of industrial materials—are bringing down the barriers to accelerating the flow of things on the Internet. We call this new ecosystem of open-source tools for designing, sharing, and producing physical artifacts open fabrication.

The key principles of open fabrication are simple:

- **Stay flexible**—The resources for open fabrication (the printers, software, and materials) are still rudimentary and rough, but the call to arms is to explore the flexibility of cheap and accessible desktop manufacturing.
- **Leverage Web scale**—The maker movement started in garages and workshops but soon formed communities on the Web; now open fabrication is systematically leveraging the Web's scale through the creation of standards and knowledge repositories such as Thingiverse.
- **Be open**—This simple dictum is often in short supply in the world of design and industrial manufacturing. Open fabricators share intellectual property in the form of object designs, code, and process innovations, accelerating the learning of all.

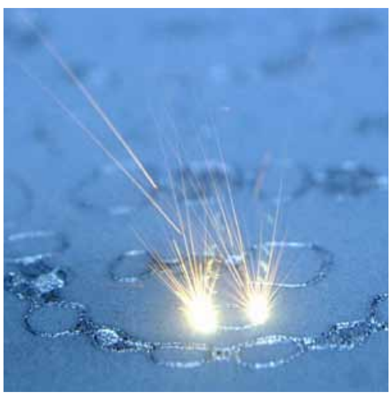
Thingiverse is an online community of designers of printable objects.

Source: thingiverse.com



Stereolithography creates solid print objects in a vat of liquid photopolymer.

Source: Flickr user philrenato



Laser sintering melts layers of fine metal filings into a solid object.

Source: renishaw.com

Fused deposition modeling prints by depositing layers of material.

Source: shapeways.com

Processes: the fundamentals of 3D printing

Current additive fabrication processes—or 3D printing, as it is widely known—rely on one of several layering approaches.

The oldest of these, stereolithography, involves using laser light to solidify layers of a photo-sensitive liquid polymer. Once the layers of polymer have hardened, the platform is raised out of the remaining liquid to reveal the completed structure. By making automated fabrication of whole objects possible, this groundbreaking approach kicked off the 3D printing revolution in the mid-1980s.

Successive approaches have similarly involved building up layers of material. Sintering, for example, uses lasers to actually melt layers of metal, glass, or plastic into place.

A parallel suite of technologies is taking shape that may move more easily into widespread home use. Fused deposition modeling, for example, actually squirts precise layers of melted plastic, sugar, or even ice to build a freestanding structure. Another process uses a binder or glue to fuse layers of modeling powder.

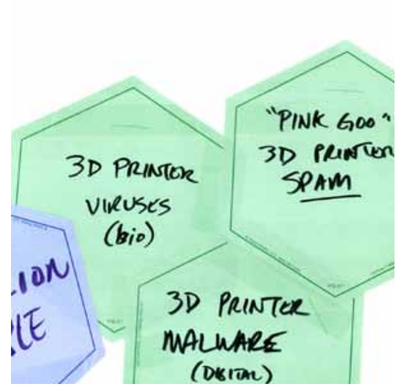
While 3D printing technologies continue to spread, at present, actual high-quality printers are very expensive and available to only a small collection of organizations. However, a number of commercial “print centers” have emerged to address this gap. For example, Ponoko and Shapeways allow users to send digital models for printing. The models are printed and then shipped to the user.

Beyond this, wildcards in this space include marginal applications taking shape for use in construction, electronic circuitry, and stem cell applications. One of these may ultimately turn out to be the true “killer app” for additive fabrication.

Overall, however, while the potential for additive fabrication is now becoming clear, new techniques will need to be introduced for the field to truly mature. Each of the existing approaches will experience marginal technical advances over the next several years. But they also each have fundamental limitations that inhibit the easy expansion of 3D printing into the creation of complex forms involving a diverse array of materials and properties—that is, into mainstream production of final products.

As they exist today, most 3D printing technologies might more readily be classified as sophisticated sculpting techniques than as mature manufacturing technologies. However, this will begin to change over the coming decade.

Limits: atoms are different from bits



Even if the worst risks are unrealized, 3D printing could be held back by inherent limits to scalability.

Source: IFTF Open Fab Expert Workshop

Even as a brave cadre of open fabbers pioneers a new way of making and sharing things, significant hurdles could slow the spread of 3D printing and limit its range of applications. Even among lead innovators, deep skepticism exists about the future rate of progress in open fabrication. As one participant asked in our expert workshop, "I am still printing the same stuff I printed ten years ago in grad school. Will I still be printing the same thing ten years from now?"

Open fabrication seeks to leverage the scalability of the Web. The network effects of sharing knowledge are accelerating grassroots innovation, similar to what we saw with open-source software in the past decade. But atoms are different from bits, and open fabbing can't be expected to play out like open-source software, for a couple of reasons.

For one thing, the IT revolution also benefited from rapid underlying advances in "feedstocks" such as broadband, processing power, and storage. It's not clear those underlying accelerators will exist in the messy world of stuff in which open fabricators reside, where physics and geography keep coming back to create complex logistical problems. As one expert workshop participant remarked: "The beauty of the Web (and Web tools, like open-source software) is that you can get to 50 million people in a keystroke. Physical products require a distribution channel."

For another thing, manufacturing is already a highly refined practice. While many opportunities for disruption exist, 3D printing shows no sign of displacing the highly tailored processes and tools for mass production of standardized objects, such as injection-molded plastics. These methods have been honed over decades and deliver astonishingly cheap, high-quality results. In almost every large-run case, it will be cheaper to tool an object than to 3D print it. Open fabrication will open many doors, but its disruptive potential has some clear limits.

From production line to manufacturing web to fabrication cloud

Over the course of the 20th century, the assembly line model evolved within a changing landscape of more flexible machinery and complex supply chains and distribution networks. What we have today looks more like an interconnected manufacturing web than isolated production-line factories.

Another way of thinking about these shifts is in terms of how they transform raw materials into finished products. The moving assembly line, first introduced at Ford's Highland Park, Michigan plant in 1913, employed a wide variety of material and resource inputs and a vast number of manufacturing processes to steadily produce a strictly limited set of objects in massive numbers. Today's manufacturing web, in contrast, is far more flexible, diversified, and agile. Plants and machines can quickly be retooled and revved up or down to "burst-produce" far smaller runs of a much larger set of products.

3D printing presents yet a third model, a fabrication cloud that takes a very limited number of input materials and processes but can flexibly manipulate them to cost-effectively produce an almost infinite array of products in batches as small as one.

The following chart summarizes the role of machines, labor, materials, and distribution networks in each era:

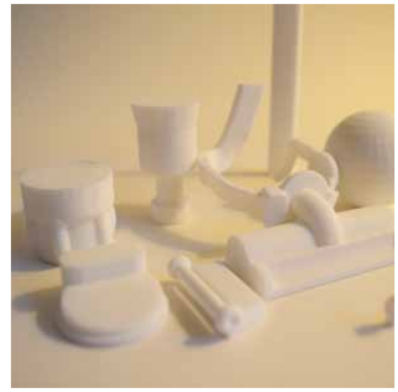
Evolution in manufacturing

	Production Line	Manufacturing Web	Fabrication Cloud
Machinery	Manually-operated machine tools	Computerized numerical control machine tools (CNC)	Rapid prototyping/ additive manufacturing
Labor's Added Value	Skilled machine operators	Programmers	Designers
Materials	Metal, wood, rubber	Metal, wood, plastic, foam	Plastic, low melting-point metals, powdered materials, cells, binders
Distribution	Wholesalers	Retailers, direct to consumers	Fabricate-on-demand, fabricate on-site
Recycling/ Use of Products	None	Select components	Entire objects

Source: IFTF

Perils: a world of "crapjects"

As 3D printing lowers the cost of engaging in a production run, it will bring both opportunities and perils. For one thing, it is likely to encourage the production of substandard goods—what some may see as frivolous production. Surely, the world is awash in low-quality mass-produced goods today. But several aspects of 3D printing and open fabrication could reinforce this trend.



A world of physical spam?

Source: Flickr user MaskedRetreiver

First, the diffusion of 3D printing will present a fairly steep learning curve for both designers and consumers. Learning how to 3D print often involves making many useless, substandard objects. Even if most will eventually move on to more carefully selected designs for production, the broader perception of 3D printing is often likely to be associated with flawed, low-quality, disposable outcomes. Much of what comes out of 3D printers will be "crapjects" (a contraction of "crappy objects")—unwanted waste created by unskilled designers and fabricated using inferior materials with poor surface resolution.

Additionally, there is the scenario of "physical spam," where people simply use 3D printers with abandon, producing a large number of objects of infinitesimally small value. This may be reinforced by future 3D printers that can easily recycle feedstocks, greatly lowering the perceived ecological or economic impact of overproduction. Still, the novelty of rapid fabrication may wear off as the high expectations we have developed around mass-produced objects' strength and durability, surface texture, and luster prove hard to leave behind.

Opportunities: a world of totems

3D printing and open design also present us with the opportunity to break down the standardization and uniformity that's been enforced by mass production for a century. In its place, we will see an explosion of personalized objects, introducing for the first time artisanal characteristics to manufactured products. These objects may incorporate features based on sensory or scanned data from individuals, such as "Be Your Own Souvenir," a hack that combined 3D scanning with a RepRap 3D printer to allow tourists to create personal figurines of themselves.

A totem from the film *Inception*

Source: pulsarmedia.eu

In the 2010 science fiction film *Inception*, corporate spies who enter the dreams of their targets carry "totems," small objects whose precise physical characteristics are kept as a personal secret to allow the spy a reference point to recover his sense of reality and escape the dream. In anthropological terms, a totem is an object that serves as an emblem or symbol of a clan, family, or individual. Personalized fabricated objects have the potential to become totems and be imbued by their possessors with spiritual significance.

These new possibilities mean that open fabrication will take the spectrum of consumer product experiences we are familiar with and push it to the extreme edges—at the same time rendering objects both more meaningless and banal and also giving them uniqueness and personality.

Manufacturing's big bang

Open fabrication will challenge key assumptions of industrial production: that there are always increasing returns to scale, that complex supply chains are needed to fabricate complex objects, and that manufacturing processes (rather than design, which can easily be copied) are the core intellectual property.

As these foundations are disrupted in manufacturing's version of the Big Bang, we'll see the ways manufacturing is organized in physical space fragment and recombine along several dimensions:

From centralized factories to distributed, mobile fabs

Traditional assembly lines have long placed limitations on where and how objects can be produced because the scale needed to reduce unit costs requires massive centralization. 3D printing will allow production to be moved closer to the site of consumption and allow supply chains to fragment into many very small-scale parts producers. Also, 3D printers are self-contained, more standardized than computer-controlled machine tools, and require a supply chain to provide only two things: electric power and a limited set of feedstocks. This will enable new kinds of manufacturing business models based on short-run, site-, and event-specific or even ad hoc production runs.

From fixed to mobile machines

3D printers will also offer the possibility of being moved during the production process, allowing for the creation of structures in the field. Ironically, self-propelled 3D printers will be able to industrialize the production of some goods that have traditionally been too large to manufacture in factories. In building construction, for example, 3D printed masonry could ultimately be cheaper than labor-intensive traditional building methods. Contour crafting, a technology under development at the University of Southern California, has sought to make 3D printing the pivotal technology in what amounts to a house-building factory on wheels. The researchers involved project mainstream commercialization within the next ten years.

Dominic Muren's Humblefactory seeks to source materials locally to create sustainable electronics.

Source: Dominic Muren

From desktop back to factory

While open fabbing will diffuse manufacturing capabilities broadly throughout the economy, countercurrents will develop as these technologies creep back up the supply chain and transform the factory itself. 3D printing is already playing a role in the factory—for instance, printing complex new shapes for aircraft assemblies that would be nearly impossible to manufacture using traditional techniques. In certain production niches, from 10 units to 10,000 units, 3D printing will allow more kinds of local manufacturing enterprises to thrive, both by bringing the unit costs of small-scale production down and by being small and unobtrusive enough to be slipped into nonindustrial urban spaces. Organizations such as Dominic Muren's Humblefactory—a Seattle-based development consultancy offering strategic design consulting in open hardware for the everyday industrialist—are emerging to bring manufacturing out of the factory and into the home of the "cottage industrialist."

2 THE FOUNDATIONS OF OPEN FABRICATION

The open-source software movement, in which original source code is made freely available and can be redistributed, has had a tremendous impact within the IT industry over the last two decades. Now, emerging technologies promise to similarly move the fabrication of physical things toward greater digitization and democratization. We are entering a world in which software code can be used to produce objects, and in this world, new technologies will allow for more free availability and distribution of actual things. At the center of this shift is the emergence of systems for using software to build physical objects—for example, 3D printing or additive fabrication technologies.

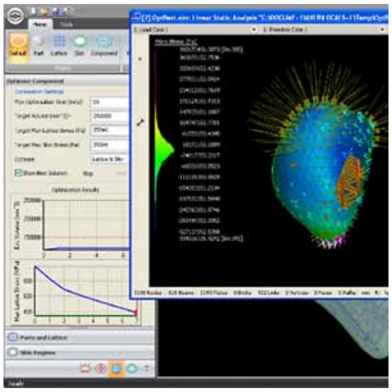
Additive fabrication is still very young when compared to many other manufacturing approaches. Yet, in just over two decades the field has managed to expand from a near-exclusive focus on stereolithography (a technology focused on solidifying liquid polymers with laser light exposure) for prototyping, to a wide range of processes and materials, including final product manufacturing and preliminary entry into the home consumer market. The process has developed distinct advantages for many projects involving low production runs, unique or complex design, shipping constraints, and time limitations. However, fundamental limitations in process, software, and materials remain to be addressed. Still, there are signs of emerging capabilities in both the software and materials spaces that could have a transformative impact on the future direction of this technology.

Software frontiers

More cost-effective design

Future generations of design software will address the issues currently holding back progress in open fabrication. For example, when compared to traditional injection molding, additive manufacturing is nearly always a trade-off between a savings in fixed costs and a greater unit price. Still, there are many small production-run niches where 3D printing makes economic sense, although current tools do not help designers understand these trade-offs.

Within the next decade, design software is likely to emerge that will begin to take on this challenge, allowing users to better judge the cost of a 3D-printed manufacturing run relative to traditional manufacturing methods. Already, early signals of this transition are beginning to take shape. For example, the Within Enhance software program allows fabricators to design more cost-effective parts and to more efficiently orient their products in the printing machine so that they take advantage of the fact, for instance, that printing horizontally instead of vertically offers significant cost reductions.



Within's Intelligent CAD Software: Within Enhance

Source: Within Labs

Mass customization

One of the key potential applications of digital fabrication is giving users the ability to customize mass products for individual use. Kevlar body armor, for example, could be modified to exactly fit an individual soldier or law enforcement officer, and standard prosthetics could be precisely customized for individual use.

From a software standpoint, this feature relies on the ability to change individual design parameters while holding all other product characteristics constant. This ability to change one parameter at a time is rare in current software but is an emerging feature in a new generation of "parametric design software," which will become more common over the intermediate term. Invisalign orthodontic products are already based on this principle, and other dental applications are currently a particularly strong driver in this area.

Software advances allow fabricated products to be easily tailored to individual parameters.

Source: Invisalign

Rendering "impossible" forms

3D printing allows for the production of complex forms that would be extremely difficult, or even impossible, for traditional manufacturing. Yet, current rendering software is also often not adequate for taking full advantage of the complex, often biomimetic, designs that are a core strength of additive manufacturing production techniques. Digital rendering of 3D objects for printing often does not allow users much control over how exactly an object is printed, yet this factor has material consequences. Within a decade, software will better realize the complex design details that additive fabrication hardware is already excellent at producing.

In fact, this step toward better design software will need to begin with fundamental lab work, since the exact effects that 3D printing has on materials, particularly using different build approaches and energy levels, are still only beginning to be understood. A number of new materials for use in digital fabrication processes have become available over time, yet there has been no disciplined approach to screening for suitable candidates or even to understanding the precise physical properties that these materials take after printing.

The aviation industry's adoption of 3D printing will be a barometer of this process. The sector is a leader in demand for fabricated parts and tools and this further basic research will be a necessary precursor to the widespread adoption of 3D fabrication often touted as an industry goal. For consumers and regulators to become comfortable with widespread use of mission-critical 3D printed parts, better modeling of the physics of 3D printing and printed products will be essential.

Artist Bathsheba Grossman incorporates 3D printed "impossible" forms into her work.

Source: Bathsheba Grossman

Haptic design interfaces

At a more basic level, the software capabilities orbiting additive fabrication technologies are poised to diversify. For home users this trend is likely to translate into more user-friendly programs with simpler interfaces. For industrial applications, a suite of new options and features is likely to come online. In both cases, more intuitive modeling approaches will emerge, including multi-material modeling, 3D visualization, and more haptic (gesture-based) interfaces.

The recent introduction of Microsoft's Kinect system is a powerful demonstration of the early momentum of haptic technologies. While the device was not intended to be used for sculpting applications, inventive users created a number of sculpting hacks within just a few weeks of its release.

The RepRap virtual pottery wheel allows users to directly shape objects for printing.

Source: RepRap

Along similar lines, the RepRap open-source 3D printing project has already seen the introduction of a haptic virtual "pottery wheel" which can be used to directly shape objects for printing. These technologies will come together and improve over time, finally moving toward eventual mass commercialization.

Material advances

Reusable feedstocks

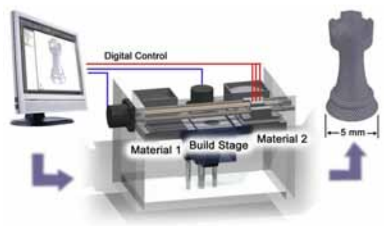
Materials are also on the threshold of a number of likely advances. The promise of fully recyclable materials could be the most revolutionary innovation on the horizon in this area. From a technical standpoint, this could be relatively low-hanging fruit, tracking other materials recycling efforts. However, the payoff in terms of both 3D printing popularization and the impact on overall consumption patterns could be tremendous.

3D printing is often criticized for its tendency to encourage wastefulness. So it is exciting to imagine the possibilities of individual consumers simply reusing the same half-pound or so of homogeneous hard polymer printing material again and again, rather than cycling through hundreds of disposable plastic products over the course of a lifetime.

We are still a ways away from this goal, but there are signals that we are headed toward at least some applications that use materials more responsibly. For example, a hack to the MakerBot home printing system allows users to make their own feedstock from used milk bottles.

The Recyclebot allows users to use shredded milk bottles as feedstock.

Source: Society of Plastics Engineers



A depiction of Cornell University research into fabrication with physical "voxels".

Source: Cornell University

Platforms and business models for reusable feedstocks

If taken to an extreme, the capability to completely reconfigure printed objects could ultimately transform our attachment to physical goods. Indeed, work under way at Cornell University hints at this possibility. There, researchers at the Computational Synthesis Lab are working on a project for "rapid fabrication of physical voxels." Essentially, the idea is to print future products by precisely adhering thousands of individual microscopic spheres made of a wide variety of different materials. The "voxels" here can be thought of as the 3D physical equivalent of image pixels. The researchers speculate that these voxels could be completely recycled by using a solvent that breaks down the adhesive.

The potential to employ reusable feedstocks in open fabrication may rely on the relative openness of the architecture of the machines themselves. There may be little incentive to facilitate full material recycling unless 3D printing machines have an open architecture. Otherwise, the home fabrication industry may end up copying the home printing business model, in which the printer itself is relatively inexpensive but offset by large profit margins on ink cartridges. Under this type of scenario, the drive to radically reduce the amount of material used is something for the industry to actively block rather than encourage.

Biological feedstocks

Over the shorter term, biological applications will gradually become more central to fabrication. The process will likely begin with food. There is, for example, no reason that the statues standing atop future wedding cakes could not be accurate 3D models of the actual couple created from only a few photo images. This kind of food printing is likely to be a large market for next-stage commercialization of 3D printing. Because many common foods are already in liquid form at some point in their processing, it is not difficult to imagine commercial services, home products, and even toys that take advantage of these properties.

Beyond this, biomedical applications currently under development have more astonishing implications. Ongoing stem-cell research, rather than fabrication *per se*, is the real miracle, but 3D printing offers a means to precisely position and shape the cells for broader applications. Indeed, successful experiments have manipulated stem cells with technology no more sophisticated than a standard home ink-jet printer.

The successful addition of a scaffolding material implies that 3D fabrication will likely take its place as an integral part of future tissue engineering efforts. While still many years from clinical use, organic forms are already being printed from live organ stem cells, as was demonstrated on stage at the 2011 TED conference by presenter Dr. Anthony Atala.

On a still more novel front, this capability will likely extend into experiments with in-vitvo meat. If "grown meat" becomes a viable product in the future, it is likely that 3D printing will play a key role in this transition.

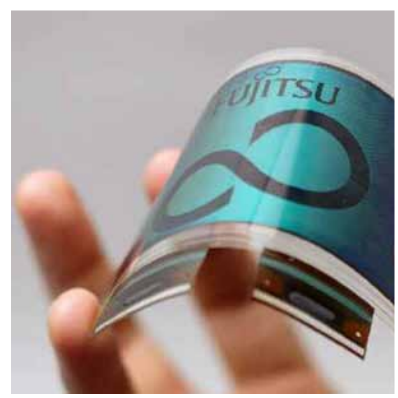
Printed electronics

Despite the limitations imposed by materials, 3D printing is already approaching what might sound like science fiction on some fronts. Printed electronics, for example, are already being produced by a number of laboratories and are likely to come to market within the next decade, bringing consumer applications ranging from flexible circuit boards to rollable television screens into production. Within ten years, this printed “digital paper” will be a common consumer item.

The capabilities of the technique may be enhanced with integration into other manufacturing processes, including multiple treatments of printed objects similar to chip lithography processes currently used in the semiconductor industry. Right now, these are multi-stage processes involving multiple steps, rather than processes for producing fully realized products. Should this be a dominant application, additive fabrication may be less democratized than initial enthusiasts have hoped, at least over the intermediate term. However, the trade-off here is in exchange for greater degrees of control over products and processes.

Organ printing in Dr. Anthony Atala’s Lab

Source: Dr. Anthony Atala



“Electronic paper” technologies rely on many of the same underlying technologies as additive fabrication.

Source: Fujitsu

3 OPEN FABRICATION COMMUNITIES

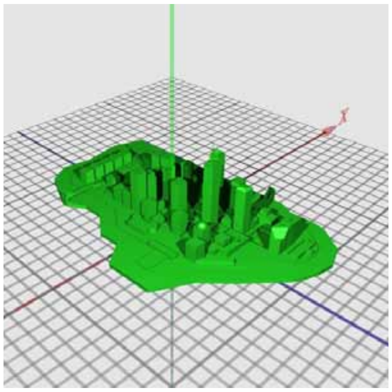
Over the next decade, open fabrication will develop within a new network of collaborative production. We will see a more diverse manufacturing ecosystem that depends as much on social factors as it does on technological ones. In a world where objects become digital, the single most critical factor shaping this future may be our ability to develop a new framework for regulating information ownership and knowledge sharing. Here we explore two of the most important open fabrication communities: the leading-edge makers, fabricators, and designers who are experimenting with 3D technologies, and the Chinese shanzhai, or "bandit," manufacturers who are changing the game for global entrepreneurship. Understanding how these groups approach the idea of intellectual property reveals clues about the challenges and disruptions to come.

The MakerBot Thingiverse

An emergent community of hackers, designers, and fabbers are applying the principles of DIY, open-source, and cooperative collaboration around two new platforms—the MakerBot Thing-O-Matic desktop printer and the Thingiverse object repository. This community is setting the stage for wide-scale combinatorial innovation in fabrication, and pioneering new business models around open standards, open platforms, and open intellectual property.

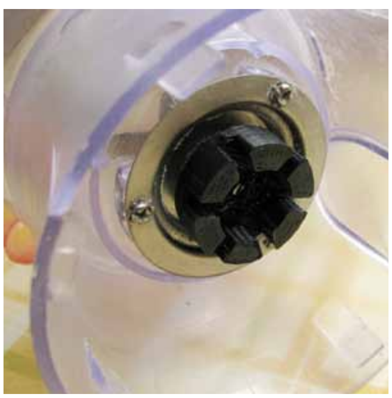
China's manufacturing innovators

China is currently home to the most robust and diverse manufacturing ecosystem on the planet, including legitimate businesses and the *shanzhai* (pronounced shahn-jai) or "bandit" manufacturers. Cutting regulatory corners by operating outside the law is, perhaps not surprisingly, a great way to make a profit. But it turns out that it also creates new kinds of knowledge sharing and sparks bottom-up process innovation. This community is setting the stage for a disruptive product development and manufacturing network that will enable fabricator entrepreneurs around the world to realize their products at a pace and scale that will rival traditional manufacturers and, possibly, transform the retail landscape.



Lower Manhattan has been 3D rendered and shared on Thingiverse for anyone to download, modify, and print.

Source:thingiverse.com



Lazslo used personal fabrication to repair his blender, complete with printed gear.

Source: thingiverse.com

Open fab community 1: the MakerBot Thingiverse

The gap between the theoretical capacity to print any 3D object and actually printing an object in 3D is currently quite large. First and foremost, the Thing-O-Matic—MakerBot's current model printer—retails for $1,299. Then there is the fact that the Thing-O-Matic does not come preassembled. Depending on the DIY skills of the purchaser, construction of the printer takes anywhere from 12 to 48 hours. Finally, although it is not a fragile piece of machinery, the Thing-O-Matic nevertheless requires a large amount of troubleshooting in order to stay in functioning order. Indeed, another type of desktop 3D printer called the RepRap costs slightly less than the Thing-O-Matic but requires a great deal more technical expertise to construct and keep in working order.

Furthermore, the ability to create 3D objects with the Thing-O-Matic is dependent on the fabricator's ability to create accurate 3D models. Some computer-assisted design (CAD) software is free—Sketchup and Blender, for instance—but the more powerful commercial software can cost between $500 (for tools by Rhinoceros, for example) and $5000 (for Autocad's Design Suite). While it may be easy for an experienced designer to envision and fashion a digital representation of an object in 3D space, currently no "intuitive" design software exists. By providing designs for download and modification, thingiverse.com takes the burden of design off the fabricator, as users with limited design skill can alter existing designs rather than starting from first principles.

For companies concerned about digital design piracy, the ability to use CAD tools to customize official designs of brand-name objects offers a potential future business model. In exchange for paying to download an officially certified design that can be printed at home, consumers may be able to work within preexisting parameters to create versions of objects that are tailored to personal tastes and needs.

The fabricator also needs to know how to work with the materials desktop 3D printers are capable of using—currently, superheated plastic extruded in layers to create the desired shape. Since the molten plastic needs time to cool before another layer of material can be added, creating small objects becomes difficult, as improperly cooled plastic can result in an uneven build surface, which can lead to deformed objects. Given the need for a stable build surface, it is also currently not possible to create objects with large overhanging areas.

What does it mean to be a personal fabricator?

Clearly, the future of personal fabrication depends on a wide array of skills and tools that empower the end user with the capacity to create any object that he or she desires or needs. Given these limitations, what is perhaps most remarkable is the number of truly innovative and useful things that have been created by the still-nascent fabricator community. One already classic example comes from the Thingiverse user Laszlo. Laszlo's blender broke, and instead of trying to track down replacement parts or having to throw it away and then buy a new one, Laszlo created a model of the broken part and printed out the replacement.

Blogging about this process, Laszlo notes that the modeling of the replacement part took approximately 15 minutes, indicating that he is clearly a power user of modeling software. Even so, as the design skills to accurately model simple objects in 3D digital space begin to spread, it is possible that we will begin to enter a world in which the lifecycle of simple household goods—like Laszlo's blender—can be extended through personal fabrication.

It takes a world to make MakerBot

The promise of 3D printing technology is that it empowers the individual to create things that have, until now, required resources and capital that were only feasible for corporations or the very wealthy. And although personal fabricators do unlock a wide array of capacities for the individual user, these capacities are enmeshed within a network of enabling people, communities, and technologies. The example of Laszlo shows how a trained, financially stable user who is patient enough to tolerate an imperfect machine can create objects of great utility. The network of goods and knowledge that Laszlo had to harness in order to get to the point where he could fix his own blender is nothing short of astonishing. Going through the parts list for the Thing-O-Matic, as well as the things needed in order to construct the MakerBot (solder, wire strippers, etc.), one encounters at least six different visible country-of-origin stamps. The illustrations at right show some examples of where various portions of the MakerBot originated.

And this is only what is readily identifiable. If one were to further track the provenance of the other 50-odd parts of the Thing-O-Matic, this list of origin countries would grow. Furthermore, the community of people who participate in the forum discussions and help threads on the MakerBot wiki, and who provide modifiable models on Thingiverse, represent a truly global source of intellectual capital.

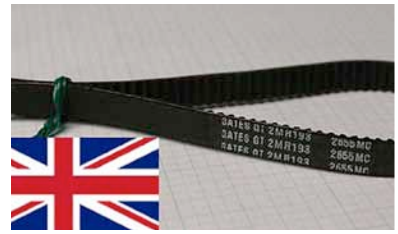
Which is to say, it takes a world to make a MakerBot. The advent of personal fabrication—technology that has the potential to change the human relationship to personal goods—is only possible thanks to the mobilization of a number of complicated global manufacturing, supply, and support chains.

Open fab community 2: China's shanzhai

As we look out over a new landscape of open fab tools, materials, and processes, we see changes taking place in global manufacturing that will accelerate and complement open fabrication. Chinese industrialization is perhaps the most important—particularly the sector of Chinese industry known as shanzhai manufacturing.

China is transforming the world economy, upsetting the economic balance of power to a greater extent than any other "developing country" since the United States emerged as a global superpower. This shift has been under way for the past several decades, but it is only in the last ten years that most global businesses have started to see the real effects of these changes. We'll be seeing a lot more in the decade to come. By 2021, according to global economic forecaster IHS, China's Shanghai-Jiangsu region alone will be a bigger economic player than the Netherlands, Australia, Brazil, Mexico, Korea, or Canada.

Manufacturing has been at the heart of this growth. After a more than century-long run as the top manufacturer for the world, the United States now stands at number two. China produced 19.8% of the world's manufacturing output as compared to



The Thing-O-Matic's timing belts move its build platform and come from the United Kingdom.

Source: Mathias Crawford

Arduino, an open-source electronics prototyping platform based on flexible, easy-to-use hardware and software, was designed in Italy but likely assembled elsewhere.

Source: Mathias Crawford

The power resistors, from Mexico, are responsible for heating the nozzle that distributes the melted plastic.

Source: Mathias Crawford

19.4% for the United States in 2010. Much of this happened in the last ten years. In 2000, 6.9% of the world's total manufacturing came from China; that nearly tripled by 2010. Analysts expect China to maintain this position for some time to come, but probably not at such a fast rate of growth. Over the next decade there will be two main drivers of growth in Chinese manufacturing: (1) Chinese companies will continue to make goods for the rest of the world, and (2) the world's businesses will locate more factories in China to service the growing Chinese consumer market.

Chinese maker ecosystem

Production is woven into daily life across China. Over the past 60 years, a socialist focus on industrialization developed into a "market socialist" export-led economic miracle. Along the way, rural communities built factories, hundreds of millions of people left the land for work along the eastern coast, and robust networks of industrial clusters emerged. These regional networks are comprised of thousands or even tens of thousands of companies that benefit from co-location, creating a competitive local economy of knowledge, skills, and processes. They have been concentrated in the coastal regions, most notably in the Pearl River Delta near Hong Kong, the Yangtze River Delta near Shanghai, and the Bohai-rim region near Beijing.

New manufacturing clusters are also growing as industry moves into China's western half, drawn by cheaper local labor, growing domestic consumer markets, and the raw materials of the less-developed west. Regional governments have become more involved in branding themselves by specific industries, for everything from Wuxi photovoltaics to the consumer electronics sector in Dongguan. As Yu Zhou, professor of geography at Vassar College, notes, "These clusters take a long time to form. Even though they seem to react fast, it is not something you can build quickly." During a period in which American manufacturing has declined, China has created a vibrant ecology of production that has no global rival in terms of scale and diversity. "It is not just about low cost," notes Liam Casey, CEO of supply chain management company PCH, "but about skills and ecosystem and infrastructure." Think of it as a foundation for future growth—not just for the Chinese nation, but for a new kind of manufacturing that will disrupt traditional models of innovation, product cycles, and profits.

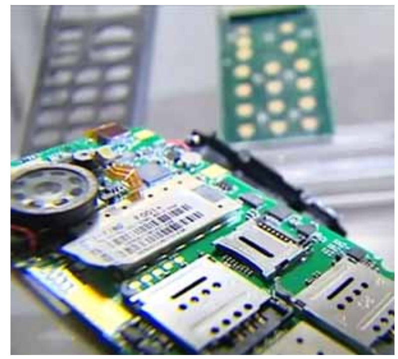
China's tightly integrated manufacturing web has also become a force for the production of black market goods at a scale and pace that has upended global consumer electronics, apparel, and cosmetics industries, though this list may grow. It is a giant experiment in global commerce with erratic conformity to current laws on intellectual property. This experiment offers us one evolving model of open fabrication that raises important questions for the future.

Shanzhai factories and knowledge sharing

Shanzhai factories, named after the mountain fortresses housing bandits in traditional Chinese novels such as *Outlaws of Marsh*, are the murky underweb of China's industrial clusters. Like the bandits of yore, they live by their own code, steal from the rich, and provide to the poor. Over the past decade, the shanzhai have grown from small-time producers of shoddy copycat goods to capture an estimated 10% of the global mobile phone market. With their unique features, quirky designs, and low price-points, shanzhai phones can be found across India, Africa, Russia, and South America. In fact, it was likely these affordable Chinese-made phones that fueled the Twitter and Facebook revolutions of the Middle East. The shanzhai also make athletic shoes, cosmetics, and clothing.

As with their legitimate counterparts, the shanzhai are a network of highly specialized subcontractor producers. Small-scale players continuously hone their part of the design, manufacturing, packaging, and distribution processes, shaving off cost and improving quality. All of this requires an extraordinary amount of network coordination between the different parties. They do not invest in marketing research or R&D; they don't own stores, stock finished goods inventory, hire sales staff, or fund logistics networks. They also don't pay taxes or conform to labor and safety regulations.

Where the shanzhai go beyond lawful manufacturers is in their approach to knowledge sharing. It's not simply that they flout Western IP laws and all forms of proprietary knowledge—they have their secrets, too. But they have discovered that sharing certain kinds of information leads to more profits. What should interest us is that their system also accelerates new inventions, manufacturing, and more fine-grained responsiveness to local consumer tastes.



A screenshot from an in-depth video tour of the Shanzhai market.

Source: M.I.C. Gadget

Shanzhai rules

Here are the rules the shanzhai live by:

- Do nothing from scratch; build on the best of what others have already done.
- Innovate process ceaselessly at small scales for speed and cost savings.
- Share as much as you can to make it easy for others to see your value and to add value to your process.
- Sell it before you make it.
- Act responsibly within the supply chain to preserve your reputation.

The shanzhai regularly exchange ideas and have a keen sense of who is good at what. Eric Pan, founder and CEO of Seeed Studio, reports that without concern for intellectual property, the shanzhai have created a set of public, or open, tools and processes, such as an open Bill of Manufacturing, open boards, and open cases used for phones, tablets, and other electronic devices, that make their supply networks transparent. Keeping secrets in the supply chain has a cost that shanzhai are not willing to bear. "If sharing my specs with you means I close a deal faster, I will share it with you. Waiting a day to sign an NDA means a day longer I sit on my inventory," says Bunnie Huang, well-known American hacker and Founder and VP of Hardware Engineering at Chumby.

Since the system relies on outsourcing everything, a set of common processes also helps efficiently circulate work to the most skilled players. Transparency is a form of self-promotion and helps others see where they can add value to your supply chain without you having to search them out yourself. There is also a certain fatalism about trying to keep new inventions secret in a world of knock-offs. "If it's going to be copied anyway," says David Li, social gaming consultant and Foreman at China's first hackerspace, Xinchejian, "it may just as well be open and shared."

What doesn't get shared is what lies at the heart of the shanzhai value proposition for the consumer. On top of the hyperspecialized platform of the Chinese industrial

The Mi-Obama phone, modeled after the Nokia 5300 XpressMusic, was produced for the Kenyan market in just a few months after Barack Obama's election as president of the United States, and sells for around $30.00.

Source: cellular-news.com

clusters, the source of individual value for each shanzhai manufacturer is an eye-popping, never-ending diversity of features and designs that create new consumer experiences. Take a tightly integrated and highly competitive design-to-shelf supply chain, combine it with a lack of IP enforcement, and you get a class of small-scale manufacturers who can respond more flexibly to the emerging whims and desires of the market.

Evolutionary product "mash-ups"

Some of the things that shanzhai manufacturers come up with are a bit comical: traditional Chinese slippers with a Nike swoosh or Adidas stripes, a mobile phone that can store your cigarettes and light them for you too, phones shaped like beetles, pandas, or Mickey Mouse.

Others, especially in the consumer electronics sector, are giving consumers things they actually want, but multinational corporations have been unwilling or unable to provide: a phone with a heavy battery that lasts several weeks on a single charge; or a handheld that doubles as communication device and boom box.

In a 2009 blog post giving hackers outside of China their first glimpse of the makers behind shanzhai, Bunnie Huang wrote:

> "They are doing to hardware what the web did for rip/mix/burn or mashup compilations. … They are not copies of any single idea but they mix IP from multiple sources to create a new heterogeneous composition, such that the original source material is still distinctly recognizable in the final product. Also, like many Web mash-ups, the final result might seem nonsensical to a mass market (like the Ferrari phone) but extremely relevant to a select long-tail market."

Transparent processes and hyperspecialization allow these very small firms to combine the capacity in the region and react extremely quickly to things they've never seen before. In a kind of rapid evolution, nothing is designed from scratch; everything is built on top of previous products. The shanzhai system is unlikely to invent the next iPad. But it will innovate furiously on top of the iPad, creating a wide range of new tablets with all kinds of different features (they are already flooding global markets in 2011). High-priced design and technology is becoming available to a global mass market through shanzhai.

Future of shanzhai

In the past decade the Chinese manufacturing system has grown from making components to making complex goods that compete with multinationals in lower-end consumer markets around the world. What are the major forces shaping the evolution of the next decade of shanzhai?

- **Increased enforcement of IPR**
  China's entry into the World Trade Organization in 2001 coincided with the growth of the shanzhai and their IP-flaunting processes.

Shanzhai have begun to take real bites out of the market share of multinational corporations such as Nokia and will impact tablet and PC makers as well in the next few years. The higher the stakes, the higher the pressure on the Chinese government to enforce international intellectual property rights. In January 2011 two Chinese agencies—the Ministry of Industry and Information Technology, and the State Administration of Industry and Commerce—declared a crackdown on shanzhai electronics manufacturers.

- **Increased R&D spending**
  Research by Dr. Yu Zhou of Vassar College shows that Chinese firms have significantly increased their R&D spending in the past two years. With their growing global success, Chinese shanzhai are catering more to a global market. David Li of Xinchejian notes that many of the shanzhai phones now sold in China come preinstalled with Twitter and Facebook apps. While both of these services are blocked in China, the phones are targeting users in other countries.

- **Move from shanzhai to legitimate business**
  In many cases, Shanzhai factories aim to become legitimate businesses and develop their own brands. The Chinese government seems to be allowing some bootleg businesses to grow, hoping they will follow this path. As Xinhua News reports, Chinese hybrid vehicle and battery manufacturer BYD, in which Warren Buffet has a 10% stake, began as a shanzhai plant producing cheap batteries.

Designed for young women, this phone takes the shape of a compact mirror.

Source: clonedinchina.com

4 FORECASTS FOR OPEN FABRICATION

As the foundational technologies of open fabrication unleash new innovation ecosystems—be they DIY grassroots hackers or agile, globalized manufacturing networks—they will enable disruptive futures that transform the material world. The following forecasts are snapshots of plausible futures that can serve as provocations for strategic discussions. As you read these forecasts, think about how you or your organization would respond if this future came true. Alternately, ask yourself how you would act differently today if you knew for certain it would come true.

Democratizing industrial design

In the early 2000s, keeping a Web diary was a fairly challenging task that involved coding Web pages and manually archiving and indexing old posts. The development of open-source and hosted blogging platforms made it much easier for a neophyte to design and manage a "Web log" of their daily insights. These tools deskilled the process by taking the need for Web design and system administration out of the loop, leaving creative direction as the blogger's sole task.

A similar trend is at work in open fabrication. While it's not yet as simple as writing a blog post, advances in design software are automating many of the more technical aspects of object design and pre-print preparation. This democratization of industrial design will certainly lead to as many poor designs as there are unread blogs but will also expand the cadre of designers far beyond its current bounds.

New collaborative design processes that apply crowdsourcing principles will bring some of the rapid, lightweight innovation potential of open-source and wikis to industrial design. New objects will be able to break free of long-lead-time design cycles, as widespread availability of object design files will allow actual users to modify and adapt goods to suit particular needs, or to address unforeseen problems in the object's implementation.

This future is largely contingent on two things: (1) the development of communities such as Thingiverse, which are aimed at fostering an open exchange of design files and ideas about how objects are to be made, and (2) improved accessibility of ever more powerful design software to individuals with limited or no design experience. Design concerns that software will have to take into account include the aesthetics of objects, specific limitations of materials used in building (for example, the need for plastic layers to solidify partially before a new layer is added), and the load-bearing capacities of the materials that are used to create objects.

The next generation of CAD software will take into account the physical and molecular capabilities of objects used in printing. Users will be able to indicate the stresses that will be placed on objects and will benefit from computational processes built into the software that will help the user create designs that are durable and representative of the desired final aesthetic. Software such as Within Enhance is leading the charge to internalize real-world physics and material capabilities into the designs it creates.

This will also be driven by a larger cultural trend that increasingly values design. Paul Goldberger, architecture critic for *The New Yorker*, sums up the new emphasis on design nicely:

> “I think the truly transformative development in the world of design over the last generation has been its evolution into the mainstream. We are a much more visual culture than we once were; people care more about design and architecture, and it has become more accessible to them. That doesn’t mean everything is suddenly great, and that we’re in some kind of design nirvana. A lot of what we do now is lousy, as it always has been. But if you look at the difference between, say, an iPhone and a Princess phone, or a flat-screen television and the faux–French Provincial TV cabinets we grew up seeing, or the difference between IKEA and the furniture stores our parents shopped in, you see how much more sophisticated as works of design the objects people live with today are.”

Many colors are currently available for 3D printing, but only in a small range of materials.

Source: SolidSmack.com

The long now of materials

The “long now,” a term coined by Brian Eno, seeks to challenge people to stretch out their understanding of what “now” means and to contemplate a slower sense of time. Nothing could better explain one of the most crucial retarding forces on the pace of innovation in open fabrication—the slow flow of new materials to the open-fabbing community. As one expert workshop participant remarked, “We would be lucky to get one new material a decade” for 3D printing. Many other experts share this pessimism. While tools advance quickly, and software more slowly, materials are the laggard in open fabrication.

The slow pace of materials innovation is the result of the messiness of stuff. Open fabbing is often compared to open-source software, but the feedstocks for open-source software were 1s and 0s; the feedstocks for fabbing could potentially number in the hundreds of thousands of different substances with a vast range of physical properties and potentially toxic chemicals.

These properties are closely guarded secrets and not widely available to the public. Today, there is no equivalent open repository of materials data sheets, and the movement has not yet mobilized (or resorted to creating) its own materials—a strategy we've seen in open bioengineering communities that have developed, for example, the Registry of Standard Biological Parts. Until this information gap is plugged, material choices for 3D printing will be sharply limited.

Extreme customization

The combination of improved interfaces, 3D printing technology, and 3D software will unleash a new world of extreme customization. Industrial designer Scott Summit, co-founder of Bespoke Innovations, is using 3D modeling and printing to pioneer a new approach to the creation of prosthetic limbs. Summit's company uses the exact shape and measurement of people's bodies to create custom wearables: a backpack for firefighters that is molded individually to each user's body, or a prosthetic lower leg precisely modeled on the shape of the other, healthy leg and custom-designed for the wearer.

Personalized snap-on covers for prosthetic limbs are an example of totemic objects.

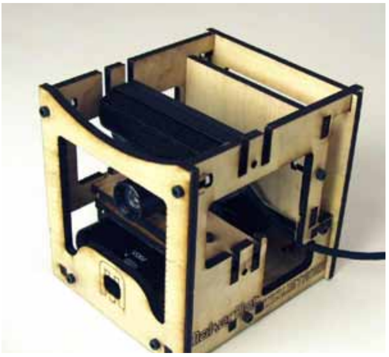
Source: Bespoke Innovations

We will also see all kinds of creative fun products derived from unique, individual physical characteristics. In early 2011, hacker artists built a "Be Your Own Souvenir" installation on the streets of Barcelona. Three Kinect light scanners created volumetric reconstructions of poses struck by passers-by, then printed them on-the-spot with a RapMan 3.1 3D printer. Imagine a world in which you could capture an image of anything you did or saw, convert it to a software model, and send it to a printer.

See it, capture it, make it

In China, the advent of high-resolution 3D scanners, and of photosynthesis technology that allows users to create 3D models out of multiple photos of an object, offers another path for increasing the usability of desktop fabricators. The ability to produce relatively high-fidelity approximations of existing objects, when combined with the ability to modify and refine digital designs within a restricted set of parameters, creates an opportunity for fabricators to rapidly identify and use objects in the real world as the basis for their particular niche needs. Imagine seeing something you like, taking a series of photos with your phone, uploading to your computer, and asking it to go to work to create a 3D design of the object.

Indeed, early versions of this type of technology already exist. Thing-O-Matic producer MakerBot Industries sells a 3D scanner kit that allows fabricators to create simple wire-frame models of objects in their environment. The kit functions by "(1) projecting a line onto an object, (2) recording the line's position relative to any flat reference, and then (3) computing the 3D geometry based on those numbers."



The MakerBot Cyclops 3D Scanner allows fabricators to make wire-frame models of objects.

Source: Makerbot.com

In China, 3D technology is being used to capture, model, and reproduce deteriorating ancient Buddhist statues from the Longshan Grottoes, offering a glimpse into a new form of historical preservation.

Furthermore, recently-released Trimensional software gives mobile phone users the ability to create 3D models using nothing more than their mobile phones, and then allows them to export these models as file formats that can be printed on 3D printers. It is only a matter of years before the computational power of cloud computing will make it possible for high-resolution images of any object in the built environment to be transformed into a 3D printable model.

New blue-collar skills

Economist Paul Krugman recently argued that a college education is no longer a guarantor of economic success, as automation and offshoring of many white-collar jobs reduces demand for college graduates. But the rise of open fabrication, and a growing body of "tinkerers," as science fiction writer David Brin calls them, may chart a path to a re-invigorated blue collar workforce wielding sophisticated new skills. As Krugman argues:

> "Most of the manual labor still being done in our economy seems to be of the kind that's hard to automate. Notably, with production workers in manufacturing down to about 6% of U.S. employment, there aren't many assembly-line jobs left to lose."

David Brin's science fiction novel *Tinkerers* describes a future renaissance of fabrication skills.

Source: David Brin

If Krugman is right, open fabrication could be a powerful growth accelerant for a stable base of non-routine manufacturing jobs. Rather than being a Hail Mary pass to save American industry as we know it, open fabrication will be the next stage of its evolution.

From a public policy perspective, this strongly points toward the need for training in 3D design and printing. Indeed, in a recent report commissioned by the U.S. Office of Science and Technology Policy, the top five recommendations to the government were all focused on beefing up support, curriculum, and facilities to teach design and manufacturing in public schools and regional manufacturing clusters.

From a larger cultural perspective, manufacturing itself is enjoying a resurgence in the public eye. Chrysler's "This is the Motor City, this is what we do" Superbowl ad in 2011, which starred Detroit rapper Eminem, received acclaim from critics and fans alike. Tagline: "Imported from Detroit."

Community workshops, not personal desktops

Given the set of raw materials, design skills, and manufacturing capabilities that are required for an individual to harness the power of a 3D printer, we do not think it likely that in the next ten years there will be a personal 3D printer in every house. Housing the materials alone is something that many eco-aware households would shy away from. A more realistic possibility for the distribution of 3D printers would be to house them in community resource centers such as schools, small businesses, and community "fab labs." These physical locations could serve as repositories for a diverse array of materials, user-generated designs, and resources for helping fabricators create and modify 3D models.

TechShops may serve as the copy shops of the future for 3D printing.

Source: Flickr user Solsken

A few organizations, including TechShop in Menlo Park, California, and the Web-based 100KGarages are already starting to implement these possibilities. They and similar firms will expand their role in the community, acting as part workshop, library, part toolshed, and part coffee shop. People who have purchased the latest IKEA printable Målmo lamp design online, for example, will be able to come here to make a few customizations in consultation with their neighborhood design expert. Perhaps they will shorten the height of the lamp shade or expand the diameter of the base before printing out their own unique version of the product to take home.

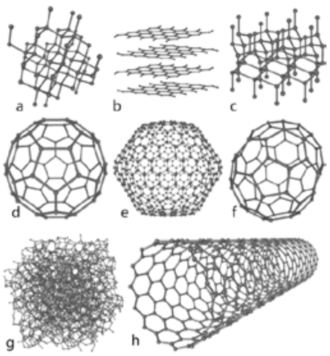
10 to 10,000: the sweet spot for 3D printing

The sweet spot for 3D printing is likely to fall somewhere between one-off creation of unique objects and mass production: short runs of 10 to 10,000 units. This is because 3D printing is not cost-competitive for single objects vs handcrafted production, nor is it so for creating the massive number of standardized parts that the modern economy relies on—for instance, nuts, bolts, and screws of uniform size and quality.

An example of this model currently exists for many electronics goods. Since many components such as circuit boards have periodic demand that doesn't necessarily require the scale of centralized mass production and global distribution, specialized tools have been developed that allow small businesses to create versions of centrally designed components in relatively small batches.

Similarly, there may be an opportunity for local businesses to act as the fabrication and distribution hubs for professionally designed objects that have sporadic demand. These hubs would benefit from providing officially certified versions of brand-designed objects, avoiding quality control issues that might otherwise be associated with home 3D printing.

The global success of shanzhai products suggests that consumers are hungry for things they can't always afford—and that many are even willing to buy non-branded products if they meet their needs. Where price points are creating under-served markets, expect new micro-manufacturers to jump in with locally relevant products that can be made more quickly and for far less overhead than those produced and marketed by large companies.



Eight allotropes of carbon: (a) diamond, (b) graphite, (c) Lonsdaleite, (d) C60 (Buckminsterfullerene or buckyball), (e) C540, (f) C70, (g) amorphous carbon, and (h) single-walled carbon nanotube or buckytube.

Source: Wikipedia

Multi-purpose, safer materials

The future of open fabrication will largely be determined by the materials that are used by 3D printing. Machines currently cannot use a differentiated feedstock—that is, they can only print one type of material, or one type of material at a time—and thus the type of object that can be printed is limited.

One possible future that would obviate the materials constraint would be the development of carbon printing technology. Current experimentation with carbon nanotubes additive manufacturing hints at the revolutionary potential of this type of printing. Since carbon can be configured in allotropes ranging from super-soft graphite to ultra-hard diamond, the resulting creations could take on any number of complex shapes. As a result, these objects would have much greater utility than the current plastic-only models—perhaps combining carbon fiber and diamond to produce extremely resilient and intricate works of art.

A large concern with current plastic-based printing is that the common plastic materials used—notably ABS (acrylonitrile butadiene styrene)—are not particularly beneficial to human health. Producing plastic objects may induce concerns about health and safety factors (especially if materials printed are used for kids' toys or for objects that come into contact with food). In contrast, carbon-based objects would not be subject to the same scrutiny.

Maker culture meets the Web

The DIY culture of the Maker movement that we forecast three years ago has benefited greatly from using the Web as a knowledge sharing and social communication medium. However, Web platforms at the heart of the Maker movement, such as Instructables, are not highly structured in terms of how they share information about production and tools. As a result, we've not yet seen the sophisticated distributed forms of highly structured collaboration as we see routinely in open-source software, for instance.

The development of libraries and data standards for encoding manufacturing specifications and sharing them electronically will bring Web scale to the open fabrication movement. This wave will be driven by projects such as skdb, which describes itself as an "apt-get for hardware," comparing itself to a critical piece of Linux software used to distribute source code and machine instructions for compiling it into working software. For objects, such a data package would consist of 3D CAD models, a bill of materials, and fabrication instructions. This common data structure will bring a new level of interoperatiliby and universality to the Maker movement.

Global crowdsourced micromanufacturing

China's shanzhai manufacturing networks are poised to respond to the designs and 3D prototypes of the rest of the world's fabricator entrepreneurs. Over the next decade we will see the growth of a new kind of product development where designers create things to match the tastes of small-scale markets and use Chinese manufacturing to ramp up production in a few weeks or months.

Take the recent example of TikTok and Lunatik Multi-touch Watch Kits, a project dreamed up by American designer Scott Wilson. Wilson wanted to make a well-designed, well-engineered watch strap that would hold the iPod Nano. He posted a video description on the crowdsourced funding site Kickstarter, asking for $15,000. Donors were urged to “be a part of making a cool product that no one else would take the risk on.” The product became Kickstarter’s biggest success to date, attracting 13,512 backers who pledged nearly a million dollars in support, in just 30 days.

Just like the shanzhai makers, Wilson had sold his product before he made it. And like the shanzhai, he relied on China’s innovative manufacturing networks to produce his final products, closing on a deal to manufacture 200,000 watch bands within 60 days of receiving funds. Wilson posted videos of his trip to Shanghai for backers to watch the manufacturing process close up.

Shanzhai design grows up

As we have shown, China’s shanzhai makers can respond to evolving consumer needs more quickly than any manufacturing system in the world. While the shanzhai don’t have the skills to create new technologies, they are top-of-class in absorbing new products, iterating small process innovations, and building out a dizzying variety of new designs. When a new product or design looks good to a wholesaler, it is produced in small batches and quickly replicated if it catches on.

Currently there is a distinct lack of skilled 3D modelers in the shanzhai sector. As industrial design software becomes more powerful and user-friendly, however, Chinese programmers and designers will skill up. New designs will be funneled into the Chinese network via the growth of collaborative micromanufacturing relationships between fabricator entrepreneurs in the West and Chinese makers in the East. And Chinese entrepreneurs will begin to take advantage of the open design libraries now being developed, to produce their own goods.

Local design tastes will begin to be accessible to designers around the world, who will iterate, improve, and expand them to create design mash-ups at a greater scale than we’ve yet seen. The process innovations that now drive the constant evolution of shanzhai networks will slowly become design innovations, making both the shanzhai and China’s legitimate manufacturers more successful on the world market.

Tissue printing

Advances in computing over the last quarter century were the key to unlocking the science of life. Future generations are likely to view bioinformatics as the most important and far-reaching application for computing. While the Web and social media allow our civilization to evolve in new ways, computational biology is allowing us to redefine life itself. You could say that doing biology is what computing was meant for, in the grand scheme of human history—every other use was just a footnote.

In a similar vein, 3D printing using biomaterials will allow us to produce living tissue cheaply, cleanly, and efficiently, transforming the way we think of organisms, bodies, and food.

In that sense, the current wave of experimentation and innovation around 3D printing with inorganic materials may just be a transitional phase. It’s merely a stepping-stone that ultimately serves to create a cadre of technical improvements that innovators who understand this technology can apply to life science in the future. We'll need biologists to become as good at using 3D printing as many are today at computing.

In this view, 3D printing using inorganic materials is actually quite dull—there are a limited range of applications where it makes more sense than traditional manufacturing, which is already highly evolved after a century. But tissue production must, by necessity, always be bespoke. Every one of the 6,000 livers transplanted in the United States each year, if produced using 3D stem cell printing, would have to be customized. There's no other way to do it.

Wild card: self-replication

Over the longer term, self-replication is another intriguing possibility. If a printer, or perhaps a combination of printers, were to achieve the material facility necessary to print multiple replicas of its own electronic and physical components with relatively simple user involvement, the result could be a manufacturing phenomenon commonly found in biology but never before achieved by human production—geometric expansion.

This is the explicit aim of the RepRap project, an open-source effort to produce a self-replicating printer for home use. While RepRap is likely a signal of the possibility here rather than a fulfillment of it, the implications are eye-opening. If successful, digital fabrication capabilities would naturally tend toward ubiquity, much as computing has. Beyond this, the process of technological evolution that underlies the maturation of all technologies would be logarithmically accelerated. Within such a scenario, it is difficult to imagine that digital fabrication would not overtake traditional manufacturing in nearly every sphere of production.

Ultimately, while this development is likely much further than a decade from realization, it should not be dismissed as science fiction. Proof-of-concept for the technology of self-replication already exists in nature, and we, along with all other organisms, are products of it. This direction is the explicit longer-term target of much of the nanotechnology research currently under way.

Indeed, this natural transition toward nanofabrication may be the most revealing perspective from which to view the future of digital fabrication. While the next decade is likely to see relatively marginal material and software improvements, these in turn will have subtle feedback effects, nudging manufacturing as a whole toward more refined levels of material manipulation. From this perspective, it is only a matter of time—albeit a potentially long time—before digital fabrication takes hold.

As much as anything else, the next decade is likely to lay the groundwork for subsequent developments and the near certainty of far more critical advances to come.

5 TAKEAWAYS

IFTF held a one-day workshop at the Autodesk Gallery in San Francisco on April 19, 2011 to explore the implications of this report for business and policy innovation over the next decade. The key takeaways from our concluding discussions are highlighted here.

Key obstacles

The group raised three top-level issues that limit the potential growth of Open Fabrication.

- **Design tools remain too specialized.** Reality capture tools and 3D design software are undergoing consumerization (see Autodesk's latest consumer offering, PhotoFly, which generates 3D models from ordinary photographs and exports them to standard 3D formats for further editing), but they will need to become much easier to use. Mainstream audiences of educators, students, artists, and other makers will need much more user-friendly tools. (See our forecast, Democratizing Industrial Design.)
- **Intellectual property frameworks favor big players.** Without more flexible structures, legally protected spaces of innovation may be disincentives to innovation. The premise of openness is that more participants mean faster innovation. The legal role of patents, copyright, and trademarks in the manufacturing sector, at least in developed countries, will need to be reinterpreted. (See our forecast IP—The Great Uncertainty/Patents and Innovation.)
- **A Gordian knot limits the applicability of 3D printing.** Most products are assemblies of various parts, and the material feedstocks used to create them are complex. The materials development cycle is very slow for 3D printing and there is a real limit to what can be created without significant advances in multi-material processes. (See our forecast, The Long Now of Materials.)

Key opportunities

After a day of immersion in the future of open fabrication, clients highlighted four strategic implications:

- **Open fabrication will extend the life and value of a product over time.** Dynamic local access to replacement parts could dovetail with the desire for more resource-light lifestyles. This could also fill the vast need for replacement parts for out-of-production consumer electronics, vehicles, and tools.
- **A world of open fabrication will transform the role of the retailer.** Retailers will need to offer access to a much wider range of SKUs, and people will need more filters to manage longtail manufactured goods.
- **Open fabrication will enable extreme customization,** creating more physically nuanced and emotionally meaningful goods. We will be able to personalize our physical objects to a much greater extent, tying them not simply to words and images that are meaningful to us, but to our own physiologies and actual environments.
- **Open fabrication offers new development opportunities for manufacturers and designers.** There is a groundswell of interest in the convergence of manufacturing, design, and digital tools, coming from a wide variety of communities. Today, these communities are only loosely connected. There is a lot of space for companies to play a leading role in helping to grow this conversation, create new tools, and build new products and services.