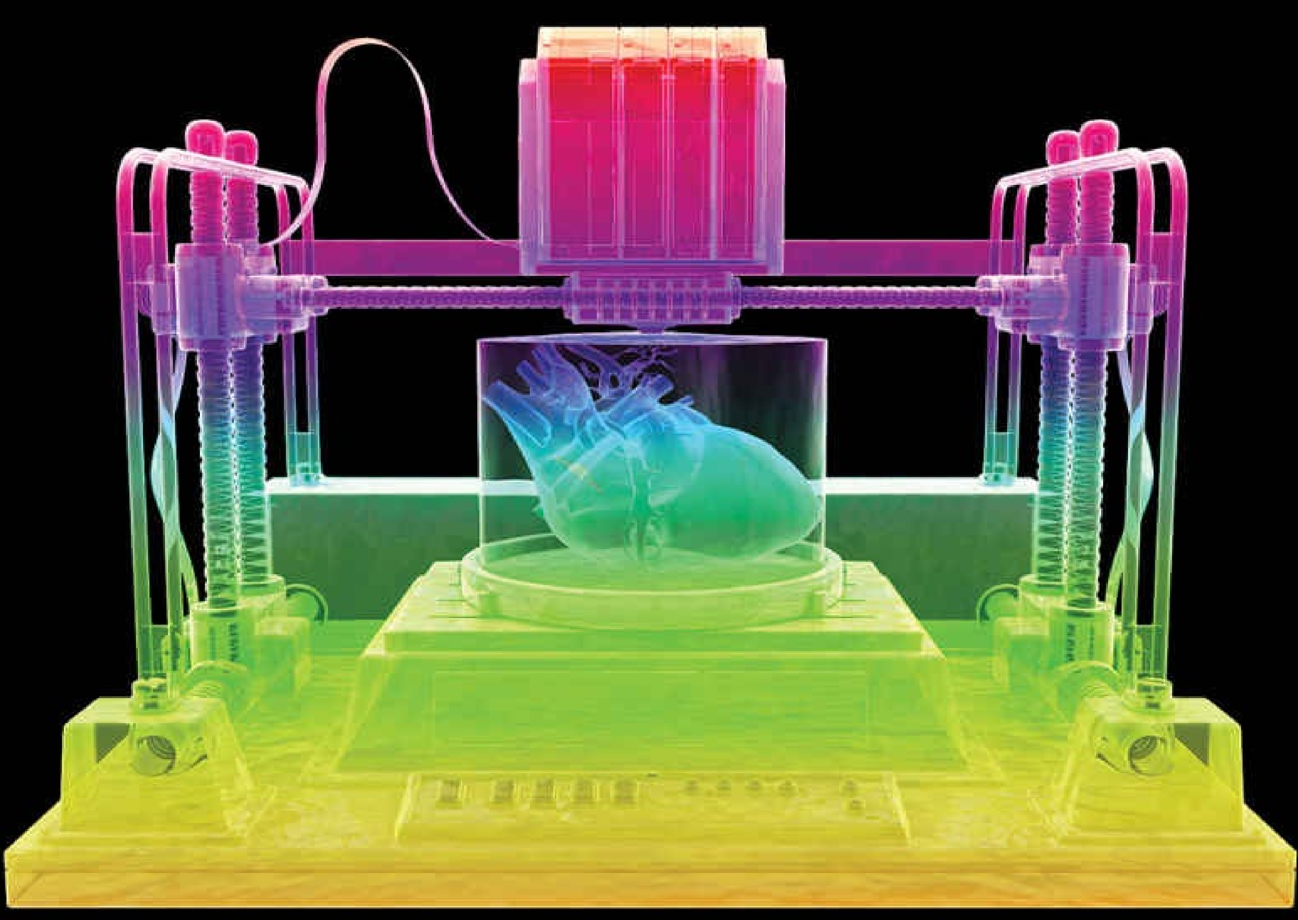
3D PRINTING

THIRD EDITION



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3D PRINTING

Third Edition

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Preface: Beyond the Hype

3D printing transforms digital models into physical reality by building them up in layers. When the first edition of this book was published in May 2013, the idea of 'additively manufacturing' things in this manner had just started to capture the public imagination, with the popular press reporting that it would soon be possible for anybody to 3D print almost anything. Indeed, in another 2013 book called *Fabricated: The New World of 3D Printing*, Hod Lipson and Melba Kurman wrote that the field was moving 'faster than the speed of light', with technological advances taking place 'in huge leaps and bounds'.

By the time that the second edition of this book was published in November 2014, the mainstream appraisal of 3D printing had changed dramatically. To industry insiders it remained clear that innovations were accruing at a steady pace. But the popular perception was that all of those claims made in 2013 had been no more than hype. Most journalists subsequently abandoned ship, apparently surprised that personal fabricators capable of producing anything they could imagine were not yet on sale. Since late 2014 investors have also been spooked, with the share prices of many 3D printing companies having fallen dramatically.

The now-widespread view that 3D printing has been over-hyped remains to the field's detriment. As one of those who strove to bring 3D printing to mainstream attention, it is also a matter that I feel a need to specifically address. Back in 2013, I gave the first edition of this book the subtitle *The Next Industrial Revolution*. It is therefore not a surprise that, a year or so later, I ended up in the firing line of those journalists and academics who believed that false hopes had been raised.

While labelling 3D printing as the Next Industrial Revolution, in both the first and second editions of this book I nailed my futurist colours to the mast in a fairly precise manner. Specifically, I noted that:

> … 3D printing is not going to replace all forms of traditional manufacturing. 3D printing will be 'revolutionary' even if it changes how perhaps 20 per cent of things are manufactured, transported and stored. The key thing for us to try and foresee is therefore just which industrial activities 3D printing is most likely to 'revolutionize', as well as those which are more probable to remain untouched.

The idea that a technological development should be labelled 'revolutionary' if it changes how 20 per cent of things are manufactured, transported and stored is, I think, a very reasonable proposition. Back in 2013, I was also very strongly of the opinion that, within two decades, 3D printing would be used directly or indirectly in the manufacture of about 20 per cent of products. Occasionally in 2014 and 2015 I did start to believe the naysayers and to doubt whether this will actually occur. But the more that I study the development of 3D printing technologies and the 3D printing industry, the more convinced I become of my previous '20 per cent in 20 years' prediction. Today, I am therefore once again staunchly of the view that a 3D printing revolution is on the cards.

There are two reasons that I have cast my doubts aside. Firstly, it is clear that the composition of the 3D printing industry is in transition. For its first few decades the sector was dominated by ‘pure play’ startups – like 3D Systems and Stratasys – who created and brought to market the world’s first 3D printing technologies. Such companies also continue to innovate. Yet they are no longer alone, with very large, traditional manufacturing corporations – including Canon, Groupe Gorgé, HP, Kinpo, Ricoh and Toshiba – now entering or about to enter the fray. These companies are already bringing a great deal of financial and innovative muscle to the table, and will subsequently help to make 3D printing more widely utilized and cost-effective. The fact that all of these firms have chosen to enter the marketplace *since 2013* also has to signal their belief in a large and profitable near-future 3D printing industry.

The second reason for my rekindled faith is the continued invention of new technologies. Not least, in May 2016 a 3D printing method called nanoparticle jetting (NPJ) was showcased by Israeli pioneer XJet. As we shall see in chapter 2, this can directly produce highly accurate metal parts via an inkjet-style process. Nanoparticle jetting may therefore prove transformative in the low-run production of certain metal components. Even more significantly, the very recent announcement of nanoparticle jetting ought to provide a powerful reminder that the 3D Printing Revolution is likely to be based, at least in part, on technologies and processes that are yet to be invented. There are going to be many more watershed innovations in the next 20 years.

In 1939 the first TV sets to go on sale in the United States were showcased at the World Fair in New York. These early TVs cost between $200 and $600 (or about the same as an automobile), and had rather fuzzy, five inch, black-and-white screens. Most of those who attended the World Fair subsequently dismissed television as a fad that would never catch on. After all, how many people could reasonably be expected to spend a large proportion of their time staring at a tiny, flickering image?

The mistake made by those who dismissed television in 1939 was to judge a revolutionary technology on the basis of its earliest manifestation. Over 75 years later, those who believe that 3D printing has been over-hyped are in danger of making exactly the same error. Current 3D printing methods are certainly far too niche, too slow and too costly to change the world. But this will not stop next generation technologies from transforming the manufacturing landscape.

With this last point firmly in mind, the goal of this book is to explain the practicalities and potential of 3D printing both today and in the future. From the outset, I am unashamedly assuming that 3D printing will help to drive a revolution in local, on-demand and highly customized manufacturing. Even if you disagree, I trust that you will find my work a valuable guide to the 3D printing industry, its current technologies, and their existing applications. But over the following seven chapters, I hope to more broadly convince you that we stand on the brink of something very special indeed.

Christopher Barnatt,

November 2016.

1. The Revolution Continues

The 3D Printing Revolution is starting to materialize. According to market research group CONTEXT, in 2015 the 500,000th 3D printer was shipped, with the millionth unit expected to be sold in 2017. 3D printing is also just starting to be adopted as an end-use manufacturing technology. For example, in 2016 GE began selling an aircraft engine with 3D printed fuel nozzles, an Atlas V rocket launched into space with 3D printed parts, both Under Armour and New Balance sold small batches of partially-3D-printed sports shoes, and Organovo started to commercially 'bioprint' human kidney tissue. Absolutely the 3D Printing Revolution is in its infancy. But very solid foundations continue to be laid.

Across history there have been many technological revolutions, all of which have progressed through three distinct phases. The first has been that of 'conceptualization', where visions and ideas have been generated that have defined the road ahead. Each technological revolution has then entered a phase of 'realization', during which time apparently impossible ideas have started to be turned into at least some form of operational reality. Finally we have arrived at a phase of 'mass commercialization', where businesses have learnt how to manufacture and operate a new technology in a robust and highly cost-effective manner.

So where does 3D printing sit on the technological revolution continuum? Well, today the idea of using a 3D printer to turn a digital file into a physical object has propagated widely and is well understood. Indeed across disciplines as diverse as engineering, law, economics, business, geography and fine art, there is already much debate concerning the potential implications of being able to routinely share objects across the Internet for 3D printout on demand. Clearly we are a very long way from the day in which personal 3D fabricators may bring capitalism to an end by putting the means of production into the hands of the majority. Yet there can be no doubt that the 3D Printing Revolution has already been rigorously *conceptualized*.

Further, we have already invented a fairly wide range of methods for fabricating solid objects by printing them out in many thin, successive layers. In fact, the most established 3D printing technologies have been around for decades. The 3D Printing Revolution is therefore making at least some progress when it comes to its practical *realization*.

While 3D printing continues to advance, I would contend that it is still at least ten years away from its final revolutionary phase of *mass commercialization*. Granted, as we shall see across this book, 3D printing pioneers are now using the technology to fabricate all kinds of things. Yet right now – at least as an end-use manufacturing process – 3D printing remains limited in its commercial application to a few niche markets. Specifically, these are sectors that are prepared to pay a premium to engage in low-run, customized or personalized production, or to manufacture items that cannot be made using traditional methods.

The above point noted, we should remember that a decade ago no industrial sector was reporting the sale of final products made in whole or part using a 3D printer. The fact that this is now occurring in *any* marketplace is therefore impressive. As new 3D printing methods are developed, and as older processes become faster and cheaper, we should therefore expect 3D printing to accelerate toward mass commercialization in the late 2020s or early 2030s. The most innovative pioneers are also set to take advantage of 3D printing well before that.

3D PRINTING TECHNOLOGIES

So how, you may be wondering, does 3D printing actually work? Well, to a large extent, the processes involved are no more than a logical evolution of the 2D printing technologies already in use in a great many offices and homes.

Most people are familiar with the inkjet or laser printers that produce most of today's documents or photographs. These create text or images by controlling the placement of ink or toner on the surface of a piece of paper. In a similar fashion, 3D printers fabricate objects by controlling the placement and adhesion of successive layers of a 'build material' in 3D space. It is indeed for this reason that 3D printing is also known as 'additive layer manufacturing' (ALM) or 'additive manufacturing' (AM).

To 3D print an object, a digital model first needs to exist in a computer. This may be created using a computer aided design (CAD) application, or some other variety of 3D modelling software. Alternatively, a digital model may be captured by scanning a real object with a 3D scanner, or derived from a 3D scan that is later manipulated with CAD or other software tools.

Regardless of how a digital model comes into existence, once it is ready to be fabricated it needs to be put through some 'slicing software' that will divide it into a great many cross sectional layers that are typically about 0.1 mm thick. These digital slivers are then sent to a 3D printer that fabricates them, one on top of the other, until they are built up into a complete 3D printed object. Figure 1.1 illustrates a 3D model in the popular, open-source slicing software Cura, while figure 1.2 shows the same model being fabricated on an Ultimaker 2 desktop 3D printer.

Figure 1.1: A 3D Model in the Cura Slicing Application.

Figure 1.2: 3D Printing on an Ultimaker 2.

Exactly how a 3D printer outputs an object one thin layer at a time depends on the particular technology on which it is based. As I shall explain in depth in chapter 2, already there are a great many 3D printing technologies. This said, most of them work in one of four basic ways.

Firstly, there are 3D printers that create objects by extruding a molten or otherwise semi-liquid material from a print head nozzle. Most commonly this involves extruding a molten thermoplastic that very rapidly sets after it has left the print head. Other extrusion-based 3D printers manufacture objects by outputting molten metal, or by extruding chocolate or cake frosting (icing) to 3D print culinary creations. There are also 3D printers that extrude concrete, a ceramic paste or clay.

A second category of 3D printer creates object layers by selectively solidifying a liquid resin – known as a 'photopolymer' – that hardens when exposed to a laser or other light source. Some such 'photopolymerization' 3D printers build object layers within a tank of liquid. Meanwhile others jet a single layer of resin from a print head and use ultraviolet light to set it solid before the next layer is added. A few of the 3D printers based on the latter technology are able to mix several different photopolymers in the same print job, so allowing them to output colour objects made from multiple materials. Most notably, the latest such 3D printer – the J750 from Stratasys – offers a palette of 360,000 colour shades, and can fabricate objects in a mix of different materials including 'rubber-like' and 'digital ABS'.

A third and very broad category of 3D printing hardware builds object layers by selectively sticking together the granules of a very fine powder. Such 'granular materials binding' can be achieved by jetting an adhesive onto successive powder layers, or by fusing powder granules together using a laser or other heat source. Various forms of powder adhesion are already commonly used to 3D print in a wide range of materials. These include nylon, wax, bronze, stainless steel, cobalt chrome and titanium.

A final category of 3D printer is based on lamination. Here, successive layers of cut paper, metal or plastic are stuck together to build up a solid object. Where sheets of paper are used as the build material, they are cut by blade or laser and glued together. They may also be sprayed with multiple inks during the printing process to create low-cost, full-colour 3D printed objects.

MARKETS & APPLICATIONS

3D printing is already being used to build product prototypes, to make molds and other industrial tooling, for the 'direct digital manufacture' of final products, and for personal fabrication. This means that hardware, software and material suppliers within the 3D printing industry are already serving the needs of four different market sectors. To truly appreciate the forces driving the 3D Printing Revolution, an understanding of the four different areas of 3D printing application is therefore required.

RAPID PROTOTYPING

Today, 3D printers are most commonly used for rapid prototyping (RP). This is where the hardware is employed to create either concept models or functional prototypes. Concept models are usually fairly basic, non-functional printouts of a new product design (for example a shampoo bottle without a removable top), and are intended to allow designers to communicate their ideas in a physical format. In contrast, functional prototypes are more sophisticated, and allow the form, fit and function of each product part to be accurately assessed before committing to production.

Traditionally, prototypes and concept models have been created by skilled craftspeople using labour-intensive workshop techniques. It is therefore not uncommon for them to take many days, weeks or even months to produce, and to cost thousands or tens of thousands of dollars, pounds, euro or yen. In contrast, 3D printers can now produce concept models and functional prototypes in a few days or even a few hours for a fraction of the price of traditional methods. Industries that make extensive use of 3D printing to create prototypes include automobile manufacture and Formula 1.

In addition to saving time and money, the 3D printing of prototypes allows improved final products to be brought to market, as designs can evolve through a great many iterations. For example, vacuum flask manufacturer Thermos now uses Stratasys 3D printers to make its own prototypes in hours rather than days, and for a fifth of the cost of outsourcing their production to an external vendor. Because its designers are now free to 'make as many prototypes as they need', the company has been able to optimize product features such as cap-fit and pouring performance.

As capabilities to 3D print in colour, in multiple materials, and in metals, continue to improve, so the range and quality of products and components that can be rapidly prototyped continues to expand. As illustrated in figure 1.3, a company called Nano Dimension has even showcased a new desktop 3D printer – the DragonFly 2020 – that can fabricate functional, prototype 3D printed circuit boards. This amazing hardware uses an inkjet technology to output highly conductive 'nano-inks', and can produce multilayer boards, including all interconnections between layers. While currently many companies wait many days or weeks to obtain a prototype circuit board from an external vendor, the

DragonFly 2020 can 3D print one in a matter of hours.

Figure 1.3: The DragonFly 2020 Circuit Board 3D Printer.
Image courtesy of Nano Dimension.

PRODUCING MOLDS & OTHER TOOLING

In addition to rapid prototypes, 3D printers are increasingly being used to make molds, jigs, fixtures and other production tooling. Most production processes require such items to be created in order to fashion metals or plastics into final product parts. Like product prototypes, molds and other production tooling have traditionally been painstakingly crafted by hand. The use of 3D printers to help tool-up factories for traditional production may therefore save a great deal of time and money. For example, by employing Stratasys Fortus 3D printers, Volvo Trucks in Lyon, France have reduced the time required to manufacture some of their engine assembly tools from 36 days to 2 days.

Equally demonstrating the extraordinary potential, in August 2016 the Oak Ridge National Laboratory in the United States 3D printed a 5.34 x 1.34 x 0.46 m (17.5 x 4.4 x 1.5 foot) trim-and-drill tool for Boeing. This will be used during the construction of the aircraft manufacturer’s forthcoming 777X passenger jets, and was 3D printed in a carbon fiber reinforced plastic in about 30 hours. In contrast, the existing metallic tooling option for the part would have taken three months to manufacture. As Boeing’s Leo Christodoulou explained, ‘additively manufactured tools, such as the 777X wing trim tool, will save energy, time, labor and production cost and are part of our overall strategy to apply 3D printing technology in key production areas’.

Another particularly promising application is in the production of the molds used in traditional metal casting. Here 3D printers can directly produce the required molds, as well as any of the additional ‘core’ shapes required to fit inside them, by laying down thin layers of casting sand that are then selectively sprayed with a binder. The resultant 3D printouts are taken to a foundry, where molten metal is poured in to produce final components.

One of the companies that specializes in making 3D printers that additively manufacture in casting sand is ExOne. As they report, by 3D printing sand cast molds and cores, manufacturers can not only save time and reduce costs, but may also improve accuracy and cast more intricate parts. This is because the production of 3D printed molds and cores does not depend on packing sand around a physical ‘pattern’, which then needs to be removed without inflicting damage. Figure 1.4 shows a sand casting core produced on an ExOne 3D printer.

Figure 1.4: A 3D Printed Sand Casting Core.

3D printers can now also be used to fabricate the molds used to injection-mold plastic parts. Such molds typically cost tens of thousands of dollars, and are traditionally machined from aluminium. Technically, it is now possible to make aluminium injection molds using a direct metal, powder-based 3D printer. However, at least at present, 3D printers are more commonly used to make low-run injection molds from resin using photopolymerization hardware. Resin molds are inevitably not as hard-wearing as their aluminium counterparts. They are, however, cheaper and quicker to fabricate, and may be used to produce up to about 200 plastic parts before they need to be replaced. Figure 1.5 shows a two-part, 3D printed resin injection mold created on a Stratasys 3D printer.

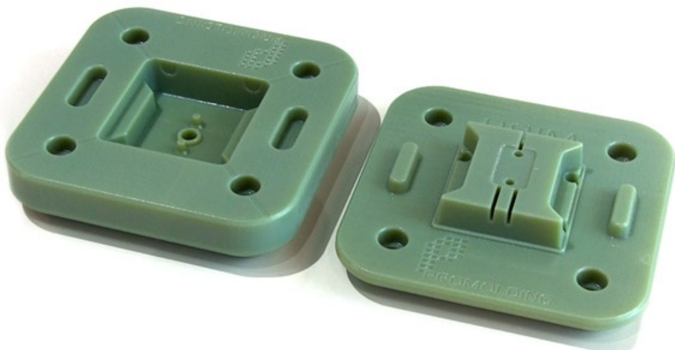

Figure 1.5: A 3D Printed Resin Injection Mold.

Just one company now benefitting from the ability to 3D print low-run, resin injection molds is Bi-Link, based in Bloomingdale, Illinois, which makes parts for electronics and medical manufacturers around the world. Here a ProJet 3500 HD Max 3D printer from 3D Systems is used to make molds in hours rather than weeks. As noted by R&D Director

Frank Ziberna, 'customers love this service. They would typically have to wait two to three weeks to get just tooling, never mind test parts. With the ProJet 3500 HD Max we made one customer four different part designs over the course of six days, shipping them 10-12 [injection-molded] parts for each iteration overnight'.

Several manufacturers now also produce 3D printers that can build objects in wax (or wax substitutes) in order to create patterns for lost-wax casting. Here, a wax object is 3D printed, and a mold is formed around it using a material such as plaster. The mold is then heated, which causes the wax to 'burnout' and drain away. Molten metal, or another liquid casting material, is subsequently poured into the mold to produce the final item. Using 3D printers to make lost-wax patterns is now fairly common in jewelry making and other industries in which small, intricate, high-priced objects need to be manufactured. Like sand cast molds, lost-wax 3D printed patterns are 'sacrificial', as the process of producing a final object from them results in their destruction.

DIRECT DIGITAL MANUFACTURING

As I showcased at the start of this chapter, in a few niche markets 3D printers are already being used to manufacture end-use industrial components and even final consumer products. This exciting development is increasingly referred to as 'direct digital manufacturing' (DDM), and is gaining significant traction in aviation in particular. Indeed, as we shall see in chapter 4, Airbus, Boeing and GE have now collectively installed tens of thousands of 3D printed aircraft components.

Other sectors at the forefront of DDM include automobile manufacture, medicine, jewelry making, and the production of specialist footwear. Here one of the leading pioneers is Nike, which in October 2015 announced that it was 'turbo charging' its 3D printing efforts. Indeed, to cite Chief Operating Officer Eric Sprunk, Nike has 'made a series of design and manufacturing discoveries with 3D printing that we believe will allow us to deliver a completely new, personal, performance cushioning system'. To this end, a 125,000-square-foot Advanced Product Creation Center is being built at Nike's headquarters to house 3D printing and other advanced design and manufacturing technologies.

In the future, it is possible that almost anything could be manufactured using a 3D printer, and that even includes replacement parts for ourselves. Most prominently at present, dentistry is 'going digital', with wax-ups, orthodontic appliances, try-ins, surgical guides and veneer models now routinely 3D printed.

Beyond the creation of inorganic prosthesis, there are already also specialist 3D printers that can build up human tissue by laying down layer-after-layer of living cells. Such 'bioprinters' have the potential to transform many areas of medicine, and may cut organ donor waiting lists to zero. Already a bioprinting pioneer called Organovo is selling bioprinted human liver and human kidney tissues as commercial products for use in drug testing.

In addition to 3D printing human tissues outside of the body, *in vivo* bioprinting is also in development. This involves 3D printing layers of cultured cells directly onto a wound, or even inside the body using keyhole surgery techniques. Should this kind of technology become advanced enough, one day instruments may be able to be inserted into a patient that will remove damaged cells and replace them with new ones. Such instruments may even be able to repair the wound created by their own insertion on their way out. I will explore bioprinting in depth in chapter 6.

PERSONAL FABRICATION

In parallel with the growth of industrial 3D printing, we are starting to witness the rise of personal fabrication. This refers to all situations in which individual 'makers' 3D print their own stuff, so by-passing the need for everything they own to have started life in a distant factory. As we shall see in chapter 5, already there are several hundred personal and prosumer 3D printers on the market, with prices starting at around $230.

In addition to the growing number of personal 3D printers, there is also an increasing provision of free or for-a-fee 3D models that can be downloaded for personal printout. Chief among the providers of free content is Thingiverse, which hosts over a million 3D objects, some of which can be customized to user specification. The provision of online 3D content is likely to be key to any mass uptake of personal fabrication, as it removes the need for all makers to possess a raft of creative, CAD and engineering skills.

Right now, personal and prosumer 3D printers are limited to fabricating objects in thermoplastics, thermoplastic composites and sometimes photocurable resins. The range and quality of items that can be personally fabricated on such hardware therefore remains limited. This said, an increasing number of 3D printing services – such as Shapeways and i.materialise – now allow anybody to upload a 3D object that they will 3D print for them on industrial hardware. Over the next five-to-ten years, it is also likely to be the broadening availability of such 3D printing services – and not the sale of personal 3D printers – that will drive any revolution in personal manufacturing.

If a reasonable proportion of people do start to fabricate some of their own possessions, the impact on some industries could be very significant. Not least companies that trade in spare parts are already starting to take the threat of mass personal fabrication extremely seriously. So too are those in the logistics and transport sector who may experience a change in demand for their services.

In an attempt to map out the road ahead, in 2014 the IBM Institute for Business Value published an Executive Report that highlighted four distinctly different futures for personal fabrication. These it encapsulated in a 2x2 matrix, which I reproduce in an adapted and augmented format in figure 1.6.

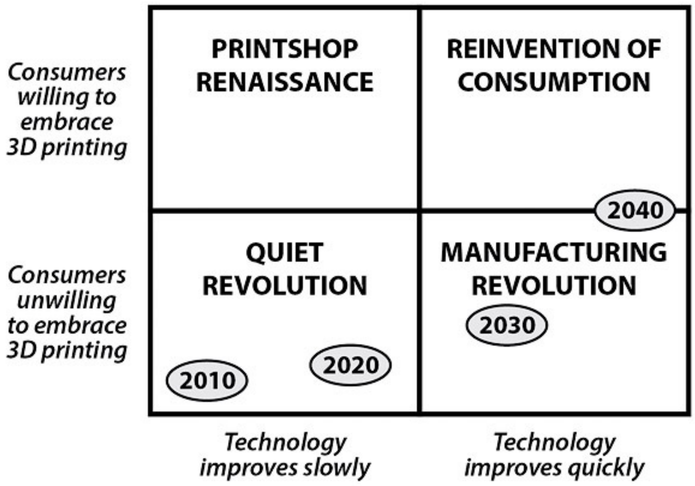

Figure 1.6: The Future of Personal Fabrication.
Adapted from IBM Institute for Business Value (2014).
Date augmentations by Christopher Barnatt.

As the figure suggests, the two great unknowns (which constitute the two axes of the matrix) are the speed at which 3D printing technology will develop, and the willingness of end consumers to embrace personal fabrication. To work through the possible scenarios, if technology improves slowly and end-consumers are unwilling to embrace 3D printing in the home, then we will see little more than a 'quiet revolution' with only incremental change. Alternatively, if technology improves slowly but many end-consumers are keen to become makers, then we will see a 'print shop renaissance', with an increasing number of our possessions personally-fabricated by a bureau service.

Looking to the right side of the matrix, if 3D printing technology improves rapidly but consumers remain ambivalent, then 3D printing will become a major industrial manufacturing technology, but will have little impact on the consumer marketplace. Finally, if 3D printing technology improves rapidly and end-consumers choose to engage with it in significant numbers, then we will witness the 'reinvention of consumption'. This means that we would see retailers large and small offering products 3D printed on demand, as well as many people 3D printing their own stuff in their kitchens, dens, garages, offices and sheds.

Right now, my hunch is that end-consumer engagement with 3D printing will rise in step with technological improvement, if at a slower rate. This means that, over the next few decades, we may progress from IBM's 'quiet revolution', across into a 'manufacturing revolution', and up into a 'reinvention of consumption' as I have indicated in the diagram.

3D PRINTING INDUSTRY DEVELOPMENT

Staying with the theme of how the 3D Printing Revolution may potentially unfold, it is important to appreciate not just the existence of the 3D printing industry's four, distinct market segments, but also the fact that they are all in very different stages of development. To highlight this frequently ignored reality, figure 1.7 plots four curves that are indicative of the different rates of 3D printing adoption for rapid prototyping, the production of molds and other tooling, direct digital manufacturing, and personal fabrication. As you will see, each adoption curve conforms to a well understood pattern in which use rises exponentially from zero, achieves consistent growth, and then falls away as application approaches market saturation.

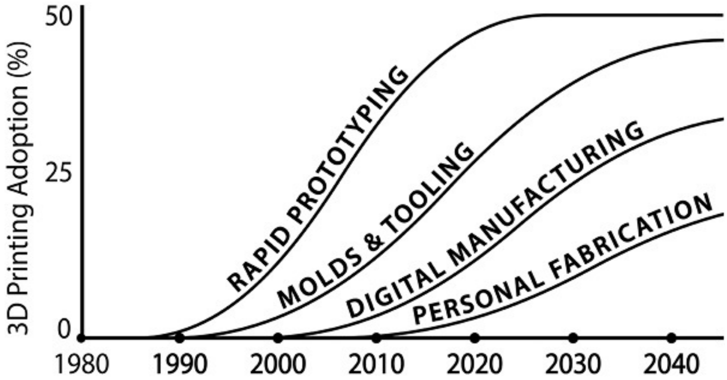

Figure 1.7: 3D Printing Adoption Curves.

The adoption curves plotted in the figure are based on my own industry analysis, and are intended to assist our understanding of likely 3D printing development. Not least, they remind us that while the very first 3D printers started to be used to make product prototypes in the late 1980s, the use of 3D printing to create molds and other tooling did not commence until a few years after that. It was then not until the turn of the millennium that anybody started to make end-use components or works of art using 3D printers. Finally, personal fabrication only became a possibility around 2007 with the development of the first ‘open source’ 3D printers that private individuals could afford to own.

As figure 1.7 suggests, my personal best-guess is that by mid-next-decade, the traditional 3D printing market segment of rapid prototyping will saturate, with maybe half of all concept models and prototypes being 3D printed by 2025. Some may question why I have this adoption curve maxing out at 50 per cent market penetration. But I think this is realistic for two reasons. Firstly, 3D printing is not the only rapid prototyping technology. And secondly, there will always be instances where traditional methods will remain the most appropriate for prototype production. I simply cannot imagine a time when inventors will stop mocking things up out of bits of wood, card, metal, clay, and anything else they happen to have to hand in their studios, labs, workshops, sheds or kitchens.

Turning to the 3D printing of molds and other tooling, this market currently lags behind rapid prototyping, but is set to become a mainstay of additive manufacturing very soon indeed. As figure 1.7 indicates, my prediction is that it will take decades for this market to saturate. Talk to industrial 3D printer manufacturers, and they are also well aware of this. Right now, in most industries, the 3D printing of molds and other tooling represents the largest market opportunity.

Moving on to direct digital manufacturing, as we have already seen this is just starting to take place, if currently as a very niche activity. However, in the next ten years or so, many industries – most notably including aerospace, the automotive sector, healthcare, fashion, footwear and designer goods – are set to embrace 3D printing as one of their core manufacturing technologies. This will undoubtedly allow entirely new kinds of products to be created, and will garner popular media attention. Even so, in 10 or 20 years time, the vast majority of the objects in our lives will still be produced via traditional methods, if often using 3D printed molds, jigs and other tooling.

In a similar fashion, for many decades personal fabrication will remain a niche if fascinating market segment, and a small proportion of both the 3D printing industry and total global manufacturing. Right now, no more than 10 per cent of 3D printing industry revenues are generated via the sale of personal 3D printers. Many such printers are also sold to companies, not individuals. This is not to suggest that the sale of personal 3D printers for use in the home does not represent a significant market opportunity, with the annual global sale of around 500,000 consumer-grade 3D printers by 2020 being a very reasonable prediction. But this point noted, by 2020 the average personal 3D printer will probably cost under $1,000, so making the annual sale of 500,000 units worth less than $500 million. This means that, by 2020, personal 3D printing will account for no more than a few per cent of a global 3D printing market that will probably be worth well in excess of $10 billion, and perhaps as much as $20 billion.

Due to the above, I feel very safe in my prediction that domestic personal fabrication is not going to be the driving force behind the 3D Printing Revolution – and I do not know a serious industry participant who does not agree with me on this one. I am, nevertheless, very much looking forward to the $99 3D printers that will be on the market by 2020, and which will be able to fabricate small, plastic objects beamed to them from a tablet or smartphone.

MAKING NEW THINGS IN NEW WAYS

Just like the Internet Revolution that preceded it, the 3D Printing Revolution will increasingly allow both companies and individuals to achieve the previously impossible. This is because 3D printing will enable us not just to prototype and manufacture old things in new ways, but to create and deliver new products in new ways according to radically new business models. Just how this will happen is in effect the subject of chapters 3 to 7 of this book. But before we get there, it is worth signalling those key opportunities that I have not yet highlighted in this chapter.

ONE-OFF & LOW-RUN PRODUCTION

Using traditional manufacturing methods, one-off or low-run production is usually very expensive, and often prohibitively so. In contrast, when things are 3D printed there is virtually no cost difference per item between making 1 or 100 or 1,000 copies of a component, as there are no tooling costs and few if any learning curves for production workers to climb. In many situations where a few hundred or less components are required, 3D printing is therefore already the most cost effective means of manufacturing, and often the *only* cost effective option. It is indeed for this reason that 3D printing has such a high level of adoption in rapid prototyping, and is finding increasing application in the production of molds and other tooling.

Already availing himself of 3D printing for one-off production is classic car enthusiast Jay Leno. As just one example, when some broken vents needed replacing on Jay's rare EcoJet concept car, he turned to 3D Systems who scanned the broken parts, mended them digitally in CAD software, and sent the resultant data to their Quickparts service provider. Here new vents were 3D printed in a lightweight, fiber-filled nylon material called DuraForm HST. This resulted in robust replacement parts that had a better strength-to-weight ratio than the broken originals.

Others using 3D printing for one-off or small batch production include those who make props for TV, film and theatre productions, SpaceX (who are 3D printing the engine chambers for their new Crew Dragon spacecraft), and NASA, who have 3D printed about 70 parts for their experimental human Mars rover.

CUSTOMIZATION & PERSONALIZATION

In addition to facilitating the small batch production of identical things, 3D printing is already allowing products to be both customized in accordance with their purchaser's tastes, and personalized to match an individual's physical requirements. For example, the Robot Bike Co. now use 3D printing to help them manufacture their custom-fit R160 mountain bike frame. This is made from carbon fibre tubing that extends between titanium lugs that are additively manufactured on Renishaw 3D printers. Over on Robotbike.co, purchasers enter their height, inside leg and arm span measurements, which enables a custom-fit frame to be produced.

The R160 is a great example of a real product that combines custom 3D printed parts with other standard components in order to deliver a product to individual specification in a cost-effective manner. In time, I am certain that many other manufacturers will realize the potential to create bespoke products by 3D printing certain key parts. The more you think about it, the possibilities are very significant indeed.

OPTIMIZING DESIGN & ASSEMBLY

Another key benefit of 3D printing is that it relaxes the inevitable and long-standing constraints of traditional production methods. Today, while a designer can come up with any design they like, if its components cannot be cast, molded, machined and assembled, the product will never arrive on the market. But in the Brave New World of 3D printing, it is now possible to make things that were previously impossible to manufacture. For example, a 3D printer can make a chain or necklace made up of links that do not have a break in them, and which will therefore never come apart at a seam.

Highlighting the potential, a MotoGP World Championship motorcycle racing team called TransFIORmers have used a Renishaw direct-metal 3D printer to fabricate a new wishbone suspension with an optimized design. The original component was hand-fabricated in steel, with assembly requiring twelve separately machined parts to be welded together. But using 3D printing, TransFIORmers were able to consolidate their design into a single titanium component that required no assembly, and which resulted in a performance-critical 40 per cent weight reduction.

Using plastic or resin build materials, some 3D printers can even create working, pre-assembled, multipart mechanisms like gearboxes. Traditionally, the manufacture of multi-component products has had to involve a final assembly stage. But when things are 3D printed this no longer has to remain the case.

DEMOCRATIZING ACCESS TO MARKET

In addition to improving the characteristics of the products that people purchase, 3D printing will additionally allow far more of us to actually become manufacturers. In part this is because the cost of making prototypes and production tooling will no longer prove prohibitive, with 3D printing making low-run production an increasingly viable proposition. Yet even more fundamentally, the increasing availability of 3D printing service bureaus will allow almost any talented artist or designer to find a market for their creations.

Today, it is very difficult for a private individual or even a small company to bring a product to market, let alone on a global scale. One of the few exceptions is in the world of book publishing, where a sole author – like myself – can create and distribute a product that is printed-on-demand. If, for example, you are reading this book in hardcopy, then you are currently holding a product that was printed in an Amazon warehouse within eight hours of it being ordered. This amazing innovation allows me to sell books worldwide without having to pre-print and distribute stock in the traditional manner.

In a similar fashion, 3D printing is starting to allow individual designers to bring products to market with no investment in capital equipment or stock. For example, over 8,000 designers have now opened a store via the website of the 3D printing service provider Shapeways. Just one of these is a self-described ‘bot maker, guerrilla product developer [and] newbie modeller’ who goes by the name of Kidmechano. His particular creation is ‘Modibots’, which is an ever-expanding range of highly poseable 3D-printed action figures with a snap-fit, ball joint construction. You can think of Modibots as a form of transformer-style, character building Lego.

Kidmechano uses the Shapeways platform to sell over 400 ModiBot figures and accessories, with these including a wide array of armour, weapons and stands. Prices start from a few dollars, and when an order is placed Shapeways 3D print whatever is required, ship the printouts to the purchaser, and provide Kidmechano with his share of the proceeds. Others using Shapeways to market, manufacture and ship their wares include the sculptress Bathsheba Grossman, who I interview in some depth in chapter 4.

DIGITAL STORAGE & TRANSPORTATION

As well as enabling low-run production, mass customization, and democratizing access to market, 3D printing will facilitate digital object storage and digital object transportation. What this means is that if, in the future, you want to send something to somebody far away, you will have two options. The first will be to despatch the physical item via courier or mail, while the second will be to send a digital file over the Internet for 3D printout at the recipient's location.

Many people now regularly share text, photos and video online, and thanks to 3D printing, digital objects will soon be added to many social media collections. By making possible online storage and transportation, 3D printing is therefore set to do for physical things what computers and the Internet have already done for the storage and communication of digital information.

In some industries, digital object storage is already starting to prove advantageous. Most dentists, for example, have traditionally had to store a great many plaster casts taken from impressions of their patient's mouths. While the vast majority of these have only ever been used once, there has been no way to predict which may be required for future reference, so leading to boxes and cabinets piled high with plaster models. But now dentists are going digital, with 3D scanners and 3D printers replacing alginate mold making materials and plaster casting. In turn, this is starting to allow impressions of patient's mouths to be stored digitally for future 3D printout only if required.

MATERIAL SAVINGS & SUSTAINABILITY

In addition to all of the aforementioned opportunities, some of the greatest benefits of 3D printing arise from material savings and the broader sustainability agenda. Today, a great deal of manufacturing is a subtractive process. In other words, factories start with a block of metal or another raw material, and then cut, lathe, file, drill or otherwise remove bits from it in order to fashion a final component. In contrast, 3D printing is an additive activity that starts with nothing and adds only the material that the final part requires. As a consequence, when things are fabricated using 3D printers it is possible to obtain very substantial raw material savings.

In addition, 3D printed products can feature internal structures that are optimized to consume the minimum of materials. 3D printed plastic or metal parts can, for example, be fabricated with internal air gaps or open lattice work that cannot exist inside an object produced using many traditional production techniques. This again can result in material savings, as well as the creation of lighter parts that can be used to make aircraft and other vehicles more fuel efficient.

More broadly, 3D printing may turn out to be the cornerstone of a future transition toward 'local digital manufacturing' (LDM). Today, a great deal of manufacturing takes place in factories that are far removed from most customers. As a consequence, vast quantities of oil and other resources are used to move products around the planet, with many goods spending the majority of their lives in transportation and storage. Given the increasing pressure on natural resource supplies – coupled with measures to try and mitigate climate change – within a decade or two such mass transportation and storage may be neither feasible nor culturally acceptable. Pressures to improve sustainability could therefore turn out to be the greatest force that will drive the mainstream adoption of 3D printing, as the technology will increasingly assist in the production of products on a far more local basis.

CHALLENGES AHEAD?

Like any new technology, 3D printing has the potential to be highly disruptive in negative as well as positive ways. Not least, there are already concerns that the further development of 3D printing will destroy manufacturing jobs. For those in some occupations this is indeed very likely to be the case, with employment certainly under threat for those who currently produce prototypes, molds and tooling via traditional methods.

Employment in nations who currently mass manufacture products for export is also likely to be reduced as and when 3D printing starts to facilitate more local production. Indeed, in his 2013 State of the Union address, President Obama highlighted 3D printing as the technology with 'the potential to revolutionize how we make almost everything', and in a manner that would bring manufacturing jobs back from Asia to the United States. Make no mistake, the global economic implications of 3D printing have already been recognized at the government level.

The above points noted, and in common with previous revolutionary technologies, 3D printing is likely to create new employment opportunities. It is going to be a very long time indeed before we can 3D print final products without significant, skilled human intervention. New kinds of manufacturing jobs will therefore be created as the 3D Printing Revolution takes hold, and such employment is likely to be fairly evenly spread across nations and their regions in a manner uncharacteristic of previous manufacturing revolutions.

Some non-manufacturing industries are also likely to benefit from the rise of 3D printing. Not least, parts of the logistics sector have started to recognize significant opportunities. For example, in July 2014 the Office of the Inspector General of the US Postal Service published a White Paper in which it noted that the postal service could 'benefit tremendously' from the rise of 3D printing due to an anticipated increase in the last-mile delivery of small packages. Specifically, the White Paper forecast that 3D printing could result in its local parcel delivery service experiencing revenue increases of $486 million every year. This projection was based on the proposition that most 3D printed goods will be manufactured in relatively local service bureaus, from where they will need transporting to people's homes.

Beyond the impact on employment, two other challenges are intellectual property infringement and the use of 3D printing for criminal purposes. Already it is possible to use consumer hardware to scan an object – for example a model of Mickey Mouse – and to 3D print a plastic replica. Just as mp3 files and the Internet had a massive impact on the music industry, so 3D printing looks set to alter how future intellectual property rights may or may not be defended.

More worryingly, it is already possible to 3D print working weapons. At present, a $230 personal 3D printer can only make a single-use plastic gun. But when it becomes possible to domestically 3D print in metal, we may have a significant problem on our hands.

A final and potentially massive minefield associated with 3D printing and personal fabrication is health and safety. Today, almost all of the products we purchase are subject to strict production standards and testing, with manufacturers held liable for any accidents and injuries that arise if their products inappropriately break or malfunction. But who would be liable if, for example, your son or daughter downloaded a free toy from a social media website, printed it out, gave it to a friend, a part broke off, and the second child choked on the broken-off part and died? Would fault lie with the person who designed the object (possibly also a child), the social media website via which it was shared, the manufacturer of your 3D printer, the supplier of your printing consumables, or even yourself as the parent of the maker of a dangerous item? There is currently no good answer to this question. Yet it is the kind of conundrum that we will fairly soon be unable to ignore.

IN THE WORDS OF PIONEERS

The 3D Printing Revolution is – like any other – the product of the actions, energies and visions of those people who are brave enough to make it happen. Over the past few years I have had the privilege to interview many such pioneers, and throughout this book I will divulge what they have told me and exactly what they are accomplishing. But right now, in this chapter, my goal is to capture your imagination rather than to focus on too many details and practicalities (we do, after all, have the rest of the book for that). So, as we head toward the end of this introductory chapter, I thought I would report the responses of just a few 3D printing pioneers when I asked them the fundamental question ‘why 3D print?’.

One of the first people I spoke to was Anssi Mustonen, who runs a 3D printing and design company in Finland called AMD-TEC. For Anssi, the reason to 3D print is to allow customer service to be maintained. As he explained:

> We live in a hectic world and for me 3D printing is almost the only way to serve my clients as well as I can. For prototyping I don’t have time to program [CNC machines] and I don’t have time to send quotations to machining companies to get parts. 3D printing is not the only way to make parts, but it’s faster when creating complex shapes and configurations than traditional methods.

Constantine Ivanov is the co-founder and CEO of 3DPrintus.ru in Russia, and told me how 3D printing is allowing him to deliver radically new kinds of products and services. As he enthused:

> 3D printing allows us to deliver solutions that are at a crossroads between

> manufacturing and the digital technology of the Internet. Our customers are discovering how easy it is to create and produce almost anything. I'm sure that the most important benefit for customers is the opportunity to use a simple interface to obtain a personalized product.

Over in the UK, Gary Miller – Managing Director of the 3D Print Bureau – told a similar story, if one tinged with a realistic note of caution. To quote Gary:

> We should 3D print because it's quicker – lead times are reduced – and we can achieve any geometry, almost! I started [using Objet 3D printers] over ten years ago, [and then] I had one material. The years have passed and now I've got over 2,000 materials to print with. So just imagine where we'll be in ten years' time. This said, however many materials you have, it's about placing those materials in the right hands. It's up to users to find the right applications. We need to keep expectations level, because the hype is too much. People need to use their expertise in their industry to find where the applications are right, and where it will add value and make their lives easier.
>
> A few years ago I was sceptical that 3D Printing would move into manufacturing, [but] in the first half of 2016 we have seen movement and increased orders for manufacturing. It's exciting to see where 3D Printing moves to next and what materials develop.

One of the most interesting, formal conversations I have ever had about 3D printing was with Jon Cobb, who is the Executive Vice President of Corporate Affairs for 3D printing giant Stratasys in the United States. Soon after we started talking, Jon focused in on the potential of 3D printing to change product design and distribution:

> So much of the emphasis with 3D printing is about adapting it to our traditional manufacturing processes, and to me it's really more about changing the fundamentals of design, which then allows you to change the way products are manufactured, and then that really starts to effect distribution as well. So you may imagine having a plumbing problem at home. And you take a picture of it on your iPhone, you send the problem to Home Depot, and then you walk in an hour or two later to collect a custom part that you didn't have to go through a wide variety of parts bins to locate. This is maybe two or five years down the road, but you can see it starting to happen.

Miranda Bastijns is Director of the Belgium-based 3D printing service i.materialise, and focused in on new kinds of market opportunity from yet another perspective. As she explained:

> 3D printing helps create a world where the products we buy have a better fit, a better match to one's personal style, and where we all have the ability to own something that is truly unique. For consumers, it is exciting that individuals can now not only create products that better serve their own needs and interests, but also start to sell the result to others like them. For example, a jewelry designer can offer their latest ring to a global audience and test the demand for the design. If

> there are no orders, no problem – and if there are, then the rings will be printed, delivered to the customer, and the designer will receive their share of the profit.

Also recognising the potential of 3D printing to make products with a 'better fit' is Lucy Beard, the founder and 'chief visionary' for Feetz. This is a 'digital cobbler' that is already using 3D printers to make shoes that are individually fabricated-to-measure. As Lucy told me:

> 3D printing is allowing us to change how we make and consume products. In particular, the use of 3D printing means that we can make personalized products sustainably and recycle things more easily.

What Lucy and her team are doing over at Feetz.com really is amazing, and we will look at their work in more depth in chapter 4.

Marc Saunders is the Director of Global Solutions Centres at direct metal 3D printer manufacturer Renishaw. Like Miranda and Lucy, when asked why we should 3D print, he also focused on the opportunities that it can offer to manufacturers. As he explained:

> More and more companies are seeking to exploit the potential … to improve product performance, making products more efficient and better adapted to their application. [The technology's] unique ability to create complex geometries from high performance materials offers huge scope for innovation in both product design and business models. We expect additive manufacturing to play an increasing role in further unlocking process and product improvements to deliver exceptional value.

Finally Sylvain Preumont – the founder and Executive Chairman of the iMakr 3D printer stores and the My Mini Factory 3D content website – noted how 3D printing will free the imagination. As he told me:

> The wide availability of 3D printing will unleash creativity, because people will be able to invent, design and make in almost no time at low cost. They'll also be able to download curated content that is ready to print, and easy to adapt to their own needs and personality. Tomorrow's children will ask "is it true that when you were young you didn't have a 3D printer?"

THE ADDITIVE FRONTIER

As the words of Anssi, Constantine, Gary, Jon, Miranda, Lucy, Marc and Sylvain make very clear, 3D printing continues to evoke a powerful passion among its most ardent pioneers. Following the hype bubble of 2012 and 2013, the 3D printing industry is also stronger than ever before. Not least, since 2013, many large, traditional manufacturers have chosen to *enter* the 3D printing marketplace, and this has to be a very positive signal.

Nobody can tell you the future of 3D printing. Yet I think we now have very strong grounds to believe that it is going to have a radical, transformational impact across many manufacturing sectors. Right now, most 3D prints are still prototypes. But in a lot less than a decade this is no longer going to be the case. Indeed, by 2020, it is highly likely that tens of millions of people will have flown on an aircraft that has 3D printed components, will have been fitted with a 3D printed dental appliance, will have worn a pair of shoes with some 3D printed parts, and will have been 3D scanned and 3D printed as a figurine for somebody's mantlepiece.

My intention in the rest of this book is to explore and explain the world of 3D printing in as down-to-earth a manner as possible. To this end I will be including as many specific examples as I can, with these based on supplier information, case studies, company reports, interviews, and other sources that most people would reasonably consider as 'fact'. Inevitably, I will also offer some of my own insight and opinion, with my primary occupation as a futurist rising to the fore in parts of our last two chapters. But my main intention is to provide you – my valued reader – with as much factual information as possible so that you can decide for yourself whether or not 3D printing really is the next industrial revolution. This said, I do hope that you will end up agreeing with me that it is.

2. 3D Printing Technologies

When a 3D printer is pictured in the mainstream media, it is almost always a desktop consumer device shown fabricating a small, plastic model. This is hardly a surprise, as it is very easy for a newspaper, TV company or YouTube channel to get a shot of such hardware. However, as a result, many people have gained the firm but incorrect impression that 3D printing is far more technologically limited than it actually is. Indeed, cynics frequently tell me that there will never be a 3D Printing Revolution 'because not everything is made out of plastic'.

When I inform such individuals that there are already 3D printers that can additively manufacture not just in thermoplastics, but in composites, metals, resins, ceramics, foodstuffs, casting sand, clay, concrete and living cells, they are usually more than a little surprised. 3D printing is not a single technology, but rather a broad basket of quite distinct if potentially complementary processes.

As I outlined in the last chapter, most 3D printing technologies work in one of four basic ways. Firstly, there are extrusion-based processes that form object layers by outputting a semi-liquid material from a print head nozzle. Secondly, 'photopolymerization' may be used to selectively solidify a liquid resin. Thirdly, there are techniques that bind the particles of a powder. And finally, there are lamination-based approaches that stick together thin sheets of build material. Across this chapter we will explore every current or developmental variant of these four basic types of additive manufacturing. Or, at least, we will cover every single one of them that uses dead build materials, as the 'bioprinting' of living tissue gets a chapter all to itself later in this book.

AVOIDING THE LEXICAL QUAGMIRE

Given what I have just outlined, you may expect this chapter to focus in turn on 3D printing technologies based on extrusion, photopolymerization, powder-binding and lamination. To a reasonable extent, this is also exactly what is going to happen. But sadly life is rarely quite this simple, and so before we begin I do need to throw a complicating spanner into the works.

The problem we face is that the 3D printing industry is awash with a great many patented processes and trademarked technology labels. In writing this chapter, I am therefore presented with a lexical nightmare. Like it or not, for both legal and marketing reasons, individual manufacturers remain intent on using different terms and acronyms to refer to what are effectively the same 3D printing processes. The situation is just like it was in the early days of personal computing, when – for example – some manufacturers marketed their proprietary 'bubble-jet' printers as a distinct alternative to their technologically identical 'inkjet' competitors. Fortunately in personal computing, commentators and customers soon grew weary, and standard terms emerged that all manufacturers adopted. But alas in 3D printing this has yet to happen.

Given the level of confusion that continues to result from many 3D printer manufacturers using different names for the same additive manufacturing processes, over the past five years the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) have developed various standards. The latest of these was introduced in December 2015, is known as ISO/ASTM 52900, and defines seven additive manufacturing process categories. These expand on the four generic build methods that I have already outlined, and are summarized in Exhibit 2.1.

Material Extrusion:	a nozzle extrudes a semi-liquid material to build up successive object layers.
Vat Photopolymerization:	a laser or other light source solidifies successive object layers on the surface or base of a vat of liquid photopolymer.
Material Jetting:	A print head selectively deposits droplets of a liquid build material that is cured or fused solid using UV light or heat, or which solidifies on contact.
Binder Jetting:	a print head selectively sprays a binder onto successive layers of powder.
Powder Bed Fusion:	a laser or other heat source selectively fuses successive layers of powder.
Directed Energy Deposition:	a laser or other heat source fuses a powdered build material as it is being deposited.
Sheet Lamination:	sheets of cut paper, plastic or metal are stuck together.

Exhibit 2.1: 3D Printing Technologies.
Based on ISO/ASTM 52900.

Few major manufacturers currently market their 3D printers under the ISO/ASTM 52900 process categories. Nevertheless, many 3D printer users and purchasers are becoming aware of the need for standardization. Keeping at least one hopeful eye on the future, I will therefore adopt ISO/ASTM 52900 in this chapter, with my technology review presented under its seven generic headings. This said, there are already some technologies that are not ISO/ASTM ‘compliant’, and which I will hence cover right at the end.

MATERIAL EXTRUSION

In terms of hardware units sold, the most common 3D printing technology is ‘material extrusion’. This refers to any process that builds up objects in layers by outputting a semi-liquid material from a computer-controlled nozzle. As we shall see, many different build materials – including concrete, ceramics, chocolate and even metals – can be 3D printed using material extrusion. This said, the most widely extruded materials are plastics –

technically known as thermoplastics – that can be temporarily melted for output through a nozzle.

The material extrusion of thermoplastics was invented by a now-market-leading company called Stratasys that labelled the technology ‘fused deposition modelling’ or ‘FDM’. The term FDM has subsequently become widely used (and misused) to refer to the extrusion of thermoplastics, and even to material extrusion technologies more generally. Stratasys is, however, the only 3D printer manufacturer that can use the labels ‘fused deposition modelling’ and ‘FDM’, as it has them trademarked. Rival 3D printing giant 3D Systems subsequently refers to this technology as ‘plastic jet printing’ (PJP). Other names for the process are ‘fused filament modelling’ (FFM), ‘melted and extruded modelling’ (MEM), ‘fused filament fabrication’ (FFF) or the ‘fused deposition method’. The fact that the latter also happens to bear the acronym FDM is of course a complete coincidence!

Figure 2.1 provides an illustration of material extrusion. Here a spool of build material referred to as ‘filament’ is slowly fed to a print head that is heated to somewhere between 180°C and 250°C. This melts the filament, which is then extruded through a fine nozzle and usually flattened slightly by the print head on its way out.

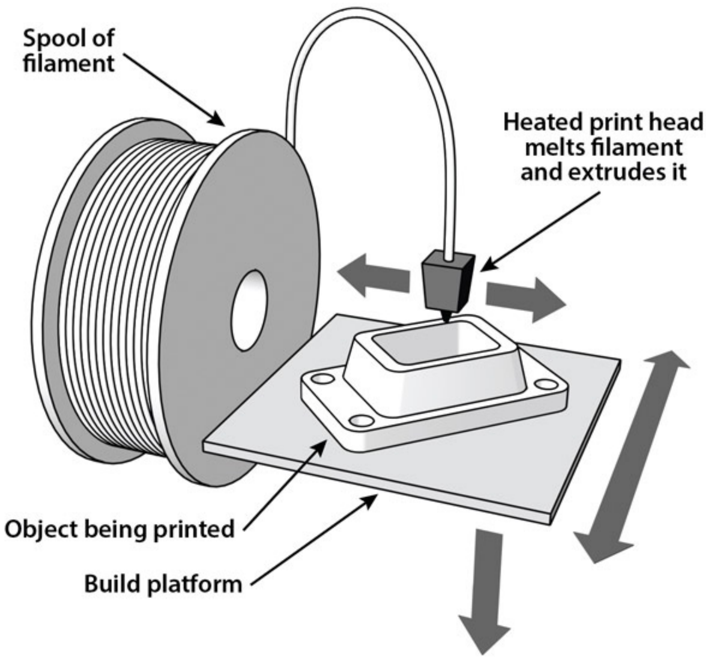

Figure 2.1: Material Extrusion 3D Printing.

Initially, molten filament is deposited directly onto a flat, horizontal surface known as a 3D printer’s ‘build platform’ or ‘print bed’. Here the filament very rapidly cools and solidifies, with the print head moving in 2D space to trace out the first layer of the object being printed. Some material extrusion printers achieve this motion by moving the print head itself on both a North-South and a West-East axis. Alternatively, others slide the print head back-and-forth on one axis, while moving the build platform on the other.

Once the first layer of an object has been traced out, the build platform lowers very slightly and the next layer of filament is deposited on top of it. This process then repeats – usually over a period of many hours – until a complete object has been fabricated. In essence, the whole process is a bit like building up an object with a computer-controlled hot glue gun.

While figure 2.1 illustrates a mechanism with a single nozzle, already multi-nozzle 3D printers are becoming fairly common. Typically these can output two or three materials in the same build, although four nozzle print heads are now on the market. Thermoplastic extrusion 3D printers have even been constructed with 'mixer extruders' that can blend different thermoplastics in a single print head, so allowing them to print plastic objects in full colour.

Most notably, a company called botObjects developed a desktop material extrusion 3D printer with a 5-colour CMYKW cartridge system. In January 2015, botObjects was acquired by 3D Systems, who announced plans to launch a desktop full-colour material extrusion 3D printer called the CubePro C. But, to date, no more than a brochure has been publicly released.

New, hoped-for full-colour hardware aside, 3D printers that extrude thermoplastics are very widely available. Entry-level printers can currently be purchased in kit form from around $200, with fully assembled consumer models starting at around $230 and rising to about $5,000. At the other end of the spectrum, low-end professional thermoplastic extrusion hardware is priced in the $5,000 to $20,000 bracket, with mid-range machines typically costing between about $20,000 and $200,000. This said, very-high-end machines intended for factory use, and called '3D production systems', cost well in excess of $500,000. Figure 2.2 shows several Stratasys Fortus 900mc 3D production systems in an industrial setting.

Figure 2.2 Stratasys Fortus 900mc 3D Production Systems.
Photo courtesy of Stratasys.

Just as 2D printers have a maximum 'print area', so all 3D printers have a 'build envelope' or 'build volume' that determines the largest object they can print. On personal hardware, build volumes typically start at around 100 x 100 x 100 mm (or about 4 x 4 x 4 inches). Industrial 3D production systems then currently max out with the 914 x 610 x 914 mm (36 x 24 x 36 inches) of the Fortus 900mc. A 3D printer of this size can be used not just to make large objects, but also to manufacture many smaller items side-by-side in a single print job.

Pushing the envelope still further are BigRep with the BigRep ONE v3, which offers a build volume of 1,100 x 1,050 x 1,000 mm (43.3 x 41.3 x 39.3 inches). However, at present the largest build volume available on a thermoplastic extrusion 3D printer belongs to a machine called the BAAM, manufactured by Cincinnati Incorporated. Standing for ‘Big Area Additive Manufacturing Machine’, a BAAM can print single workpieces as large as 6.1 x 2.3 x 1.8 m (240 x 90 x 72 inches), and is fed its carbon reinforced ABS build material in pellet form. As we will see in chapter 4, BAAM hardware has already been used to make several full-size car bodies.

THERMOPLASTIC EXTRUSION PRACTICALITIES

The material extrusion of thermoplastics can 3D print a very wide range of items in a straight-forward manner. There are, nevertheless, a few caveats to be aware of. Firstly, in comparison to other 3D printing methods, objects created via thermoplastic extrusion may have significant stepping. In other words, when you look at a printed object up close it can be very obvious that it has been built in layers. This may be particularly apparent on sloping or curved surfaces. Figure 2.3 provides a simple illustration of what a pyramid produced via thermoplastic extrusion may look like in comparison to one made using traditional injection molding techniques.

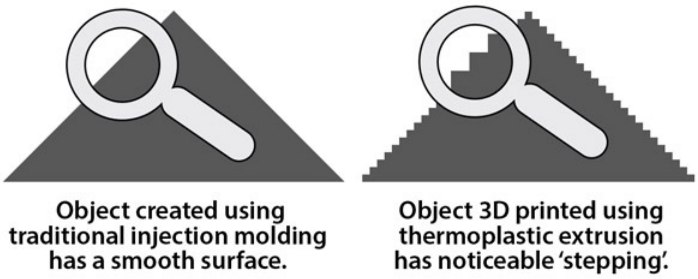

Figure 2.3: Injection Molding v. Thermoplastic Extrusion.

Whether or not an object will appear stepped depends on the resolution and accuracy of the 3D printer that created it. The best industrial printers can currently extrude plastic objects in layers that are 0.1 mm thin, and can also achieve an accuracy on their other two axes of about 0.1 mm. In comparison, printers that cost hundreds rather than thousands of dollars typically achieve a minimum layer thickness in the 0.15 to 0.5 mm range (whatever their manufacturers may claim), and an accuracy on their other two axes of around 0.2 mm.

It is generally accepted that the unaided human eye cannot discern steps of less than 0.1

mm, although even when such a level of detail is achieved an object’s surface is likely to feel somewhat rough. Indeed in practice today, no object produced via thermoplastic extrusion ever feels entirely smooth unless it has been lightly sanded or chemically treated after printout (for example by placing it in a cloud of acetone vapour).

Even when a thermoplastic extrusion 3D printer can produce objects in extremely thin layers, users may choose to build things in slightly thicker layers in order to save time. After all, while an object that is 3D printed in 0.2 mm thick layers will be rougher than one printed in 0.1 mm layers, it will also take half the time to print. Given that some objects may take tens of hours to fabricate, such a time saving may be very significant. If the item being printed is a shelf bracket, door stop, machine tool or a rough prototype, its surface quality may also be pretty irrelevant.

In addition to noticeable stepping, objects 3D printed using thermoplastic extrusion may warp, curl or shrink during printout, and sometimes significantly. This can occur as the material they are made from cools down, with different parts of the object potentially cooling at different rates. To try and prevent this, most thermoplastic extrusion printers are fitted with a heated build platform. This stops the lower layers of a printout from cooling significantly more quickly than those above them, so helping to prevent internal thermal stresses from tugging them out of shape. Heated build platforms also help to keep objects securely in place during printout.

To further minimize warping or shrinkage, most industrial and some consumer printers feature enclosed build areas. These prevent drafts, and are usually temperature controlled. Manufacturers of high-end thermoplastic extrusion 3D printers now state that warping and shrinkage are no longer a significant concern.

The same claim can unfortunately not be made when it comes to most cheaper 3D printers. To try and deal with the issue, tiny fans are often fitted on the print head to increase the cooling speed of the layers just printed. Many argue that warping and shrinkage can be reduced by printing objects more slowly, and by paying close attention to the starting height of the print head above the build platform. Another strategy is to print an object with a plastic lattice or ‘raft’ beneath its lowest layer. This has to be cut away or otherwise removed from the object after printout, but can help to adhere the object more securely to the build platform, and hence to warp less.

Finally, regardless of printer type, warping may be controlled via effective object design. For example, reducing the level of ‘infill’ in an object will make it less likely to warp. While plastic parts created via traditional injection molding have to be entirely solid, items that are 3D printed may be hollow, solid, or made semi-solid by printing their insides as an open lattice. Making the inside of an object less solid will usually reduce the chance of its innards pulling on and distorting its outside as it cools. Printing objects that are not entirely solid also takes less time and uses less filament, in turn reducing printing costs. It is indeed rare to 3D print totally solid plastic objects.

SUPPORT STRUCTURES

A final practicality to be dealt with is the support of any overhanging or ‘orphan’ parts. To highlight the issues involved, figure 2.4 illustrates four plastic letters that we may consider creating on a thermoplastic extrusion 3D printer. Here, the capital ‘L’ can be printed with no problems at all. In contrast, the capital ‘Y’ has upward-sloping overhangs. This means that there is a risk of each successive object layer overhanging the one beneath it so significantly that it may fall away during printout. Here we would probably get away with the upper arms of the letter ‘Y’, as an upward slope that overhangs at no more than 45 degrees usually prints OK. But if we move on to the ‘T’, the upper parts of the letter jut out at a straight 90 degrees and would certainly fall away if no action were taken. Similarly, the capital ‘M’ may initially appear impossible to print, as during the early stages of the process the middle part of the letter would have to hang unsupported in space.

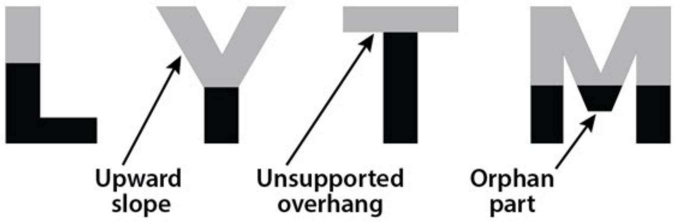

Figure 2.4: Overhangs and Orphan Parts.

Of course, the ‘T’ and the ‘M’ could be printed quite easily by outputting them lying flat on the build platform – and indeed optimal object orientation is critical when planning the 3D printout of almost anything. But unfortunately, many complex objects cannot be orientated so that they have no unsupported or initially orphan parts. To deal with this issue, almost all thermoplastic extrusion printers do on occasion have to print ‘support structures’ that keep everything in place. These temporary additions to the object then need to be removed after printout is complete.

Required support structures can be created in two ways. The first method is to add a fine lattice of ‘breakaway supports’ that are 3D printed using the same plastic used to make the final object. After printout, all of these extra bits of plastic must be removed with a knife or other implement, or else snapped-away by hand. Once the support structures have been removed, some further clean-up of the final object using sandpaper or other tools may then be necessary to remove any evidence that supports were attached.

Alternatively, some printers can create support structures using a second print head nozzle that outputs a soluble support material, such as polyvinyl acetate (PVA). Once an object has been printed, it is then placed in a tank of water that dissolves the support.

While most 3D printers that create soluble support structures are large, high-end industrial machines, the technology is now available on some cheaper desktop hardware. For example, the Creatr range from Leapfrog, and the Sigma from BCN3D Technologies, can both print soluble supports. Some 3D printer manufacturers refer to mechanisms that create and remove soluble support structures as ‘SST’ or ‘soluble support technology’. 3D printers that rely on breakaway supports are then referred to as relying on ‘BST’ or ‘breakaway support technology’.

In an effort to make support structures easier to remove, in July 2016 a company called Rise Inc announced the launch of its first 3D printer, the Rise One. This uses a thermoplastic extrusion technology that they call ‘augmented polymer deposition’ (APD) to build objects and support structures in a traditional manner. However, the clever bit is that a ‘repelling ink’ is jetted between the object and its supports, so making separation far easier. Rise state that their hardware is the ‘only zero-post-processing 3D printer’, and go on to claim that the ‘elimination’ of time-consuming support removal’ can ‘produce a usable part 50% faster than other systems’.

THERMOPLASTIC EXTRUSION BUILD MATERIALS

While many build materials can potentially be used in a thermoplastic extrusion 3D printer, the most common is acrylonitrile butadiene styrene, otherwise known as ‘ABS’. This is a petroleum-based thermoplastic that is widely used to injection mold a great many things. For example, Lego bricks, cycle helmets and biros are all injection molded in various grades of ABS. In fact, if you are reading this book on an e-reader or other computing device, then its outer casing and buttons were almost certainly injection molded in ABS.

Spools of ABS filament are available in a variety of colours, with a typical filament being either 1.75 mm or about 3 mm in diameter. Other thermoplastic build materials include nylon and other polyamides, acrylonitrile styrene acrylate (ASA), polycarbonates (PC), polyethylene terephthalate glycol-modified (PETG), high impact polystyrene (HIPS), and ABS-polycarbonate composites.

To fabricate end-use objects that must possess a very high temperature and chemical resistance, it is also possible to use polyphenylsulfone (PPSF) on some high-end industrial printers. In addition, there is a thermoplastic called polymethylmethacrylate (PMMA) that has the key feature of being transparent. Also transparent is ABSi, which can be sterilized with gamma radiation or ethylene oxide, so allowing plastic parts to be 3D printed for use in the food industry or for medical applications. A thermoplastic called PC-ISO (polycarbonate-ISO) can also be sterilized with gamma radiation or ethylene oxide, and offers good biocompatibility for the fabrication of 3D printed medical devices.

If flexible, rubber-like components need to be 3D printed, thermoplastic elastomer (TPE) filaments are now also available for both consumer and industrial use. These are often made from a thermoplastic polyurethane (known as TPU or TPE-U), and include the popular Ninjaflex from Fenner Drives and WolfBend from AirWolf 3D.

In addition to the aforementioned petroleum-based build materials, another very popular filament is polylactic acid, otherwise known as ‘PLA’. This is a bioplastic that is currently made from agricultural produce such as corn starch or sugar cane, and which is subsequently more environmentally friendly than ABS. PLA is also very safe to work with as it does not emit toxic fumes when heated. It is hence favoured by educators wishing to introduce children to 3D printers in schools or colleges. To further enhance domestic and educational safety, Korean manufacturer BnK produces an antibacterial PLA filament called Purement. This can allow children to design and print toys and household items that are far less likely to harbour germs on their rough, multi-layered surfaces.

PLA filament comes in a variety of solid and translucent colours, and is popular with many 3D printing enthusiasts as it is easier to print with than ABS. Recently a stronger and more durable filament called HTPLA (high temperature PLA) has also become available. Other bioplastic filaments include polyhydroxyalkanoate (PHA), which is sometimes mixed to create a PLA/PHA composite. Both PLA and PHA are biodegradable, and may in the future be produced locally via synthetic biological processes. Indeed, as I shall discuss in chapter 7, it is theoretically possible that future domestic fabricators will cultivate their own bioplastic filaments.

WOOD & METAL COMPOSITE FILAMENTS

At the consumer and prosumer end of the material extrusion marketplace, one of the most notable developments over the past few years has been the arrival of specialist composite filaments. These combine a thermoplastic with another material, and increasingly offer amazing new low-cost 3D printing possibilities.

One of the first such composite materials was Laywood, also termed Laywoo-D3. This was invented in 2012 by an enthusiast called Kai Parthy in a successful attempt to produce a filament that was less prone to warpage and shrinking. As the name suggests, Laywood is a composite of wood (effectively sawdust) and a thermoplastic, and can be 3D printed to make objects that actually feel and smell like wood. Printouts can even be sanded and otherwise worked on like any object made of a wood composite, such as medium density fibreboard (MDF).

Since Laywood was launched, many other wood/polymer composite (WPC) filaments have come to market, all of which are made from 70 to 80 per cent PLA mixed with a wood additive. These include woodFill from colorFabb, and Timberfill from Fillamentum. The latter is available in ‘Light Wood Tone’, ‘Rosewood’, ‘Cinnamon’ and ‘Champagne’ hues, while colorFabb also offer bambooFill. Not to be outdone, Laywood today comes in ‘pine’ and ‘cherry’.

Yet other composite filaments include Laybrick from Parthy (which is a great stone-additive material for architectural models), and corkFill from colourFabb. But where things start to get really interesting is when thermoplastics are combined with a metal.

The first metal composite filament was bronzeFill, a composite of PLA and PHA mixed with a fine bronze powder. The resultant material is about three times heavier than a pure thermoplastic, and initially 3D prints with a matte finish. However, with some careful sanding and polishing, bronzeFill can be made to shimmer and shine.

Over time, and in response to very popular demand, colorFabb have expanded their metal filament range, and now offer copperFill, brassFill and steelFill. Another specialist filament manufacturer called Proto-Pasta sells a ‘Polishable Stainless Steel’ composite PLA filament, along with another really cool one called ‘Rustable Magnetic Iron’. The days when lower-cost desktop 3D printers could only make things that looked and felt like plastic are already receding into history.

REINFORCED & CONDUCTIVE FILAMENTS

In the quest to increase the strength and durability of final objects, there are various ongoing attempts to introduce strands of carbon fiber into thermoplastic 3D printouts. For example, ‘Proto-Pasta Carbon Fiber’ is already commercially available. This is made from PLA compounded 15 per cent by weight with very short-chopped carbon fibers. Printouts made with this material are stiffer and resist bending far more than standard thermoplastic parts. They also have a solid feel and a slightly metallic shimmer in direct light. A similar carbon fiber filament called XT-CF20 is available from colorFabb.

Taking a different approach, a company called Markforged has developed a $5,499 ‘industrial strength’ 3D printer that can materially extrude nylon parts embedded with continuous strands of carbon fiber, fiberglass or Kevlar. One of these reinforcing materials is laced into the object during printout (rather than being pre-mixed into an extruded filament) in a process that they term ‘composite filament fabrication’ (CFF). The result is a piece of desktop hardware that can 3D print fiber reinforced nylon objects that are stiffer than aluminium.

The creation of highly specialist plastic composite 3D printing materials is likely to become a major area of development. Signalling the direction of travel, in 2014 a company called 3DXTech launched two carbon nanotube reinforced filaments called 3DXNano ESD ABS and 3DXNano ESD PETG. These are composites of carbon nanotubes mixed with the thermoplastics ABS or PETG, and allow low-cost 3D printers to fabricate parts that offer electrostatic discharge (ESD) protection. In practice this means that the 3DXNano filaments may be used to 3D print parts of hard drives and other electronic components.

Pushing the boat out even further, Graphene 3D Lab have developed an electrically conductive graphene filament. I shall say more about Graphene 3D Lab and their broader intentions when we look at 3D printing and nanotechnology in chapter 7.

THE MATERIAL EXTRUSION OF METALS

Potentially a great many entirely non-plastic materials can be 3D printed using the process shown in figure 2.1. After all, many substances may be supplied to a print head in solid form, heated into a molten state, and deposited under computer control. The only real issue is the complexity of achieving this with non-plastic materials.

Over the past few years several research teams have investigated the ‘fused deposition modelling of metals’, otherwise known as ‘FDMm’. For example, a team led by Jorge

Mireles from the University of Texas has conducted tests using a modified thermoplastic extrusion printer fed with a coil of metal alloy. The alloy used has to have a relatively low melting point (of less than 300°C). But subject to this constraint, metals have been successfully heated and extruded to form objects in layers that were just under a millimetre thick.

Taking an alternative approach, other researchers have successfully adapted gas metal arc fusion welding robots for 3D printing purposes. For example, researchers at Cranfield University have developed ‘wire and arc additive manufacturing’ (WAAM). Here a thin titanium wire is threaded through a computer-controlled, movable arm to a print head where it is heated and extruded to build up successive object layers. Working with BAE Systems, the Cranfield team have used WAAM to produce a 1.2 m spar section of an aircraft wing. This was 3D printed in titanium in just 37 hours, compared to the many weeks that would have been required for traditional manufacturing methods. You can learn more about WAAM at waammat.com.

While Cranfield are hoping to commercialize WAAM in the future, some industrial metal extrusion processes have already come to market. For example, Norsk Titanium have developed a method called ‘rapid plasma deposition’ (RPD) in which a titanium wire is melted in a cloud of argon gas to build up object layers. Using this process, aerospace-grade titanium structures can be additively manufactured until they are about 80 per cent complete. Parts are then finished via traditional machining methods.

Also 3D printing in metal using a process akin to material extrusion are Sciaky. Here the involved technology is termed electron beam additive manufacturing (EBAM), and feeds two solid metal wire feedstocks into an electron beam that fuses them into large, industrial parts. The resultant printouts have clearly stepped layers, but may be post processed by CNC machining to achieve a smooth surface. Build materials for EBAM currently include nickel-based alloys, titanium and tantalum. Because two metal wires are fed into EBAM’s electron beam, it is possible to 3D print objects from continuously variable alloys, so allowing objects to be created with different material properties in different locations.

EBAM can rapidly manufacture high-value metal structures up to 5.8 x 1.2 x 1.2 m (19 x 4 x 4 feet) in size in a matter of days, and with very little material wastage. Sciaky claim that EBAM is the fastest and most cost-effective direct metal 3D printing process, with lead time and material cost savings of up to 80 percent compared to traditional production methods. A large metal part produced using EBAM is illustrated in figure 2.5.

Figure 2.5: A Large Metal Part Produced by Sciaky's EBAM.

THE MATERIAL EXTRUSION OF CONCRETE

In the construction industry concrete is a very widely used build material. Given that it is initially mixed into a viscous form that is poured before it sets, concrete is also a prime candidate for large-scale material extrusion.

The first experiments to create a 3D concrete printer took place at the University of Southern California in 2004. Since that time, Behrokh Khoshnevis, a professor of Industrial & Systems Engineering at the University, has been working to perfect what he terms 'contour crafting'. This 'mega scale layered fabrication process' uses a motion-controlled nozzle to extrude concrete in layers in its naturally pre-set state. Professor Khoshnevis anticipates that within a few years it will be possible to commercially 3D print a 2,500-square-foot home in about 18 or 19 hours with a workforce of about four people.

Professor Khoshnevis is also not alone in his ambition. For example, the Freeform Construction Project at the University of Loughborough has created a 3D printer that uses a material extrusion process to output large concrete objects. The machine outputs a cement-based mortar from its print head, and has a build volume of 2 x 2.5 x 5 m (about 6.5 x 8.2 x 16.3 feet). While an earlier version of the printer was based on a 3-axis gantry, the most recent model has its nozzle mounted on a 7-axis robotic arm to further enhance print quality, speed and potential object size.

Working on an even grander scale, in September 2015 the Technical University of Eindhoven began experimenting with a concrete printer with a build volume of 11 x 5 x 4 m (36.1 x 16.4 x 13.1 feet). Working in conjunction with the building industry, the intention is to learn how to create large concrete products, including complete walls with all service ducts and other relevant features included in the print.

Demonstrating the true potential, a Chinese company called WinSun Decoration Design Engineering has similarly created a 3D concrete printer. In its latest iteration, the machine is 6.1 x 40.3 x 10.1 m in size (20 x 132 x 33 feet), and extrudes a mix of cement, natural stone, glass fiber and construction waste. In April 2014, WinSun used its amazing hardware to produce 10 full-size houses in 24 hours. As illustrated in figure 2.6, in January 2015 it then showcased a 1,100 square metre 3D printed mansion, together with a five storey 3D printed apartment block. And most recently, in May 2016, WinSun revealed a 250 square metre office complex in Dubai that it had 3D printed in just 17 days and which was installed on site in only 48 hours.

Figure 2.6: WinSun 3D Printed Mansion.
Image courtesy of 3Ders.org.

THE MATERIAL EXTRUSION OF CLAY

Very closely related to the 3D printing of concrete is ceramic extrusion, a process sometimes referred to as the 'fused deposition of ceramics' (FDC). As you may expect, here a semi-liquid clay is extruded through a fine nozzle to create an object that is fired and glazed in the normal fashion. Early pioneers in this field included Dries Verbruggen and Claire Warnier of Unfold in Belgium, as well as British artist Jonathan Keep. You can view examples of Jonathan's work and learn more about his 'potting in the digital age' at keep-art.co.uk.

Also opening up this marketspace are the World's Advanced Savings Project or WASP, based in Italy. The company makes a range of material extrusion 3D printers in various sizes, many of which can extrude clay. These start with their 'DeltaWASP 20 40 with Clay Extruder', which has a build volume of 200 mm (7.9 inches) in diameter by 400 mm (15.7 inches) high, and which sells for about $4,000. However, beyond selling desktop hardware, WASP has a grander vision to use 3D printers to encourage sustainable development. In particular, they are aiming to build 'zero-mile' homes using materials found in the surrounding area. To this end, WASP has developed several very large 3D printers that extrude clay or soil mixed with resin or water.

As illustrated in figure 2.7, back in 2013 I saw one of WASP's early Big Delta 3D printers making a clay model of a house about 1 metre across. But since then things have moved on, with the latest 'Big Delta WASP 12m' being a truly massive machine capable of 3D printing a full-size clay dwelling from on-site materials. In July 2016, WASP put their Big Delta 12 and some of its smaller cousins to work 3D printing an experimental outdoor 'technological village' called Shamballa. This is intended to demonstrate the feasibility of 3D printing sustainable dwellings, and has in part been funded by the development and sale of far more 'traditional' desktop 3D printers that extrude thermoplastics.

Figure 2.7: A WASP Big Delta 3D Printing in Clay. The model building being printed here is about 1 m across.

THE MATERIAL EXTRUSION OF FOOD

Some of the most delicious substances prepared by chefs in their kitchens – including chocolate, ice-cream, candy and cake frosting – are mixed during their preparation into a potentially extrudable format. It is therefore hardly surprising that additive manufacturing enthusiasts have for some years been experimenting with the 3D printing of food. For example, in Spain a research group called Robots in Gastronomy have developed a 3D printer called FoodForm that can extrude edible build materials onto any surface, including a hot grill or frying pan, or a chilled anti-griddle.

Experimenting with the FoodForm, Robots in Gastronomy have already managed to 3D print using bread, cake and cookie doughs, hazelnut and chocolate creams, honey, cheese, ice cream, cheesecake, meringue, various frostings, pasta, eggs, pâté and purees.

Focusing solely on chocolate, a company called Choc Edge manufacture a desktop 3D printer called the Choc Creator. The first version of this went on sale in 2012 as the world's first commercial food printer. Since that time, the initial Choc Creator has been replaced with the Choc Creator V2.0 Plus, which sells for just over $3,000, and has a build volume of 185 x 185 x 50 mm (or about 7.3 x 7.3 x 2 inches). The printer is capable of producing logos and simple 3D models, with its edible creations having already included Christmas trees, bells, snowflakes, snowmen and scanned human faces.

Also keen to bring their 'Foodini' food printer to market are Natural Machines. When the last edition of this book went to press in November 2014, the Foodini was due to be launched within a few months. Two years later, and we are still waiting for it to be 'ready'. This lack of delivery is also not uncommon in the very young food printing marketplace. Indeed, back in January 2014, 3D Systems showcased its 'Chefjet' as 'the world's first and only professionally certified, kitchen-ready 3D food printer', and this too has yet to see the light of day.

In theory, the market for 3D printers that use material extrusion to produce custom cake decorations, Christmas gifts, Easter eggs, Valentine's Day chocolates and so on is ripe for exploitation. The technology on which the hardware may be based is relatively mature and well understood, and as Choc Edge have shown, it is possible to produce a commercial product for a few thousand dollars. Granted, at this price, few end-consumers are likely to go out and buy such a printer. But chefs, high-end restaurants and caterers do represent a viable market.

So why has the material extrusion of food not taken off? Well, the answer is that it requires a robust and hygienically-certified consumables ecosystem – probably based on a cartridge mechanism – and this is something that no current 3D printing company can deliver. Right now the Choc Creator V2.0 Plus requires users to hand melt and temper Belgian dark chocolate in a saucepan to load into the machine's syringe, and this is hardly ideal. I know from my client work that there is commercial interest in extrusion-based food printing. But I also suspect that it will be a mainstream food manufacturer with expertise in packaging and supplying the necessary consumables that will actually bring it to market.

VAT PHOTOPOLYMERIZATION

As we have now seen, material extrusion is a form of 3D printing that can output a very wide range of existing materials. It is also a technology that is relatively easy to construct, and which can hence be sold for a relatively low price. This said, while almost all consumer hardware is currently based on material extrusion, many industrial 3D printers use more accurate if more expensive processes that bind powders, solidify liquids, or bond sheets of material together. The first category of these technologies goes under the generic heading of 'vat photopolymerization', and uses a light source to solidify successive object layers on the surface or base of a vat of liquid photopolymer. While this may sound quite a specific thing to do, vat photopolymerization is already achieved via a great many distinct technology variations as detailed below.

STEREOLITHOGRAPHY (SLA)

Stereolithography was the first commercial 3D printing process, and uses a computer-controlled laser beam to build a 3D object within a vat (or tank) of liquid photopolymer. The first stereolithographic 3D printers were manufactured by 3D Systems, which refers to them as 'StereoLithographic Apparatus' or 'SLA'.

In most large SLA 3D printers, objects are formed on a perforated build platform which is initially positioned just under the surface of a photopolymer vat. A UV laser beam then traces out the shape of the initial object layer on the surface of the liquid. This causes it to cure (set solid), and the build platform lowers just a little. More liquid photopolymer then either naturally flows over the top of the first object layer, or is forced across it by a mechanical mechanism that skims the surface of the vat, and the next object layer is traced out and set solid by the laser. This process then repeats until the whole object has been printed. Finally, the build platform is returned to the surface and the object is detached.

Figure 2.8 provides an illustration of the stereolithographic 3D printing method.

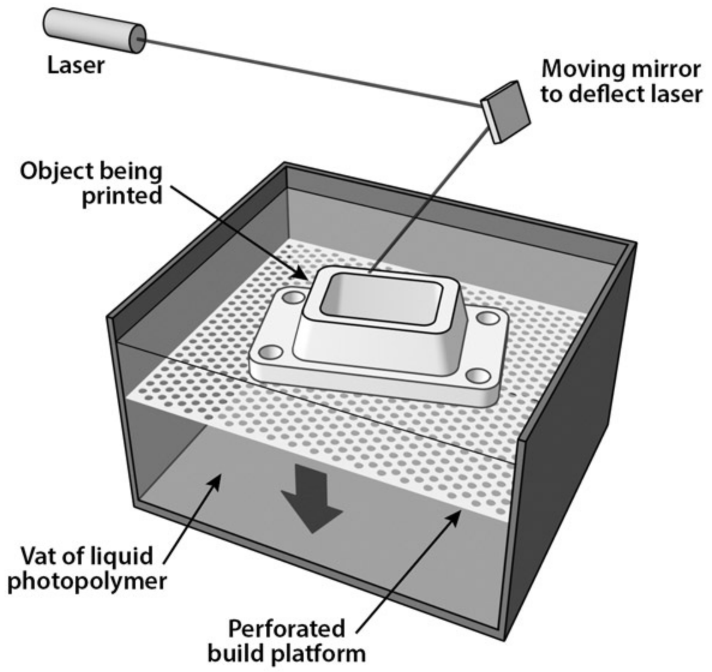

Figure 2.8: Stereolithographic 3D Printing. Note that in some printers the technology is inverted, with the laser beam curing object layers on the bottom of a transparent photopolymer vat.

While most large stereolithographic 3D printers work in the above fashion, in smaller, desktop hardware the technology is inverted. This means that object layers are formed on the bottom of a build platform that is initially almost in contact with the base of a shallow reservoir of photopolymer. The base of the reservoir is an optically clear window that is coated in a release coat such as silicon, and through which a laser beam is projected to solidify object layers. After each layer is printed, the build platform is raised, the vat is agitated to fully re-coat the last object layer with fresh photopolymer, and the process repeats.

As in material extrusion, objects 3D printed using stereolithography often require additional structures to be added to support overhangs or initially orphan parts. These have to be made out of the same material as the object itself, and need to be broken away by hand or otherwise removed with tools after printout. Once this has taken place, objects next need to be washed with a solvent, and then a water rinse, to get them completely clean. Objects then sometimes require curing in a UV oven.

Items created in transparent resins may additionally be varnished to prevent discolouration if they are going to be exposed to sunlight. And on occasion, printouts may also have their surface quality improved by blasting them with glass beads. Alternatively, they may be polished-up by ‘vapour honing’ with a fine abrasive spray.

Objects produced using stereolithography are very accurate and, unlike those created using material extrusion, have a smooth surface. The largest production stereolithographic printer – the dual-laser 3D Systems ProX 950 – has a build volume of 1,500 x 750 x 550 mm (59 x 29.5 x 21.7 inches), and can produce parts that weigh up to 150 kg. This particular hardware can also achieve an accuracy of about 0.025 mm on its X and Y axes. It does, however, cost the best part of a million dollars.

While very large stereolithographic 3D printers based on the traditional SLA process remain very expensive, the prices for smaller devices based on an inverted technology have fallen dramatically over the past few years. The market started to be transformed in November 2011, when a company called Asiga released a stereolithographic printer for under $7,000. In May 2013, a $3,299 desktop stereolithographic printer called the Form 1 was then launched by Formlabs. Its successors, the Form 1+ and Form 2, now sell for $1,999 and $3,499, and have respective build volumes of 125 x 125 x 165 mm (4.9 x 4.9 x 6.5 inches) and 145 x 145 x 175 mm (5.7 x 5.7 x 6.9 inches). On both printers the minimum layer thickness is as low as 0.025 mm.

Not to be outdone, in March 2014 3D Systems launched a 'micro SLA' printer called the ProJet 1200. This sells for $4,900, and has a 43 x 27 x 150 mm (1.69 x 1.06 x 5.90 inch) print volume. At the time of writing, XYZprinting have started to sell their Nobel 1.0 desktop vat photopolymerization 3D printer for $1,500 with a 128 x 128 x 200 mm (5.0 x 5.0 x 7.9 inch) build volume. As you can see, at the low-end the market is really hotting-up.

When stereolithography was first invented it could only 3D print in brittle resins. It was therefore only used for rapid prototyping, or to fabricate pattern masters from which final production molds were then taken. But today a far wider variety of stereolithographic photopolymers have been developed. These include rubber-like plastics, many substitutes for ABS and other thermoplastics, flame retardant plastics, totally clear resins, and special photopolymers for dental modelling and jewelry design. As a consequence, while stereolithography continues to be used to make mold masters and prototypes, the technology is also starting to be employed in the manufacture of final products or parts thereof. This said, the price of photopolymers does remain far higher than that of the build materials used in thermoplastic extrusion. For example, a litre of resin for the Form 1+ costs between $149 and $399, depending on the material.

DLP PROJECTION

A second vat photopolymerization 3D printing method is DLP projection. DLP (or 'digital light processing') panels are increasingly used in video projectors, and feature a tiny imaging chip that contains an array of microscopic mirrors or 'digital micromirror devices' (DMDs). The mirrors can be rapidly rotated, so allowing them to reflect light out of the projector lens or onto a heatsink or 'light dump'. By controlling the orientation of the mirror array, a high quality image is created for projection.

In a DLP 3D printer, a DLP projector replaces the laser and is often positioned below the build platform in a similar configuration to inverted stereolithography. Images are then projected to solidify each object layer, rather than tracing the outline of each layer with a laser.

Figure 2.9 depicts a typical DLP projection 3D printing system. Note that in smaller DLP 3D printers the projected image is reflected off one or more mirrors in order to allow the projector to be rotated through 90 or 180 degrees and positioned beside rather than below the photopolymer vat.

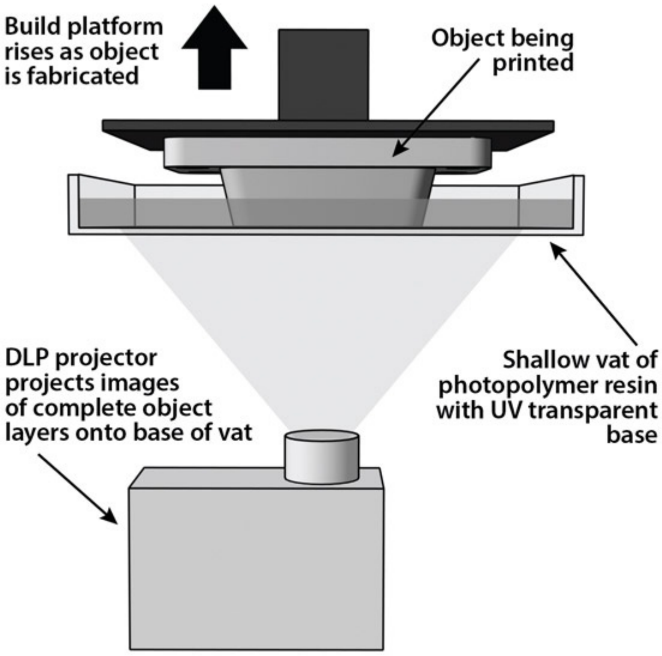

Figure 2.9: DLP Projection 3D Printing.

In common with their laser-based cousins, DLP 3D printers can achieve a high level of accuracy. The largest current DLP models have a minimum layer thickness down to about 0.025 mm and a build volume of 267 x 165 x 203 mm (10.4 x 6.5 x 8.0 inches). Smaller models tend to offer a higher resolution, as their projector is focused across a smaller area. Adobe now sell a DLP projection 3D printer called the Amber with a minimum layer thickness down to 0.01 mm. This has a build volume of 64 x 40 x 134 mm (about 2.5 x 1.5 x 5.3 inches), and costs $7,495.

Many DLP projection build materials are available. These include opaque and transparent substitutes for traditional plastics, as well as wax-based polymers and several dental and medical-grade plastics. Indeed, DLP projection 3D printers from a company called EnvisionTEC are now widely used to 3D print casings for hearing aids and in the dental profession. I will say more about these applications in the next couple of chapters.

MOVINGLIGHT

Several companies continue to innovate with DLP and related technologies, with new variants regularly coming to market. For example, in December 2013, ‘MOVINGLight’ was introduced by Prodways. This works like standard DLP projection, but achieves an even greater resolution by employing a moving, top-mounted DLP projector to shine object layers onto the surface of a vat of liquid photopolymer. The technology also enhances print speed by using the latest UV LEDs as its DLP projector's light source.

By sweeping a high-resolution, 70 x 40 mm projected image across a large build area, Prodway's printers achieve a resolution of hundreds of millions of pixels per layer. Build volumes vary by printer model, and include 720 x 230 x 150 mm (28 x 9 x 6 inches) on the ProMaker D35, and 800 x 330 x 200 mm (31 x 13 x 8 inches) on the ProMaker L7000 D, with a minimum layer thickness of 0.025 mm. Figure 2.10 shows a Prodways MOVINGLight printout.

Figure 2.10: A MOVINGLight DLP Printout.

Also selling vat photopolymerization hardware that uses a moving DLP projector are Atlanta-based DDM Systems. Here the technology is termed 'large area maskless photopolymerization' (LAMP), and employs build materials that are a mixture of a photopolymer and a ceramic powder. This allows LAMP to be used to make casting molds and cores, as well as intricate ceramic engineering components.

DAYLIGHT POLYMER PRINTING

While Prodways and DDM Systems make high-end industrial hardware, in 2015 a company called PhotoCentric introduced a cheaper, desktop technology variant that they call 'Daylight Polymer Printing' (DPP). This uses special photopolymers than can be solidified using natural light (rather than UV), and employs a traditional LCD panel to project complete object layers onto the base of its photopolymer tank. The cheapest PhotoCentric printer is the LC10. This has a build volume of 200 x 100 x 200 mm (7.9 x 3.9 x 7.9 inches), a minimum layer thickness of 0.025 mm, and costs £699 (about $920).

SCAN, SPIN & SELECTIVELY PHOTOCURE

Scan, spin and selectively photocure – or '3SP' – is another vat photopolymerization process introduced by DLP pioneer EnvisionTEC in 2013. In 3SP printers, light is reflected through a spinning drum and then passed through a series of optical elements that move its focused beam across the surface of a tank of photopolymer on the Y-axis. The UV light source and its imaging assembly then move as required on the X-axis. 3SP allows for larger build sizes than available with DLP, with the build volume on EnvisionTEC's Xede 3SP printer being 457 mm (18 inches) cubed.

LITHOGRAPHY-BASED CERAMIC MANUFACTURING

A sixth vat photopolymerization technology has been developed by Lithoz, which terms its process lithography-based ceramic manufacturing (LCM). This is a form of DLP projection that selectively cures a photopolymer resin that contains ceramic particles. After printout, extensive post processing is required in order to remove the photopolymer, and to sinter the remaining material into a compact ceramic part.

The build envelope of the CeraFab 7500 3D printer from Lithoz is 76 x 43 x 150 mm (3.0 x 1.7 x5.9 inches), with a minimum layer thickness of 0.025 mm. Once printout and post-processing is complete, LCM results in objects that are made entirely of a ceramic material.

CONTINUOUS LIQUID INTERFACE PRODUCTION (CLIP)

Seeking to develop a 3D printing technology that can produce final parts with the same surface and material qualities as injection molding, a company called Carbon3D has developed a technology known as 'CLIP'. Standing for 'continuous liquid interface production', this is pretty similar in its physical logistics to inverted stereolithography (and DLP projection), but places a 'dead zone' of uncured resin between the bottom of the vat and the object being printed. UV light passes through the dead zone, curing the resin above it to form a solid part. But in addition, resin also flows beneath the curing part as the print progresses, so maintaining what Carbon3D term a 'continuous liquid interface'. As the company further explain:

> Our breakthrough CLIP process is paired with a secondary curing stage to unlock engineering properties. Traditional additive approaches to photopolymerization typically produce weak, brittle parts. Carbon overcomes this by embedding a second heat-activated reactive chemistry in our materials. This results in high-resolution parts with engineering-grade mechanical properties.

Carbon3D's first 3D printer – the M1 – launched in April 2016. It has a build volume of 144 x 81 x 330 mm (5.7 x 3.2 x 13 inches), and is sold via subscription.

FIGURE 4

In April 2016, 3D Systems showcased a new variant of its SLA vat photopolymerization process that it terms 'Figure 4'. This is currently developmental, and is intended to turn stereolithography into an assembly line technology that according to 3D Systems will produce ‘parts in minutes, versus hours on conventional systems’.

Figure 4 achieves its promise using modular hardware that incorporates multiple vats and robotic arms to automate aspects of fabrication including build plate reload, material delivery, part removal, material recovery, washing, curing, finishing and part verification. 3D Systems has already built a Figure 4 system – its SLAbot-2 – and claims speed improvements of up to 50 times over other vat photopolymerization methods.

Figure 4 is named after an illustration in the original 3D Systems SLA patent. In addition to leveraging modular and robotic automation, the technology achieves speed increases using new ‘hybrid resins’. These make use of ‘multi-mode polymerization’, and have become a chemical possibility due to the fact that high speed printing reduces the time that resins have to remain stable in the vat. According to 3D Systems, its new materials improve part ‘toughness, durability, biocompatibility, high temperature deflection, and even elastomeric properties’, and will subsequently facilitate ‘new end-use applications in the fields of consumer goods, automotive, aerospace, medical, and beyond’.

By combining multiple Figure 4 hardware units, the idea is that companies will be able to put together 3D printing production lines that will rival the capabilities of traditional manufacturing. At the time of writing, 3D Systems is ‘actively looking for companies that would like to use this technology to bring mass customized products to market, or [to] convert their manufacturing to a digital process and eliminate the time and costs of conventional tooling’. Information on the technology remains scant at present, although 3D Systems has released some cool YouTube videos of its SLAbot-2 in action.

TWO-PHOTON POLYMERIZATION

Our final vat photopolymerization technology is two-photon polymerization (2PP). This is a ‘nanophotonic’ 3D printing method that is very similar to stereolithography, and which may turn out to be a mainstream 3D printing process in the future. 2PP is being developed by several research teams worldwide. These include the Additive Manufacturing Technologies (AMT) group led by Professors Robert Liska and Jürgen Stampfl at the Technical University of Vienna. Also developing 2PP are Nanoscribe in Germany, a spin-off from the Karlsruhe Institute of Technology (KIT).

2PP uses a ‘femtosecond pulsed laser’ to selectively solidify a photopolymer resin. OK, so this probably sounds much like stereolithography. Well yes, until you learn that 2PP 3D printers have already achieved a layer thickness and an X-Y resolution of between 100 and 200 nanometres. So whereas most conventional stereolithographic systems have a finest resolution of about 0.025 mm on their X and Y axes and a 0.05 mm minimum layer thickness (Z axis), 2PP is achieving a resolution as tiny as 0.0001 mm on all axes. Or to put it another way, 2PP currently has about a 250 times higher resolution than conventional stereolithography, and is capable of printing things far smaller than an average bacterium. 2PP is also far faster than conventional stereolithography, and is potentially able to build up object layers at several metres per second.

In the future 2PP may enable the very precise 3D printing of very tiny things – such as microelectronic and optoelectronic circuits – as well as the rapid manufacture of larger objects. In particular, 2PP may allow future 3D printed objects to be both light and strong, as they could be made from nanoscale lattices that are largely empty space. Right now, nanoscale lattice structures only exist in nature, with prime examples including human bone and wood. By allowing such structures to be artificially created, 2PP could therefore open up a whole new area of manufacturing.

To develop 2PP, scientists in a number of disciplines at the Technical University of Vienna have worked to improve both photopolymer resin and mirror technologies. The photopolymer they have developed contains special 'initiator' molecules that cause the monomers of resin around them to solidify only when struck by two photons. Because this happens only at the exact centre of a laser beam, this facilitates an extremely precise 3D printing process that allows solid material to be created anywhere within a photopolymer vat, rather than just on its surface.

When it comes to moving the 3D printer's laser beam, the Vienna team have developed a very high-speed system that keeps the mirrors constantly in motion. This reduces time lost in acceleration and deceleration, so speeding the 3D printing process.

To prove their metal, researchers in Vienna have already used their 2PP 3D printer to create a model of a Formula 1 racing car that is only 0.25 mm long, and which they printed in about four minutes. As illustrated in figure 2.11, they have also created an extremely tiny model of Vienna's St. Stephen's cathedral that is only 0.1 mm in length.

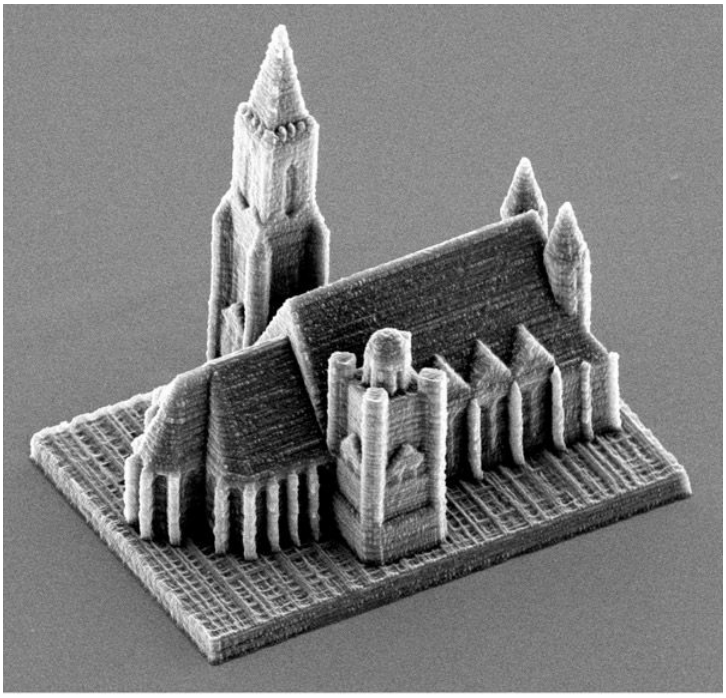

Figure 2.11: Two-Photon Polymerization 3D Print.
This model of St. Steven's cathedral in Vienna was created by the ATM Group at the Technical University of Vienna and is only 0.1 mm in length. Image produced with the permission of Robert Liska.

Over in Germany, Nanoscribe now market a 2PP 3D printer called the Photonic Professional GT. This is the highest resolution commercial hardware available for ‘3D micro printing’, and is currently being used in many cutting-edge fields of research. These include tissue engineering, as well as the creation of new kinds of electronic devices, bioadhesives and nanoscale micromachines.

MATERIAL JETTING

Returning to the mainstream, another 3D printing technology based on the solidification of liquids is ‘material jetting’. This exists in various formats, most of which spray a liquid photopolymer from a multi-nozzle, inkjet-style print head. As illustrated in figure 2.12, in this kind of 3D printer the print head moves across the build platform depositing one layer of liquid photopolymer. This is then set solid with UV light also emitted from the print head. 3D printer manufacturer Stratasys sells hardware based on this process under their trademarked name ‘PolyJet’ (short for ‘photopolymer jetting’), while 3D Systems have labelled the technology ‘MultiJet Printing’ or ‘MJP’.

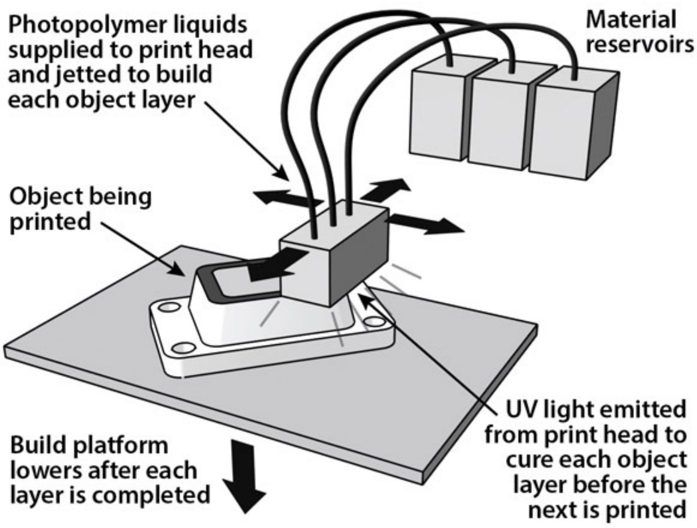

Figure 2.12: Photopolymer Material Jetting

Material jetting usually outputs support structures in a gel-like material that is removed after printout either directly by hand, with water, or in a solution bath. Once all supports have been removed, no further post processing is normally required. This makes material jetting technologies less messy for the user than any form of vat photopolymerization.

A wide range of rigid, flexible, opaque and clear photopolymers have been created for use in photopolymer material jetting. These include compounds that simulate the properties of ABS, polypropylene and rubber. Many material jetting printers also have the capability to output multiple materials in the same print job, and to mix them together, so creating up to 1,000 material options. By adding different inks into the mix, material jetting can additionally deliver multi-material printouts in full-colour. For example, the latest J750 material jetting printer from Stratasys can create objects made from a pallet of six different base materials, and in 360,000 colour shades. The J750 has a build volume of 490 x 390 x 200 mm (19.3 x 15.35 x 7.9 inches), with an amazing printout from the machine pictured in figure 2.13.

Figure 2.13: A Stratasys J750 3D Print.

Alongside hardware that jets and cures liquid photopolymers, there are some material jetting printers that create casting patterns by spraying droplets of hot wax. For example, 3D Systems has a range of ProJet 3D printers that create 'RealWax' objects using its specialist VisiJet wax and wax support materials.

Similarly used to create wax patterns – for industries such as dentistry and jewelry making – are 3D printers from Stratasys based on their 'wax deposition modelling' (WDM) process. This was developed by a company called SolidScape (now part of Stratasys), who named it 'drop on demand' (DOD). Like the 3D Systems RealWax technology, this creates objects in special wax-like plastics, and differs from photopolymer material jetting as a liquid build material is not cured with UV light. Rather, the 'TrueWax' thermoplastic and support materials used by the printer are solids that are pre-heated in reservoirs to become liquids. After jetting, they then solidify naturally as they rapidly cool.

PRINTOPTICAL

Another material jetting variant is a specialist process called Printoptical. This has been developed by LUXeXceL in Holland, and is used to prototype or manufacture functional optical components with no visible layers. Printoptical uses what LUXeXceL term their 'One-Step-CAD-to-Optic' printing process, with their 3D printer jetting droplets of a transparent acrylic photopolymer according to the shape of a CAD design. LUXeXceL's software then decides on a per-droplet basis if it should be immediately set solid with UV light 'like a Lego block', or if the droplet should be left to flow to create smoothness. With the invention of this technology, LUXeXceL has very cleverly developed the ability to 3D print lenses so smooth that they do not require any polishing or other post processing. This means that LUXeXceL already have a very precise, high speed and easy-to-scale process for 3D printing substantial volumes of quality lenses that can be used straight from the print bed.

Right now, LUXeXceL is focusing on the 3D printout of lenses used in illumination – such as those fitted in LED lighting systems – rather than lenses used in imaging. However, they have already used their technology to 3D print a pair of prescription spectacles.

NANOPARTICLE JETTING

The most recent material jetting technology is a game-changing process called NanoParticle Jetting (NPJ). This has been developed by an company called XJet, and in effect facilitates the fabrication of high resolution metal parts using an inkjet 3D printing process. Each object layer is formed from droplets sprayed from a print head as in other material jetting technologies. But the droplets sprayed via NPJ are solid metal nanoparticles in a liquid suspension. Heat is then used to bind the nanoparticles together. Or as XJet further explain:

> Inside the system's build envelope extremely high temperatures cause the liquid 'jacket' around the metal nanoparticles to evaporate. This results in strong binding of the metal with virtually the same metallurgy as traditionally-made metal parts. [After printout] the metal part needs to undergo an easy sintering process, with [any] supports removed simply and with almost no manual intervention.

XJet claim that their NJP technology will 3D print very high resolution metal parts far faster and at a lower cost than any other direct metal 3D printing technique. Build materials are supplied in sealed cartridges, and since they are based on nanoparticles, each requires its own research and development. The first build material is stainless steel, with 'other major metals' planned.

XJet's first 3D printer is due to be showcased to the world on 15 November 2016, just a few days after this book is published. And if it proves a success, it could well turn out to be a watershed innovation. Certainly there is a lot of interest in NJP, with financial backers including CAD software giant Autodesk.

BINDER JETTING

Moving on from 3D printers that solidify liquids, we come to three sets of technologies that stick together powdered build materials. The first of these is binder jetting, as illustrated in figure 2.14. Here a layer of powder is laid on a build platform termed a 'powder bed'. This is usually achieved by raising the base of an adjacent 'powder reservoir', and using a blade or a roller to sweep or push the elevated powder out across the bed. A multi-nozzle inkjet print head then selectively jets a binder solution in the shape of the first object layer. The powder bed is then lowered, another layer of powder is laid down, another layer of binder is jetted onto it, and so on.

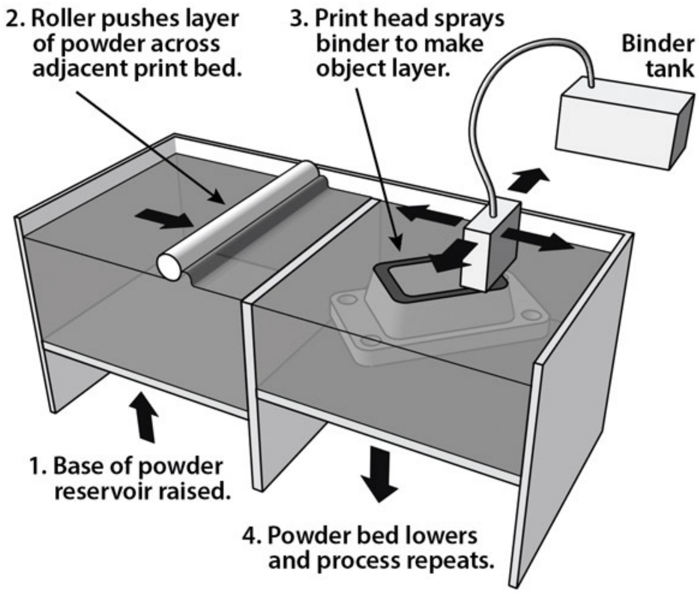

Figure 2.14: Binder Jetting.

When a complete object has been printed, it remains encased in a block of loose powder, from which it has to be removed by hand. It then needs to be transferred to a 'depowdering chamber' where it is sprayed with compressed air until it is completely clean. Depowdering chambers are usually built-in to binder jetting 3D printers, and use a closed-loop negative-pressure vacuum system to recycle all excess powder so that practically no unused build material is wasted.

Binder jetting printing is sometimes termed inkjet-powder printing or 'Z printing'. The latter name derives from the fact that the technology is heavily associated with a company called Z Corporation who initially developed it, and who sold a range of 'ZPrinters'. However, back in 2012, Z Corporation was acquired by 3D Systems, with its Z printing process now relabelled ColorJet Printing (CJP). In October 2016, 3D Systems produced five different CJP printers under its 'ProJet' branding. Of these, the ProJet CJP 860Pro has the largest build volume (at 508 x 381 x 229 mm or 20 x 15 x 9 inches). Prices for CJP hardware range from about $28,000 to $114,000.

Binder jetting offers a number of advantages over other 3D printing methods. Firstly, in common with most other powder-based 3D printing processes, no support structures have to be printed or removed, as overhangs or orphan parts are supported by the loose powder that surrounds an object while it is being printed. Secondly, the technology typically builds objects more quickly than alternative 3D printing methods. Thirdly, the price of objects created via binder jetting is generally lower than that achieved with other 3D printing technologies. And finally, binder jetting is capable of fabricating objects in full colour.

To 3D print in colour, binder jetting sprays coloured inks as well as a binder solution onto each layer of powder. The technology is exactly the same as that used in traditional, 2D photo printers, with cyan, magenta, yellow and black inks applied in an appropriate combination. The CJP printers sold by 3D Systems are clever enough to only spray colour a few millimetres deep into the surface of an object, hence saving on ink consumption.

CJP 3D printers generally build objects from a proprietary, gypsum-based powder called VisiJet PXL. Once objects have been printed, they need to be left to cure (for around an hour) before removal from the printer. Even after curing, objects remain quite brittle and very fragile. Hence, while VisiJet PXL printouts may on occasion be used as printed (for example as display models), most need to undergo some form of post processing. This is called ‘infiltration’, and involves brushing, spraying or otherwise coating an object with a chemical that will fill in microscopic air pockets and seal its surface.

Freshly printed or ‘green’ VisiJet PXL objects can be infiltrated with a variety of chemicals. Objects that will receive minimal handling can simply be cured with a solution of salt and water. Those objects requiring more strength may alternatively be infiltrated with a one-part resin called ‘ColorBond’, while objects that have to be really strong require infiltration with a two-part, high-strength resin called ‘StrengthMax’. Objects finished with the latter become very strong indeed, and may be used as functional prototypes and even final production parts. Items such as spanners and robot assemblies have, for example, been successfully fabricated using binder jetting with a Strength-Max infiltration. Once suitably infiltrated, objects can be sanded, drilled, painted and electroplated as required.

In addition to its gypsum-powder hardware, in December 2013 3D Systems launched a full-colour binder jetting printer – the ProJet 4500 – that made objects from a plastic powder called VisiJet C4 Spectrum. However, less than three years later, this appears to have disappeared from the line.

While 3D Systems is the only company to offer colour printing in plastic powders, a German company called voxeljet (spelt with a small ‘v’!) has developed hardware that binder-jets large, single-colour objects. These are built using a powder called PMMA that is made from a modified acrylic glass which may be infiltrated with a single colour after printout. PMMA can also be infiltrated with wax for use in casting. Some voxeljet printers have an enormous build volume, with the mighty voxeljet 4000 able to make objects up to 4 x 2 x 1 m (about 13.1 x 6.5 x 3.3 feet) in size.

BINDER JETTING SAND CAST MOLDS & CORES

In addition to building objects from gypsum or plastic powders, some binder jetting 3D printers – including the voxeljet 4000 – can use casting sand as their granular build material. This allows molds and interior mold sections known as ‘cores’ to be 3D printed, with very significant industrial implications.

For thousands of years, sand casting has been a common process used to manufacture items in metals including iron, bronze, brass, steel, aluminium and gold. The age-old technique involves forming a mold by packing a special, resin-impregnated sand around a ‘pattern’ of the object to be manufactured. Such patterns are often made out of a material like wood that is relatively easy for craftspeople to shape. Once the sand has been compacted around it, the pattern is somehow removed in a process that may require the mold to be broken into pieces and reassembled. A molten metal is then poured in. Finally, once the metal has cooled and solidified, the sand mold is broken away to reveal the final object.

3D printers that binder-jet sand cast molds use exactly the same process shown in Figure 2.14. The only difference is that, on larger printers, the specially engineered sand is laid down from a hopper that passes over the print bed, rather than being rolled or swept from a rising powder reservoir. Once printing is complete, the loose sand that surrounds the object is removed, and the resultant mold is filled with metal in a normal sand casting process.

One of the benefits of 3D printing sand cast molds is that there is no need to create a physical pattern of an object before it is printed (a process that requires time and craft skills, or the use of another 3D printing technology). The binder jetting of sand cast molds also allows very complex and sometimes very large molds to be created that do not have to be broken apart to remove the pattern before casting. The application of this technology can therefore save a great deal of time and money.

BINDER JETTING METAL PRINTING

Binder jetting 3D printers were first created by Z Corporation to 3D print high resolution display models and prototypes in a gypsum composite. But an enterprising company called ExOne has pushed the boundary to create hardware that can manufacture objects from bronze, stainless steel, cobalt-chrome, the specialist nickel-based alloys Inconel 625 and Inconel 718, and so-termed ‘matrix’ powder mixes of iron and bronze, or iron, chrome and aluminium. Here, as in figure 2.14, a layer of metal powder is laid down and a print head moves across it to jet on a binder solution that glues together the metal granules where required. A heating lamp then dries the layer, and fresh powder is laid down.

Once all layers have been output, the powder box containing the very fragile and porous object is placed in a curing oven at about 175°C for 24 hours. This evaporates any moisture and hardens the binder. Next, all unused, loose metal powder is removed, revealing a still-delicate object that is about 60 per cent metal and 40 per cent air.

To make the object stronger, it must be infused with more metal. To achieve this, the object is arranged in a box with additional metal powder and surrounded by aluminium oxide grit to support it. It is then placed in a kiln for another 24 hours at over 2,000°C. Within the kiln the loose metal powder liquefies to infiltrate the object and turn it into something that is at least 99.9 per cent solid metal.

Once cooled, the final object is taken out of the kiln. Any supports or ‘sprues’ that had to be added to facilitate the infiltration are then removed by hand. Most objects created using binder jetting metal printing are also polished as part of their final post processing.

Binder jetting metal printing is, as you can see, a somewhat involved undertaking (although do please appreciate that many objects are usually cured and infiltrated in a curing oven or kiln at the same time). Even so, the technology currently offers the cheapest form of direct, powder-based metal printing. Parts produced in Inconel 625 or Inconel 718 may even be used to make final aerospace, turbine and other high-end industrial components. Binder jetting metal printing can also offer a range of surface finishes, including gold plating. The technology is therefore popular with some artists and jewelry makers. The maximum build volume is currently 800 x 500 x 400 mm (31.5 x 19.68 x 15.75 inches) on ExOne's M-Print machine.

BINDER JETTING CERAMIC PRINTING

Binder jetting processes also facilitate the 3D printing of ceramics. Here successive layers of powder – such as an alumina silica – are laid down and sprayed with a binder. Once all layers have been printed, the object is dried in an oven, after which excess powder is removed. The object is then fired in a kiln, pre-glazed, fired again, glazed, and fired for a final time. The result is a shiny, ceramic object that is highly heat resistant and food-safe.

While final objects created by ceramic binder jetting are smooth, due to the detail lost in glazing the resolution of this kind of 3D printing is limited to about 2 mm on all axes. Nevertheless, for the production of vases, plates, cups, bowls, egg cups and other tableware, the process is ideal.

BINDER JETTING GLASS PRINTING

As a final technology variant, ExOne has binder jetting hardware that can create glass objects. Here a powdered soda lime glass is laid down and its particles are selectively sprayed with a binder. The resultant object again needs to be cured in an oven, before being de-powdered. As in binder jetting metal printing, the resultant fragile object must finally be placed in a box with additional glass powder and fired in a kiln at 750°C. Objects produced using binder jetting glass printing are porous, brittle, and feel rough when touched. The technology can at present only produce relatively small objects (around 75 x 75 x 75 mm, or 3 x 3 x 3 inches), and is generally used for making sculptures and other decorative pieces.

POWDER BED FUSION

While binder jetting is a powder-based technology with many areas of application, it does have its limitations. Not least, even when objects are cured and infused post-printout, it is impossible to make things that are 100 per cent solid. Where this is essential, it is therefore necessary to turn to another 3D printing process called powder bed fusion. This is similar to binder jetting, but uses the selective application of heat to bond adjacent powder granules.

LASER SINTERING

Powder bed fusion can be achieved in a variety of ways, with the most widespread process being 'laser sintering' (LS). Here a layer of powder is rolled or swept across a powder bed, following which a laser beam traces out the cross-section of the first object layer. The heat from the laser 'sinters' the powder granules that it touches, so causing them to at least partially melt and fuse with adjacent granules. Figure 2.15 illustrates the process.

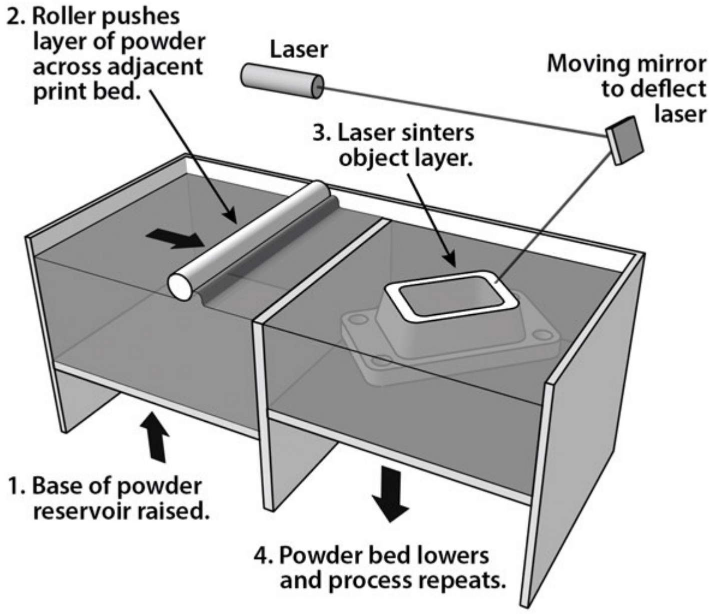

Figure 2.15: Laser Sintering Powder Bed Fusion.

Laser sintering can be used to build prototypes, tooling or final parts from a wide variety of powdered materials. These include plastics such as polyamides, many metals, ceramics, sand and wax. Where sand or wax are laser sintered, the resultant objects are used as patterns in a traditional casting process as previously outlined.

The powders used for laser sintering – and all other forms of powder bed fusion – must be graded to a very high quality to ensure that they form consistently thin and accurate object layers. In practice this means working with powder granulates that have a diameter of between 40 and 90 microns (0.04 to 0.09 mm) for plastic build materials, and 20 microns (0.02 mm) or less for metals.

Sometimes laser sintering is used to build objects from a two-component material. In such instances a powder with a high melting point (like glass or a metal) is mixed and in the process coated with a material with a lower melting point (such as a nylon polyamide). This allows the laser to only have to melt the material with the lower melting point in order to fuse the powder granules into a solid. In particular, a two-component material called 'alumide' has become popular. This is a nylon powder mixed with aluminium, and provides a means of fairly easily and cheaply producing objects with a metal sparkle at relatively low temperatures.

Laser sintering is a very accurate process that produces excellent results when building objects from plastic powders, such as the popular polyamide PA12. However, the sintering (or non-complete melting) of metal powders cannot produce final objects that have material properties suitable for engineering applications, such as the production of engine components. Because of this, various specialist and trademarked variants of laser sintering exist that use a laser beam to fully melt the granules of a powdered build material – such as aluminium, copper, steel, nickel alloys, cobalt-chrome, iron, silver, gold or titanium – in order to produce purer metal objects. All such processes have subtle differences depending on their implementation and the particular 3D printer manufacturer, and are variously known as 'direct metal laser sintering' (DMLS), 'selective laser melting' (SLM), 'laser beam melting' (LBM), 'direct metal printing' (DMP), 'laser metal fusion' (LMF) and laserCUSING. EOS e-Manufacturing Solutions in Germany has also developed what it terms 'micro laser sintering' (MLS) for producing small and intricate metal parts. Figure 2.16 shows a DMLS copper component produced by the UK 3D printing service 3T RPD.

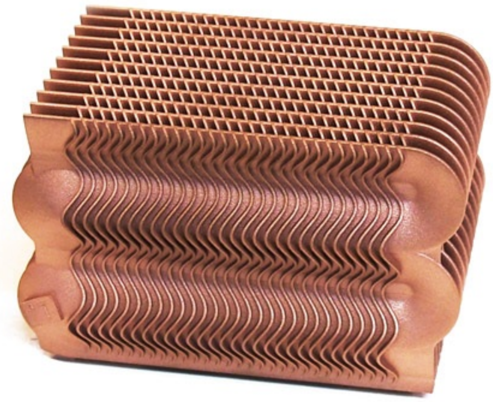

Figure 2.16: A Copper Part Printed by 3T RPD Using DMLS.

While it may sound fairly straight-forward, laser sintering is a challenging process. When working with polyamides and other non-metal materials, to make it easier for a laser to fuse the powder granules together the printer's build chamber is pre-heated to a temperature just below the material's melting point. When working with metals, pre-heating to just below melting point is not possible, and very high-power lasers need to be employed. While non-metal parts can be laser sintered without any support structures (as non-used loose powder holds overhangs and orphan sections in place), when printing with metal materials, support struts are normally required. These are necessary both to support overhangs and orphan sections, as well as to dissipate heat.

Commercial 3D printers that can laser sinter in plastics, waxes and composite materials can achieve a minimum layer thickness of about 0.08 mm, with the maximum build volume on such a machine being the 1,400 x 1,400 x 500 mm (55.0 x 55.0 x 19.7 inches) available on the mighty HRPS-VIII manufactured by the Wuhan Binhu Mechanical & Electrical Co in China. DMLS, SLM and related specialist metal technologies have a similar accuracy, but until fairly recently possessed a smaller build volume. For example, the top-of-the-range RenAM 500M from Renishaw has a build volume of 250 x 250 x 350 mm (9.8 x 9.8 x 13.8 inches), while the ProX DMP 320 from 3D Systems maxes out at

275 x 275 x 420 mm (10.8 x 10.8 x 16.5 inches). This said, in 2015 Concept Laser began shipping its X line 2000R with a build volume of 800 x 400 x 500 mm (31.5 x 15.7 x 19.7 inches).

The surface quality of objects produced via laser sintering and related technology variants is excellent, and a range of finishes can be achieved. For metal objects, these include polishing up to mirror quality. Laser sintering is therefore often the technology of choice for 3D printing final components. The only problem is that the hardware tends to be rather large and very expensive, particularly if it directly 3D prints in metals. Indeed, according to a January 2016 report from CONTEXT, the average weighted list price for a direct metal 3D printer in 2015 was $490,000. Figure 2.17 illustrates such a system – here the RenAM 500M from Renishaw.

Figure 2.17: A Renishaw RenAM 500M Industrial Metal Additive Manufacturing System. Image courtesy of Renishaw.

Smaller and cheaper hardware is, however, now coming to market. For example, German manufacturer Realizer have launched their SLM 50. This is the first 3D printer that can directly manufacture small metal items on the desktop, and has a cylindrical build volume of 70 mm (2.8 inches) in diameter by 40 mm (1.6 inches) high.

Even the SLM 50 costs in the region of $100,000. However, a company called Sintratec now sell a €4,999 (c.$5,600) kit for building your own laser sintering 3D printer. While this cannot fabricate in metal, it can print plastic objects (using the popular polyamide PA12) up to 110 mm (4.3 inches) cubed. Sintratec have also announced a pre-built laser sintering 3D printer called the S1 with a build volume of 150 x 150 x 200 mm (5.9 x 5.9 x 7.9 inches). This is expected to sell for about €9,000 or $10,000.

Additionally challenging the norm with low-cost powder bed fusion hardware are

Sinterit, who have launched a printer called the Lisa. This can similarly laser sinter highly detailed PA12 plastic objects, has a build volume of 110 x 150 x 130 mm (4.3 x 5.9 x 5.1 inches), and a price tag of €12,500 (about $14,000).

ELECTRON BEAM MELTING

In addition to laser sintering and its direct-metal variants, two other 3D printing technologies use heat to selectively solidify object layers on a powder bed. The first is electron beam melting (EBM). As you have probably guessed, this uses an electron beam to achieve the process illustrated in figure 2.15.

EBM 3D printers have been pioneered by a company called Arcam, and achieve very high quality results by building metal objects layer-by-layer in a vacuum, with the electron beam making multiple passes of each object layer. The first of these passes scans the powder bed to pre-heat the build material to an optimal temperature. A second pass then melts the outline of the object layer, while the following passes melt the bulk of material inside the outline.

The technology involved in EBM is highly sophisticated, with the electron beam moved around via electromagnetic deflection, rather than being directed by mechanically-mechanized mirrors. A claimed advantage of EBM over laser-based direct metal technologies is that completely dense (or in other words 100 per cent solid) components can be accurately created with zero distortion. In part this is due to the fact that objects are 3D printed in a vacuum.

EBM's use is restricted to high-value build materials, such as various grades of titanium and cobalt chrome. Using these, end-use components are now being manufactured for aerospace and other specialist industrial sectors. Medical implants have also been produced using the technology. The maximum build volume for EBM is currently 200 x 200 x 380 mm (7.8 x 7.8 x 15.0 inches) on an Arcam A2X.

SELECTIVE HEAT SINTERING

Also pioneering a powder bed fusion 3D printing method are a company called Blueprinter. Their innovation is known as 'selective heat sintering' (SHS), and uses a thermal print head to selectively solidify plastic powders. The key advantage is the ability to create entirely solid plastic objects with far lower-cost hardware than traditionally required for laser sintering, and also on the desktop.

Inside an SHS printer, a distributing blade spreads powder across the build area. A thermal print head then scans across it to melt the required particles together, and the process repeats.

As with all non-metal powder-based technologies, SHS produces objects that do not require the addition of support structures. Potentially, SHS may therefore develop into a popular alternative to the 3D printing of plastics via thermoplastic extrusion. A Blueprinter currently costs €25,450.00 (about $28,500), has a build volume of 157 x 200 x 150 mm (6.3 x 7.9 x 5.5 inches), and produces models in layers 0.1 mm thin.

DIRECTED ENERGY DEPOSITION

Yet another means of creating final-use metal objects from powdered materials is 'directed energy deposition' (DED), sometimes also known as 'laser powder forming'. Here a motion-controlled nozzle directs metal powder into a high-power laser beam for deposition as a molten build material, with the build platform sometimes also motion-controlled on multiple axis. Unlike all other current 3D printing technologies, directed energy deposition is therefore not limited to building objects from a progression of successive, flat layers. Various companies have developed the directed energy deposition process, including Optomec, who refer to it as 'laser engineered net shaping' (LENS), as well as TRUMPF and BeAM, who call their technology 'laser metal deposition' (LMD).

A variety of materials can be printed using directed energy deposition, including stainless steel, copper, nickel, cobalt, aluminium and titanium. Unlike in powder bed fusion, the metal powder fed to the print head can be altered continuously during printout. Directed energy deposition can therefore fabricate objects with properties that cannot be obtained using traditional production methods. Final objects do require some degree of surface finishing (such as machine polishing), but can otherwise be used directly after printout as fully-dense metal parts. The maximum build volume for the technology is currently the 1,200 x 800 x 800 mm (47.2 x 31.5 x 31.5 inches) of the 'MAGIC 2.0 Machine' made by BeAM.

Because printout does not take place on a flat powder bed, directed energy deposition has the unique advantage of being able to repair existing objects as well as fabricating new ones. Recently, for example, I visited the Rolls Royce factory in Derby in the United Kingdom, where directed energy deposition is being used to add metal back onto the surface of worn turbine blades.

SHEET LAMINATION

Most 3D printing processes extrude semi-molten materials, solidify photopolymers, or bond powders. There is, however, a final and quite different generic technology category that ought to be on our radar. This goes by the name of 'sheet lamination', and sticks together sheets of paper, plastic or metal foil. Where sheet lamination adheres sheets of paper, it is sometimes also known as 'laminated object manufacture' (LOM).

Sheet lamination can be achieved using a variety of mechanisms, but all somehow advance a sheet of build material onto a build platform. This material may have an adhesive backing, or during the build process may have adhesive applied. A laser or blade is used to cut the outline of an object layer into the sheet, and the build platform lowers just a little. The process then repeats until all object layers have been created.

As with most powder-based 3D printing technologies, objects created via sheet lamination do not require support structures, as the unused build material that surrounds them holds everything in place. To ease excess material removal, it may be cross-hatched during printout. This allows unwanted paper, plastic or foil to be removed by hand in small blocks.

Back in 2001, one of the first 3D printers I ever saw in operation was a sheet lamination machine about the size of a small automobile. The device was printing out a test design for the sole for a new pair of shoes, and was making a very good job of it indeed. In fact, by sticking together layer-after layer of laser-cut paper laminate, the printer managed to create a very solid and quite beautiful object that looked and felt like it was carved out of wood. (I should note that laser cutting can brown the edges of paper sheets very slightly). Quite by chance, in 2012 I came across the very same machine gathering dust in a 3D printing research lab to which it had been donated. Unfortunately, this particular LOM hardware only came with software drivers for Windows 3.1, and had therefore not been used in years.

Sheet lamination was invented by a company called Helisys in 1991 that has since gone out of business. Several other sheet lamination 3D printer manufacturers have also entered and left the market since that time, and many commentators therefore dismiss the technology as being in decline. This is, however, premature, as recently some new sheet lamination printers have successfully come to market. In particular, since 2012 an Irish company called Mcor Technologies has launched three printers that use a proprietary process which it terms ‘selective deposition lamination’ (SDL) to build objects out of standard copier paper.

Mcor’s hardware allows the 3D printout of objects at a far lower cost than achievable with any other technology. Their larger Iris HD or Matrix 300+ 3D printers have a build volume of 256 x 169 x 150 mm when fed with A4 paper, or 9.39 x 6.89 x 5.9 inches when fed with letter paper, and a resolution of 0.1 mm. The Iris HD also has an integrated inkjet print head that can spray coloured inks onto each paper layer, so permitting the printout of full-colour objects that it describes as ‘tough, durable and eco-friendly’.

Also capable of fabricating full-colour 3D objects in paper is Mcor’s latest offering, the ARKe. This is ‘the world’s first colour desktop 3D printer’, and can produce photorealistic objects up to 240 x 205 x 125 mm (9.5 x 8.1 x 4.9 inches) in size.

Another successful sheet lamination pioneer is Fabrisonic, who have developed a process called ‘ultrasonic additive manufacturing’ (UAM). This creates objects out of layers of metal tape that are welded together using high frequency (20,000 hertz) vibrations. Fabrisonic’s technology has the advantage of being able to fuse different metals into the same part, so allowing the creation of items – such as metal objects with embedded sensors – that could not be created using traditional manufacturing techniques.

HYBRID HORIZONS

The seven ISO/ASTM 52900 3D printing process categories outlined over the last few score pages are incredibly useful in structuring our current and future understanding of 3D printing. Nevertheless, innovative new technologies will continue to be developed that do not sit neatly – or at all! – within their classification boundaries. For example, a company called ADMATEC has developed a process that it calls ‘Admaflex 2.0’ for 3D printing funtional ceramic components. This uses a UV laser to cure a photosensitive resin that is mixed with a ceramic powder and spread onto a moving plastic sheet.

Another very high-profile innovator is HP, which has developed a technology that it calls ‘Multi Jet Fusion’ (MJF). This lays down a layer of powder from one print carriage, before a print head or ‘HP Thermal Inkjet array’ on a second carriage (and which travels at 90 degrees to the first) selectively sprays droplets of liquid ‘fusing and detailing agents’ that are fused solid by applying heat. To maximise speed, not only do the two print carriages move across the print bed on different axis, but they also change direction on each pass (travelling right-to-left on one pass, left-to-right on the next pass, and so on).

HP claim that their technology can produce prototypes and final parts up to ten times faster and for half the cost of rival technologies. The first two MJP 3D printers – the HP Fusion 3D 4200 and 3200 – were revealed to the world in May 2016. They were also accompanied by processing stations that are used both before printout to load materials, as well as after printout for part cooling, part removal and the recovery of unused powder. To optimize operations, the print bed, together with the materials required for each print run, are housed in a wheeled pedestal – known as the ‘HP Jet Fusion 3D Build Unit’ – that is moved back and forth between the printer and its processing station. This facilitates continuous production, as one build unit can be in the printer while another is being loaded or unloaded. Prices for a complete HP Jet Fusion 3D printing system – including a printer, build unit and processing station – start at around $155,000.

The MJF process has clearly been developed with the intention of improving not just raw 3D printing speed, but overall production workflow. Alongside HP, other 3D printer manufacturers are also starting to make production workflow a priority. For example, as we shall see in the next chapter, both ExOne and voxelJet have now developed 3D printers to help facilitate the continuous production of sand cast molds. And as we saw earlier in this chapter, 3D Systems is developing a modular form of vat photopolymerization (SLA) hardware called Figure 4 that integrates robotic arms and which is intended for production line applications.

As 3D printing evolves from being a niche prototyping technology into a mainstream production process, achieving workflow enhancements will be absolutely critical. Most probably, many of these will be delivered via the integration of 3D printing technologies with more traditional production methods. Or as David Burns of Global Business Advisory Services argued in July 2016, ‘a few years ago, industrial 3D printing was basically in the experimental stage, and in stand-alone configurations. Now, just a few years later, major machine tool companies are embracing industrial 3D printing and integrating it into their core products and processes’.

Just one 3D printer manufacturer that is actively encouraging such traditional process integration is Optomec, who now sell not just complete 3D printers, but also their LENS print engine as a separate, modular component. This allows machine tools to be created that integrate LENS 3D printing with other metal manufacturing technologies including computer numerically controlled (CNC) mills, lathes, robots, custom gantries, laser cutters and welding systems.

Specific machine tools that already integrate 3D printing with subtractive processes include the OPM250L from Sodick. This combines laser-based, direct-metal powder bed fusion with CNC milling to provide a ‘one stop solution’ for manufacturing metal components. As a second example, the INTEGREX i-400AM from machine tool manufacturer Mazak combines a directed energy deposition print head again with CNC milling. As the company explain, ‘this hybrid, multi-tasking machine uses its additive capability to easily generate near-net-shape component features and then completes them via high-precision finish machining operations’.

The integration of 3D printing with traditional CNC technologies is a fairly new trend that is going to accelerate. As we saw earlier in this chapter, already companies like Sciaky (with their EBAM direct metal 3D printing process) and Norsk Titanium (with rapid plasma deposition) create printouts that are intended to be CNC machined to produce final parts. Using 3D printing to complete the stage of the production process at which it excels, and then employing other methods to finish things off, is also eminently sensible for all of those seeking to reap the benefits of additive manufacturing most effectively at lowest cost.

A SOLID FOUNDATION

So here we are, at the end of this gargantuan review of all current 3D printing technologies. As we have seen, there are already a plethora of methods that facilitate additive manufacturing. No current technology is without its drawbacks. Yet most current 3D printing processes are ripe for further improvement, and potentially an integration not just with conventional, manufacturing methods, but also with each other. In ten or twenty years time we may, for example, have digital production systems that produce plastic parts via material extrusion, metal parts via powder bed fusion, improve the surface quality of both via CNC milling, and then employ robotic mechanisms to put different components together.

One or two decades from now, there may even be hardware that uses the technology of life itself to assist in the digital fabrication of both inorganic and organic artificial structures. This would require the integration of the technologies covered in this chapter with developments in ‘bioprinting’, ‘synthetic biology’ and ‘molecular self-assembly’. Such extraordinary developments are now all being worked on and will be explored in chapter 7. So, if you thought you had finished reading about additive manufacturing methods, be forewarned that we still have a few more to go.

As I argued in the *Preface*, I remain convinced that 3D printing is set to transform how a great many things are indirectly or directly manufactured. The technologies covered in this chapter do, I suggest, provide a very solid foundation for such an industrial transformation. But, at least at the present time, they are not nearly enough. Technological revolutions are always a process of constant re-invention, and the 3D Printing Revolution can be no different.

If I ever get to write the tenth edition of this book, I am certain that it will detail additive manufacturing technologies that are yet to be imagined, let alone experimented with in the lab. Progress toward the 3D Printing Revolution is subsequently set to rely at least as heavily on the as-yet-unknown activities of innovative and visionary organizations as it is on the bedrock of current 3D printing technologies. The next chapter will therefore shift our focus to the major and emerging players in the 3D printing industry.

3. The 3D Printing Industry

In terms of revenue generated, 3D printing is an increasingly successful technology sector. Indeed, according to veteran industry analysts Wohlers Associates, in 2015 the global market for 3D printing products and services was worth $5.1 billion, compared to $4.1 billion in 2014, $3.1 billion in 2013, and $2.2 billion in 2012. The rate at which the 3D printing industry will continue to grow is exceedingly difficult to predict. This said, in June 2016, research group CONTEXT forecast that the market would be worth $17.8 billion by 2020, while in August 2016 Mordor Intelligence put the 2020 figure at $20.7 billion.

Other analysts come up with completely different estimates. For example, International Data Corporation (IDC) suggest that the global 3D printing market was actually worth about $11 billion in 2015, and will grow to $26.7 billion by 2019. IDC may even be right, although personally I have more faith in the figures from Wohlers Associates and CONTEXT. But regardless, the opening take-away here is that all major market analysts report 3D printing to be growing by at least 25 per cent per annum, and to already be worth many billions of dollars.

Financials aside, in the first half of this decade the 3D printing industry was characterized by two signature developments. The first was a wave of acquisitions as its largest players gobbled up smaller innovators and competitors. The second was then the *perceived* impact of the arrival lower-cost consumer and prosumer 3D printers on an industry that had got used to selling expensive hardware to a very niche, industrial market.

As we head toward 2020, at least 90 per cent of 3D printers sold are consumer or prosumer desktop models costing $5,000 or less. This said, the majority of industry revenues – probably a good 90 per cent of them – continue to come from the sale, rental and servicing of far-higher-priced industrial hardware, along with associated materials supply. There is no doubt that developments on the desktop have driven down some prices and have given some longstanding industry players quite a shock. But, while the market for consumer/prosumer devices will continue to expand (to perhaps 500,000 units a year by 2020), all serious analysts expect the vast majority of value added in 3D printing to remain industrially-based for the foreseeable future.

Due to the above, the 3D printing industry is not about to transition from the delivery of niche industrial technology to the supply of mainstream consumer hardware. But what we *are* starting to witness is an evolution from the sale and rental of industrial 3D printers used to make prototypes, to the supply of equally industrial 3D production systems used to manufacture end-use components. This transition is inevitably starting to draw a broadening range of traditional manufacturers into the previously close-knit 3D printing community. And it is the entrance of large, traditional manufacturers that is likely to define the 3D printing industry's evolution in the next five years.

This chapter overviews the current 3D printing industry and looks ahead to its future.

Initially, we will examine those companies who actually make 3D printers, and who are continuing to refine 3D printing technologies. We will then turn our attention to 3D software pioneers, and finally to just a few of those organizations who offer 3D printing services. Please note that I will not even attempt to detail every single business involved. You can, however, find an extensive company listing in the 3D Printing Directory that appears at the end of this book, and which is continually updated on ExplainingTheFuture.com. Information on the 3D printing industry can also be found on the website 3DPrintingStocks.com, run by my friend Gary Anderson.

PURE PLAY, PUBLIC 3D PRINTER MANUFACTURERS

The 3D printing industry came into existence in the mid-to-late 1980s when its founding pioneers invented the first additive manufacturing processes, filed patents, and created startup organizations. Today such 'pure play' companies – or in other words, firms dedicated entirely to 3D printing – still dominate the industry. As I have already indicated, in five years time this may no longer be the case. Even so, any analysis of the 3D printing industry ought to begin with 3D printer manufacturer pure plays, and in particular with those organizations that are large and successful enough to have floated on a stock market.

Before we get to the companies themselves, it is worth pointing out that over the past four years 3D printing stocks have been on an interesting journey, quadrupling in value and then falling just as much. For example, on 15 October 2014 the two largest players – 3D Systems and Stratasys – had market capitalizations of $4.51 billion and $5.47 billion. And yet wind forward two years, and in mid October 2016 they were worth $1.66 billion and $1.11 billion. At the time of writing, the market feeling seems to be that we are in a 3D printing stock price trough with a new peak on the horizon. But, as always when it comes to financing new technologies with revolutionary potential, investors continue to face risky and testing times ahead.

3D SYSTEMS

On March 9th 1983, inventor Charles 'Chuck' Hull used a computer-controlled laser to solidify the first layer of an object on the surface of a tank of liquid photopolymer. The perforated platform on which this layer was formed then lowered a fraction of a millimetre, and the process repeated until Hull had created a small, blue plastic cup.

With the successful completion of his groundbreaking experiment, Hull had invented 3D printing. After much development work, on 11 March 1986 he subsequently obtained US patent 4,575,330 for his 'Apparatus for Production of Three-Dimensional Objects by Stereolithography'. Also in 1986, Hull founded 3D Systems Corporation. Two years later, the company sold its first commercial 3D printer – or 'StereoLithography Apparatus' (SLA) – the SLA-250. To make all of this possible, around the same time Hull and his team also created the STL file format that is still widely used to save 3D printable CAD files. In May 2011, 3D Systems floated on the New York Stock Exchange (NYSE).

3D Systems had total revenues of $513.4 million in 2013, $653.7 million in 2014 and $666.2 million in 2015. This said, in February 2015 the company's management stated that they expected '2015 revenue to be in the range of $850 million to $900 million', which is a significant distance from the final reported figure of $666.2 million. While 3D Systems remains a very successful business, its numbers over the past few years do tell the story of a company whose expansion has peaked, and which has failed to achieve the growth seen across its industry as a whole. Indeed, in the first half of 2016, 3D Systems shipped fewer printers and generated lower revenues than in the first half of 2015.

In addition to making its SLA vat photopolymerization hardware, 3D Systems now sells 3D printers that are based on material extrusion (a process it terms plastic jet printing), powder bed fusion (under the banners of selective laser sintering and direct metal laser sintering) material jetting (MultiJet Printing), and binder jetting (ColorJet Printing). Hardware based on the latter technology was initially commercialized by company called Z Corporation that 3D Systems acquired in 2012.

3D Systems currently describes itself as a provider of 'comprehensive 3D products and services, including 3D printers, print materials, on-demand parts services and digital design tools'. As it further notes:

> As the originator of 3D printing and a shaper of future 3D solutions, 3D Systems has spent its 30 year history enabling professionals and companies to optimize their designs, transform their workflows, bring innovative products to market, and drive new business models.

To achieve its market position, 3D Systems has in recent years gone on a purchasing spree and has acquired not just Z Corporation, but over 20 other 3D printing pioneers. These have included the 3D printing service providers Easyway Design, Formero, Kemo Modelmakerij, Paramount Industries, Quickparts, Robtec and The Innovative Modelmakers; 3D content and software developers Alibre, Cimatron, Geomagic, My Robot Nation, Rapidform, Sycode, The3Dstudio.com and Viztu Technologies; 3D printed prosthetics pioneer Bespoke Innovations; the 3D printing design company Freedom of Creation; imaging specialist Vidar Systems; direct metal 3D printer manufacturer Phenix Systems; desktop 3D printer manufacturer Bits From Bytes; ceramics 3D printing company Figulo; the direct metal printing specialist LayerWise; 3D printing food specialist The Sugar Lab; and colour 3D printing pioneers botObjects. As you can see, 3D Systems really has been on a purchasing spree.

In January 2012, 3D Systems entered the consumer market when it released a $1,299 material extrusion 3D printer called the Cube. Pretty much concurrently it also launched an online 3D printing platform named Cubify to sell collections of customizable 3D printed objects. Further consumer Cube models were launched in January 2013 and January 2014. But then, on 28 December 2015, a press release was issued indicating that 3D Systems was to 'end-of-life' its entry-level Cube and to close Cubify on 31 January 2016.

The decision to kill Cubify and the consumer-grade Cube 3D printer reflected management plans 'to focus its resources and strategic initiatives on near-term opportunities and profitability'. More expensive Cube Pro printers (costing between \$3,000 and \$5,000) do continue to be sold. But 3D Systems clearly does not currently consider consumer 3D printing to be a viable market in which to operate.

Between 2014 and 2016, 3D Systems had announced several very interesting lower-cost desktop printers, including two 'CeraJet' colour ceramics printers to 'democratize pottery making in the digital age'; a full-colour desktop material extrusion model called the 'CubePro C'; two 'ChefJet' food printers; and a 'CocoJet' chocolate printer. Sadly – and perhaps not surprisingly given the above decision – at the time of writing none of these models have arrived on the market.

The above noted, on 28 October 2015 3D Systems did open its '3DS Culinary Lab' as a space 'where chefs, mixologists and culinary innovators can experience the intersection of their traditional craft and 3D printing'. The Culinary Lab is also 'designed to be a testing ground where the industry can experience the 3DS ChefJet Pro culinary printer firsthand ahead of its release'. This provides at least some hope that this hardware will one day become available. Although, as I argued in the last chapter, I suspect it will take a traditional food manufacturer to deliver the first viable, mass-market ecosystem for food printing.

In April 2016 3D Systems announced a developmental, industrial additive manufacturing system called the SLAbot-2. Based on the company's 'Figure 4' technology, this offers very high speed SLA 3D printing in a modular machine tool that also incorporates robot arms that undertake post-processing and other operations. 3D Systems claims that the SLAbot-2 is up to 50 times faster than existing vat photopolymerization 3D printing systems, in turn making it a viable end-use manufacturing tool. Should 3D Systems convince manufacturing companies to successfully adopt this technology, it could have very positive implications for the future of the business.

STRATASYS

Alongside 3D Systems, the other corporate giant in the 3D printing world is Stratasys. The company is of a similar scale to 3D Systems, with revenues of \$484.4 million in 2013, \$750.1 million in 2014 and \$696.0 million in 2015. As we saw with 3D Systems, recent times have been tougher than those before them, even though the industry as a whole has experienced very healthy expansion. Reflecting its changing fortunes, Stratasys reduced its global workforce by about 10 per cent during the fourth quarter of 2015.

While 3D Systems was founded on the back of vat photopolymerization, Stratasys was born following the invention of the material extrusion 3D printing process, which it named fused deposition modelling (FDM). This was devised by Scott Crump in 1988 when he made a toy frog for his daughter by building it up in layers using a hot glue gun. The same year Scott established Stratasys with his wife Lisa, and in 1989 filed a patent application for the FDM process.

By 1992, Stratasys was shipping its first commercial 3D printer – the '3D Modeler' –

and in 1994 went public on the US NASDAQ stock exchange. For a time Stratasys even owned the trademark on the term ‘3D printer’, although in 1999 it allowed the phrase to enter the public domain. Between its foundation and 31 December 2015, Stratasys has reported the sale of 146,024 3D printing systems.

Like 3D Systems, Stratasys has grown in part via acquisition, with the company having taken over or merged with 3D printer manufacturers Solidscape, Objet and MakerBot Industries; service providers Solid Concepts and Harvest Technologies; collaborative CAD pioneer GrabCAD; and 3D printing consultancy Econolyst. With the completion of its merger with Objet in January 2013, Stratasys Inc. became Stratasys Limited.

The purchase of MakerBot Industries in June 2013 was also a game changer. When I completed the first edition of this book in April 2013, I signed off the Stratasys entry by stating that the company ‘currently focuses its business solely on serving high-end, industrial clients, with its customers including Boeing, Intel and Ford’. And at the time this was true. But in a single stroke, the purchase of MakerBot gave Stratasys a major foothold in the consumer/prosumer market.

Currently operating as a subsidiary of Stratasys, MakerBot continues to trade under its own name, and produces a range of lower-cost desktop 3D printers – or ‘Replicators’ – that use material extrusion to create plastic objects. The company was founded in January 2009 by Bre Pettis, Adam Mayer, and Zach ‘Hoeken’ Smith, who had been working on the RepRap open source 3D printing initiative. As we shall see in chapter 5, the RepRap community develops free 3D printer designs and build instructions in an attempt to make 3D printing more accessible. Though as the MakerBot founders recognised, not everybody has the skills or time to scratch build their own 3D printer. Pettis, Mayer and Smith subsequently quit their jobs to set up a company that would start from the RepRap designs to create a low-cost, commercial ‘robot that would make things’, or ‘MakerBot’.

MakerBot initially sold 3D printer kits for enthusiasts, with the first – the Cupcake – launched in 2009. Since that time, MakerBot has gone on to produce fully-assembled hardware, with its current range including a fifth generation MakerBot Replicator, the MakerBot Mini, and the MakerBot Digitizer 3D scanner. On 5th April 2016, Stratasys announced that the 100,000th MakerBot had been sold.

MakerBot also created and still runs Thingiverse. This is the world’s largest 3D-object-sharing website, and allows MakerBot owners – and indeed anybody else – to access and contribute to a ‘universe of things’.

MakerBot was also the first 3D printer manufacturer to open retail outlets, and began welcoming customers at 298 Mulberry Street in the NoHo district of Manhattan in September 2012. Two other stores then followed. But sadly, on 17 April 2015, it was announced that all three MakerBot stores were to close, with the company also firing around a fifth of its employees. At the time of writing Stratasys clearly remains committed to consumer/prosumer 3D printing. But, in common with 3D Systems, it has clearly had to concede that the time and technology are not yet right to sustain more than a relatively modest enthusiast and educational user base.

In addition to trading under its own name, and as MakerBot Industries, Stratasys still runs SolidScape as a separately branded division, GrabCAD as ‘the hub for digital manufacturing’, and Stratasys Strategic Consulting. It also operates a large 3D printing service provider called Stratasys Direct Manufacturing. This was formed in February 2015 via the merger of its previous 3D printing service divisions RedEye On Demand, Harvest Technologies and Solid Concepts.

Stratasys describes itself as ‘the 3D printing solutions company’, a ‘world leader in 3D printing – and its biggest fan’. As it goes on to note:

> We are passionate believers in the value and power of 3D printing, and in the change it can bring to the world. We create the systems, materials and communities that make 3D printing essential for manufacturers, empowering for designers and educators, and inspiring for makers.

Following its acquisitions of Solidscape and Objet, today Stratasys sells 3D printers based not just on its material extrusion (FDM) technology, but also two variants of material jetting. These it calls PolyJet (which delivers very high quality, multi-material printing that can be in full colour), and wax deposition modelling (WDM), which is used to create casting patterns in the dental sector and other industries.

All of the 3D printing technologies offered by Stratasys remain widely in demand, with FDM and Polyjet increasingly being adopted for end-use manufacturing and mold making. However, it should be noted that Stratasys has no technology that is capable of 3D printing in metal. The acquisition of another company capable of direct metal additive manufacturing is therefore in the firm’s medium- and long-term strategic interest, and may hence be expected.

ARCAM

In addition to Stratasys and 3D Systems, at the time of writing (in early November 2016) there are six other smaller, publicly-listed, pure play 3D printer manufacturers. The first of these is the Swedish pioneer Arcam, whose shares are traded on the NASDAQ OMX stock exchange in Stockholm. Arcam had sales revenues of 199.40 million Swedish Krona (SEK) in 2013, SEK 339.0 million in 2014 and SEK 576.1 million in 2015. Allowing for exchange rate changes over time, these figures equate to a turnover of about $31.1 million in 2013, $40.2 million in 2014 and $68.1 million in 2015. As these financials indicate, Arcam continues both to thrive, and to outperform the rest of the 3D printing industry. Perhaps reflecting this fact, on 6 September 2016 GE made a bid to purchase Arcam. And so by the time that you read this, Arcam may no longer be an independent company.

Like many other 3D printer manufacturers, Arcam was founded on the back of a unique technology, which in this instance was a powder bed fusion process called electron beam melting (EBM). Here object layers are created by fusing together the particles of a fine metal powder in a vacuum. The process produces very accurate objects with a high degree of material purity, and is increasingly popular for those seeking to create high-value, end-use metal parts.

Arcam's roots date back to development work initially undertaken in collaboration with the Chalmers University of Technology in Gothenburg. By 1993 a patent application was filed for the process of 'melting electrically conductive powder, layer by layer, with an electron beam, for the manufacturing of three-dimensional bodies'. Arcam was subsequently founded in 1997, with its first production 3D printer – the EBM S12 – launched in 2002.

Arcam states that its vision is to 'revolutionize the art of manufacturing complex parts', in which pursuit it 'provides a cost-efficient additive manufacturing solution for [the] production of metal components'. Most of Arcam's customers are currently in the orthopedic implant and aerospace industries. For example, the Adler Ortho Group – an Italian manufacturer of orthopedic implants – launched a medically certified hip implant manufactured using Arcam 3D hardware as far back as 2006.

Arcam currently sells three different EBM printers. Of these, the Arcam Q10plus is intended for orthopedic implant manufacturing, while the larger Q20X and A2X are targeted at those seeking to make aerospace components. In 2015, Arcam shipped 50 printers, and in December 2015 received its largest order to date. This was from Avio Aero, a subsidiary of GE Aviation, who required ten new EBM machines to allow them to move into the series production of 3D printed aircraft turbine blades. It really is not that much of a surprise that GE has plans to purchase Arcam.

EXONE

The ExOne Company was founded in 2005 as a spin-off from the Extrude Hone Corporation – a business with over 40 years experience in non-traditional machining processes. The company had an initial public offering of its shares on the US NASDAQ stock exchange in February 2013. Annual sales revenues were $39.6 million in 2013, $43.9 million in 2014 and $40.4 million in 2015.

ExOne specializes in the production of binder jetting systems that 3D print in metals, casting sand or glass. The company describes itself as a provider of '3D printing machines [and] 3D printed products and related services to industrial customers in multiple segments, including pumps, automotive, aerospace, heavy equipment and energy'. It also notes that its binder jetting technology 'gives traditional manufacturers an opportunity to reduce costs, [to] lower the risk of trial and error, and [to] create opportunities for design innovation'. As the company further explains:

> We collaborate with our clients through the entire development and production process so that they are able to 'materialize' new concepts – designs, prototypes, and production parts – precisely when needed. Production scale is irrelevant and lot quantities of one are just as efficient as lot quantities of one thousand. We offer both the services and the equipment to enable point-of-use manufacturing using additive manufacturing processes.

ExOne currently sells ten different 3D printer models, and like other major pioneers it continues to innovate. For example, in May 2014 it announced the addition of Inconel 625 (a nickel-based alloy commonly used for aerospace components) to the list of materials it can 3D print. This development was highly significant, as it opened up many new areas of industrial application for binder-jetted direct metal printing. Since that time, Inconel 718 has also been added to ExOne's material palette.

In addition to direct metal output, the 3D printing of casting sand using ExOne's hardware has tremendous industrial potential. Until quite recently, 3D printed sand cast molds and cores were mainly used to cast prototype, one-off or very-low-run parts. However, in March 2015, ExOne added a new printer to its range – the Exerial – that is specifically designed to allow industrial scale, series production. To facilitate this, the Exerial features multiple workstations and two job boxes (powder beds). ExOne sold 38 3D printers in 2015, four of which were Exerial production systems.

SLM SOLUTIONS

SLM Solutions is the most recent 3D printer manufacturer to have gone public, having listed in the Prime Standard segment of the Frankfurt Stock Exchange in May 2014. Based in Lübeck in Germany, the company produces powder bed fusion hardware that can directly 3D print in metal using selective laser melting (SLM). Revenues were €21.6 million in 2013, €36.6 million in 2014 and €61.1 million in 2015. Allowing for exchange rate changes over time, these figures equate to about $29.7 million in 2013, $44.3 million in 2014 and $72.5 million in 2015.

Once again, such financials demonstrate a very solid performance for a public European 3D printer manufacturer. Perhaps for this reason, on 6 September 2016 GE made a bid to purchase SLM Solutions for about $740 million. However, by late October GE abandoned this bid due to the actions of an activist investor.

While SLM Solutions brought its 3D printing technology to the market in 2000, it has only been trading under its current name since 2011. This followed the break-up of the previous MTT Technologies Group of which it comprised one element.

SLM Solutions currently manufactures three 3D printers, with its customers including Audi, BMW, GE, NASA and Siemens. The business has continued to expand at pace – for example opening a Shanghai office in November 2015, and a Russian branch in Moscow in February 2016.

VOXELJET

Another public, pure play industrial 3D printer manufacturer is voxeljet, with its name spelt with a small 'v'. This German pioneer floated on the New York Stock Exchange in October 2013, and turned over €11.7 million in 2013, €16.2 million in 2014 and €24.1 million in 2015. Allowing for exchange rate changes over time, these figures equate to a turnover of about $16.1 million, $19.6 million and $26.1 million in 2013, 2014 and 2015 respectively.

Voxeljet currently sells six 3D printer models. The biggest of these – the VX4000 – has a build volume of 4 x 2 x 1 m (about 13 x 6.5 x 3.3 feet), and is the world's largest 3D printing system for producing sand cast molds. Another voxeljet offering – the VXC800 – was also the world's first continuous 3D printer. As the company explains, the VXC800:

> … establishes a completely new generation of machines that allows the building and unpacking process steps to run simultaneously, without having to interrupt system operations. This leap in technology has become possible thanks to a novel pending patent design featuring a horizontal belt conveyor that controls the layer building process. The layers are built at the entrance of the belt conveyor, while the unpacking takes place at the exit. The finished component can simply be removed from the rear end of the system once all of the material has been utilized.

In addition to manufacturing 3D printers, voxeljet offers a range of related services. These comprise 3D modelling, mold design, and casting in a range of metals. In May 2011, 3D Systems signed an agreement with voxeljet to distribute its products in the United States. VoxelJet notes that its customers include 'prominent companies' in the automotive, aerospace, engineering, shipbuilding and other heavy industries, as well as those involved in 'architecture, film and art'.

TINKERINE STUDIOS

Sitting alone as a pure play, public 3D printer manufacturer at the consumer end of the market is Tinkerine Studios. This Canadian company launched its first printer – the $999 Litto – in the Spring of 2012, and floated on the TKSTF stock market in June 2014. Revenues were $122,739 in 2013, $342,839 in 2014, and $1.27 million in 2015, with the company making a net loss in all three of these years.

Today, Tinkerine sells two DIY material extrusion printer kits – the Litto and the Ditto – for $1,249 and $999 respectively, as well as the fully-assembled Ditto Pro for $1,899. These are nice pieces of hardware, if hardly anything special, and there are many other far more successful manufacturers of personal 3D printers. Tinkerine Studios just happens to have managed to float on a stock market during the first 3D printing bubble. We will look at the best-selling manufacturers of low-cost, personal 3D printers and their hardware in chapter 5.

ORGANOVO

Another 3D printer creator whose shares are publicly traded is Organovo. This is at the cutting-edge of research into organic 'bioprinting', and has developed a 3D printer called the Novogen MMX that outputs layers of living human cells. Organovo declared revenues of $400,000, $600,000 and $1.5 million in its fiscal years ending 31 March 2014, 2015 and 2016 respectively. It is yet to turn a profit, but this is hardly a surprise for a research-focused organization pioneering a new medical field. We will look in detail at Organovo and other bioprinting pioneers in chapter 6.

DIVERSIFIED PUBLIC 3D PRINTER MANUFACTURERS

As the market for 3D printers matures, so traditional, diversified public companies are likely to play an increasing role in its development. This is, after all, what happened in other technology sectors like personal computing. We probably also need well-established manufacturers with deep pockets and long-standing research expertise to take 3D printing to the next level. Below I therefore feature those companies who may dominate the industry in the future.

KINPO GROUP / XYZPRINTING

Personally, I think that the most interesting public company to have entered 3D printing is a Taiwanese manufacturing conglomerate called the Kinpo Group. This has annual revenues of about $30 billion, and in 2013 created a new division called XYZprinting.

You may not have heard of Kinpo, but it has been making electronic products (such as calculators, printers, storage hardware and set-top boxes) since 1973. Most of the things Kinpo produces are sub-contract manufactured for big brands, with the company still making about 70 per cent of the world's calculators and perhaps half of all traditional '2D printers'. However, when it comes to 3D printing, Kinpo has decided to jump in ahead of other established players and to launch its own brand.

Kinpo's XYZprinting unveiled its first 3D printer – a desktop material extrusion model known as the da Vinci 1.0 – in January 2014. This promptly won a *CES Best of Show Award*, and hit the Western market in March 2014 priced at $499. Since that time, nine siblings have been launched that range from the $230 da Vinci miniMaker and $349 da Vinci Jr. 1.0, up to the $899 da Vinci 1.0 Pro 3-in-1 (which integrates a laser scanner and can also be fitted with an optional laser engraver). When you look at these prices, it perhaps becomes clear why 3D Systems chose to stop competing in the consumer market. In July 2016, CONTEXT revealed that XYZprinting had a 25 per cent share of the global, personal 3D printing market by units sold, so making it the number one player.

XYZprinting currently also sells a $1,500 'prosumer-grade SLA 3D printer' called the Nobel 1.0. In addition, it has revealed plans for a full-colour, material jetting machine (the 3PP0A) that is intended to be both cheaper and four-to-ten times faster than comparable hardware from 3D Systems.

Given progress to date, it appears that XYZprinting is employing a strategy of starting at the low end of the market and working upwards (which is exactly the reverse of the approach adopted by rivals 3D Systems and Stratasys). There also seems little doubt that XYZprinting is so far living up to its goal of 'bringing cost-effective 3D printing to consumers and businesses around the world'.

RENISHAW

The Renishaw Group began life in 1973 in the United Kingdom, with its first product being a trigger probe for the engines used in the Concorde supersonic aircraft. Since that time, the company has grown into a world-leading engineering and scientific technology business, with offices in 35 countries and a particular expertise in metrology, precision measurement and healthcare. An early non-pure-play pioneer, in 2011 Renishaw began making powder bed fusion, direct metal additive manufacturing systems. At the time of writing, it remains the only British manufacturer of such hardware.

Renishaw systems are currently used to 3D print both tooling and final metal parts in the dental, other medical, automotive, motorsport and creative sectors. To help customers to leverage the possibilities afforded by 3D printing, the company has established a network of ‘Additive Manufacturing Solutions Centres’. In June 2016, the latest of these was opened in Pune in India.

GROUPE GORGÉ / PRODWAYS

Established in 1990, Group Gorgé is a French industrial conglomerate. The organization operates globally, mainly working to ensure the safety of people and property in sectors that include the nuclear industry, robotics and fire prevention. In December 2013 Group Gorgé also entered the 3D printing marketplace with the launch of a new division called Prodways. This started out selling industrial 3D printers that manufacture objects using a unique DLP vat photopolymerization technology called ‘DLP MOVINGLight’. By October 2016, Prodways offered a range of eight different MOVINGLight systems.

In March 2015, Prodways acquired Norge Systems, and in September 2015 also signed a strategic partnership with Chinese 3D printer manufacturer Farsoon Technologies. These undertakings allowed Prodways to develop and start selling a range of plastic and direct-metal powder bed fusion printers. One of these is the ProMaker P1000, which builds objects from plastic powders, and which was launched in May 2016 as the ‘first industrial laser sintering printer [to sell for] under €100,000’.

With its Prodways division, Group Gorgé has ambitions to challenge the current market dominance of 3D Systems and Stratasys. And in this it may succeed.

HP INC

From 1939 to 2015, Hewlett-Packard was a world-leading American IT company that grew to a turnover of well over $100 billion. In November 2015, it split into two companies called HP Inc and Hewlett Packard Enterprise. The drivers and results of this split are beyond the scope and interest of this book. But what does concern us is HP Inc’s long-awaited re-entry into 3D printing.

HP first dipped its corporate toes into the 3D printing ocean in April 2010, when it launched two ‘DesignJet’ 3D printers. These were sub-contract manufactured by Stratasys, and sold for a couple of years in France, Germany, Italy, Spain and the United Kingdom. Things then went very quiet, until rumours started to circulate that HP was to re-enter the market with its own, unique technology. This was confirmed on 29 October 2014, when HP revealed that it would start selling industrial 3D printers based on a process called ‘Multi Jet Fusion’ (MJF).

When MJF was announced, no hardware was put on show, and 18 months later people were starting to wonder if it would ever appear. But then, on 17 May 2016, HP Inc unveiled what it termed ‘the world’s first production-ready commercial 3D printing system’. This, HP claims, is capable of delivering ‘superior quality physical parts up to 10 times faster and at half the cost of current 3D print systems’. Figure 3.1 illustrates HP’s much anticipated Jet Fusion 3D 4200 hardware.

Figure 3.1: An HP Jet Fusion 3D 4200 & Build Unit.
Photograph: Christopher Barnatt.

At the time of writing, MJP 3D printers are limited to a single plastic build material (and specifically the polyamide PA12). But in time, the plan is to increase the palette of materials and colours using an open-platform approach and working with partners that initially included Arkema, BASF, Evonik and Lehmann & Voss. HP is also already working with a second set of ‘development and strategic partners’ with whom it hopes to ‘transform the global manufacturing industry’. At product launch, these companies comprised Nike, BMW, Johnson & Johnson, Jabil and Siemens, as well as 3D software pioneer Autodesk, and the leading 3D printing service providers Materialise and Shapeways.

CANON

Canon Inc is a Japanese multinational that specializes in imaging and print technologies. In March 2014 and April 2015, the company announced that its Japanese and then its European divisions would begin distributing printers from 3D Systems. As Canon has explained, this arrangement allows it to combine its own ‘sales, service and operations with 3D System’s broad technology portfolio’. It is also a strategically smart partnership for 3D Systems, as no 3D printing pure play has yet developed the sales and logistical capabilities of a tried-and-tested conglomerate.

At an Expo in Paris in October 2015, Canon also unveiled the in-house development of an own-brand ‘concept 3D printer’ based on what it termed a ‘resin-based lamination process’. This ‘entirely new’ 3D printing method is intended to be faster and to produce stronger prints than current technologies, and will be suitable not only for rapid prototyping ‘but rapid manufacturing as well’. No more details are currently available, and the 3D printing industry awaits further announcements with baited breath.

TOSHIBA

Similarly working toward the launch of potentially transformative hardware is the Japanese manufacturing conglomerate Toshiba. Here a direct metal 3D printer is being developed, with sponsorship from Japan’s Ministry of Economy, Trade and Industry (METI). Toshiba’s printer uses a technology termed laser metal deposition (LMD), which ‘deposits powdered metal and delivers a laser beam in tandem’. This is probably best characterised as a new form of directed energy deposition, and is claimed by Toshiba to be both cheaper and ten times faster than existing powder bed fusion technologies. In November 2015, Toshiba showcased a working prototype of its hardware, which it expects to become commercially available ‘around 2017’.

RICOH

Also in Japan, imaging and electronics giant Ricoh entered the 3D printing marketplace in September 2014. Like Canon, it started its additive manufacturing ‘AM Business’ division by selling printers from third parties, as well as opening ‘Rapid Fab Facilities’ in Yokohama and Atsugi. However, in October 2015, it also launched the RICOH AM S5500P as its first Ricoh branded 3D printer. This is a powder bed fusion device that produces objects in nylon and polypropylene. Like HP, Canon and Toshiba, Ricoh is very much in pursuit of a slice of the industrial 3D printing market.

MATSUURA & MITSUBISHI

A final Japanese conglomerate with its toes in the water of the industrial 3D printing business is Mitsubishi. In 2014, the company struck a deal with the Matsuura Machinery Corporation to begin selling ‘hybrid’ metal 3D printers in Japan, and via Mitsubishi subsidiary MC Machinery Systems Inc in the United States. The hardware currently on offer is the LUMEX Avance-25, which combines the powder bed fusion of stainless steel, cobalt chrome or titanium with high-speed CNC milling. This allows final metal parts to be additively manufactured, and then surface finished to a very high quality, within a single machine.

GE

On 6 September 2016, GE announced plans to purchase the European 3D printer manufacturers Arcam and SLM Solutions for a combined total of $1.4 billion. By late October the bid for SLM Solutions had been abandoned, and an improved offer had been made for Arcam, with the deadline for this deal extended. At the time of writing (in early November 2016) whether or not GE will acquire Arcam therefore remains unknown. However, on 27 October 2016, GE announced that it was purchasing a 75 per cent stake in the privately-held 3D printer manufacturer Concept Laser for $599 million. I hence include GE in this listing of diversified, public 3D printer manufacturers with a high level of certainty, as all that remains to be determined is the size of the company's stake in the 3D printing marketplace.

In the press release announcing its initial intent to purchase Arcam and SLM Solutions, GE signalled the importance of 3D printing to the company. As its chairman noted:

> Additive manufacturing is a key part of GE's evolution into a digital industrial company. We are creating a more productive world with our innovative world-class machines, materials and software. We are poised to not only benefit from this movement as a customer, but spearhead it as a leading supplier. Additive manufacturing will drive new levels of productivity for GE, our customers, including a wide array of additive manufacturing customers, and for the industrial world.

PRIVATE 3D PRINTER MANUFACTURERS

As well as its publicly traded giants, the 3D printer manufacturing sector has a great many smaller and privately-held market players. As far as I could ascertain, by the end of October 2016, there were 48 manufacturers of industrial 3D printers. My own 3D Printing Directory then listed 33 companies that manufactured consumer/prosumer models.

If I detailed below even just the remaining private industrial 3D printer manufacturers then your eyes would probably glaze over and may even be at risk of healing up. So here I will highlight only those companies that I consider particularly important in terms of their actual or potential contribution to industrial 3D printing. Chapter 5 (on personal manufacturing) will then detail some of the most significant manufacturers of lower-end personal and prosumer hardware.

ASPECT

Aspect is a Japanese manufacturer of powder bed fusion printers that build objects from polypropylene. The company was founded in 1996 by Seiji Hayano, who had previously worked on the development of additive manufacturing at Mitsubishi, and who established the Japan Rapid Prototyping Association. In 2006, Aspect launched its first powder bed fusion hardware, the SEMPlice series. The company's current RaFaEl series was launched in 2011, with these printers designed in collaboration with Ricoh.

BEAM

Founded in 2012, BeAM is a French company that makes 3D printers based on a directed energy deposition process called laser metal deposition (LMD). This injects metal powders though a print nozzle, where they are melted with a laser and deposited to produce fully-dense, end-use metal parts. In addition to fabricating new components from scratch, LMD 3D printers can add metal onto existing parts in order to augment components produced via traditional manufacturing, or to effect repairs.

BeAM's 'MAGIC 2.0 Machine' has a very impressive build volume of 1,200 x 800 x 800mm (47.2 x 31.5 x 31.5 inches). The company's clients and partners include businesses working in the aerospace, defence, nuclear, oil and gas industries.

CONCEPT LASER

At the time of writing (in early November 2016), Concept Laser is a German manufacturer of industrial powder bed fusion 3D printers based on a high-end process known as LaserCUSING. However, on 27 October 2016, GE purchased a 75 per cent stake in Concept Laser, with an agreement to allow it to take full ownership in a number of years. The deal will see Concept Laser founder Frank Herzog continuing as CEO of the company, as well as assuming a senior leadership position within GE.

ENVISIONTEC

EnvisionTEC's 3D printers – or 'computer aided modelling devices' (CAMOD) – build objects via vat photopolymerization. Most of its 3D printers are based on DLP projection, and are marketed under the 'personal factory' or 'Perfactory' brand. However, in its Ultra range of printers, EnvisionTEC employs its own alternative technology which it calls 'scan, spin and selectively photocure' or '3SP'. EnvisionTEC additionally sells a '3D-Bioplotter' for use in tissue engineering. The latter is a very interesting device indeed, which we will look at further in chapter 6 on bioprinting.

EnvisionTEC was founded in 2002, and now has headquarters and manufacturing facilities in both Germany and the United States. While customers span industries as diverse as aerospace, architecture, jewelry making and toy manufacture, EnvisionTEC is particularly well known in the medical sector. Here its printers are widely used by dental technicians in the creation of crowns, bridges and temporary teeth, as well as by hearing aid manufacturers to produce ear molds and final product casings.

EOS

Established in 1989, EOS (standing for Electro Optical Systems) is a German manufacturer of industrial, powder bed fusion 3D printers. The company makes systems that additively manufacture in both metals and plastics, with its largest direct metal 3D printer – the EOS M 400 – having a build volume of 400 mm (15.7 inches) cubed. This is intended for 'the production of large metal parts on an industrial scale'. Meanwhile, the EOSINT P 800 'Plastic Laser Sintering System' can make high quality plastic components as large as 700 mm x 380 mm x 560 mm (27.6 x 15 x 22.05 inches).

Working at a much smaller scale, EOS has partnered with 3DMicromac to develop 'micro laser sintering' (MLS). As the name suggests, this facilitates the powder bed fusion of very small metal objects. The process operates in an inert atmosphere, and achieves a layer thickness ranging from 1 to 5 μm (or 0.001 to 0.005 mm). Application areas are anticipated to include the production of endoscopic surgical tools, miniature fluid mixing valves, and customized jewelry.

FARSOON

Hunan Farsoon Technologies is a Chinese manufacturer of direct metal 3D printers based on powder bed fusion, and claims to be the third largest manufacturer of such systems in the world. The company was founded in 2009, and in 2010 developed China's first high-end selective laser sintering (SLS) 3D printer. The company currently sells five systems that laser sinter in plastics, together with its FS271M for fabricating end-use metal parts. In September 2015, Farsoon signed a strategic partnership with the French 3D printer manufacturer Prodways.

MCOR TECHNOLOGIES

Specializing in sheet lamination is Irish manufacturer Mcor Technologies. The company's 3D printers build objects from sheets of paper that are cut with a tungsten carbide blade. In addition to adhering paper layers, Mcor's Iris and ARKe models also spray coloured inks during printout, so providing the lowest-cost, full-colour 3D printing currently on the market. Indeed, according to Mcor, the cost per object printed is just '5 per cent that of competing technologies, and the ongoing cost about one fifth that of any other 3D printing technology'. Granted, final objects are made of a block of paper. But for many concept models, prototypes and artworks, this is perfectly sufficient.

OPTOMEC

Established in 1997 in the United States, Optomec is a manufacturer of high-end, industrial 3D printers based on directed energy deposition. The company terms its implementation of the technology 'laser engineered net shaping' (LENS), and delivered its first 3D printer in 1998. By 2003 the company was working with Boeing, Rolls-Royce, Siemens and the US Navy, and since that time has continued to grow rapidly and to win numerous awards.

In addition to its LENS hardware, Optomec has also developed 'Aerosol Jet' 3D printing. This can deposit materials onto surfaces – including 3D surfaces – to create 3D printed electronic components. For example, Aerosol Jet hardware can 3D print working circuit interconnects or sensors directly onto the surfaces of objects such as aeroplane wings.

Aerosol Jet materials currently include metal inks, carbon ‘resistor inks’, dielectrics, organic semiconductors, adhesives, solvents, and non-metallic ‘conductor inks’ made using carbon nanotubes. Emerging applications are anticipated to range from the fabrication of touchscreen displays and solar panels, through to the development of microscale Internet of Things (IoT) sensors. Or as Optomec explain, ‘by tightly integrating electronic circuitry with physical packaging, Aerosol Jet is fueling growth in new consumer and military applications where increased functionality in smaller spaces is a key driving factor’.

SCIAKY

Sciaky is located in Chicago, Illinois, and has been supplying advanced welding systems and services since 1939. In the 1950s, the company developed its first electron beam welding systems. In 1995 it then began to develop a 3D printing process it calls ‘electron beam additive manufacturing’ (EBAM). This feeds two wire feedstocks into an electron beam, and may be described as a form of direct metal material extrusion. Build volume is a massive 5.8 x 1.2 x 1.2 m (19 x 4 x 4 feet).

Sciaky launched a commercial, in-house EBAM service in 2009, began selling turnkey systems in 2014, and claims EBAM to be the fastest and most cost-effective direct metal 3D printing process. To further the advancement of direct digital manufacturing, the company has worked with partners and clients that include Lockheed Martin Aeronautics and the US Defense Advanced Research Projects Agency (DARPA).

TIERTIME

Beijing Tiertime Technology Co Ltd was founded in 2003, and is a leading Chinese 3D printer manufacturer. The company was formerly known as Beijing Yinhua Laser Rapid Prototyping and Mould Technology Co. Ltd, and was founded by Professor Yan Yongnian, who was one of the first people in China to become involved in 3D printing.

Tiertime’s hardware is based on the material extrusion of thermoplastics, which it terms ‘melted and extruded modelling’ (MEM). Tiertime launched its first industrial 3D printer domestically in 2003, and began exporting outside of China in 2006. In 2009 it then launched its first desktop hardware, and today offers four very-competitively-priced consumer printers. Tiertime is most certainly a manufacturer to watch, and not least because its activities successfully straddle both the industrial and consumer 3D printing markets.

WUHAN BINHU MECHANICAL & ELECTRICAL CO

The Wuhan Binhu Mechanical & Electrical Company is a Chinese 3D printer manufacturer linked to the Huazhong University of Science & Technology (HUST). An offspring of the Rapid Prototyping and Manufacturing Center at HUST, in 1991 Wuhan Binhu opened the first rapid prototyping facility in China. In 1994 it then launched its first 3D printer, a sheet lamination (laminated object manufacture) system called the HRP-1.

By 1998 Wuhan Binhu had developed a suite of powder bed fusion hardware capable of additive manufacturing in plastics, wax or a casting sand substitute. In 2013, the largest printer in this range – the HRPS-VIII – was launched with a build volume of 1,400 x 1,400 x 500 mm (55.0 x 55.0 x 19.7 inches). At the time of writing this is the largest build envelope available on this kind of hardware.

Wuhan Binhu also sell a printer called the HRPM-II that can directly fabricate metal parts from build materials including nickel alloys and titanium. It also sells two ‘HRP’ printers that build resin objects via vat photopolymerization, and for good measure has developed a desktop material extrusion model. There can be no doubt that the Wuhan Binhu Mechanical & Electrical Company is a world leading 3D printer manufacturer with a technology base only challenged by 3D Systems.

3D PRINTING SOFTWARE PIONEERS

Like all digital hardware devices, 3D printers are of no value whatsoever without appropriate software. We would indeed not be at the start of a 3D Printing Revolution were it not at least in part for the efforts of those who have coded the computer aided design (CAD) applications that are required to construct 3D models.

This section contains a brief review of some of the key software houses that are contributing to the advancement of 3D printing. Before we get to them, it is worth remembering that the creation of 3D design software pre-dates the invention of 3D printing. We should also note that a great many 3D computer modelling applications are used for traditional design purposes, as well as to create 3D graphics for use in print, television and movies. Because of this, it should come as no surprise that few companies specialise entirely in 3D-printing-related applications.

It should also be noted that many 3D printer manufacturers develop and supply their own slicing application. This is the software that imports an industry-standard STL, 3MF or other 3D file and then digitally cuts it into layers for 3D printout, as well as adding suitable support structures where required. I have, however, not included any 3D printer manufacturers in the following line-up, as software creation is not their primary business.

As in 3D printer manufacture, two companies currently dominate the 3D software landscape. The first is Autodesk, and the second Dassault Systèmes. Both of these produce a range of CAD applications, with most commercially 3D printed objects likely to have begun their life in software written by one of these companies.

AUTODESK

Autodesk was established in 1982 by John Walker. Walker had obtained the rights to an early CAD program called Interact from its inventor Michael Riddle, and developed it into a product named AutoCAD. This rapidly became very popular, and helped Autodesk to become the largest design and animation software house on the planet. The company floated on the US stock market in 1985.

In addition to AutoCAD, Autodesk offers a wide range of other 3D design packages. These include a high-end 3D modelling and animation application called 3D Studio Max, and versions of AutoCAD tailored for mechanical, civil or electrical engineering. In December 2012, Autodesk even established a partnership with bioprinting pioneer Organovo to develop software for the 3D design of replacement human tissues.

For those wishing to 3D print their creations, AutoCAD and other Autodesk products can directly export industry standard STL and 3MF files. Many Autodesk applications also integrate with a number of online 3D printing services, so allowing designs to be directly sent to a service provider from within the software.

In an acknowledgment of the growing demand for 3D modelling applications that virtually anybody can use, in 2012 Autodesk launched a range of free consumer apps under the banner ‘Autodesk 123D’. These now include a basic 3D modelling program called 123D Design, a 3D sculpting app called 123D Sculpt, and a program called 123D Catch that can turn a set of photographs into a printable 3D object. Also freely available is an excellent, web-based 3D modelling application called TinkerCAD. This was created by Kai Backman and Mikko Mononen in 2011, developed a cult following, and joined the Autodesk family in June 2013.

In addition to the above, May 2016 saw the launch of Autodesk ReMake (previously known as Autodesk Memento), as ‘an end-to-end solution for converting reality captured with photos or scans into high-definition 3D meshes’. In practice, this means that you can walk around any object taking pictures with a digital camera, and have them turned into a high-resolution 3D model that may then be printed out. ReMake works either locally or in the cloud, and is available in both free and pro (for-a-fee) versions.

As all of the above signals, Autodesk is a very big proponent of 3D printing. In addition to its many software offerings, in May 2014 it even announced a new open source 3D printing software platform called Spark. As Autodesk explained at the time:

> While additive manufacturing offers unprecedented opportunities, it is still complex, expensive and not always reliable. Until now, proprietary technologies and fragmented processes have limited innovation and adoption in 3D printing. To address these challenges, Autodesk [has] developed Spark [as] an open 3D printing platform that any company can build on.

Spark already provides a range of tools and application programming interfaces (APIs) for use in 3D print preparation, printer management, and the connection of 3D applications to online 3D printing services. In September 2014, tool manufacturer Dremel launched a desktop, material extrusion 3D printer called the 3D Idea Builder that makes use of the Spark platform. In early 2015, Autodesk itself then launched a Spark-based ‘open source, production quality 3D printer’. Known as Ember, this $7,495 desktop vat photopolymerization device produces 64 x 40 x 134 mm (2.5 x 1.6 x 5.3 inch), high-resolution printouts for use in jewelry making, research and related applications.

Shortly after releasing Ember, Autodesk additionally announced that it had partnered with toy maker Mattel to ‘create a family-friendly ecosystem that allows [children] to design, customize, and 3D print the next generation of toys’. To this end, in 2016 Autodesk released the ‘ThingMaker’ tablet app to accompany Mattel’s new $299 ThingMaker 3D printer.

DASSAULT SYSTÈMES

Dassault Systèmes is a French software house that describes itself as ‘the 3D Experience Company’. The business was established in 1981 through the spin-off of a small software development team from Dassault Aviation. The company grew rapidly, and went public in 1996.

For the creation of 3D printable objects, Dassault Systèmes most popular product is SolidWorks. Like AutoCAD, this outputs STL and 3MF files for 3D printout, and can directly control a 3D printer.

To provide ‘intuitive navigational access’ to all of its applications, Dassault Systèmes has developed its ‘3DEXPERIENCE’ platform to power ‘industry solution experiences’ that are ‘based on 3D design, analysis, simulation, and intelligence software in a collaborative, interactive environment’.

TRIMBLE NAVIGATION

While AutoCAD and SolidWorks are excellent applications, they are complex and time-consuming to learn. The price tag for a full version of either package is also well over $3,000. Because of this, many non-designers and a rising tide of 3D printing enthusiasts create objects in a number of alternative applications that are more accessible both technically and financially. While Autodesk’s 123D apps do fall into this category, at present the most popular low-end 3D design software is SketchUp from Trimble Navigation. Trimble’s core business is GPS navigation, and in 2015 the company generated revenues of $2.3 billion.

The SketchUp product has had an interesting history. The program was first developed by a company called @Last Software which was co-founded by Brad Schell and Joe Esch in 1999. SketchUp then arrived on the market in 2000, to offer ‘3D for everybody’, and immediately won awards for its ease of use. In March 2006, Google purchased @Last Software and made the standard version of SketchUp free for personal use. This inevitably expanded the product’s user base, with over 500,000 downloads to date.

To many people’s surprise, in April 2012 Google sold SketchUp to Trimble Navigation. While this initially alarmed the consumer 3D printing community, Trimble continues to allow the basic version of SketchUp – renamed SketchUp Make – to be downloaded for free. The meatier SketchUp Pro then costs $695.

OTHER 3D DESIGN SOFTWARE SUPPLIERS

In addition to Autodesk, Dassault Systèmes and Trimble Navigation, other widely recognized suppliers of 3D design software include IMSI Design (who supply a mid-range package called TurboCAD), Robert McNeel & Associates (who have created another mid-range CAD package called Rhinoceros), and Pixologic (who supply a high-end 3D sculpting package called ZBrush with a low-end sibling named Sculptris).

In December 2015, we also saw the commercial launch of a cloud-based CAD offering called Onshape. This was created by the team originally behind SolidWorks, and allows 'everyone on a design team [to] simultaneously work together using a web browser, phone or tablet'. For those wishing to experiment, a free account can be created over at onshape.com.

3D PRINTING SERVICE PROVIDERS

Not all of the most significant 3D printing pioneers are hardware manufacturers or publishers of software code. Rather, a final group of companies driving the industry forward are service providers. Such organizations allow anybody to transform their digital designs into physical objects, and are likely to play a critical role in bringing 3D printing into the mainstream.

Already there are scores of companies that offer a 3D printing bureau service, and the number is growing rapidly. Many of these firms offer design and manufacturing expertise beyond 3D printing, and are in the business of helping commercial designers and manufacturers to produce concept models, prototypes, molds, tooling and final parts. You can find a listing of 45 3D printing service providers in the 3D Printing Directory at the end of this book.

While most 3D printing services only deal with business customers, some allow anybody with a 3D object file to upload it, provide online payment, and receive a printout by courier. To round up this review of the 3D printing industry, I am therefore going to introduce you to four of the biggest 3D printing services that can be used by anybody with a 3D object file, a credit card, and an Internet connection.

SHAPEWAYS

Shapeways describes itself as 'the world's largest 3D printing service, marketplace and community'. As well as allowing anybody to upload a file for printout, the company offers and integrates with a wide range of apps that allow those without design skills or specialist software to create their own 3D stuff. In addition, Shapeways permits designers to sell their creations from an online 'Shapeways shop'. All products sold from these virtual stores are printed-on-demand when somebody orders them, and currently include works or art, jewelry, homewares, miniatures and games. One design that has become particularly iconic is the 'Itty Bitty Sad Keanu Reaves' from a designer called 'neuralfirings'. This tiny figure is 3D printed in full colour and can be purchased in different sizes that are equally sad.

Shapeways was founded in 2007 by Peter Weijmarshausen, Robert Schouwenburg and Marleen Vogelaar as a spin-off from Royal Philips Electronics in the Netherlands. It was developed under a scheme called the Philips Lifestyle Incubator, and launched its 'print as a service' (PaaS) business in 2008. In 2011 the company relocated its headquarters to New York.

At the time of writing Shapeways can fabricate objects in 56 materials that range from ABS, alumide and porcelain, through to photopolymer resins, aluminium, silver, gold and stainless steel. The company has been termed the 'Amazon of 3D printing', and in March 2012 opened a 25,000 square foot factory in New York. In September 2014, it also took up residence in an expanded factory space in the middle of Eindhoven in the Netherlands. At present Shapeways produces 'roughly 3,000 unique products every day and over 1 million unique products annually'.

MATERIALISE

Another service pioneer that hails from mainland Europe is Materialise. This is headquartered in Leuven in Belgium, and was established by Wilfried Vancraen in 1990, initially as a joint venture with the University of Leuven. Since that time the company has become widely recognised as a veritable powerhouse of 3D printing innovation. Materialise floated on the NASDAQ stock market in June 2014.

Materialise works with industrial clients to produce prototypes and 3D printed final products, as well as developing 3D software for specialist medical and engineering applications. These activities are coordinated through several divisions, including Materialise Industrial Services and .MGX. The former helps companies to produce prototypes and small production runs, while .MGX uses 3D printers to manufacture high-end design products that it sells from its online store.

For the general public and individual designers, Materialise also offers an online service called i.materialise. Like Shapeways, this allows anybody to upload their 3D designs and to get them printed out. Objects can be output in a wide 'Periodic Table of Materials' that includes ABS, alumide, brass, bronze, photocurable resins, rubber-like, stainless steel and titanium.

In addition, once an object has been uploaded and successfully printed, its designer can offer it for sale either via the gallery on the i.materialise.com website, or through their own web pages. As with the service offered by Shapeways, this allows anybody to create a product and to sell it without having to invest in any tooling or stock. Via the i.materialise website, designers can also sell their 3D object creation services, as well as producing prototypes and rewards for crowdfunded projects.

SCULPTEO

Like Shapeways and i.materialise, Sculpteo is an upload-and-print web service with a wide palette of available build materials. In a similar fashion to its competitors, Sculpteo also allows individuals or professionals to open up an online store in order to 'run a 3D printing factory online'.

Sculpteo describes itself as the '3D Printing Cloud Engine', is headquartered in France, but also operates an office in San Francisco. The company was established in 2009, and began offering its online 3D printing services in 2011.

In comparison to its larger competitors, Sculpteo has done much to make its 3D printing services as accessible as possible. For example, its website accepts object uploads in a very wide range of file formats. This allows 3D objects created in mid-price 3D animation packages – such as LightWave and TrueSpace – to be directly uploaded for 3D print. Sculpteo also provides a number of plugins that allow design packages like SketchUp to directly integrate with its service. Also available are a number of custom apps that allow anybody to create simple, customized objects such as key rings, iPhone cases, or 3D pictures based on an uploaded image.

3D HUBS

Bringing online 3D print services to the masses in a completely different fashion is 3DHubs. Here, the business model is to connect those who own a 3D printer with those locally who want to print something out. Customers who upload models for printout experience an average turnaround time of 48 hours, and can choose exactly which printer owner fabricates their creation, as well as whether they want to collect it in person or have it sent on. Since it began trading in 2013, 3DHubs has facilitated the production of over 430,000 objects, and now outputs over 40,000 items a month.

3DHubs was established with a mission 'to connect all 3D printers globally into one online platform and make them locally accessible'. To this end, the service already provides 'over one billion people with access to 3D printing within 10 miles of their home'. Most 3D printing industry pundits agree that the local printout of objects using shared hardware is the most likely driver of any future personal 3D printing revolution. 3DHubs is therefore most definitely a 3D printing pioneer to watch.

DRIVING THE REVOLUTION

Only a few years ago, to analyze the 3D printing industry you basically had to keep track of the activities of a handful of public, pure play 3D printer manufacturers, plus a few other specialist private firms. By the end of 2016, things have got a lot more complex – and a lot more interesting! – with more and diversified companies entering the market. It also appears that most new technologies and process innovations are likely to come from an expanding array of new players, rather than the traditional 3D printing old hands. Indeed, to cite Chris Connery, VP for Global Analysis at CONTEXT, in a July 2016 press release:

> … the 3D Printer market continues to witness a great deal of change. Long time market leaders Stratasys and 3D Systems [are looking] to overhaul their businesses while high profile brands like HP, Ricoh and others [are beginning] to lay the groundwork for their vision to kick-start the industry.

As Connery suggests, 3D Systems and Stratasys are now learning to focus more strategically on those things they do best, and this is definitely not selling low-cost consumer hardware. Without doubt, in the 1980s and 1990s personal computing became a bigger business than corporate computing, but there is no such transition on the cards in the world of 3D printing. As we shall explore in chapter 5, personal fabrication is a viable and expanding market sector. However, it is going to remain far more niche than industrial 3D printing, with the spoils likely to be divided between many very small players focused on quality, together with a few very large, diversified Asian electronics manufacturers who are already starting to compete aggressively on price.

Within the majority market of industrial 3D printing, we stand at the start of a slow transition from the supply of hardware used predominantly for rapid prototyping, to the sale of additive manufacturing systems – including hybrid systems – capable of making final products or components thereof. Leading the way are those companies that produce hardware that can 3D print in metal, or in sand for the production of casting molds and cores. To again cite Chris Connery of CONTEXT:

> The challenge on the professional side of the 3D printing market is to see if the entrance of new major players can, along with their advanced technology and promotional efforts, help the bigger manufacturing markets embrace 3D printing for short to mid-size production runs of finished good parts … The market has already embraced the ability of 3D printing to provide detailed, functional, load-bearing [metal] parts [within the] aerospace, orthopedics and other markets … with the next challenge being to convince the world of plastics manufacturing that additive manufacturing can suit their needs for final part production as well.

As 3D printing becomes more mainstream, these are very exciting, if also somewhat risky and extremely uncertain times. Long gone are the rose-tinted, hype-fuelled days of 2012 and 2013 in which investors raised few questions and blind faith was enough to secure many an order. Today, 3D printing is actually far better placed than it was in 2012 and 2013 to help transform the product offering and the bottom line in many a manufacturing sector. But the 3D printing industry does need to step up to compete as a seller of mainstream production technology – as opposed to being a niche supplier of prototyping hardware – and this requires a different business approach. This is also, I am sure, why new market entrants and niche players (particularly in direct metal 3D printing) are currently enjoying more growth than Stratasys and 3D Systems.

To build up confidence, an increasing number of industries, manufacturers and end consumers need to gain knowledge and practical experience of final 3D printed products and end-use components. And in such pursuit, a small but increasing number of companies are now trailblazing the additive manufacturing road ahead. The next chapter will investigate what some of these early digital fabrication pioneers are up to, and the potentially profound implications of their foresighted endeavours.

4. Direct Digital Manufacturing

In July 2014 I interviewed Jon Cobb, Executive Vice President of Global Marketing at 3D printer manufacturer Stratasys. During our discussion Jon predicted that, within five years, the majority of things that are 3D printed will be industrial tooling, end-use components, or entire final products. A couple of years later, his belief that rapid prototyping will soon become a minority 3D printing activity is increasingly widely held. It is indeed now reasonable to state that, by 2020, 3D printing will mainly be used as a manufacturing technology.

The 3D printing of final products is often termed 'direct digital manufacturing' or 'DDM'. Not least, the Society of Manufacturing Engineers has endorsed DDM as the preferred term for 'the process of going directly from an electronic digital representation of a part to the final product via additive manufacturing'.

The generic drivers for DDM were laid down in a 2009 white paper by Stratasys founder and CEO Scott Crump. As he explained, 'DDM presents a radical departure that allows designers, engineers and manufacturers to do what was previously impractical or impossible. DDM has opened the door for new product designs, new markets and new business models'. As Crump went on to more specifically detail, DDM will increasingly allow manufacturers to reduce lead times, to lower manufacturing constraints in product design, to achieve high levels of customization, and to engage in cost-effective low-run production.

To help us to understand the potential of DDM, this chapter will explore the work of some of those pioneering industrial sectors, companies and individuals who are already 3D printing final products and end-use parts, or who have credible plans to start doing so. From the outset, I want to stress that I am in no way suggesting that 3D printing is about to replace all traditional manufacturing methods. But, in an increasing number of instances, it will become an alternative option, and sometimes the one that is preferred.

ADDITIVE IN AVIATION

Today, the industry making the greatest advancements and investments in DDM is aviation. Not least, aircraft manufacturers are particularly attracted to 3D printing because it presents opportunities to make lighter parts. This is because the manufacturing constraints of traditional casting and machining are removed, so allowing designs to be fabricated with a geometry that is structurally optimized for material efficiency. Indeed, according to a study conducted by Professor Eric Masanet at Northwestern University in the United States, the 3D printing of materially-optimized metal parts – such as brackets and hinges – can reduce the weight of an entire aircraft by up to 7 per cent. In turn, this can deliver very substantial fuel and carbon emissions savings.

3D printing similarly allows aircraft manufacturers to make components with a previously impossible technical specification. It can also improve construction efficiency by fabricating complex components 'pre-assembled' in one piece. As yet another killer advantage, because 3D printing is an additive process, it wastes as little as 5 per cent of its build material during production. This means that 3D printing can potentially deliver a 'buy-to-fly' ratio of material-in to material-out of approaching 1:1. In contrast, traditional machining is a subtractive activity that can result in a buy-to-fly ratio of up to 20:1. Given that many aeroplane parts are made from expensive metals like titanium, this gives manufacturers a great incentive to explore the 3D printing option.

For several years 3D printing has been used to make out-of-production, replacement plastic parts for older aircraft, such as the Airbus A300 and A310. Boeing has also fitted over 20,000 3D printed plastic parts in its planes, with the company having filed a patent application to cover the entire ecosystem necessary to store and 3D print aircraft spares.

When it comes to new aircraft, in December 2014 Airbus began delivery of its A350 XWB airliner, which includes some 3D printed components in order to increase supply chain flexibility. By April 2016, over 2,700 3D printed flight parts had been fitted in new A350s, many of which were made on Stratasys 3D production systems from the thermoplastic ULTEM 9085. This specialist material is certified to meet the strength-to-weight ratio and FST (flame, smoke and toxicity) characteristics necessary for aircraft interiors. According to Stratasys, 3D printing A350 components 'enables Airbus to manufacture strong, lighter weight parts while substantially reducing production time and manufacturing costs'.

Aircraft components directly 3D printed in metal are also starting to enter service. The first of these was a compressor inlet temperature sensor for the GE90-94B jet engine, which was certified for flight by the US Federal Aviation Administration (FAA) in April 2015. The part is produced by GE Aviation using powder bed fusion, and in time will be retrofitted to over 400 engines already in use on Boeing 777 aircraft.

In July 2016, GE Aviation, in conjunction with Safran Aircraft Engines, also launched into service a new aircraft engine called the LEAP. Each of these features 19 3D printed fuel nozzles that have a geometry that could not be made using traditional manufacturing techniques. These cutting-edge components are 25 per cent lighter than previous models, as well as five times more durable. At the time of writing, over 8,500 LEAP engines have been ordered, which means that in excess of 160,000 3D printed fuel nozzles will end up operating in the skies.

Not to be outdone, Airbus is also putting additively manufactured metal parts into service. For example, in January 2016, its subsidiary Premium AEROTEC began the serial production of 3D printed titanium components. The first of these was a double-walled pipe elbow for the fuel system of the A400M military transport aircraft. These were previously made from several individually cast sections that had to be welded together. But today, the pipe elbows are 3D printed in a single job, saving both assembly time and the tooling that was previously required to produce the component castings.

In March 2016, another Airbus subsidiary, APWorks, took delivery of the first MetalFAB1 3D printer from Additive Industries. This 26 foot long, €1.8 million machine has multiple build chambers, and was designed for a production environment. According to Daan Kersten, the co-founder of Additive Industries, Airbus will be using the MetalFAB1 to build metal aircraft components including 'lightweight attachments and seat parts'. As Kresten went on to report 'Airbus is thinking about reaching a point where half of their airplanes are 3D printed'. Potentially signposting exactly this intent, in June 2016 Airbus put on public display a four-metre, 21 kilogram pilotless aircraft known as THOR. Over 90 per cent of the structural components in this mini plane were 3D printed in nylon, with THOR's name standing for 'testing high-tech objectives in reality'.

3D PRINTING AUTOMOBILES

Another large industrial sector that is starting to explore the potential of 3D printing is automobile manufacture. Here, one of the first pioneers was Jim Kor with his company Kor EcoLogic. In 2011, Kor worked with Stratasys to 3D print the outer shell of a low-energy, two-passenger hybrid vehicle called the Urbee. As pictured in figure 4.1, the body of the Urbee was crafted in ten thermoplastic sections. I saw the prototype Urbee for myself at a tradeshow in November 2013, and it was most impressive.

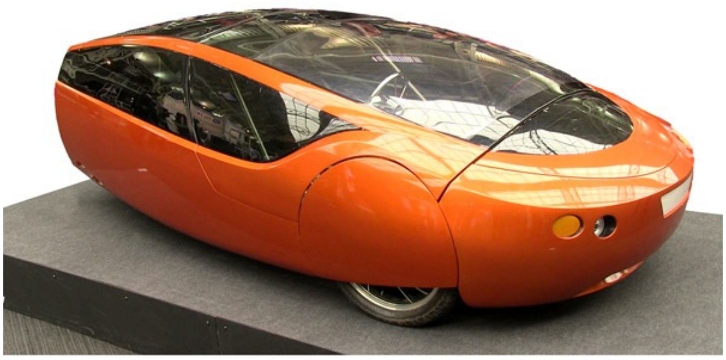

Figure 4.1: The Urbee 3D Printed Car by Jim Kor / EcoLogic.
Photographed at the 2013 London 3D Printshow.

The downside of the first Urbee was that its body shell took 2,500 hours to 3D print. It is therefore somewhat amazing that the world's second 3D printed automobile was created in just six days during the International Manufacturing Technology Show held in Chicago in September 2014. The vehicle in question was the Strati from Local Motors, and in contrast to the Urbee had both a 3D printed body shell and a 3D printed chassis. All locomotive components for the Strati were sourced from a Renault Twizzy.

The Strati's rugged frame and outer casing were extruded from a carbon-reinforced ABS build material called LNP STAT-KON AE003, which is produced by Saudi Basic Industries Corporation (SABIC). The material was supplied in pellet form to the Big Area Additive Manufacturing (BAAM) machine developed by toolmaker Cincinnati Incorporated. The BAAM then fabricated the Strati body and chassis in one piece within its 6.1 x 2.3 x 1.8 m (240 x 90 x 72 inches) build envelope.

Just over a year after creating the Strati, Local Motors unveiled its ‘LM3D Swim’ as the first in a series of commercial 3D printed cars. This again has a body and chassis fabricated on a BAAM, and is illustrated in figure 4.2. As Local Motors CEO Jay Rogers told the crowd at the SEMA speciality auto show in November 2015, ‘we are using the power of DDM to create new vehicles at a pace unparalleled in the auto industry’. The plan is to produce the initial LM3D range at a microfactory in Knoxville, Tennessee, and in time to establish ‘an efficient, multinational microfactory network in order to build game changing products and deliver a world of vehicle innovations’.

Figure 4.2: A Local Motors 3D Printed Car in the LM3D series. Image courtesy of Local Motors.

As well as fabricating vehicles for Local Motors, Cincinnati Incorporated and the Oak Ridge National Laboratory (ORNL) have used BAAM hardware to 3D print the bodies of several replica classic cars. The first of these was a Shelby Cobra, which was recreated from scratch in just six weeks. The body of the Shelby Cobra was hand finished to achieve a totally smooth surface, unlike the Strati and LM3D, which retain the stepping characteristic of material extrusion. The Shelby Cobra was then spray painted in the normal manner, with the end result being a shiny, classic car that looks identical to one created via traditional manufacturing methods.

The ORNL Shelby Cobra replica was publicly unveiled at the North American International Auto Show in Detroit in January 2015. Since that time it, and other replicas created by Cincinnati Incorporated, have been upheld as a powerful example of what 3D printing is capable of, and where it may take the automobile sector in the future. Not least, the world of custom and classic cars – and their repair – is likely to be transformed. For example, crashed vehicles considered write-offs by insurance companies today may in the future be salvageable if it becomes routinely possible to replicate any body shape and body panel in a matter of hours.

By 3D printing replacement engine and other components, it will also increasingly be possible to get old vehicles back into working order even if parts are unavailable. Proving the point, in August 2016 KW Special Projects (KWSP) in the United Kingdom reported how it had used 3D scanning and 3D printing to restore an Alfa Romeo Tipo 33/3 racing car built in the late 1960s. The restoration involved reproducing the front cover of the

Tipo’s engine, as well as its water pump and housing. Here 3D printers were used to create plastic replicas, from which molds were taken and final parts cast. The Tipo subsequently went on to compete in the World Sportscar Championships.

Within traditional, large auto manufacturers, 3D printing is very commonly used to create prototype parts. For example, GM’s Rapid Prototype Laboratory additively manufactures over 20,000 prototype components every year, while in December 2013 Ford revealed that it had produced a prototype Mustang engine cover as its 500,000th 3D printed auto part. But beyond the world of R&D, traditional auto manufacturers are also looking to a future in which additive manufacturing will become an end-use production technology.

For example, in November 2015 Audi revealed that it has an aim of incorporating 3D printed metal parts into ‘regular car production’. Demonstrating its commitment, in the same month the German car maker showcased a drivable, half-scale model of an Auto Union Type C race car build from metal 3D printed parts.

MEDICAL 3D PRINTING

Given the current state of the technology, right now the best things to 3D print are small, customized and expensive. In turn, this makes healthcare well suited for DDM, with a wide range of medical practitioners and other innovators already stepping up to the plate. In fact, a September 2013 Morgan Stanley blue paper found that nearly 40 per cent of 3D printing patent applications were in the medical sector. Credible estimates for the growth and future size of the medical 3D printing industry inevitably vary, with Markets and Markets predicting that it will be worth $2.13 billion by 2020, while Mdor Intelligence put the figure at more like $3.0 billion by decade’s end.

In chapter 6 we shall see how the ‘bioprinting’ of living human tissue is likely to transform healthcare. Yet even before this occurs, today’s tried-and-tested 3D printing technologies are starting to assist with patient diagnosis and therapy, as well as being used to manufacture personalized prosthetics and other customized medical devices.

For example, at the Kobe University School of Medicine in Japan, a surgeon called Maki Sugimoto is using 3D printing to create medically-accurate models of patient kidneys, livers and other organs. These are derived from MRI and CT scan data, and can prove invaluable in planning surgery. The model organs are created using material jetting 3D printers that can build things in multiple materials. This allows their outer form to be transparent, so making it possible to view their internal structures, including possible cancers, other abnormalities and scar tissues as captured in patient scan data. Figure 4.3 illustrates a 3D printed liver model created by Maki Sugimoto.

Figure 4.3: 3D Printed Liver Model by Maki Sugimoto/Fasotec.

The organ printouts created by Dr Sugimoto even have the texture and feel of real biological parts. To achieve this unique characteristic, the surgeon has teamed up with Fasotec, a Japanese 3D printing company that has developed what it calls ‘bio-texture modelling’. Here jetting materials are chosen to simulate the wetness and texture of human organs, so allowing printouts to be produced that feel organic to the touch.

Other pioneers using 3D printing to produce surgical planning models include Cavendish Imaging and Replica 3DM, both based in the United Kingdom. The latter can produce 3D printed models from patient scan data in around five days. These allow surgeons to perform quicker, less invasive operations because possible complications are anticipated before flesh is cut. The use of 3D printed surgical planning models subsequently improves patient outcomes and reduces costs. Or as Matthew Sherry, Managing Director and Founder of Replica3D, explained to *3D Printing Industry*:

> A 3D model equips surgeons with a hands-on perspective which cannot be achieved by looking at a computer screen. They can easily rotate, inspect and analyze each surgical procedure on a case-by-case basis, enabling them to pre-bend implants knowing that they will perfectly fit the patient. This is instrumental in eliminating potential problems during operations and can be used as a visual aid when explaining the surgical procedure to patients.

In addition to providing doctors with planning models, 3D printing is increasingly being used to make end-use medical appliances. Most notably, many dentists or their labs now use 3D printers to help create models of their patient’s teeth. The required 3D data is gathered directly using an intraoral scanner (which takes about two minutes to scan an entire mouth), or indirectly by scanning a traditional physical impression.

Several 3D printing manufacturers now provide dedicated dental services and hardware, including 3D Systems, EnvisionTEC and Stratasys. Figure 4.4 illustrates some dental wax-ups made on a Stratasys CrownWorx dental 3D printer, while figure 4.5 shows a batch of dental models on the print bed of an EDEN 260V Dental Advantage. To meet rising market demand, in February 2014 Stratasys even introduced a dedicated dental material called VeroGlaze. This is an exact colour match to the A2 tooth shade favoured by dentists, and can be used to 3D print extremely natural-looking dental models such as try-in veneers.

Figure 4.4: CrownWorx 3D Printed Dental Wax-Ups.
Photo courtesy of Stratasys.

Figure 4.5: Dental Models on EDEN 260V Dental Advantage.
Photo courtesy of Stratasys.

While most dental 3D printing is currently a means to an end, as long ago as 2011 EnvisionTEC had an FDA-approved material that could be used to additively manufacture long-term temporary teeth. As the company's Jenna Franklin explained to me at the time, such 'temporaries' can reside in a patient's mouth for years. However, it was not until January 2016 that the first person was fitted with an intentionally-permanent 3D printed dental crown.

The patient in question was Rik Jabobs, the CEO of a company called Next Dent that produced the material from which his new prosthesis was made. The photopolymer in question was NextDent C&B MFH (standing for micro filled hybrid), and was 3D printed down to an accuracy of 0.001 mm to achieve a perfect fit. How long Mr Jacobs had to wait to develop the need for a 3D printed crown fabricated in a material made by his own business we will probably never know.

With NextDent C&B MFH now on the market in several shades, and many other dental 3D printing pioneers working on similar technology, it is likely that fairly soon crowns will be routinely 3D printed in minutes. This will remove the need for their highly specialist production in a remote dental lab, and could reduce the requirement for a patient to visit a dentist on multiple occasions to have a crown fitted.

Closely related, 3D printers have for several years been used in the direct production of teeth-straightening prosthesis. For example, a company called ClearCorrect uses a small fleet of Objet Eden500V material jetting 3D printers from Stratasys in the mass manufacture of its transparent plastic aligners. The process involves making a computer model of the current and desired location of a patient's teeth. The CAD data is then used to 3D print a range of transitionary former models from which a progression of aligners can be created using traditional techniques. Both the aligners and the 3D printed formers that they have been made from are sent to the patient's dentist. Supplying a 3D printed former with each aligner is a great innovation that can assist a dentist with fitting, as well as facilitating the rapid production of aligner replacements.

For ClearCorrect, one of the biggest advantages of moving to 3D printed manufacture has been the ability to scale its growing operation simply by investing in more printers. Another critical benefit has been the ability to offer 40 per cent lower lab fees than other providers of clear aligners – so benefiting patients, doctors, and the company's bottom line.

3D printers are additionally already widely used to make the outer shells of personalized hearing aids. Here, a mold is made of a patient's ear canal. This is then laser scanned to produce 3D data that is used to design and 3D print a custom casing into which standard electronics are fitted.

Today around 95 percent of all custom-manufactured hearing aids have their shells 3D printed. Indeed, according to the *Harvard Business Review*, in the United States 100 per cent of custom hearing aid shells are now 3D printed, with the sector having converted from traditional methods to additive manufacturing in less than 500 days. Figure 4.6 illustrates a batch of hearing aid shells made on an EnvisionTEC Perfactory 3D printer.

Figure 4.6: Hearing Aid Shells Made Using An EnvisionTEC Perfactory 3D Printer. Photo: Christopher Barnatt.

3D printing is also becoming established for the manufacture of orthopedic implant components. Here, one of the key players is the Adler Ortho Group, who since 2006 have been using Arcam electron beam melting 3D printers to produce items such as acetabular cups. These are the top part of an artificial hip joint that is screwed into a patient's pelvis. The cups are 3D printed to patient specification in titanium, and have a unique, 'porous' surface structure that cannot be fabricated using traditional manufacturing methods. In turn this means that the 3D printed acetabular cups provide the best long-term fixation, as the patient's bone actually grows into them.

Direct metal 3D printing is even starting to be used for entire bone replacements. As a signature example, in 2012 an 83-year-old woman was fitted with an artificial jaw that was laser-sintered in titanium. The elderly lady had been suffering from a bone infection called osteomyelitis that had destroyed much of her own jaw. Her 3D printed replacement was created by a company called LayerWise (which in September 2014 was acquired by 3D Systems), with an identical copy illustrated in figure 4.7.

Figure 4.7: Jaw Bone Laser Sintered in Titanium.
Photo: Christopher Barnatt. With thanks to 3D Systems.

According to *Orthopedic Design & Technology* magazine, the market for 3D printed orthopedic implants is currently small, if growing rapidly. In a May 2016 article, it estimated that approaching 50 tonnes of 3D printed titanium orthopedic components were implanted into patients in 2015, representing a little less than 3 per cent of the total market.

For amputees, 3D printing is also starting to be used in the direct manufacture of limb prosthetics. For example, a company called Open Bionics has started to 3D print low-cost, customized, myoelectric-controlled prosthetic hands in an attempt to help the several million hand amputees worldwide. Figure 4.8 shows an early but fully-functional version of their prosthetic that I saw in operation in May 2015.

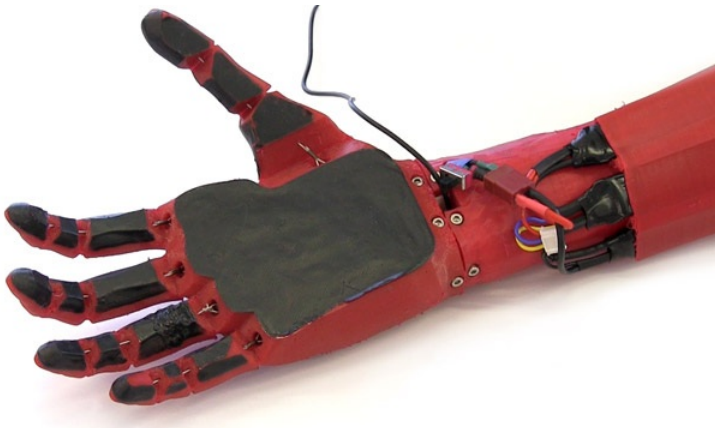

Figure 4.8: An Open Bionics 3D Printed Prosthetic Hand.
Photograph: Christopher Barnatt.

3D PRINTED ART & JEWELRY

Moving on from life's more brutal practicalities, some of the first individuals to delve into the world of digital manufacturing were artists, and in particular those who make jewelry and other small, intricate sculptural forms. For example, in 2007 a studio called Nervous System was founded in Somerville, Massachusetts by Jessica Rosenkrantz and Jesse Louis-Rosenberg. Here they have created a process that uses computer simulations to generate digital designs based on patterns found in nature. The resultant CAD files are sent to the Shapeways bureau for fabrication, where they are either directly laser sintered in nylon, or cast in metal from 3D printed molds and patterns. Products on offer from the studio's website at n-e-r-v-ou-s.com include a unique range of rings, bracelets, earrings, pendants, lamps and other artworks, some of which are illustrated in figure 4.9.

Figure 4.9: Hyphae Brooch, Pendant, Rhizome Cuff and Ring by Nervous System. For more information or to purchase these items visit n-e-r-v-o-u-s.com.

Back in 2013, I talked to Nervous System co-founder Jessica Rosenkrantz to find out how the company got into 3D printing and why. As she recalled:

> We started making works using 3D printing in 2009 with our project Cell Cycle. We

> are interested in digital fabrication processes like 3D printing because they enable us to create complex, organic forms that would be difficult to create otherwise, and they allow us to create one-of-a-kind, customized products. Cell Cycle is a web-based app that allows people to design their own complex, cellular jewelry and sculpture that can be purchased and 3D printed.

Next I asked about the challenges that face digital manufacturing pioneers, and here the cost of production was clearly a major concern:

> The main issues we've had to overcome have to do with price. Compared to other techniques for producing plastic parts, like injection molding, 3D printing is a very expensive process. We want to make unique designs that [are] price competitive with traditionally manufactured goods. The service provider we work with – Shapeways – prices 3D prints by volume of material used to produce the item, so we've written software that creates designs with a small amount of material enclosing a large volume of space.
>
> One of our collections, Cell Cycle, was inspired by the skeletons of radiolarians and is made up of cellular jewelry computed from a physics model of spring meshes. These cellular structures are very strong but have thin members. Our other 3D printed collection, Hyphae, is based on how veins form in leaves. After defining an initial surface and several starting points, or roots, we 'grow' a structure of veins on the surface. The result is a surface made up of very thin branches that interconnect into a closed cell network like the veins of a deciduous plant. With Hyphae, we are printing members that are at the limit of what Shapeways allows, but the overall structure's high degree of interconnectedness means they are still strong.

Another artist who has made a name for herself by utilizing additive manufacturing is Bathsheba Grossman, who describes herself as 'a designer, mostly in 3D printed steel'. Like Nervous System, Bathsheba utilizes 3D printing services (here i.materialise and Shapeways) to allow her to sell a range of metal and plastic sculptures and jewelry from her website at bathsheba.com. As with Nervous System, Bathsheba makes use of a range of technologies. These include the binder jetting metal printing technology developed by ExOne.

One of Bathsheba's specialities is the creation of metal sculptures based on highly complex mathematical forms. Just one of these is the 'Zarf', as illustrated in figure 4.10. Like other artworks, this can be ordered in a range of sizes. As Bathsheba explains on her website:

Figure 4.10: 'The Zarf' by Bathsheba Grossman.
For more information or to purchase this item visit bathsheba.com.

> I'm an artist exploring the region between art and mathematics. My work is about life in three dimensions: working with symmetry and balance, getting from the origin to infinity, and always finding beauty in geometry …
>
> I have a grass-roots business model. I don't limit editions, I price as low as costs permit, and most of my selling is direct to [customers] by way of [my website]. My plan is to make these designs available, rather than restrict the supply. It's more like publishing than like gallery-based art marketing: we don't feel that a book has lost anything because many people have read it. In fact it becomes more valuable as it gains readership and currency. With the advent of 3D printing, this is the first moment in art history when sculpture can be, in this sense, published. I think it's the wave of the future.

Intrigued by her innovative approach, I contacted Bathsheba to find out what led her to start making 3D printed works of art. As she explained:

> I got into it because I was – still am – very attracted to sculptural forms that are difficult to produce by traditional manufacturing means.
>
> The root of all my problems is undercuts: that's any sort of overhang, through hole, reverse draft angle, or other feature that makes it impossible to remove an object from a mold, without breaking either the mold or the object itself. My designs are all undercuts all the time, and before 3D printing that made them very difficult to produce as economically viable sculpture. The early part of my artistic career was very unpromising.
>
> In the late 1990's I had a portfolio of designs that were too unmoldable to make, and too geeky to sell in galleries. Cheap 3D printing and web marketing appeared at that time and suddenly those particular problems were solved.

What is clear from the cases of Nervous System and Bathsheba Grossman is that 3D printing is already liberating artists to create works that were previously impossible, both technically and financially. Using online 3D printing service providers, anybody can now produce plastic or metal items without any investment in tooling or stock, and this is a real sign of a revolution in the making. Well aware of the extraordinary possibilities, Bathsheba Grossman concluded our interview as follows:

> Overall, this is the greatest time to be a designer since lost-wax casting was invented, 6,000 years ago or whatever, and in the long run this is going to be bigger than that was. Can't wait to see what's next.

SHOE MANUFACTURE

In April 2012 I made a YouTube video called *The 3D Printing Revolution*. This included an animated section where I illustrated future footwear being 3D printed to match a scan of the purchaser's feet. The video did really well – garnering over a million views – but also accrued many angry comments from those who thought that 3D printing shoes was ridiculous. Parts of aeroplanes and cars, or jewelry and prosthetics? Well that was fine. But shoes? Well I was told that shoes would never be 3D printed.

I mention the above because, today, 3D printing is just starting to be used in final shoe production by manufacturers large and small. For example, since 2013 Nike has been using 3D printing to manufacture specialist cleat plates for some of its high-end trainers. These have included the Vapor Laser Talon that was built to enhance linear speed in the 40-yard-dash; the Vapor HyperAgility that was made to provide 'explosive lateral acceleration'; and the Vapor Carbon II that is designed to maximize the gameday speed of football players. All of these specialist cleat plates are fabricated in plastic using powder bed fusion, with the 3D printing process allowing Nike to manufacture complex, geometrically optimized forms that could not be made using conventional molding techniques.

In May 2016, Nike announced a partnership with HP Inc to help develop and scale the use of 3D printing 'to manufacture performance products to help athletes reach their full potential'. In time for the Rio Olympics, it also used 3D printing to create a custom track spike called the Zoom Superfly Flyknit for sprinter Allyson Felix. Wearing this, Allyson went on to win an individual silver and two team-relay gold medals.

In October 2015, Nike rival Adidas unveiled the 'future of performance footwear' with its Futurecraft 3D printed running shoe midsole. This is currently 'a prototype and a statement of intent', but is intended to lead toward delivering the 'ultimate personalised experience for all athletes'. Or as the Adidas press release noted:

> Imagine walking into an Adidas store, running briefly on a treadmill and instantly getting a 3D-printed running shoe – this is the ambition of the Adidas 3D printed midsole. Creating a flexible, fully breathable carbon copy of the athlete's own footprint, matching exact contours and pressure points, it will set the athlete up for the best running experience. Linked with existing data sourcing and footscan technologies, it opens unique opportunities for immediate in-store fittings.

While the Adidas Futurecraft 3D is not in production, other manufacturers have already sold very low runs of shoes with 3D printed parts. For example, in April 2016 the Boston-based New Balance sold 44 pairs of a $400 running shoe called the Zante Generate. Developed with Nervous System, this featured a 3D printed midsole, which like Nike's performance cleats was fabricated in plastic using powder bed fusion.

A month earlier, and utilizing the same technology, Under Armour launched a $300, limited edition training shoe called the Architech. This also has an open-lattice 3D printed midsole that can only be created via 3D printing. An initial 96 pairs of the Architech were offered for sale online, and sold out in 20 minutes. Under Armour has plans to launch more 3D printed footwear both online, as well as in its flagship store in Baltimore.

As Chris Lindgren, Under Armour's Vice President of Training and Outdoor Footwear, explained when the Architech went on sale, 3D printing had enabled his company 'to develop a performance training shoe that [is] a hybrid of stability and cushioning'. In the future, the hope is that the technology 'will allow for personalised and customised footwear based on an athlete or consumer's height, weight, and athletic needs'.

Moving beyond the printout of a single, high-performance component, a few pioneers are already 3D printing entire shoes. One such pioneering individual is New York designer Francis Bitonti, who created the 'pixelated footwear' shown in figure 14.11. Also targeting the high fashion market is designer Neta Soreq, whose 'Energetic Pass One' shoes can be purchased for $900 from 3DShoes.com. The latter is a fascinating website which focuses on 'disrupting the traditional footwear model'.

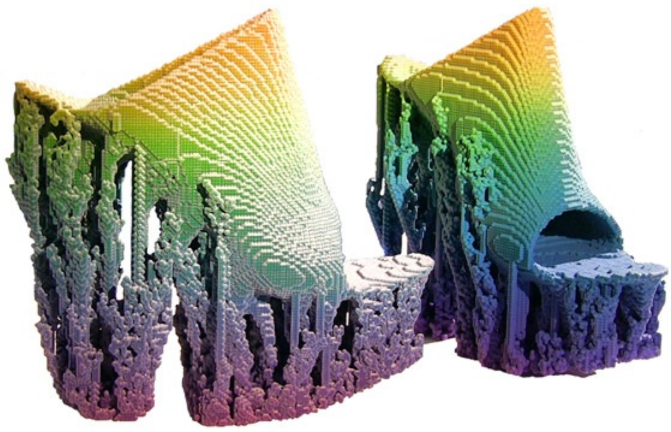

Figure 4.11: 3D Printed Pixilated Shoes by Francis Bitonti.
Photographed at the 2014 London 3D Printshow.

Returning to the mainstream, a final and quite extraordinary 3D printed footwear pioneer is Feetz. Over at Feetz.com, this 'digital cobbler' is on a mission to change the footwear industry by providing customers 'with affordable, sustainably made, custom-fit shoes'. To this end Feetz sell personalized shoes that are 3D printed from plastic for the soles, and a rubber knit for the uppers. Customers download the Feetz App for their smartphone or tablet, and use it to take three photographs of each foot. These images are then converted into a CAD model containing 5,000 data points, with the customer provided with a 'SizeMe' code that allows Feetz to 3D print shoes that are guaranteed to fit. The end result of the Feetz process is illustrated in figure 14.12.

Figure 4.12: The Feetz Gemini Custom-Fit 3D Printed Shoes.
Photo courtesy of Feetz.

Feetz was founded in 2013 by Lucy Beard, who got fed up of being unable to find shoes that fit her. She hence went on a quest to build '3D printers to make shoes in hours' as well as 'software to custom fit our shoe designs to your feet'. Lucy even managed to make all of this possible using recyclable materials.

The two current Feetz styles – the BFF and the Gemini – can be ordered in eight colours, are delivered within two weeks, and are priced at $199. While this is relatively expensive, as Feetz argue 'traditional bespoke shoes cost thousands of dollars and take months to produce'. In contrast, Feetz offer 'truly custom fit for the masses'. They also offer the exact service that I envisaged in my *3D Printing Revolution* video a few years ago, and which so many people told me would never happen.

OTHER PERSONALIZED GOODS

As the example of Feetz very powerfully illustrates, 3D printing offers manufacturers the opportunity to produce goods that are not just customized to an individual's tastes, but which are actually personalized according to their own unique physical characteristics. It is therefore not surprising that, in addition to the shoes, dental appliances and hearing aid shells already covered in this chapter, other personalized 3D printed products are now starting to come to market. These include personalized orthopedic insoles, such as those developed by Materialise and RS Scan International, and now sold via a joint venture called RSPrint Powered by Materialise (see phits.be/en). Also offering the 'world's first truly dynamic 3D printed custom foot orthotics' are Podfo, over at podfo.com.

Outside of the medical and clothing arena, many companies have combined 3D scanning with colour binder jetting in order to 3D print scale models or toys that feature their customer's face or even their entire body. Just one company to successfully offer this service is my3Dtwin.com, who use an array of 64 DSLR cameras to scan and then 3D print both private individuals, and also corporate clients. As shown in figure 4.13, my3Dtwin have even scanned and 3D printed pet dogs. Other companies in this market include the UK supermarket Asda (who will sell you an ‘Asda 3Dme’); iMakr (who sell a ‘Mini You’ as the ‘ultimate selfie’); and ThatsMyFace.com (who can put your head on a superhero action figure).

Figure 4.13 Two my3Dtwin Personalized 3D Prints.

Offering yet another variety of personalized product is Normal, who in 2015 started selling 3D printed earphones that exactly fit their user’s ears. These are fabricated at Normal’s flagship store in New York using a fleet of 10 Stratasys material extrusion 3D printers. As Normal’s Founder and CEO Nikki Kaufman explains, ‘we’re excited to be able to create accessible, tailor-made earphones that sound incredible’, with 3D printing being the technology that allows her company to ‘build a product that is completely personalized’.

In time, every product that fits or otherwise interfaces directly with the human body has the potential to be 3D-printed-to-fit. Not least, spectacle frames are a prime candidate for personalized fabrication, with such glasses now available from several companies including Boulton Eyewear and Monoqool. Oh, and just in case you are wondering, there is already a market for personalized 3D printed sex toys, such as those offered by Sexshop3D.com.

THE FINAL FRONTIER

The best new technologies have always enabled humanity to access and conquer new realms. For example, sailing ships allowed us to cross the oceans, aeroplanes took us into the air, and computers opened up the electronic frontier of cyberspace. And 3D printing? Well, 3D printing may prove rather helpful in allowing us to more readily access the final frontier of space.

Since the retirement of the space shuttle, NASA has been dependent on foreign nations or private space contractors to get to the international space station (ISS). One of two US companies currently helping out is SpaceX, which since late 2012 has been sending its Dragon space capsules on cargo supply missions aboard its Falcon-9 rockets. In the next few years, the intention is for SpaceX to also start providing an astronaut ferry service. To allow this to happen, in May 2014 SpaceX unveiled its Dragon Version 2 or 'Crew Dragon' spacecraft. This is capable of carrying seven people, and unlike previous space capsules will make a soft touchdown on land. It will also achieve this using eight 'SuperDraco' rocket thrusters that are in part 3D printed.

Specifically, the SuperDraco engine chambers for the Crew Dragon are manufactured in an Inconel superalloy using powder bed fusion. As Elon Musk, the Chief Designer and CEO of SpaceX explained in a press release:

> Through 3D printing, robust and high-performing engine parts can be created at a fraction of the cost and time of traditional manufacturing methods. SpaceX is pushing the boundaries of what additive manufacturing can do in the 21st century, ultimately making our vehicles more efficient, reliable and robust than ever before.

While the Dragon V2 has yet to enter service, in July 2014 SpaceX revealed that in January that year one of its Falcon 9 rockets was successfully launched into space with a 3D printed main oxidizer valve fitted in one of its nine Merlin 1D engines. This mission therefore marked the first time SpaceX – or anybody else – had launched a functional 3D printed rocket part. It also proved categorically that 3D printed metal components can have the required structural integrity to perform at least as well as traditionally manufactured items.

The following year, Boeing notched up another space-first when it 3D printed a metal receive antenna deployment actuator (RADA) cage for a 702MP satellite. By employing 3D printing, Boeing engineers were able to cut the total number of parts in the cage from 21 to 6, so reducing assembly time and costs. As Mike Neuman, the 702MP product line director, noted, 'our goal is to deliver the spacecraft to our customer on time and on budget, so when innovations become available that enhance and improve the manufacturing process, the team gets excited. We're eager to do more work with additive manufacturing'.

In addition to metal components, 3D printed plastic parts are also being incorporated into spacecraft. For example, the United Launch Alliance (ULA) – a joint venture between Boeing and Lockheed Martin – is currently 3D printing flight-ready internal components for its Atlas V rocket. These include environmental control system ducts, instrument support brackets, cooling nozzles, and close-off panels, and are fabricated via material extrusion in the specialist thermoplastic ULTEM 9085. The parts were previously made from metal, but are cheaper and lighter to 3D print in plastic. Not least, time and money are saved in component assembly, with one duct system that used to contain 140 parts now being 3D printed in just 16 pieces. According to ULA estimates, accumulated costs savings are already up to $1m a year. The first Atlas V to fly with 3D printed plastic parts successfully launched on 22 March 2016.

The above endeavours, while very impressive, remain limited to the direct digital manufacture of rocket components here on Earth. There are, however, already several initiatives intent on making off-world manufacturing a reality. Or in other words, there are serious ventures with the goal of 3D printing in space.

Most significantly, in 2010 a company called Made in Space was formed to work in collaboration with NASA on the development of off-world 3D printing technologies. Since that time, a material extrusion 3D printer called the Zero-G has been created as the first 'machine shop for space'.

In September 2014, a Dragon spacecraft successfully carried the Zero-G to the International Space Station. Astronauts in orbit obviously do not have the option to nip down to a store for replacement components. It is therefore hoped that the Zero-G and its descendants will enable the manufacture of spare parts, tools and emergency solutions in space as a viable alternative to launching items from Earth. Or as Aaron Kemmer, the CEO of Made In Space, explained in a September 2014 press release:

> Everything that has ever been built for space has been built on the ground. Tremendous amounts of money and time have been spent to place even the simplest of items in space to aid exploration and development. This new capability will fundamentally change how the supply and development of space missions is looked at.
>
> This is more than a 3D printer. It's more than a machine shop in space. It's a landmark for humanity. For the first time in the history of our species, we will be manufacturing tools and hardware away from the Earth. Now that we've made this breakthrough, the sky is no longer the limit for additive manufacturing – the era of off-world manufacturing has begun.

Between 17 November and 15 December 2014, astronauts on the International Space Station used the Zero-G to 3D print 25 test parts. Of these, the last and most famous print was a ratchet wrench that was made from a CAD file transmitted from the Earth. The fabrication of this part hence illustrated the viability of the 'remote' supply of spares to those on a spacecraft or space station.

Some future 3D printers may even manufacture large structures on the surface of the Moon or Mars. The idea is that some form of material extrusion or binder jetting would be used to selectively solidify lunar regolith or Martian dust to create habitats for human occupation. The concept is illustrated in one of my own future visions in figure 4.14.

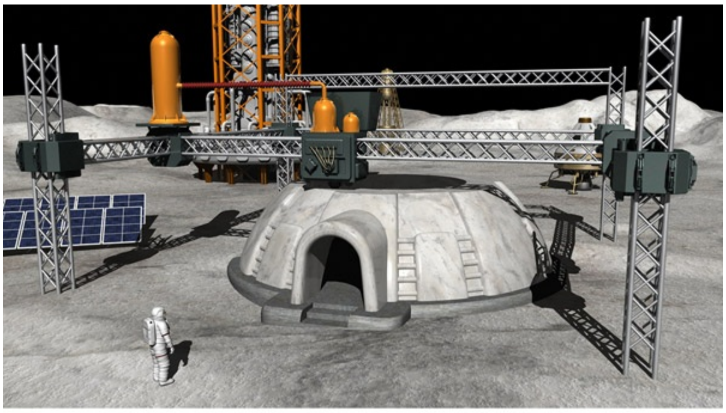

Figure 4.14: Concept Illustration of a Lunar Base 3D Printer.
Image by Christopher Barnatt, ExplainingTheFuture.com.

While the idea of printing buildings on other worlds may sound fantastical, already the European Space Agency has commissioned tests in which a giant binder jetting 3D printer called the D-Shape built a 1.5 tonne test structure by spraying a binder onto layers of simulated regolith. The D-Shape is a ‘robotic building system’ created by Italian engineer Enrico Dini and Monolite UK, and has already built many marble-like structures by spraying a binder onto layers of sand here on Earth.

Also working toward the 3D printing of other-worldly habitats is Professor Behrokh Khoshnevis. As mentioned in chapter 2, the professor has for years been developing a method of ‘contour crafting’ that can build large structures by extruding concrete from a computer-controlled nozzle. Working for NASA, Professor Khoshnevis has hatched plans for the creation of robot builders that will be able to build infrastructure on Mars before future astronauts arrive.

Demonstrating equal levels of pioneering ambition are Deep Space Industries (DSI), who plan to use 3D printers to help in their quest to mine the asteroids. According to DSI, the company will rely on a 3D printer called the Microgravity Foundry to help manufacture metal parts from space rock nickel deposits. According to Stephen Covey, co-founder of DSI and inventor of the process, the really cool thing about their intended 3D printer is that it will be able to ‘take its own parts, grind them up, and recycle them into new parts’.

Astonishingly, in January 2016 another asteroid mining hopeful – Planetary Resources – announced that it had collaborated with 3D Systems to make ‘the first ever direct metal print from asteroid metals’. This was revealed to the world at the Consumer Electronics Show in Las Vegas, and was made by a ProX DMP 320 powder bed fusion 3D printer. The build material was obtained from part of an actual asteroid that had impacted the Earth in Argentina, and was processed by Allegheny Technologies into a metal powder suitable for 3D printout. While we may be a long way from mining a celestial asteroid, we can therefore now be certain that we can additively manufacture metal parts from those lonely resources waiting for us out in the cold vacuum of space.

CLOUD MANUFACTURING?

Direct digital manufacturing is still in its infancy. This said, as we have seen in this chapter, final 3D printed parts are already being used in industries as diverse as aviation, automobile manufacture, medicine, jewelry making, footwear, and rocket construction. What is more, over half of the examples of DDM application included in this chapter did not exist when the second edition of this book was published in November 2014. The 3D printing of end-use components may be a very new industrial activity. But it is advancing very rapidly indeed.

The future development of DDM also raises some fundamental business issues. Not least, as it increasingly becomes possible to commercially 3D print final plastic and metal parts – and in time fully assembled products – so it is going to become harder and harder to determine the industry that the owner and operator of a 3D printer is actually in.

Today, most manufacturing companies are industrially classified according to their engineering expertise and machine tool investments. But once factories are equipped with 3D printers, it will be possible for them to produce aircraft parts one day, medical appliances the next, fashion goods the day after, and shoes or toys the day after that. There is in fact no reason why a factory equipped with a fleet of 3D printers will not be able to make all of the aforementioned items simultaneously. Indeed, some of the larger 3D printing service bureaus are already doing precisely this.

A few decades from now, 3D printing and related digital fabrication technologies may turn at least some forms of manufacturing into a highly generic utility service that companies large and small will purchase on demand. This is indeed what is already happening in IT, where cloud computing resources are now rented by the hour or day, so saving many firms the capital-cost of purchasing, housing, operating and maintaining a data centre. By the 2030s, 3D printing capacity may similarly start to be traded as a pay-as-you-go commodity. Barriers to entry in manufacturing will subsequently fall – which again is something that we are already starting to witness as 3D printing makes certain forms of one-off, low-run and customized manufacturing a commercial possibility.

In the last few years, DDM has started to be taken very seriously by an increasing number of organizations. Not least, manufacturers, stockists and suppliers of spare parts are starting to wonder what will happen to their business when low-cost, rapid print-on-demand arrives. In 10 years time, a mechanic called out to a breakdown may download replacement car parts on their smartphone and print them out in the back of their van.

3D printing and DDM are not going to replace the traditional manufacturing methods currently used to make most products. But I believe that they are destined to change how companies create, stock and ship maybe 20 per cent of their goods. Further, 3D printing has the potential to empower a growing army of individual ‘makers’ to produce and repair at least some of their own possessions. In the next chapter, we will therefore turn our attention to the slow but steady revolution in personal manufacturing.

5. Personal Fabrication

On 19 October 2012 I visited the first ever 3D Printshow in London. For many years previously, other industrial events – and most notably the TCT Show – had been exhibiting the best ‘time compression technologies’ used for rapid prototyping and additive manufacturing. But back in 2012, it was the arrival of the 3D Printshow that really brought the extraordinary possibilities of ‘3D printing’ to the attention of the mainstream media. Indeed, as the front of the programme proclaimed, ‘The Internet changed the world in the 1990s. The world is about to change again’.

Beyond its first outing, the 3D Printshow ran annually until 2015 in London, New York, Paris and other major cities. While industrial technology was always on display, personal 3D printing was usually to the fore, with a great many attendees having a keen interest in personal manufacturing. Sadly, since the intense media frenzy of 2012 and 2013, a widely-predicted mass market for consumer 3D printers has yet to emerge, and is unlikely to become a reality anytime soon. It is probably also for this reason that, in 2016, the 3D Printshow evolved into a new industrial event under the banner ‘Additive Manufacturing’.

While personal 3D printers are not yet as common as microwave ovens, a thriving community of individual ‘makers’ and educators are now purchasing over two hundred thousand personal 3D printers every year. Indeed, according to CONTEXT, the figure for 2015 was about 235,000 units, with sales predicted to reach a half a million personal printers annually by 2020. Even though personal manufacturing remains a relatively small part of the total 3D printing industry, it should therefore not be ignored. Not least, a buoyant personal sector provides an important catalyst for the future advancement of the broader 3D printing industry. Personal hardware does, after all, continue to account for a good 90 per cent of all 3D printers sold.

The personal 3D printing arena is also an important hotbed for innovation, with individual makers and personal 3D printer manufacturers continuing to bring a great deal of passion and an extraordinary wealth of new ideas to the 3D printing community. Just as, in the 1980s and 1990s, the personal computer rose up to drive the future of computing, so it remains possible that the personal 3D printing market will become the most important driver for industrial 3D printing innovation in the decades ahead.

This chapter explores the current state-of-play in personal 3D printing. Initially we will look at the available technologies and materials, before investigating some of the most popular pre-assembled personal 3D printers and their manufacturers. Next we will delve into the world of self-built hardware and the open source 3D printing movement, before looking at consumer 3D scanners, online object repositories, 3D printing services, and the rise of the Maker Movement.

PRICES & TECHNOLOGIES

According to most 3D printing industry pundits – including the highly respected Wohlers Associates – personal 3D printers are those with a price tag of $5,000 or less. Currently the cheapest models available for sale cost from $200 in kit form, and $230 fully constructed, which places all personal hardware in the rather broad $200 to $5,000 bracket. Given this wide price range, the capabilities and performance of different personal 3D printers varies greatly, and I would personally prefer to see lower-cost 3D printers reclassified into consumer hardware (costing up to $2,000), and prosumer hardware (costing $2,000 to $5,000). In my opinion, it will be devices priced below $2,000 that will increasingly enter the home for true 'personal fabrication', with models in the $2,000 to $5,000 range more likely to be purchased by smaller companies and educational establishments.

When categorizing personal 3D printers, we also need to be cognisant of their underlying technology. Unlike in the industrial domain, until a few years ago all personal hardware was based on the material extrusion of thermoplastics. Today this is still largely the case, with most personal printers being single or multi-nozzle thermoplastic extrusion devices. However, there is now also a choice of vat photopolymerization hardware that sells for less than $5,000, with at least one such printer priced at under $1,000.

As illustrated in figure 5.1, at the time of writing Sintratec are also offering a kit for a powder bed fusion (plastic laser sintering) 3D printer for €4,999 (c.$5,600). Within the intended two-year lifetime of this book, the first sub-$5,000 powder bed fusion device will therefore probably go on sale, leaving prosumers with a choice of at least three 3D printing technologies. I would also hazard a cautious guess that we will see the first sub-$5,000 material jetting and sheet lamination 3D printers enter the market by the end of 2018.

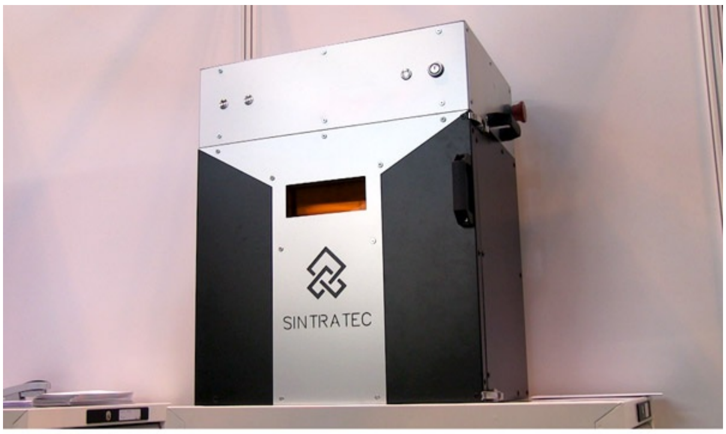

Figure 5.1: The Sintratec €4,999 Laser Sintering 3D Printer.

PERSONAL 3D PRINTING BUILD MATERIALS

Personal vat photopolymerization 3D printers build objects from brittle or flexible photocurable resins, including substitutes for casting wax. Meanwhile, all personal material extrusion models can fabricate things in the bioplastic PLA, with most also able to print in the petroleum-based plastic ABS. The latter can only really be handled by hardware that has a heated print bed, and should ideally only be used for long periods in a well-ventilated area. This is because ABS emits toxic fumes during printout, so making PLA the favoured build material in most schools and other educational establishments. This said, ABS generally produces more robust prints, as well as final parts that can easily be ‘welded’ together with solvents. In addition to PLA and ABS, some desktop material extrusion printers can be fed with nylon, PMMA, and many of those other thermoplastic build materials outlined in chapter 2.

In theory, most 3D printers that can print in PLA or ABS can also build objects from composite filaments such as those which combine ABS, PLA or another thermoplastic with wood-fiber, carbon fiber or a metal powder. Many personal 3D printers can also print in highly flexible thermoplastic elastomers, such as the increasingly popular Ninjaflex. This said, the successful use of specialist filaments in any personal printer is far from guaranteed. Some manufacturers even prevent the use of specialist materials by enclosing their filament in a proprietary microchipped cartridge, rather than allowing their printers to be fed from a generic open spool.

POPULAR PERSONAL 3D PRINTERS

There are currently at least 100 personal 3D printers on the market. The list of top-selling manufacturers is also very much in flux, with the recent rise of notable Asian players including the Taiwanese XYZprinting (part of the Kinpo Group), and the Chinese companies Tiertime and FlashForge. 3D Systems’ decision to end-of-line its low cost Cube 3D printer in December 2015 has also shaken things up, as in 2015 it still had a 10 per cent market share.

At the time of writing, the latest available figures (published in July 2016 by CONTEXT), indicated the top five personal 3D manufacturers by sales volume to be XYZprinting (at 25 per cent market share), M3D (9 per cent), Ultimaker (8 per cent), Stratasys (6 per cent), and FlashForge (with 5 per cent of the market). The best-selling printers from all of these companies are therefore worthy of our consideration here, with some of them illustrated in figure 5.2. I will also include below a summary of a few other well respected and widely known 3D printer models and manufacturers in order to provide a broader flavour of the market. You can also find an exhaustive listing of personal 3D printer manufacturers in the 3D Printing Directory at the end of this book.

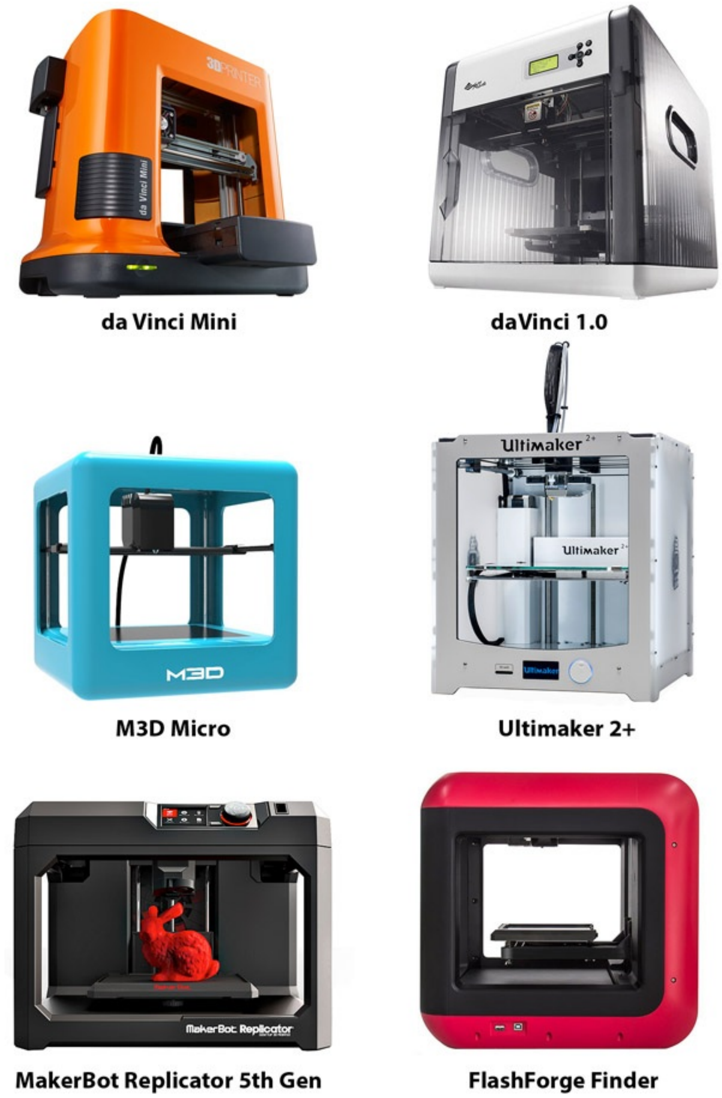

Figure 5.2: Personal 3D Printers from XYZprinting, M3D, Ultimaker, Stratasys & FlashForge. Images courtesy of respective manufacturers.

THE XYZPRINTING DA VINCIS & NOBEL 1.0

Since its formation in late 2013, Kinpo Group's XYZprinting has taken the marketplace by storm, and at the time of writing sells more personal 3D printers than anybody else. The company clearly has a strategy of leveraging its bulk manufacturing expertise and $30 billion group turnover to compete on price, rather than print quality, and so far this approach is working. In October 2016, XYZprinting offered 10 material extrusion printers, as well as one desktop vat photopolymerization model, none of which were priced above $1,500.

All of XYZ's material extrusion printers are called da Vinci, and start with the da Vinci Mini and miniMaker. These pretty much identical models cost $230 and $290, print only in PLA, and have a build volume of 150 mm (5.9 inches) cubed. There are then several da Vinci Junior 1.0 models which have the same build volume, again only print in PLA, and are priced between $350 and $550 depending on whether you want an integrated scanner and/or WiFi connectivity.

Next, the more advanced da Vinci 1.0, 1.1 and 2.0 printers can build objects in PLA, ABS and ‘flexible’ (thermoplastic elastomer) filaments. These printers sell for between $550 to $700, and push the build envelope to 150 x 200 x 200 mm (5.9 x 7.8 x 7.8 inches). For $550, the da Vinci 2.0 even offers a dual extruder (two-nozzle print head) that allows objects to be made from two different coloured filaments. Finally, the da Vinci Pro printers start at $700, with a build volume of 200 mm (7.8 inches) cubed.

With the exception of the Mini, the miniMaker and the Pro, all da Vinci 3D printers have their filament contained in a chipped cartridge. This generally prevents the use of non-proprietary build materials, although a quick Google search locates a hack that can allow generic spooled filament to be used. This said, XYZprinting has left out print nozzle and print bed temperature controls on all of its printers aside from the Pro, and this prevents the optimal use of third party filaments even if you do manage to hack a cartridge.

Currently at the top of the XYZprinting range is its Nobel 1.0 vat photopolymerization model. At $1,500, this has a build volume of 128 x 128 x 200 mm (5 x 5 x 7.9 inches). Right now, no other company manufactures and sells as wide and low-cost a range of personal 3D printers as XYZprinting. I would therefore expect the company’s market-leading position to be maintained.

THE STRATASYS MAKERBOT REPLICATORS

MakerBot Industries was founded in January 2009, and initially sold material extrusion 3D printers in kit form. However, it was soon offering a range of fully assembled ‘Replicators’, over 100,000 of which have now been sold. In June 2013, MakerBot was purchased by industrial 3D printing giant Stratasys, although to date it has continued to trade under its original name.

Somewhat akin to Apple, MakerBot has managed to garner a loyal, almost evangelical devotion from a niche fan base. This said, in recent years the company’s reputation has fallen, with its hardware being relatively expensive and obtaining variable reliability reports. It is interesting to note that the November 2015 *Make 3D Printer Buyer’s Guide* did not feature one MakerBot model.

Today, MakerBot offers three printers that sell for $5,000 or less, starting with the $1,375, PLA-only Mini which has a build volume of 100 x 100 x 125 mm (3.9 x 3.9 x 4.9 inches). For $1,999, the Replicator Fifth Generation increases the maximum printable object size to 252 x 199 x 150 mm (9.9 x 7.8 x 5.9 inches), while the slightly older $1,699 Replicator 2X adds dual filament printing for objects up to 246 x 152 x 155 mm (9.7 x 6.0 x 6.1 inches) in volume. The Replicator 2X can print in ABS in addition to PLA, and like all MakerBots is fed filament from an open spool.

THE ULTIMAKER 3, 2+ & 2 GO

Next on my list of top personal 3D printers are the Ultimaker 3, Ultimaker 2+ and

Ultimaker 2 Go. Manufactured in the Netherlands by Ultimaker, these have an excellent reputation, with the Ultimaker 2+ and Ultimaker 2 Go offering single extruder (single material) printing, while the Ultimaker 3 is a dual-extruder (two material) machine.

The first Ultimaker was a bare-plywood-bodied DIY kit. However, the breakthrough product for Ultimaker – particularly in the United States – was the Ultimaker 2, which has now evolved into the $2,499 Ultimaker 2+. This can print in ABS, PLA and most other filaments, and offers a build volume of 223 x 223 x 205 mm (8.8 x 8.8 x 8.1 inches). The Ultimaker 2 Extended+ is in effect exactly the same printer but fitted with taller sides, and subsequently manages to offer a build volume of 223 x 223 x 305 mm (8.8 x 8.8 x 12 inches) for its $2,999 price tag. Just as this book went to press the Ultimaker 3 was announced for c.$3,400. This offers a build volume of 215 x 215 x 200 mm (8.5 x 8.5 x 7.9 inches), rising to 300 mm (11.8 inches) high on the Ultimaker 3 Extended for about $4,300.

For those wanting the Ultimaker experience in a more portable format there is the Ultimaker 2 Go. This costs $1,199, prints in PLA only, and offers a build volume of 120 x 120 x 115 mm (4.7 x 4.7 x 4.5 inches). Personally, I have had very good experiences with Ultimaker 3D printers, and know that they are well respected across the industry. For example, as the manager of the iMakr 3D printer store told me a couple of years ago, once turned on and left printing, an Ultimaker 'is a piece of technology that just sells itself'.

THE FLASHFORGE FINDER, DREAMER & CREATOR PRO

FlashForge is a Chinese 3D printer manufacturer that was founded in 2011. At the time of writing it sells three material extrusion models – the Finder for $499, the Creator Pro for $899, and the Dreamer for $1,099. Of these, the Finder is a PLA/PVA only device that prints objects from a single filament, while the Creator Pro and Dreamer are dual-extruder (two filament) printers that also handle ABS and potentially specialist print materials. The build volume on the Finder is 140 mm (5.5 inches) cubed, while the Creator Pro maxes out at 225 x 145 x 150 mm (8.6 x 5.7 x 5.9 inches), and the Dreamer at 231 x 150 x 140mm (9.1 x 5.9 x 5.5 inches).

FlashForge's Dreamer model in particular has a very good reputation. So much is this the case that, in 2014, toolmaker Dremel started to sell a 3D printer called the 3D Idea Builder (also known as the 3D20) that is a re-branded FlashForge Dreamer. The Dremel version sells for $999, extrudes a single material only, lacks a heated print bed, and hence can only fabricate items in PLA.

THE M3D MICRO & MICRO PRO

The M3D Micro is very much the wild card in this list, and features here because, when it comes to total 3D printers sold, in early 2016 M3D had the second highest share of the personal 3D printer market. Their first model – the Micro – was initially priced at $349, and is being fairly widely applauded as a great piece of low-cost hardware.

Amazingly at its price point, and despite the fact that it does not have a heated print bed, the Micro can work with ABS, PLA, nylon and other filaments, all of which are fed from a non-proprietary open spool. The printer itself is an incredibly small 185 mm (7.3 inch) rounded-corner cube, and offers a slightly strange print volume that is 116 mm (4.6 inches) high, and 109 x 113 mm (4.3 x 4.4 inches) for the first 74 mm, shrinking down to 91 x 84mm (3.6 x 3.3 inches) above that. Careful planning of your object is hence essential!

Following the Micro, M3D is launching a larger, $499 printer called the Micro Pro. This features a build volume of up to 183 x 183 x 198 mm (7.2 x 7.2 x 7.8 inches), and at the time of writing can be purchased via a Kickstarter campaign.

Although competitively priced and appropriately-sized for the home, M3D's printers are reported to be about four times slower than their competition. Given the speed at which M3D has come from nowhere to be a top-five personal 3D printer manufacturer, it will be very interesting to see where the company is in a few years time.

THE LULZBOT MINI, TAZ 5 & TAZ 6

LulzBot was established in 2011 as a 'product line' of Aleph Objects Inc in the United States, which produces free software and open source hardware. The company's 3D printers all have a very good reputation, and indeed their TAZ 5 topped the November 2015 *Make 3D Printer Buyer's Guide*.

LulzBot currently sells three models: the Mini, the TAZ 5 and the TAZ 6. Of these, the Mini costs $1,250, and offers a print volume of 152 x 152 x 158 mm (6 x 6 x 6.2 inches). Higher up the range come the TAZ 5 and TAZ 6, which sell for $1,870 and $2,500, and offer respective print volumes of 290 x 275 x 250 mm (11.4 x 10.8 x 9.8 inches) and 280 x 280 x 250 mm (11.02 x 11.02 x 9.8 inches).

LulzBots are sturdy metal affairs that look more industrial than most of their competitors. This is, however, probably why the machines are so solid, so reliable, and so well-respected. LulzBot advertise that all of their printers can 'build with whatever', with approved materials including ABS, PLA, HIPS, PVA, PETT, polycarbonate, nylon, PETG, and wood or metal composites. Indeed, the only filaments that are 'discouraged' are carbon fiber composites, as they can damage the print head.

THE ZOTRAX M200 & M300

Also offering extremely robust, metal-bodied 3D printers are Zortrax with their M200. Second only to the LulzBot TAZ 5 in the aforementioned *Make Magazine* ranking, the M200 can be purchased for $1,900, and has a build volume of 200 x 200 x 180 mm (7.8 x 7.8 x 7.1 inches). At the time of writing, a larger M300 with a build volume of 300 mm (11.8 inches) cubed was due on the market for $4,199.

THE TIERTIME UP MINI 2, UP PLUS 2 & UP BOX

Tiertime is a leading Chinese 3D printer manufacturer that was founded in 2003. Alongside Stratasys, it is also the only company in this list to produce both high-end industrial and personal hardware. The company's personal range spans from the very stylish UP mini 2, through to the UP mini, UP Plus 2, and its flagship UP BOX. All of these support ABS and PLA filaments, with print volumes ranging from 120 mm (4.7 inch) cubed for the $599 UP mini and UP mini 2; 140 × 140 × 135 mm (5.5 x 5.5 x 5.3 inches) for the $799 UP Plus 2; and 255 x 205 x 205 mm (10 x 8 x 8 inches) for the UP BOX. The latter features a large, illuminated and animated logo under its print bed, and also an integrated HEPA air filter to prevent fumes escaping its build space (so making it classroom friendly even if printing in ABS).

THE PRINTRBOT PLAY, SIMPLE & PLUS

The final material extrusion 3D printers that I feel it essential to include here come from Printrbot. This was set up by a really cool guy and former pastor called Brook Drum, who I had the pleasure of meeting at the 2012 3D Printshow. For some reason, when I saw Brook the table for his stand had not arrived, and he was therefore showcasing his 3D printers on the carpet. But despite this, he was still attracting a lot more attention than most other stands!

A self-confessed maker, Brook found himself working in web design and wanted to get back to producing things that he could actually touch. The result was his range of 'Printrbots' – very distinctive, low-cost 3D printers that have garnered a very strong reputation. To get his 3D printers into production, Brook set up a Kickstarter campaign to raise $25,000. Pledges to this value were gained in 48 hours, with the final, 30 day total being $830,828. A year later all of those who had pledged money had received their Printrbots, and the company is still thriving. Or as Brook cheerfully enthused when I interviewed him in 2012, 'I'm Brook, I did a Kickstarter in November last year … and now I'm in the 3D printer business'.

While initially all Printrbots had bare plywood panels, today all of the company's models have powder-coated aluminium bodies. Prices and build volumes start at $399 for the 100 x 105 x 130 mm (3.9 x 4.1 x 5.1 inch) Printrbot Play; rise to $599 for the 150 mm (c.6 inch) cubed Printbot Simple; and top-out at $1,119 for the 250 mm (c.10 inch) cubed Printrbot Plus. Here the Play is PLA only as it does not have a heated print bed, the Plus can use ABS, PLA and other materials as it does have a heated print bed, and the Simple can be upgraded to a heated print bed for $150. As this book went to press, a new '2016 Simple' was due to launch for an anticipated price of $999. This extends the build volume by 50 mm (c.2 inches) on its X and Z axis, and features a colour touchscreen.

THE FORMLABS FORM 1+ & FORM 2

Rounding off this review are two companies who specialize in low-cost, vat photopolymerization 3D printers. The first of these is FormLabs, which in May 2013 stunned the market when it launched its $3,299 Form 1 to offer very-high-resolution, resin-based 3D printing on the desktop. The Form 1 has since been superseded by the Form 1+ and Form 2, which sell for $1,999 and $3,499 respectively, and have build volumes of 125 x 125 x 165 mm (4.9 x 4.9 x 6.5 inches) and 145 x 145 x 175 mm (5.7 x 5.7 x 6.9 inches). Formlabs describe the Form1+ as the 'the world's best-selling desktop SLA 3D Printer' and they are almost certainly right.

Like all vat photopolymerization hardware, the Form 1+ and Form 2 are popular with those needing to make very detailed printouts, including jewelry, dental and other molds and pieces. Working with a personal vat photopolymerization 3D printer is certainly a lot messier and more involved than fabricating in a thermoplastic via material extrusion, and not least due to the time required to clean surplus photopolymer liquid from final printouts. However, with the Form 2, Formlabs have made things a little easier by supplying resin to the printer in sealed cartridges.

Vat photopolymerization printers also consume more expensive build materials than their material extrusion counterparts. To give you an idea, 1 kilogram of thermoplastic filament for a typical material extrusion 3D printer generally costs between $30 and $75. In contrast, a 1 litre tank of resin for a Form 2 costs between $175 and $399 (although admittedly the latter price is for a specialist dental material).

THE PHOTOCENTRIC 10", LCHR & LC PRO

Bringing this list to a close are the British firm PhotoCentric, who since 2002 have developed and manufactured photopolymer resins. By 2015, the company had realized that such resins were increasingly being used as the build materials in vat photopolymerization 3D printers, and decided to leverage its expertise to make its own printing hardware. To this end, PhotoCentric has brought to market a technology that it terms 'Daylight Polymer Printing' (DPP). As the name suggests, this builds objects from photopolymers that are selectively solidified using natural light wavelengths, as opposed to UV light sources. The only limitation this imposes is that final objects cannot be fabricated from totally clear resins. DPP 3D printers create their object layers by projecting light through a liquid crystal display panel onto the base of their photopolymer vat.

PhotoCentric currently has three 3D printers in its range – the Liquid Crystal 10" for c.$930, the Liquid Crystal HR for c.$2,000, and the Liquid Crystal Pro, which at the time of writing is due to launch for £3,799, or around $5,000. Respective build volumes are 200 x 100 x 200 mm (7.8 x 3.9 x 7.8 inches), 160 x 120 x 200 mm (6.3 x 4.7 x 7.9 inches), and 450 x 280 x 300 mm (17.7 x 11.0 x 11.8 inches). All of these prices and print volumes are pretty amazing for desktop vat photopolymerization hardware. Figure 5.3 shows the PhotoCentric Liquid Crystal HR 3D printer.

Figure 5.3: The PhotoCentric Liquid Crystal HR.
Image courtesy of PhotoCentric.

OPEN SOURCE 3D PRINTING

A few years ago, if you wanted to own a personal 3D printer the only option was to build one yourself using 'open source' designs. Today, due to the widespread availability of pre-assembled hardware, self-manufacture is not the route to 3D printer custody that most individuals or companies choose. But even so, the open source 3D printing movement continues to thrive.

'Open source' refers to any initiative in which the involved intellectual property is made freely available, and most usually via the Internet. Within open source communities, designs, computer code or broader ideas are subsequently shared and iterated for the common good. Today, the popular face of open source is epitomized by the pioneering communities that create and distribute free software such as the Linux operating system, and popular software applications including LibreOffice and the GIMP photo editor.

In 3D printing, open source may refer to either the hardware or the software on which a 3D printer is based (or both). For example, some of the 3D printers reviewed earlier in this chapter – including those from Ultimaker and Printrbot – are based on open source software that enthusiasts can tinker with for non-commercial purposes. As noted in chapter 3, Autodesk now also offers an open source 3D printing software platform called Spark that is intended to help connect 'digital information to 3D printers in a new and streamlined way' that will 'ignite innovation'.

At the hardware level, in the mid noughties two online communities were created to develop and freely share 3D printer designs. The first of these was the RepRap Project, started in 2005 by Adrian Bowyer from the University of Bath in the United Kingdom. This was followed in 2006 by Fab@Home, which was initiated by Hod Lipson and Evan Malone at Cornell University in the United States. By 2012, Fab@Home's goal of accelerating personal 3D printing development was deemed to have been achieved, and the project was closed. However, as of October 2016, its website is still available for viewing at fabathome.org.

While Fab@Home is now resting in peace, RepRap is very much alive. RepRap stands for 'replicating rapid prototyper', with the project describing itself as developing 'humanity's first general-purpose self-replicating manufacturing machine'. From the outset the idea behind RepRap was to create 3D printer designs that would be freely available. Or as Adrian explained when interviewed on the former website 3dfuture.com.au:

> When one has a machine that self-copies, logic compels one to make it open source. The alternative is that one will spend the rest of one's life in court trying to stop people doing with the machine the one thing it was most designed to do.

RepRap is based on material extrusion technology, and while the earliest models fabricated items from a single filament, today RapRaps with multiple extruders are fairly common. Specialist parts manufacturer E3D even produce a 4-nozzle, water-cooled extruder called the Kraken that allows four print materials (or three materials and a support structure) to be included in a single print job. This is more than available on any commercial personal 3D printer, so demonstrating just one of the benefits of going open source.

Designs also exist for RepRaps with 'colour blending nozzles' (also known as 'mixer extruders'). These can combine two or three different thermoplastic filaments in the print head, so potentially permitting continuous tone multi-coloured objects to be created.

Given that RepRaps only 3D print in thermoplastics, they cannot entirely self-replicate. Nevertheless, as the RepRap website at reprap.org explains:

> Since many parts of RepRap are made from plastic and RepRap prints those parts, RepRap self-replicates by making a kit of itself – a kit that anyone can assemble given time and materials. It also means that – if you've got a RepRap – you can print lots of useful stuff, and you can print another RepRap for a friend.

What the above means in practice is that a RepRap can 3D print all of the custom, plastic parts needed to build another RepRap. In addition to these parts – which constitute about 50 per cent of the total device – some fairly standard components are also needed. These include threaded rods, servo motors, wiring, electronic circuit boards, a print head assembly, and a power supply. Such parts can be obtained both individually and as kits from a range of companies, including ReprapUniverse.com and GermanRepRap.com.

The initial RepRap design was called Darwin, and was first constructed in 2007 (with its 3D printed parts made on a Stratasys 3D printer). In the Summer of 2009 an improved RepRap variant called Mendel was introduced and remains popular to this day. A typical Mendel has a build volume of 200 x 200 x 140 mm (7.9 x 7.9 x 5.5 inches). As of 18 August 2016, 55 different RepRap designs were available for free download, including the Huxley, Wallace and several Prusa models. In October 2016, ReprapUniverse.com were selling RapRap kits (including all of the 3D printed parts) for between €499 and €999 (about $560 to $1,120). An assembled RepRap 'MendleMax' is illustrated in figure 5.4.

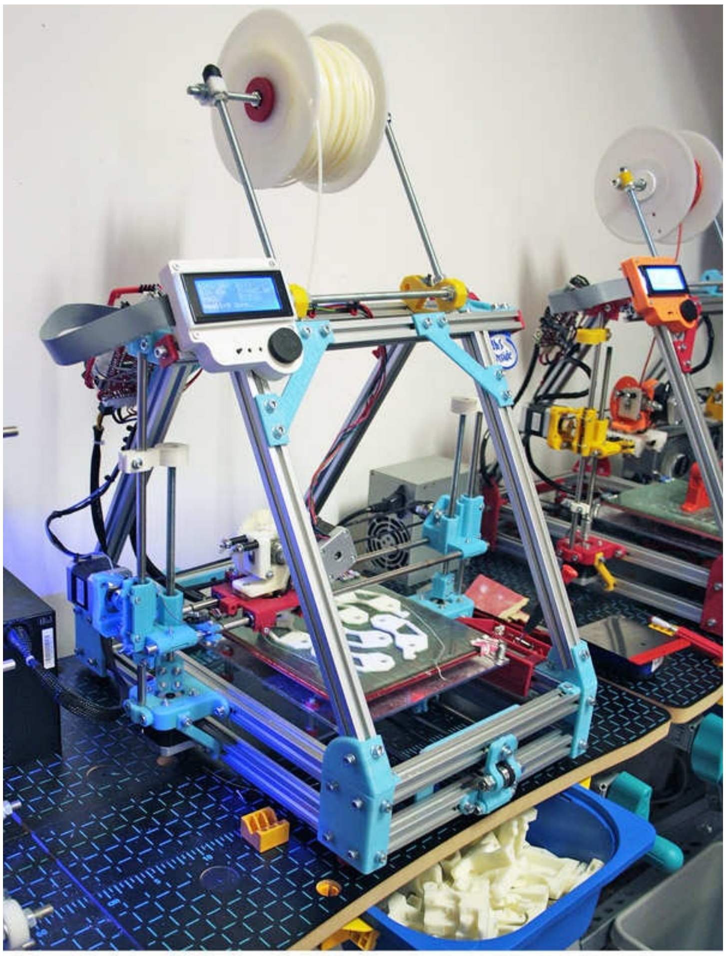

Figure 5.4: A MendleMax RepRap 3D Printer.
Image provided by RepRapUniverse.com.

PERSONAL 3D SCANNING

While owning a personal 3D printer is pretty cool, the hardware remains of little value without something to 3D print. Given time, most people can learn to design their own objects using the free or paid CAD applications I mentioned back in chapter 3. Indeed, amongst 3D printing enthusiasts, free software such as SketchUp Make from Trimble, or the TinkerCAD and 123D apps from Autodesk, are very popular. This said, the real world is bursting with objects just waiting to be replicated without mucking around with CAD software from scratch. And this is where 3D scanning comes into its own.

Over the past few years the market for personal 3D scanners has started to come of age. For example, 3D Systems now sell a handheld model called the Sense. Illustrated in figure 5.5, this $399 device features two cameras and an infrared (IR) emitter. As the user moves the Sense around an object, it sends out infrared rays, which bounce back to be received by one of the cameras. The results are then translated into 3D data, with the second camera simultaneously capturing colour information that can be applied to the scanned model as a surface texture.

Figure 5.5: The Sense 3D Scanner from 3D Systems

While the Sense struggles with small objects (to be honest anything much smaller than an apple), and cannot cope with transparent or reflective surfaces, it is pretty effective. This said, a common criticism is that it only works tethered to a PC, which can be constraining if you are trying to walk around a large object like a person.

A more expensive but very impressive personal handheld scanner is the Scanify from Fuel3D. As illustrated in operation in figure 5.6, this uses a set of pre-calibrated stereo cameras to photometrically scan objects placed next to a small target device. Or in other words, the Fuel3D extrapolates 3D data from two different cameras aimed at the same object from slightly different angles.

Figure 5.6: The Scanify 3D Scanner from Fuel 3D. Note the target device placed next to the flower being scanned.

I first saw a Fuel3D in operation at the 2014 London 3D Printshow, and it really is a very impressive piece of kit. At $1,490 it can hardly be described as cheap. But it is far less costly than the 3D laser scanners used to digitize objects in industry, which typically cost tens of thousands of dollars.

For the scanning of small objects, turntable-based scanners are often the most appropriate. Here, one lower-cost option is the $799 MakerBot Digitizer. As pictured in figure 5.7, this produces very detailed, monochrome scans of objects up to 203 mm (8 inches) in height and diameter. Operation is very straightforward, with the item to be scanned placed on the Digitizer's turntable for 12 minutes, during which time it rotates through 360 degrees while being scanned by two lasers and a CMOS sensor.

Figure 5.7: The MakerBot Digitizer 3D Scanner.

Taking a similar approach is the $520 Matter and Form 3D Scanner. This foldable device can handle objects up to 190 x 190 x 250 mm (7.48 x 7.48 x 9.84 inches) in volume. In common with the MakerBot Digitizer, final scans are detailed but monochrome, and can be completed in between 5 and 10 minutes depending on the resolution required.

As a final alternative, anybody with a standard digital camera, smartphone or tablet can use the free 123D Catch application from Autodesk to create a 3D model. The process involves rotating around an object while taking at least 20 pictures. These are then imported into 123D Catch, which uploads them to the Autodesk cloud where they are converted into a 3D model. For printout, the final result can be cleaned up in another free Autodesk app called Meshmixer.

AN INTERNET OF DOWNLOADABLE THINGS

While scanning offers an alternative means of digital object creation to building something in CAD, in practice most consumers are unlikely to either scan or design the majority of their 3D prints. Rather, we can expect most personally 3D printed items to be physical manifestations of digital files downloaded from the Internet. Already there are a growing number of online 3D content repositories, with the largest being Thingiverse.com.

Thingiverse was established by MakerBot Industries founders Zach Hoeken and Bre Pettis in 2008, and allows anybody to access and contribute to a 'universe of things'. As the site describes itself:

> Thingiverse is a thriving design community for discovering, making, and sharing 3D printable things. As the world's largest 3D printing community, we believe that everyone should be encouraged to create and remix 3D things, no matter their technical expertise or previous experience.

By October 2015, over 1 million objects had been uploaded to Thingiverse, with the site's users having made over 200 million downloads. Objects hosted on Thingiverse include engagement rings, scanned human faces, prosthetic hands, dental braces, figurines, vehicle models, flying drones, photographic accessories, tablewares, shirt buttons, and the obligatory smartphone cases.

Via its integrated 'MakerBot Customizer' app, Thingiverse even allows some objects to be customized before download. This allows users to tailor a range of designs to their own requirement. Customizable objects currently include skateboard wedges, spectacle frames, gears, pill boxes, plumbing fixtures, vases, bracelets and tool holders.

Other websites offering free or for-a-fee models for 3D printout include 3Dagogo.com, CGTrader.com, Cuboyo.com, Cults3d.com, df3d.com, Humster3D.com, MyMiniFactory.com, Pinshape.com, Redpah.com, Repables.com and 3DSquirrel.co.uk. Some 3D printer manufacturers also offer their own 3D object repositories. These include the Artist Collection from XYZprinting (at us.gallery.xyzprinting.com), and YouMagine from Ultimaker (at youmagine.com).

As 3D printers become more common domestic appliances, we should also expect an increasing number of non-3D-printing websites to start offering 3D printable content. Indeed, this is already starting to happen. For example, in December 2013 the movie *The Hobbit: Desolation of Smaug* became the first blockbuster to offer a promotional, 3D printable file in the form of a CAD design for *The Key of Erebor*. Not much later, in February 2014 Honda launched honda-3d.com to provide free, 3D printable digital models from its automobile design archives. In June 2015 Ford also followed suit and launched 3d.ford.com. This allows visitors to purchase STL files of popular Ford vehicles that allow them to 3D print model cars for themselves. Or alternatively, 3d.ford.com also sells final 3D prints.

In support of its mission to increase and diffuse knowledge, the Smithsonian now provides scans of some of its exhibits as free 3D printable files for non-commercial use. Over at 3d.si.edu, these include 3D files of dinosaur skeletons, famous statues, insects and ancient art. In July 2015, these were joined by a high-resolution scan of the *Columbia* command module from Apollo 11. Included were files for 3D printing a scale model of the exterior, a model of the pilot's seat, and a full-size Apollo 11 control panel knob. Yes, anybody can now download and 3D print part of a real spacecraft!

HACKERSPACES, FABLABS & MAKERS

Closely associated with the rise of personal fabrication are 'hackerspaces', 'FabLabs' and the broader 'Maker Movement'. All of these involve private individuals taking the means of design, production and repair into their own or community hands. None are a 3D printing development *per se*. But for most ‘hackers’, ‘fabbers’ and ‘makers’, 3D printers are a key weapon in their very practical armoury.

Hackerspaces and FabLabs may be broadly defined as open community workshops where members can share resources and knowledge to help them turn their ideas into physical reality. Many hackerspaces and all FabLabs are equipped with a variety of 3D printers and computer-controlled machine tools, with the FabLab Central website (at fab.cba.mit.edu) indicating a key element of any FabLab to be ‘digital fabrication’.

Individual hackerspaces started life in Germany in the 1990s. Hackerspaces.org was then set up in 2007 by Paul Bohm and some other pioneering enthusiasts to electronically link the different spaces together and to help the movement grow. Meanwhile, the FabLab (or ‘Fabrication Laboratory’) concept was created in 2003 by Dr. Neil Gershenfeld, Director of the Center for Bits and Atoms at the Massachusetts Institute of Technology (MIT).

To operate as a FabLab, a workshop has to provide public access to its facilities, to subscribe to the FabLab charter, to participate in the global FabLab network, and to share a common and quite extensive set of tools (which include 3D printers). Hackerspaces do not currently have such a formal list of common requirements, but very much share the same broad goal of democratizing the means of production within a local and global community.

According to the FabWiki (at wiki.fablab.is), as of 25 August 2016 there were 399 FabLabs operating in 70 countries. Meanwhile Hackerspaces.org listed 2,081 hackerspaces spread around the planet, of which 1,288 were actually ‘active’, with a further 349 marked as ‘planned’. Getting together on a community basis to engage in personal fabrication is really starting to become popular.

The above trend is also evidenced by the rise and rise of the ‘Maker Movement’. According to a neat posting by Cory Janssen on Technopedia.com, this may be defined as:

> … the name given to the increasing number of people employing do-it-yourself (DIY) and do-it-with-others (DIWO) techniques and processes to develop unique technology products. Generally, DIY and DIWO enables individuals to create sophisticated devices and gadgets, such as printers, robotics and electronic devices, using diagrammed, textual and/or video demonstration. With all the resources now available over the Internet, virtually anyone can create simple devices, which in some cases are widely adopted by users.

Unlike a hackerspace or FabLab, nobody has to join the Maker Movement. Rather, via their actions they may simply be identified as a ‘maker’ and part of it. All active members of hackerspaces and FabLabs – and indeed other ‘makerspaces’ – are likely to be ‘makers’, as are most of the private individuals who own a personal 3D printer.

Just as personal computing and the Internet empowered people to take control of information creation and exchange, so it is new production technologies – including 3D printing – that are key to the rise of the Maker Movement. As James Fallows has argued in an interesting series of articles in *The Atlantic*, ‘since the dawn of the capitalist heavy-industrial era, to succeed in manufacturing you needed capital. You needed money for giant production equipment'. But today the 'equation is changing', with a combination of 3D printing, low-cost laser cutters, other CNC machines, and low-cost microcontrollers, allowing individuals to manufacture almost anything cost-effectively at low volume.

In the United States there are now regular 'hackathons' and massive 'Maker Faires' to bring together members of the maker cause, and which celebrate the modern re-emergence of DIY and the cooperative, can-do mentality of maker culture. Just as computer geeks became cool during the PC and Internet revolutions (well, at least the successful ones), so makers, hackers and fabbers are likely to see their street cred skyrocket as a new age of personal fabrication slowly takes hold.

BUREAU SOLUTIONS

Sometimes when I give a talk on 3D printing, I ask the audience how many of them have access to a 3D printer. Usually a few hands go up, after which I reveal a slide with my prediction of how many audience members actually have 3D printer access. This always reads '100 per cent', with my explanation being that we can now all access online 3D printing services.

I suspect that many current and prospective makers, hackers and fabbers would auction off some of their less immediately vital body parts just to have their own 3D printer at home. Such individuals would probably also be very happy with their purchase, and would introduce a plethora of wacky new plastic things into their local community and close circle of family and friends. Nevertheless, I still believe that, for a good decade or more, personal fabrication will be dominated by those in-store and online 3D printing services that allow people who do not own a 3D printer to turn a digital design into a physical thing.

Back in chapter 3, I described the online printing services Shapeways, i.materialise and Sculpteo, as well as indicating the existence of many similar services. All of these are pretty easy to use, integrate well with high-end, low-end and free 3D modelling software, and provide anybody with access to high-end 3D printers based on all popular technologies. The price for getting something 3D printed in plastic, metal or another material using one of these services is admittedly rather high. But already, if you only want to 3D print a few objects a year, it is far cheaper to use a bureau service than it is to invest in your own 3D printer. And this is before the benefits of having access to all available 3D printing technologies and materials are considered.

For most people, the 3D Printing Revolution will allow the fabrication of things that they previously could not buy. Whether the 3D printer that allows this to happen is located in their own home, their local FabLab or hackerspace, in a local store, or in an online bureau like Shapeways or i.materialise, will matter far less than the possession of those final objects or components that get printed out. OK, so the first time you sit watching a 3D printer in operation it is pretty damn cool. But no sane individual sits staring at an inkjet or laser printer for hours on end as it does its stuff, and most people similarly get bored pretty quickly watching even the most amazing 3D printer. Many people will also realize this pre-purchase, avoid the capital outlay entirely, and opt to use bureau services when required. As we saw in the last chapter, many direct digital manufacturing pioneers already rely on online 3D printing services rather than their own hardware, and this should tell us a great deal.

For more private individuals to start using 3D printing services, prices will clearly need to fall and accessibility will have to increase. At least in the latter respect, there are also some signs that this is already starting to happen.

Perhaps most notably, 3D Hubs is on a mission to bring 3D printing to the masses by connecting those who own a 3D printer with those who have a file to print. As we saw in chapter 3, users of the service simply visit 3DHubs.com, where they upload their digital object and select the local 3D printer that they would like to fabricate it. If you are reading this and thinking 'hey, this means that if I purchase a 3D printer I can join 3D Hubs and use my new hardware to generate income', then yes, you are 100 per cent correct.

PERSONAL MANUFACTURING ARRIVES

By 2020, it is likely that approaching two million people will own a personal 3D printer, with local and online 3D printing services also regularly accessed by tens of millions of private individuals. Domestic 3D printing will I am certain remain a niche aspect of the broader 3D printing industry for a good decade or more. Even so, we are now starting to witness the emergence of a new age of personal fabrication.

This new age could also have profound implications. Already it is possible to visit online content repositories like Thingiverse or MyMiniFactory, and to freely download all manner of genuinely useful stuff that can be successfully 3D printed on hardware that costs a few hundred dollars. This will clearly be welcomed by those individuals who want to download and print a spare part or accessory for their vacuum cleaner, camera, fridge or coffee maker. This said, it is undeniable that many online object repositories already include a great deal of 3D-printable content – from *Star Wars* models to Lego parts – that infringe the intellectual property of another party. As we shall explore further in chapter 7, the rise of personal fabrication is therefore likely to go hand-in-hand with legal challenges that will dwarf the battles fought to stop music and video being illegally distributed online.

Equally controversial is the fact that 'personal fabrication' will one day extend far beyond the activity of 3D printing plastic or metal items at home. In addition, sometime in the 2020s or 2030s, doctors and engineers are likely to start using 3D printers to fabricate replacement human organs, to heal wounds, and to customize a person's anatomy one thin layer of cells at a time. This totally different kind of 'personal fabrication' quite literally relates to the partial fabrication of a person. It also commonly goes by the name of bioprinting, and is the subject of our penultimate chapter.

6. Bioprinting

While incredibly varied, all of the 3D printing technologies and applications detailed so far in this book have one thing in common. And this shared characteristic is that they all involve building things from non-living materials. Bioplastics like PLA that are widely used in personal 3D printers may be derived from corn or other organic feedstocks. But by the time that PLA is fed to a print nozzle it is long since dead.

Until very recently, almost all engineers left the fabrication of living things to farmers, biologists and Mother Nature. Yet in recent years this situation has started to change due to the invention of a new science known as ‘synthetic biology’ (SynBio), and the creation of a new variant of 3D printing called ‘bioadditive manufacturing’ or ‘bioprinting’.

Synthetic biology has the potential to complement 3D printing in the development of new manufacturing methods, and is hence a subject that I will return to in the last chapter of this book. But before we get to such matters, this chapter will explore how bioprinting pioneers are already learning how to fabricate living tissues by controlling the placement of layer-upon-layer of living cells. Their results are also already quite astonishing. For example, in November 2015, a Russian startup called Bioprinting Solutions reported that it had bioprinted several thyroid glands and successfully transplanted them into live mice. The rodents in question were closely monitored following their surgery, and after 11 weeks had a completely restored thyroid function.

The ultimate goal of Bioprinting Solutions is to 3D print replacement thyroids and more complex body parts for human patients. A growing number of research teams around the world have a similar goal, and there is certainly a medical demand. For example, in the United States alone, up to 100,000 patients are always waiting for an organ transplant, with less than a third of these people ever receiving one. Bioprinting therefore has the potential to deliver us into a new medical age in which damaged or diseased body parts will be routinely replaced with fully organic and ‘natural’ alternatives. Figure 6.1 visualizes a future bioprinter that is fabricating somebody a new heart.

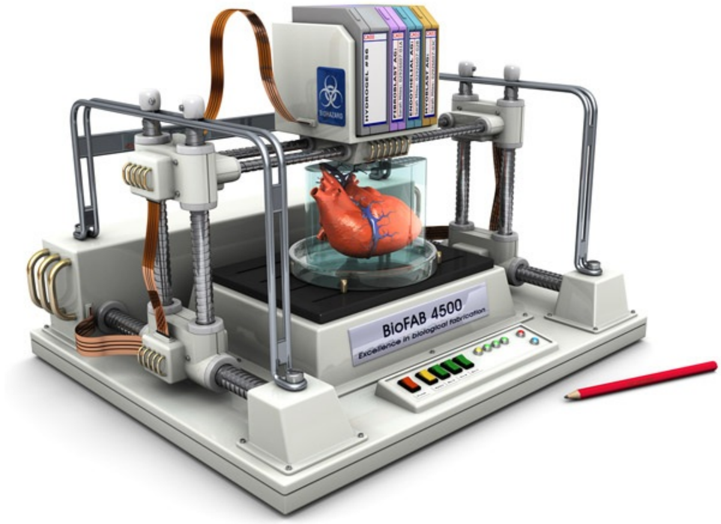

Figure 6.1: Concept Illustration of a Future Bioprinter.
Image created by Christopher Barnatt, ExplainingTheFuture.com.

In addition to allowing medical professionals to build replacement body parts in the lab, future bioprinters may even be able to treat patients *in vivo*. In other words, one day bioprinting could allow doctors to heal wounds and replace organs by bioprinting new cells directly onto and into their patients. As we shall see, *in vivo* bioprinting is already in development, and in time may transform not only how we heal the injured and the sick, but also the practice of cosmetic surgery.

FROM PHOTO PRINTER TO BIOPRINTER

Around the turn of the millennium, a Japanese paediatrician called Makoto Nakamura was becoming increasingly concerned about the number of his patients desperate for an organ transplant. He therefore started to investigate the possibility of creating mechanical, inorganic prosthesis. Then, quite by chance, Nakamura realised that the droplets of ink emitted from the print head in a standard inkjet photo printer are about the same size as human cells. The idea therefore dawned on him of turning a photo printer into a 3D bioprinter that could be loaded with a culture of human cells. The printer could then, at least in theory, output the cells via a material jetting process that would result in artificial, living tissue.

In 2002 Nakamura began his first experiments with a standard Epson photo printer. When initially loaded with cells, the device's print head simply clogged up. Undeterred, Nakamura made one of the strangest customer support calls in history. Fortunately, somebody at Epson was eventually receptive to his ideas, and with their assistance a year later the Professor managed to use a modified photo printer to successfully output cells that survived the inkjet printing process. This was achieved by encasing the cells in a sodium alginate hydrogel to stop them from drying out, and by jetting them into a calcium-chloride solution.

Between April 2005 and March 2008, Nakamura led a bioprinting project at the Kanagawa Science and Technology Academy. Here he guided a team that scratch-built an experimental bioprinter. This was then used to create ‘biotubing’ from layers of two different types of cells, with about 15 mm of 1 mm diameter material output every minute. In a few years, such biotubing may be able to be used as a living replacement for human blood vessels. Far further into the future, Nakamura’s hope is to be able to bioprint replacement organs for human transplant.

In addition to Professor Nakamura, many other researchers and organizations have built and operated bioprinters. As reported a few pages back, these include Bioprinting Solutions in Russia, who under the leadership of Vladimir Mironov have built a bioprinter called the FABION. Also advancing bioprinting frontiers with their own hardware are a team led by Anthony Atala at the Wake Forest Institute for Regenerative Medicine in the United States; Will Shu and a team at Heriot-Watt University in Scotland; and Ibrahim Ozbolat at Penn State University in the United States. Over in China, a company called Regenovo has also developed three bioprinter models called the Bio-Printer-Lite, Bio-Printer-Pro and Bio-Printer-WS.

Some businesses now even sell bioprinters as research tools. Principal among such vendors are Switzerland-based RegenHU, who market two models called the BioFactory and the 3DDiscovery, and EnvisionTEC with their 3D-Bioplotter. Meanwhile, over in South Korea, 3Dison market a ‘Hybrid Bio 3D Printer’ known as the Rokit Invivo, while the Japanese company Cyfuse Biomedical offer their CyFuse Vision 2020. Cellink also sell a desktop device called the ‘Inkredible’ which they describe as the ‘first true bench-top bioprinter’, while BioBots have developed their ‘fun to use’ BioBots 1. In case you are wondering, at the time of writing prices for these somewhat experimental but nevertheless ground-breaking bioprinters range from about $25,000 to $200,000.

A final leading player that has both developed a bioprinter, and which is now using it to produce commercial bioprinted materials, is Organovo, based in California in the United States. Organovo has the distinction of being the only pure play bioprinting company to have floated on a stock market. While I will return to the work of some of the aforementioned pioneers later in this chapter, the history and activities of Organovo are therefore worthy of our considerable attention here.

NATURE LENDS A HAND

Organovo is bringing to market the work of bioprinting pioneer Gabor Forgacs from the University of Missouri. In 1996, and following a painstaking study of chicken embryos, Forgacs recognised that cells aggregate and then later re-arrange during embryonic development in a manner that could greatly assist in artificial tissue fabrication. For years it had been assumed that embryos continuously grow their required cells in exactly the right places. But what Forgacs noted was that embryos oscillate between a phase of growing a mass of cells, and a period of moving these cells into their final required locations.

By 2004, Forgacs had used his insight to start developing his own bioprinting technology. This builds tissues not from individually jetted cells, but from ‘clumps’ of many thousands of cells. These clumps are termed ‘bio-ink spheroids’, and are injected into a water-based ‘biopaper’ by a tiny, needle-like print head.

In 2007 Forgacs founded Organovo with a mission to ‘create tissue on demand for research and surgical applications’. By March 2008, the company had developed a bioprinter that was custom-made by microelectronics manufacturer nScrypt. Forgacs and his team used this prototype to print both functional blood vessels and cardiac tissue using cells obtained from a chicken. Seventy hours after printout, the cells in the latter fused together so completely that they started beating.

In the next phase of their research, Organovo partnered with medical equipment manufacturer Invetech to create the NovoGen MMX. This was the world’s first commercial bioprinter, and like Organovo’s earlier prototype has multiple print heads. The first of these is loaded with bio-ink spheroids, while a second outputs a bio-paper support structure made from water mixed with gelatine, collagen or another hydrogel. The first NovoGen MMX was delivered to Organovo’s lab in January 2009.

The NovoGen MMX bioprinting process initially requires a sample of cells to be sourced from a patient biopsy or stem cells. These are then grown in the lab using standard biotech methods, before being cultured in a growth medium to create the required final volume of cells. All of the different cell types needed to create the tissue or organ to be printed are then mixed together into an aggregate.

For example, if a blood vessel is to be bioprinted, an aggregate is created containing a mix of primary endothelial cells (which form the lining of blood vessels), smooth muscle cells (which allow blood vessels to expand and contract) and fibroblasts (which form tough connective tissue). This cell aggregate is then put into a cell-packing device that compresses and extrudes it like a kind of bio-ink sausage. An ‘aggregate cutter’ next chops this sausage into bits, with the very tiny pieces spontaneously forming into bio-ink spheroids that each contain between 10,000 and 30,000 individual cells.

Once an adequate supply of bio-ink spheroids have been loaded into a NovoGen MMX, the bioprinting process can begin in earnest. As shown in figure 6.2, initially a single layer of bio-paper is laid out by the NovoGen’s first print head. The second print head then injects bio-ink spheroids into this bio-paper support. Additional layers of bio-paper and bio-ink spheroids are subsequently added to build up a three dimensional tissue structure.

After initial 3D printout is complete, an amazing natural process takes place, with the bio-ink spheroids self-assembling into solid tissue as shown in the lower portion of figure 6.2. Quite staggeringly, not only do the individual cells fuse together, but via natural, biological processes they somehow rearrange to end up in the correct anatomical location. So, for example, the endothelial cells from the bio-ink aggregate migrate to the inside of a bioprinted blood vessel, while the smooth muscle cells move to the middle and the fibroblasts shift to the outside. In more complex bioprinted materials, intricate capillaries and other internal structures similarly form naturally. During this ‘maturation phase’ – or shortly after it has completed – the bio-paper that initially held in place the non-fused cells either dissolves away or is otherwise removed.

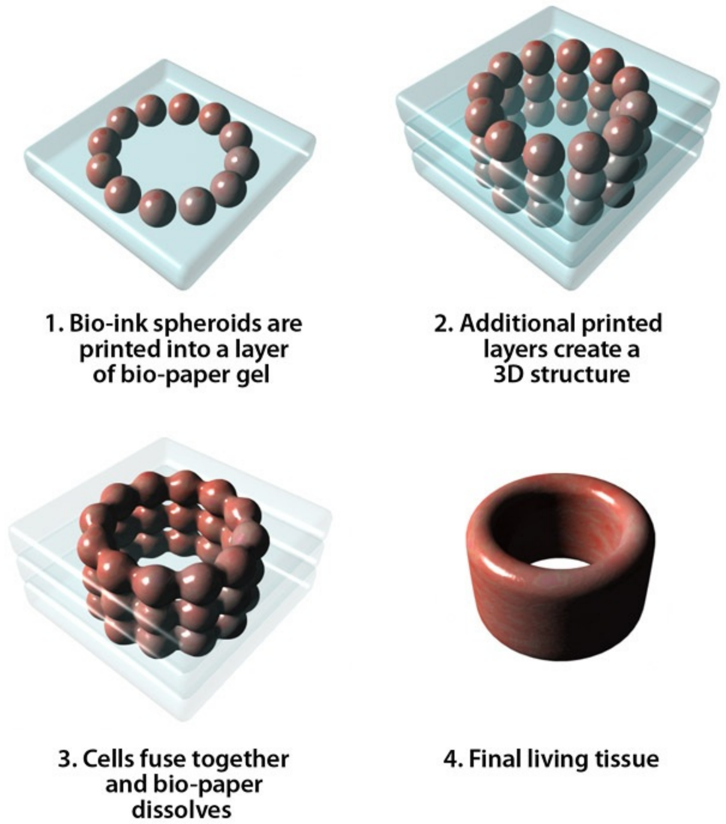

Figure 6.2: Bioprinting with Bio-ink Spheroids.

The way in which clumps of cells can bind together and rearrange after printout may sound almost magical. After all, once you have 3D printed an object using material extrusion or powder bed fusion, you do not expect it to evolve and improve. And yet this is exactly what happens after a NovoGen MMX (and other similar bioprinters) have done their stuff. While this may initially bewilder most people, as Gabor Forgacs has explained, it is no different to the cells in an embryo knowing how to (re)configure into complicated organs. Nature has been evolving such a self-assembly capability for billions of years. Once positioned in roughly the right places, appropriate cell types somehow just know what to do.

TOWARD TISSUE-ON-DEMAND

In December 2010, Organovo used a NovoGen MMX to create the first bioprinted human blood vessels. Since that time it has also managed to bioprint small samples of skeletal muscle, bone, liver and kidney tissue. The company has in addition already successfully implanted nerve grafts into rats, and has the long-term goal of being able to produce tissues for human transplantation. Indeed, as Organovo currently states on its website, 'we believe that engineered tissues will someday be a routine source of therapy for patients with damaged or diseased tissue'.

In the short-term, many of Organovo's activities are focused on helping pharmaceutical companies to speed the development of new drugs. Worldwide, trials of next generation medicines are increasingly failing, with innovative pharmaceutical compounds that worked fine in the lab very frequently not living up to expectation in clinical trials.

To assist with this situation, Organovo's first commercial products are a range of bioprinted human tissue models called ExVive that are now used in pharmaceutical R&D. The ExVive products allow drug developers to test their inventions on living human tissue at an early stage, with such tests more likely to mimic the results of clinical trials than animal experiments or traditional chemical lab tests that use '2D' cell cultures. Or as Organovo explain:

> Organovo's bioprinted human tissue models are multi-cellular, dynamic, and functional 3D human tissue models for preclinical testing and drug discovery research … . The tissues remain viable and dynamic for an extended time *in vitro* and exhibit key architectural and functional features that mimic key aspects of the natural 3D tissue environment … . ExVive 3D Bioprinted Human Tissues enable the capture of human tissue-specific data to support better predictive outcomes, de-risking total development time and resources.

The first bioprinted material to come to market was the ExVive Human Liver Tissue. This was first delivered to 'key opinion leaders' outside of Organovo in January 2014, before enjoying a full commercial release the following November. Organovo has reported the printout of 400 ExVive Human Liver Tissue samples in a month, each of which has a precise and reproducible architecture that greatly assists with consistent drug testing.

ExVive Human Liver Tissue printouts are functional and stable for at least 42 days, so enabling the assessment of drug effects over study durations well beyond those offered by traditional liver cell culture systems. Since 2014, several studies have indicated the benefits and success of using Organovo's bioprinted human liver tissues in drug research and development. For example, in July 2016, Roche Pharmaceutical Research released data indicating their superiority in assessing drug-induced toxicity compared to traditional methods.

In September 2016, Organovo announced the commercial availability of a second bioprinted product, the ExVive Human Kidney Tissue. At the time of the announcement, several orders had already been placed by companies wishing to use this for pre-clinical drug tests, with two major pharmaceutical companies already collaborating with Organovo on related research studies.

In addition to producing its bioprinted liver and kidney tissues, since 2013 Organovo has been working with the Knight Cancer Institute at Oregon Health & Science University (OHSU) to develop bioprinted cancer tissues, again for drug testing purposes. In May 2015, Organovo also announced a partnership with L'Oriel to develop bioprinted human skin tissue 'for product evaluation and other areas of advanced research'.

In yet another significant collaboration, since 2012 Organovo has been working with CAD giant Autodesk to create 3D design software for bioprinting. This is intended to improve bioprinting usability and functionality by opening up access to the NovoGen MMX to a far wider range of users. Or as Keith Murphy, Organovo's Chairman and Chief

Executive Officer, explained when the partnership was announced, working with Autodesk will offer ‘the potential long-term ability for customers to design their own 3D tissues for production by Organovo’. While today a sculptor may upload a new piece of jewelry to Shapeways or i.materialise to 3D print in plastic or metal, tomorrow a doctor may send a digital model of an arterial graft or even an entire organ to Organovo for bioprintout and return by FedEx.

While such an idea may sound far-fetched, on 5 October 2016 Organovo announced a formal program to develop bioprinted human liver tissue for human transplantation. The company even hopes to submit an Investigational New Drug (IND) application to the US Food & Drug Administration (FDA) ‘in three to five years’. As explained by Keith Murphy at the time of the press release:

> The scientific and commercial progress we have already made with ExVive Human Liver Tissue in drug toxicity testing has given us a firm foundation upon which to build a larger tissue for transplant. Advancing our first therapeutic tissue into preclinical development is an important milestone for Organovo, and it speaks to the power of our technology platform in addressing multiple applications, including preclinical safety, disease modeling and tissue replacement products for surgical implantation. We believe that 3D bioprinted tissues have an opportunity to provide options for patients who suffer from liver disorders.

To be clear, Organovo is not suggesting that it will be able to bioprint a complete human liver for transplant by the end of this decade. But what it does think it can deliver around 2020 are bioprinted human liver ‘tissue patches’ that could be surgically added to a patient’s failing organ. Such patches have the potential to ‘augment and extend organ function to give more time to those patients on transplant waiting lists’. Indeed, as Dr. John Geibel, a Professor of Surgery and Cellular and Molecular Physiology at Yale University, explained:

> There are many conditions in areas such as liver, kidney, gastrointestinal, vascular, and lung disease where supplying a tissue patch may be curative, or bridge a patient a few more years before they need a transplant. The promise of 3D bioprinting human tissues to address these unmet needs is significant.

The word ‘significant’ at the end of the above quotation is nowhere near strong enough to signal the extraordinary possibilities that lie ahead. It is very much worth noting that Organovo is a biotech and 3D printing company that has consistently delivered on its promises on or ahead of schedule. In turn, this means that the company’s announcement that it intends to develop therapeutic bioprinted tissue patches in three to five years has to be taken very seriously indeed. We are still a long way from bioprinting entire organs for human transplantation. But there is a good chance that at least some patients who take part in early trials will be given small bioprinted additions to their bodies in the 2020s.

CHALLENGES AHEAD

Organovo’s bioprinted human liver and kidney tissues are currently only a fraction of a millimetre thick, and it is likely that the company's planned transplantable liver patches will also be relatively slim. Partly this is to help speed their fabrication. But mainly it is because creating thicker bioprintouts that function successfully as living tissue remains a very real challenge. This is because living cells require a constant supply of nutrients, oxygen and other chemicals, as well as the constant removal of waste materials, in order to survive.

In complex living structures, a vascular network of capillaries provides a biological life support infrastructure to keep cells alive. Such capillaries may form 'naturally' within thick bioprinted tissues in their post-printout maturation phase as the initial layers of cells re-arrange and self-assemble. However, during the bioprinting process (which may take many hours) no such capillaries exist by default, and hence the cells in thick tissues cannot survive as living things.

Many research teams are attempting to solve the 'thick tissue' or 'vascularization' problem, with one of these being the Ozbolat Lab at Penn State University. This is led by Ibrahim Ozbolat, who has explained the challenge to be addressed as follows:

> Systems must be developed to transport nutrients, growth factors and oxygen to cells while extracting waste so the cells can grow and fuse together, forming the organ. Cells in a large 3D organ structure cannot maintain their metabolic functions without this ability, which is traditionally provided by blood vessels.

Ibrahim Ozbolat and his team hope to overcome the thick tissue problem by bioprinting 'microfluidic channels' that can temporarily take on the function of natural capillaries. As Ozbolat recently explained to *Advanced Manufacturing*, 'we can make capillaries within hydrogel. [But] the major problem is still making capillaries and integrating them with larger blood vessels. Also, maintaining their shape and structure'.

A few years ago I caught up with Ibrahim Ozbolat to ask about the progress of his work, and in particular his short- and longer-term goals. As he informed me, his short-term goal is 'to bioprint a pancreatic organ that is glucose sensitive' and which works in the lab. In the medium-term his hope is to transplant such a bioprinted organ into an animal and to successfully 'hook it up to its vascular system'. In the long-term, he wishes to develop the 'ultimate economical and feasible technology' that will allow stem cells to be used to bioprint a pancreatic organ that can be successfully transplanted anywhere inside the human body to regulate the glucose level of the blood.

As Ozbolat has highlighted in an article in the *Industrial Engineer*, achieving his above goals will not be easy. As he stressed to me, challenges ahead include not just the thick tissue problem of providing tissues with a surrogate vascular network during printout, but also reducing cell damage during the bioprinting process and improving the time taken for bioprinted cells to self-assemble into viable tissue.

A HELPING HAND

So far in this chapter I have focused on bioprinting research that results in the fabrication of living tissue. There are, however, also medical pioneers who are using 3D printers not to directly produce something organic, but to manufacture custom scaffolds that will in turn assist the organic growth or repair of body parts. This field of research is so closely associated with bioprinting that it is hard to separate the two. Not least this is because the bioprintout of thick tissue structures may depend on the successful and simultaneous fabrication of support materials that will keep living cells in place during and immediately after printout. Most traditional, inorganic 3D printing processes utilize a support structure, and there is no reason why bioprinting has to be any different (although some researchers do believe that scaffoldless bioprinting is a possibility).

The 3D-Bioplotter sold by EnvisionTEC is just one piece of hardware that is capable of bioprinting with support structures, or outputting support structures alone. Like Organovo’s NovoGen MMX, the 3D-Bioplotter can build up layers of bio-ink tissue spheroids that are kept in place and protected during printout by layers of hydrogels or ‘bio-paper’. But in addition, the EnvisonTEC device can also output a number of biodegradable polymers and ceramics that may be used to support and help form artificial organs. Alternatively, the 3D-Bioplotter may be used solely to create scaffolds for implantation into patients.

A team under the leadership of Jeremy Mao at the Tissue Engineering and Regenerative Medicine Lab at Columbia University have already demonstrated the extraordinary possibilities. For example, back in 2010, Mao and his fellow researchers pioneered techniques that may allow patients to regrow new joints around bioprinted scaffolds. In one experiment, 3D scans were taken of the hips of several mature rabbits. These were then used to bioprint 3D scaffolds upon which cartilage and bone could be regenerated.

Once printed, the scaffolds were infused with growth factors before being implanted into the rabbits in place of their own hip joints. As Mao’s team reported in *The Lancet*, over a four-month period the rabbits all grew new and fully functional joints. Some of Mao’s test subjects even began to walk and otherwise place weight on their new bone and cartilage only three or four weeks after surgery. In the future, the potential may therefore exist to 3D print and implant scaffolds that will help those with joint problems to grow their own natural replacements, rather than being fitted with artificial knees or hips.

Also working on the 3D printout of bone scaffolds are researchers at the Soman Lab at the Syracuse University in New York. Here researchers Lucas Albrecht, Stephen Sawyer and Pranav Soman have been experimenting using standard material extrusion 3D printers to produce bone scaffolds out of materials that include polycaprolactone (PCL) and PLA. A key finding of this work is that future bone scaffolds may be able to be made on low-cost and even consumer 3D printers – such as a MakerBot Replicator – so reducing the necessity to develop and pay for specialist medical equipment.

Taking yet another approach to the application of 3D printing in bone repair are a team led by Huang Wenhua at the Southern Medical University in Guangzhou, China. Here experiments are advancing using a 3D printer to create replacement bones from a bone powder adhered with a ‘biological glue’. Already the work has entered the animal testing phase, with experiments proceeding with goat and rabbit bone implants made from goat and rabbit bone powder. Huang Wenhua believes that 3D printed human bones produced using his method could be used clinically within ‘5 to 6 years’. However, this would require the availability of large quantities of human bone from which to make the powder. As this build material would not come from the patient, there is also a risk of rejection due to a lack of biological compatibility.

Hoping to avoid rejection issues with 3D printed bones are Xillogic in The Netherlands, who are working with Next 21 in Japan to develop ‘CT-Bone’. This is a calcium phosphate build material that can be 3D printed into implants that can replace diseased or damaged sections of a patient’s own bone. The intention is that CT-Bone implants will ‘unify’ with the patient’s natural bone, and in time will be converted into real bone by the patient’s body. In effect, this means that a CT-Bone printout will start its working life as an implanted prosthesis, but over time will transition into a scaffold that will eventually be replaced by natural bone.

IN VIVO BIOPRINTING

In addition to fabricating implantable living tissues, bone substitutes or scaffolds outside of the body, some future bioprinters will directly add new cells to patients one layer at a time. A key pioneer in this extraordinary field of *in vivo* bioprinting is Anthony Atala, Director & Chair of the Wake Forest Institute for Regenerative Medicine. Here experiments have already begun to bioprint cells directly onto a patient’s wound. Specifically, as the lead institution of an interdisciplinary network called the Armed Forces Institute of Regenerative Medicine (AFIRM), researchers at Wake Forest are developing bioprinting techniques that could be used to treat burn victims as a surgical alternative to using skin grafts.

In preliminary experiments, a laser scanner has been used to produce 3D models of test injuries inflicted on mice. Data from these models has then been used to guide bioprinter heads that have sprayed layers of cells, a coagulant and collagen onto the rodent’s wounds. The process bioprints two kinds of cells – fibroblasts, which make up the deep layer of the skin, and keratinocytes, which compose the top skin layer. Once the cells have been bioprinted, nature again takes over, with the cells growing and then fusing into new skin. As in ‘traditional’ *ex vivo* bioprinting, the cells used as the build material are sourced from a small patient biopsy and expanded in number in a culture in the lab.

Already the prototype *in vivo* bioprinter is fairly sophisticated, and is able to determine just what needs to be deposited on which part of the wound and to what thickness. Initial results have also proved very promising, with the injuries on the mice treated with the bioprinter healing in two or three weeks, compared to five or six weeks in a control group where the wounds were left to heal naturally. As Michael Romanko of the US Army’s Tissue Injury and Regenerative Medicine Project noted in the July/August 2014 edition of *Army Technology Magazine*, bioprinting is already a key tool being developed in the area of skin repair. It also has the potential for very widespread application not just in the military, but across the civilian population.

Already there is some evidence that the use of bioprinting to provide burn victims with new skin may result in fewer infections and less scarring than when applying a skin graft. In part this is because a major problem with skin graft burn treatment is obtaining enough tissue to cover and seal a wound. With appropriate technologies in place, the use of a 3D 'skin printer' could overcome this limitation, as enough cells could always be cultured from a patient biopsy and rapidly applied.

In an interview with *Advanced Manufacturing* in June 2016, John Jackson, an associate professor at Wake Forest, reported that their bioprinted skin heals normally, and blends in to look 'similar' to the surrounding tissue. Some of Wake Forest's bioprinted skin samples have now remained stable for two months – which is both amazing, if also a reminder that further progress is required before human tests are likely to commence.

In a separate but related development, Australian researchers from the ARC Centre of Excellence for Electromaterials Science (ACES), and orthopedic surgeons at St Vincent's Hospital, Melbourne, have developed a prototype 'biopen'. This may allow future surgeons to deliver live cells and growth factors directly onto damaged and diseased bones in the operating theatre, so accelerating the regeneration of functional bone and cartilage. The idea is quite literally that surgeons will be able to use such pens to 'draw' layers of cells onto damaged areas of bone.

As in other bioprinting methods, the cells dispensed by the biopen are encased in biopolymer hydrogels. Two such protective materials are combined in the pen during extrusion, and are then solidified with UV light to support and sustain the cells while they are built up layer-by-layer into a 3D scaffold. Once applied to the wound site, the deposited cells multiply and differentiate to form functional communities of nerve, muscle or bone cells. According to a research paper published in the journal *Biofabrication* in March 2016, the cells adhered to a patient wound site by the biopen have a survival rate in excess of 97 per cent.

As Professor Pete Choong, Director of Orthopedics at St Vincent's Hospital Melbourne, explained when initial results were published in December 2013, the biopen 'may be suitable for repairing acutely damaged bone and cartilage'. As he went on to note, the research team's work brings together 'the science of stem cells and polymer chemistry to help surgeons design and personalise solutions for reconstructing bone and joint defects in real time'.

THE FUTURE OF SURGERY?

While the work of both AFIRM and ACES is amazing, the development of *in vivo* bioprinting may one day not even be limited to printing new skin cells onto the exterior or artificially-exposed areas of the body. At present, most forms of surgery create a wound in healthy flesh through which instruments and often fingers are inserted to perform a stitch, staple, graft or transplant repair. Following an operation, patients therefore have to heal both internally and at the wound site. But fast-forward a few decades, and it may be possible for robotic surgical arms tipped with bioprint heads to enter the body, repair damage, and even heal their point of entry on their way out. Patients would still need to rest and recuperate as bioprinted materials self-assembled into cohesive living tissue. Even so, when treated in this manner, healthy patients could potentially recover from very major surgery in less than a week.

In an article in the January–February 2011 edition of *The Futurist,* Russian pioneer Vladimir Mironov – the guy who in 2015 successfully implanted bioprinted thyroids into several mice – imagined how *in vivo* bioprinting may work in practice. In a fictional future scenario, a football star injures his knee midseason with severe cartilage damage, and undergoes immediate surgery. As Mironov continues the tale:

> At the start of the operation, four endoscopic devices are introduced into the star athlete’s knee cavity. One has a miniature camera attached to it that enables the operating surgeon to see, the second provides laser technology, a third device eliminates tissue, and the fourth injects living stem cells isolated from the patient’s fat tissue and suspended in hydrogel.
>
> The robot, controlled by a surgeon visually monitoring the procedure, removes the damaged cartilage using a tissue plasma evaporator. Next, the patient’s own stem cells mixed with hydrogel are injected into the area and immediately polymerized by the laser beam. Finally, the endoscopic operating tools are removed and the injured skin is sprayed with a mixture of self-assembling skin cells suspended in hydrogel.

According to Mironov’s prediction, such an operation could be completed in 20 minutes, with the patient walking out of the operating theatre and returning to the football field the next day. In time, the procedure could be used not just to mend damaged knees, but as a cure for arthritis and even to accomplish major surgery. After all, why bioprint new organs outside of the body (so inflicting major transplant surgery on a patient) if old organs can be removed and new ones ‘fitted’ one thin layer at a time?

If the above, well-informed scenarios were not enough, some twenty to thirty years from now *in vivo* bioprinting might be so safe and routine that it starts to be used cosmetically. As I argued in my book *25 Things You Need to Know About the Future*:

> A great many technological innovations that are created for one purpose end up being used for another. For example, modern plastic surgery techniques were developed to help rebuild the bodies and lives of burn victims and others who suffered horrific accidents. However, as we all know, plastic surgery is now performed far more commonly for cosmetic reasons than out of medical necessity. As and when bioprinting evolves into a routine and refined practice, its cosmetic application is similarly likely to skyrocket.

A few decades hence it may become possible to use a bioprinter to radically, rapidly and fairly safely transform the human body. Want bigger muscles without the exercise? Then why not visit your local bioprinting clinic and have them printed into your body that afternoon? Or fancy going skiing but worried about breaking your legs? Then why not have your bones replaced with bioprinted upgrades that are reinforced with carbon nanotubes or graphene? These top-of-head scenarios may sound both fantastical and scary. Yet they may well be just the tip of a cosmetic bioprinting iceberg.

One day we may even see cosmetic bioprinters like the one I imagine in figure 6.3. Here a 'face printer' has been created that can remove unwanted layers of flesh, bone and other tissue and replace them with new bioprinted cells according to the patient's specification. Want to look like your favourite celebrity? Then just download a scan of their face from Thingiverse and have it applied in your local bioprinting bureau. Or fancy redesigning your nose on your iPad? No problem, by 2042 there may well be an app for that. Or simply worried about looking old? Once again no problem, just get your face scanned when you are a teenager and have it reapplied every five or ten years to achieve apparent perpetual youth.

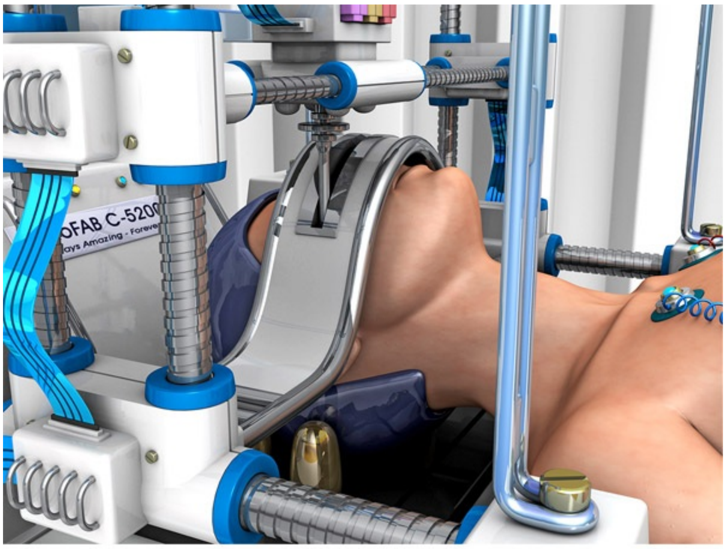

Figure 6.3: Concept Illustration of a 3D Face Printer.
Image created by Christopher Barnatt, ExplainingTheFuture.com.

These admittedly flippant scenarios may sound both ludicrous and utterly repugnant. Nevertheless, as and when *in vivo* bioprinting becomes a reality, so a machine like that shown in figure 6.3 may well be a technical possibility. Of course this does not mean that anybody would ever want to use it. Who, after all, would ever choose to have their face re-bioprinted? Let alone run the risk of such a procedure going wrong? In response I would simply note that every year millions of people already risk the considerable dangers of surgery purely to try and improve their looks.

Vanity has always been an enormous business and is very unlikely to shrink. Once the potential exists to have cosmetic face-replacement surgery, at least a few crazed individuals are subsequently likely to sign up to have an application of the ultimate in living, designer make-up. Though once they have successfully undergone the procedure, we may not know who they are.

BEYOND HUMAN FLESH

As long ago as September 2004, the first International Workshop on Bioprinting and Biopatterning was held at the University of Manchester in the UK. Since that time this annual event has brought together an increasing number of physicists, biologists and physicians all keen to push forward the boundaries of tissue engineering. A professional bioprinting research community has in fact now become very well established, with the International Society for Biofabrication (ISBF) founded in 2010, and the specialist academic journals *Biofabrication* and *Bioprinting* launched in 2009 and 2016 respectively. As Vladimir Mironov, Makoto Nakamura and Fabian Guillemot pronounced in their editorial in the second edition of *Biofabrication*, it is already ‘safe to state that bioprinting technology is coming of age’.

The above noted, it appears that all of those pioneers currently working in bioprinting are focused on additively manufacturing living tissues that will remain alive in a stable fashion for long periods after printout. For the medical application of bioprinting, this is clearly very important. However, the human race has long fabricated things out of materials that were once alive, but which we utilize in a dead state. To this day, natural materials such as wood, leather and bone possess physical properties that we find very difficult to duplicate with plastics, metals or the latest composites. Beyond the hospital and the pharmaceutical development lab, bioprinting may hence have a very wide range of future applications in the traditional manufacturing realm.

One of the great strengths of 3D printing as a manufacturing technology is that it builds objects additively in layers, so allowing any valid geometry to be fabricated. Yet one of the great drawbacks of 3D printing is also the fact that it builds objects in layers, as this invariably involves a trade-off between resolution and print speed. If objects are built out of very thin layers their surface quality can be superb. On the other hand, if objects of any size are built out of very thin layers, they inevitably also take a very long time to create.

Current direct digital manufacturing pioneers overcome the ‘layers problem’ in various ways. Most obviously, they use 3D printers to fabricate small items (such as jewelry or dental appliances) that can be output relatively quickly. Alternatively, they only 3D print very expensive or highly customized items (such as jet engine fuel nozzles or hip implants) that are cost effective to produce even if they take tens of hours or even many days to build-up in the printer.

In other instances, direct digital manufacturing pioneers do actually print in thick layers – extruding metal or plastic in a bead 10 mm or more in diameter. This greatly speeds print time, and is what occurs in the BAAM machine from Cincinnati Incorporated that has already 3D printed car bodies, the EBAM direct metal 3D printers from Sciaky, or the 3D concrete printers created by WinSun in China. In all of these instances, the resultant, highly-stepped 3D printed surface is usually post-processed after printout by filling and sanding (in the case of the BAAM), CNC milling (in the case of Sciaky’s EBAM process), or via manually rendering the surface with an outer coating (in the case of some of WinSun’s 3D printed buildings).

But what if future 3D printers could build large objects in thick layers and achieve a smooth surface without any time-consuming post-processing? Well, experience to date in bioprinting suggests that this is at least a theoretical possibility. Looking back to figure 6.2, you may recall that most of today's bioprinters deposit layers of a cell aggregate which, following printout, spontaneously rearranges and self-assembles into a cohesive, final material. Given this fact, it is not impossible to imagine future industrial 3D printers that will be fed with a living build material that will similarly rearrange and self-assemble after printout, before dying on digital cue.

At the cutting edge of materials research, there are already those who expect living materials to be the future. Not least, the US Defence Advanced Research Projects Agency (DARPA) is seeking to develop 'tools and methods for creating programmable, self-healing, living building materials'. To this end, in August 2016 it launched its Engineered Living Materials (ELM) program, which has been given the goal of:

> … creating a new class of materials that combines the structural properties of traditional building materials with attributes of living systems. Living materials represent a new opportunity to leverage engineered biology to solve existing problems associated with the construction and maintenance of built environments, and to create new capabilities to craft smart infrastructure that dynamically responds to its surroundings.

While the 20th century and its engineering practices were dominated by physics and inorganic chemistry, the 21st century is expected to be overshadowed by the biosciences. As we shall explore further in the next chapter, already biotechnologists and synthetic biologists are learning how to cut-and-paste DNA sequences in order to build living things that have never existed in the natural world. In time, the creation of new, organic materials that can be 3D printed in thick layers, and which will then use the technology of life itself to complete their own digital production process, therefore has to be a possibility. Or as I argued in my 2015 book *The Next Big Thing*:

> For millennia human beings have fashioned products from natural organic materials – such as leather, wood and bone – that were once alive, but which we use as manufacturing inputs in a dead state after we have harvested them. Future bioprinting innovations could allow digital fabrication using an entirely new range of synthetic, organic materials that remain alive throughout a production (3D printing) and post-production (maturation) process. Imagine, for example, a 3D (bio)printer that could output layers of an organic material akin to living coral, with the end result of its fabrication process being a complex and (largely) dead form like a coral reef. 3D printing in concrete may help us create more material-efficient buildings. But it will never compete in environmental terms with a future bioprinting process capable of turning a digital design into a building that is actually part of the 'natural' world.

Back in the *Preface* I argued that we should not judge the continuing 3D Printing Revolution based on its current technologies. And to this assertion I would here add that we must also not judge it based on its current build materials. By offering a digital fusion of the best of the biosciences and the best of additive manufacturing, bioprinting could end up becoming the catalyst and the lynchpin that delivers us into a new manufacturing age.

A few decades from now, we may bioprint not only parts of ourselves (and maybe our pets), but also our shoes and our clothing, our homes, our furniture, and maybe even vehicles and bioelectronic devices. Shocking as it may be to some, the face printer could be just one tiny if extraordinary facet of an organic 3D Printing Revolution.

7. Brave New World?

So far in this book we have looked at 3D printing technologies, the 3D printing industry, direct digital manufacturing, personal fabrication and bioprinting. I would also suggest that gaining some knowledge of all five of these areas is important for anybody who wants to really understand 3D printing. Granted, there are academics and engineers who have told me that a knowledge of the 3D printing industry and personal 3D printing is irrelevant, and on a purely technical level this may be correct. However, we only have to look back to the development of computing to be reminded of the importance of the personal application of any new technology, as well as the impact of those particular entrepreneurs and companies who rise to dominate a new technology sector. We really should not forget that Bill Gates and Steve Jobs were personal computing *business gurus*, not research scientists, programmers or hardware engineers.

While all of the topics we have looked at so far serve as critical, individual pieces in the 3D printing puzzle, this final chapter will broaden our analysis to place the development of 3D printing in a wider context. In particular we will consider how 3D printing has a major role to play in improving sustainability, and in parallel how it is likely to converge with other new digital manufacturing technologies. After that, the potentially negative impacts of digital manufacturing will be addressed. And finally, I will present my predictions for where 3D printing may be headed in the short- and long-term.

A MORE SUSTAINABLE FUTURE

As we have seen, 3D printing is starting to find practical application in many different industries, as well as empowering a new generation of individual makers. All of this is, I think, quite amazing. Yet, with the exception of the application of 3D printing in healthcare and possibly the aviation sector, I doubt that any of the examples included so far in this book indicate a trajectory to a fundamentally different manufacturing future. 3D printing will increasingly allow companies and individuals to create new kinds of niche, novel, customized and self-made products. But I do not believe that this is what the 3D printing revolution is really going to be about. Far more significantly, and in parallel with some other new technologies, 3D printing offers the opportunity for us to live more sustainably by reducing our consumption of natural resources. And this will happen in three distinct ways.

Firstly, 3D printing will improve the resource efficiency of our manufacturing methods. Secondly, 3D printing will facilitate increased recycling and repair. And finally, 3D printing will enable localization and manufacture-on-demand, so reducing the resources we indirectly consume in transportation, surplus production, and long-term product storage.

In my opinion, it is the tremendous opportunities to make resource and related cost savings that will drag 3D printing into the mainstream. 3D printing is never likely to become a viable alternative to most traditional production methods so long as massively global markets continue to function effectively and traditional raw materials remain in fairly plentiful supply. However, the very wasteful folly of mass globalization is starting to be questioned, while resource scarcity will be with us by the late 2020s or early 2030s. If you do not believe me, just look at the rate at which China and other rising nations are industrializing, as well as the skyrocketing prices of many critical raw materials.

Due to the fairly stark economic and environmental realities on the near horizon, in the next few decades we will need to start achieving more with less. In turn, this will require us to mainstream 3D printing and related technologies in order to maintain our current levels of prosperity and civilization. To be clear, what I am saying is that it will not be innovations in 3D printing that will bring the technology into common usage. Rather, our requirement to manufacture things more resource efficiently, to localize, and to repair and recycle more, will demand that we increasingly 3D print.

In support of this logic, it is worth pointing out that many influential bodies are now highlighting new technologies as a key part of the solution to our challenges ahead. Not least, in January 2012, the United Nations High Level Panel on Global Sustainability expressed matters thus:

> The challenges we face are great, but so too are the new possibilities that appear when we look at old problems with new and fresh eyes. These possibilities include technologies [like 3D printing] capable of pulling us back from the planetary brink.

RESOURCE-EFFICIENT PRODUCTION

Today, many industrial processes consume significant quantities of raw materials that never end up as part of a final product. This is because many current production methods are subtractive. In other words, they start with a solid block of material and then cut, lathe, file, drill or otherwise remove bits from it. In contrast, 3D printing starts with nothing and only adds the material that is required. This means that 3D printing is inherently a more resource-efficient manufacturing process.

In addition to reducing direct manufacturing waste, 3D printing can allow components to be produced with a more material efficient design. For example, while machined or cast parts have to be made of solid metal, 3D printed alternatives can have open lattice internal structures that consume less material while still possessing the required structural properties. When parts no longer have to be produced via traditional machining, casting or molding processes, it is also often possible to remove material from their design without altering their structural integrity, so again decreasing raw material use. All of this not only saves resources in manufacturing, but results in lighter components.

As we have seen in earlier chapters, in the aviation sector in particular the potential benefits of 3D printing lighter parts are being taken very seriously, as they will result in more energy-efficient aircraft. The airline industry has set itself a target to reduce its carbon emissions by 50 percent by 2050. It is therefore hardly surprising that aircraft manufacturers are intent on using 3D printing as one means of achieving this goal.

An ardent pioneer of 3D printing in aviation is Airbus, with material and weight savings comprising an important part of the company's additive manufacturing agenda. Indeed, as the company's Peter Sandler explained in a March 2014 press release entitled *Printing the Future*:

> We are on the cusp of a step-change in weight reduction and efficiency – producing aircraft parts which weight 30 to 55 per cent less, while reducing raw material used by 90 per cent. This game-changing technology also decreases total energy used in production by up to 90 percent compared to traditional methods.

Potential savings resulting from direct digital manufacturing will not be limited to the production of new vehicle components. Not least, as we saw in chapter 2, in the future it is quite possible that buildings (or parts thereof) will be 3D printed, again with materials added to the construction only where absolutely necessary. For example, homes or workplaces 3D printed in extruded concrete will be able to feature air gaps and lattices within their walls, roofs and floors. In addition to saving materials, these will improve the building's insulation and in turn make it more energy efficient.

3D PRINTING & PRODUCT REPAIR

Using 3D printing to save natural resources in production will clearly be highly beneficial. But we can also reduce our natural resource requirement by keeping products in use for longer.

Today, one of the main reasons that so many nearly-functional items are thrown away is that very few products contain replaceable parts. This is due to both poor product design, as well as the fact that most manufacturers would prefer to sell us a new product rather than helping to repair a broken one. These points noted, even when product repair is championed, it usually proves uneconomic for companies to make all possible spare parts available at the right times and in the right locations.

Widespread, local 3D printing will change the repairability landscape, with spare parts for most products able to be stocked digitally and manufactured-on-demand. I know from my client work that some companies are starting to think very seriously about creating a 3D printable inventory of replacement components. In addition, object sharing websites like Thingiverse already contain freely downloadable spare parts for products that range from domestic heating systems to cameras and coffee machines. Even when a spare part cannot be tracked down online, enterprising individuals (or future repair bureau) may be able to design a new component from scratch, or else scan a broken item, repair it digitally in CAD software, and print out a replacement.

By itself, the ability to make spare parts will be insufficient to get many things mended, as skilled people (or robots) will be required to open up broken possessions and fit replacement 3D printed components. This said, the Maker Movement is on the rise, with an increasing number of people keen to take responsibility for producing and maintaining their own possessions.

3D PRINTING & RECYCLING

3D printing will also help us to reduce waste by facilitating increased recycling. At present the most widely used 3D printing technology is material extrusion, with the most common build materials being thermoplastics that can in theory be reclaimed and turned into new 3D printing filament when items are discarded. Showing us the way, since 2014 a company called Fila-Cycle has specialised in producing '100 per cent recycled plastic materials' for use in 3D printing. The company's current products include a HIPS filament created from recycled automotive plastics, a PLA filament created from recycled yoghurt pots, and a PET filament created from recycled plastic bottles. You can learn more at fila-cycle.co.uk.

In addition to 3D printing with recycled filaments made by third parties, personal 3D printer owners may start to produce their own recycled build materials. Several personal filament makers are already on the market, and turn plastic pellets – and potentially suitably-shredded old 3D prints or other recycled plastics – into a new build material.

One particularly impressive device is the Strooder from OmniDynamics, as illustrated in figure 7.1. There really is no reason why, in a few years time, it will not be common to separate out your plastic waste, shred and extrude it at home, and 3D print it into new stuff. Indeed, as a student of mine nicely argued a few years ago, in the future we may all own a fixed quantity of physical stuff that we will constantly re-manufacture into whatever possessions we require at a particular point in time.

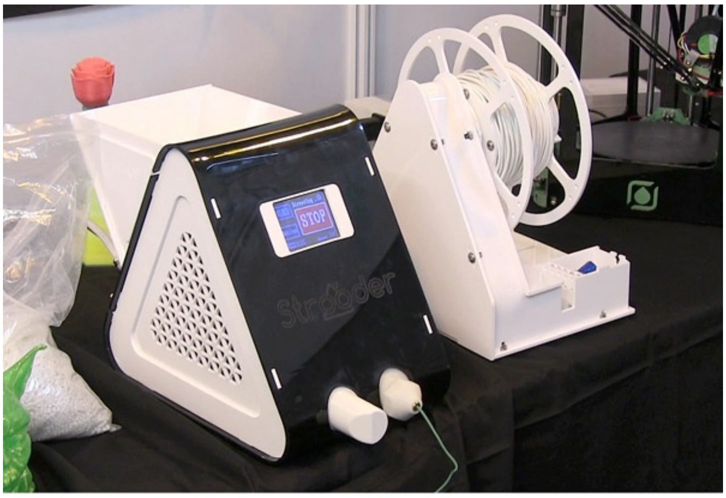

Figure 7.1: The OmniDynamics Strooder 3D Filament Maker.

If you think that the above sounds ridiculous, you may be surprised to learn that a Dutch artist call Dirk Vander Kooij is already selling a range of designer furniture and other household items that are 3D printed from recycled plastics. This all started in 2011 when Dirk created the first industrial robot that can fabricate furniture pieces from 100 per cent recycled materials. Dirk now has two such robots in his studio, both of which extrude object layers in a plastic bead 10 mm or more in diameter, and which can produce a full-size, highly-durable chair in just three hours.

Figure 7.2 illustrates one of Dirk's 'Chubby Chairs'. This may look like it has been 'squeezed from a toothpaste tube', but is actually as 'tough as oak wood'. You can find out more about Studio Dirk Vander Kooij's growing collection at dirkvanderkooij.com.

Figure 7.2: A 'Chubby Chair' from the Dirk Vander Kooij Collection. 3D printed in recycled plastic. Photo credit: Stanley van der Hoeven.

LOCAL DIGITAL MANUFACTURING

Our current industrial model works something like this. Somebody dreams up a product, a factory far distant from most potential customers is tooled up to produce it, and a large number of identical products are manufactured in the hope that somebody, someday will want to buy them. These products are then transferred to a warehouse, from where they are gradually shipped to wholesalers and retailers who attempt to sell them to potential customers.

In time, many products are sold, although about one-seventh of the income generated from their sale is spent on moving them around the planet and related logistics services. Some products are never actually wanted by anybody, and need to be written-off (which is often a polite way of saying that they are quietly discarded into landfill). This crazy system works because there are enough cheap natural resources currently available for companies to be able to waste a great deal and still make a profit. But as waste and excessive energy emissions become less economically and environmentally acceptable, so things will have to change. It really needs to be appreciated that the way we run our industries today is very different to how we ran them 30 or 40 years ago, with the current obsession of economists and large companies with globalization hardly being a natural or sustainable state of affairs.

The good news is that we are on the brink of a whole new age of local digital manufacturing (LDM). This uses digital technologies to make products on demand very close to where their final consumers actually live. Local manufacturing was the bedrock of human civilization until the Industrial Revolution. Unless they had grown their own food and locally produced most of their own clothes and other possessions, our forebears would simply have had nothing and would not have survived.

While local manufacturing is almost as old as the hills, local *digital* manufacturing is a recent innovation. To some extent, since the personal computing revolution of the early 1980s we have been able to make things out of binary data on a very local basis. 3D printing is, however, the first mainstream local digital manufacturing technology that can make physical products. As we saw in chapter 5, the Maker Movement is rapidly expanding, with many people now using desktop 3D printers to materialize objects which they have either designed themselves, or else downloaded from the Internet.

While some local digital manufacturing is likely to take place in the home – or in a nearby hackerspace or FabLab – we should expect LDM to become a mainstream industrial phenomenon. In one or two decades time, many retail outlets could be equipped with 3D printers that will locally manufacture products on demand. In addition, distributed manufacturing facilities – or DMFs – may come into existence. These relatively small and probably highly-automated mini-factories could locally fabricate the product range of a single manufacturer, or may be shared by a wide number of businesses. Some DMFs may even be run by their local community. Today, a great deal of manufacturing is contracted out to third parties. The only difference is that, in the future, such outsourced production could occur on a very local basis to minimise the distance from the manufacturing location to the final customer.

As local manufacturing using 3D printers becomes more widespread, so the digital transportation of many items will become a greater and greater possibility. Moving around bits of digital information has to be more environmentally friendly than shipping physical things made from atoms. In the future, when we purchase something from a website, we may therefore no longer receive a parcel from UPS, but instead a set of print-rights and a password that will allow us to materialize our purchase at the 3D printing bureau or DMF closest to our home. And when we do receive a package from a courier, increasingly the contents may have been fabricated not more than a few score miles from our home, and quite possibly in the courier organization’s own manufacturing facility.

Just as significant as the digital transportation of objects for local printout will be digital object storage, as this may end excessive over-production. Environmentally, it is essential that every item we make enters useful application as soon as possible after it is manufactured, and local 3D-print-on-demand could help to make this a common future reality.

In addition to 3D printing, local digital manufacturing will increasingly involve other technologies, and most notably synthetic biology (SynBio) and next-generation nanotechnologies. As our necessity to pursue local digital manufacturing accelerates, so we should also expect 3D printing, synthetic biology and nanotechnology to naturally converge. Figure 7.3 illustrates this concept.

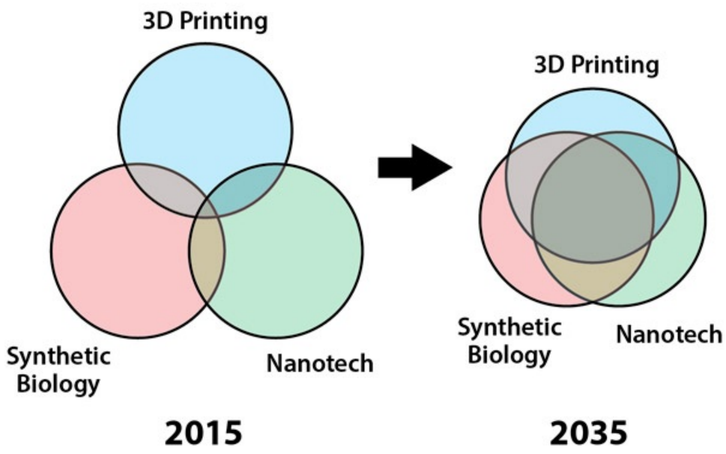

Figure 7.3: Local Digital Manufacturing Convergence.

As shown in the figure, while today the overlaps between 3D printing, synthetic biology and nanotechnology are somewhat limited, by 2035 I expect them to be extremely significant. To explain this prediction, we will now look in turn at synthetic biology, nanotechnology, and their current and likely future associations with 3D printing.

3D PRINTING & SYNTHETIC BIOLOGY

3D printers turn digital data into physical things. This is a pretty clever trick, if one that life itself has been evolving for millions of years. So what if we could use living systems as a digital manufacturing technology? Well, this is what the new science of synthetic biology is all about, with its pioneers already learning how to manipulate the digital data chemically coded in DNA in order to create 'synthetically modified organisms' (SMOs).

Some SMOs may be future products themselves. Alternatively, they may be biological machines (or in other words micro-organisms, plants or animals) that we will in turn use to manufacture future products. Either way, synthetic biology is destined to provide us with revolutionary fabrication methods. Or as German pioneer Intrexon more formally explains:

> Synthetic Biology is the engineering of biological systems to enable rational, design-based control of cellular function for a specific purpose. The programming of DNA and reformatting of genetic circuitry within cell platforms has created a paradigm shift whereby the analysis of biology is being supplanted by its synthesis.

In order to weave its apparent magic, synthetic biology breaks life into standardized genetic components – sometimes called 'BioBricks' – whose function can be fairly easily understood. These Lego-like, molecular building blocks can be pieced together in a biological CAD package, such as GenoCAD, with the final design spliced together chemically in the lab. Indeed, novel living things can now even be printed, with a company called SGI-DNA having launched the first ‘DNA printer’ in May 2015. Known as the BioXp 3200, this is loaded with liquid ‘reagents’ that are chemically assembled into DNA in about 12-17 hours. As SGI-DNA further explain, the BioXp 3200 is:

> … a machine which will allow any biotechnology company or academic laboratory to create genes, genetic elements and molecular tools on their benchtop hands-free, starting with electronically transmitted sequence data. SGI-DNA’s BioXp 3200 Instrument will dramatically improve the workflow for applications such as protein production, antibody library generation and cell engineering.

Already synthetic biology pioneers are achieving great success. For example, in May 2010, the J. Craig Venter Institute (JCVI) built the first ever entirely synthetic life form. Termed ‘JCVI-syn1.0’, this self-replicating, single-cell organism was based on an existing *Mycoplasma capricolum* bacterium. Yet, at its core was an entirely synthetic genome consisting of 901 genes constructed from 1.08 million DNA base pairs in the JCVI laboratory.

By March 2016, JCVI had cut down its first artificial cell to create the first ‘minimal synthetic cell’ that contains only the essential building blocks required for life. Labelled ‘JCVI-syn3.0’, this second synthetic cell has just 473 genes made from 531,560 base pairs. Although far less widely reported, the creation of JVCI-syn3.0 was at least as important as that of JCVI-syn1.0, as it involved synthetic biologists making a new form of life in the most efficient manner.

So what are the practical applications of synthetic biology? Not to mention the implications for 3D printing? Well, for a start, several companies – including Amyris, Intrexon, Modular Genetics and Solazyme – have begun to use synthetic biology to create synthetic micro-organisms that can turn organic materials into petrochemical substitutes including biofuels, bioacrylics and medicines. Meanwhile a company called Spiber in Sweden have engineered synthetic cells that can manufacture spider silk. In the United Kingdom, the Open Plant Initiative is even investigating how future synthetically modified plants may be used to improve and sustain the production of biomaterials and entire bioproducts.

Potentially of most short-term significance for 3D printing, a team from the Korea Advanced Institute of Science & Technology have used synthetic biology to engineer a synthetic *E. coli* bacterium that can produce the bioplastic polylactic acid (PLA) from an organic feedstock. As we have seen in other chapters, PLA is fairly widely used as a 3D printing filament. Today this organic, biodegradable material has to be produced using a two-stage process that first ferments agricultural ingredients to produce lactic acid. A second, post-processing stage is then needed to polymerize the short lactic acid molecules into long polymer chains. However, the Korean team’s work negates the need for this second, industrial process, so opening up the opportunity for PLA to be fermented in any location.

Creating synthetic bacteria that can turn an organic feedstock (such as corn, sugar beet or algae) into a bioplastic may be a complex science. Yet once such bacteria exist, they can be readily and cheaply multiplied and transported to undertake their synthetically engineered feeding and excretion far away from a traditional chemical plant. What this means in practice is that, sometime next decade, companies or even private individuals may be able to ferment old food, human excrement or animal waste directly into a bioplastic that they could then 3D print. Alternatively, algae may be cultivated in large vats as a food stock from which 3D printing filaments may be fermented using synthetic micro-organisms.

In the relatively near future, people could even grow bioplastic foodstocks in their gardens, or raise them hydroponically on their windowsills. Future makers may even ferment buckets of bioplastics in their basements rather than brewing beer.

When it comes to the future overlap of synthetic biology and 3D printing, the local synthesis of bioplastics will be just the tip of the iceberg. For a start, why stop at traditional filament materials like PLA? If some of our 3D printing feedstocks are going to be locally grown, then why not make new stronger, lighter, more flexible materials that build on the incredible qualities of living things such as wood, flesh or bone?

In the last chapter we saw how bioprinters are already being developed that lay down layers of a cell aggregate that then self-assembles into living tissue after printout. Today, all bioprinting research may be focused on the creation of living, human tissues for medical and possibly cosmetic purposes. But fast-forward two-decades, and we may have employed synthetic biology to create new bioprinter feedstocks that can be locally cultivated, and then fabricated in layers that will self-assemble into the final products we require. Already the manufacturers of industrial 3D printers are developing hybrid hardware that integrates the best of additive manufacturing with other CNC technologies in order to create next-generation production tools. And there really is no reason to believe that 3D (bio)printing and synthetic biology will not be synergistically coupled together in the same kind of fashion.

3D PRINTING & NANOTECHNOLOGY

Another increasingly natural partner for 3D printing is nanotechnology or ‘nanotech’. This is the science of measuring and manufacturing on a close-to-atomic scale, with a nanometre being just one-billionth of a metre in size. Any process that works at a level of precision of between 1 and 100 nanometres can be described as nanotechnology, with the most common application today being the manufacture of microprocessors and other electronic components using a photographic etching process called nanolithography.

Another increasingly common area of nanotech application involves the creation of new materials called nanocomposites. As an example of the latter, tiny lattices of carbon atoms known as carbon nanotubes (CNTs) are now sometimes mixed with conventional plastics, paints or glass in order to make them stronger.

Nanotechnology and 3D printing are set to converge on many frontiers. For a start, we will increasingly see the development of nanocomposite 3D printing materials. As noted in chapter 2, already 3DXTech has released two conductive, carbon nanotube composite filaments for use in standard material extrusion 3D printers. A company called Graphene

3D Lab has similarly launched a range of conductive, nanocomposite filaments with both rigid and flexible variants now available.

As their name suggests, Graphene 3D Lab are reinforcing their ABS, PLA and TPU filaments with graphene, which is a single-atom-thick hexagonal carbon lattice. The American Physical Society (APS) has described graphene as a 'wonder material' that is 'a million times thinner than paper, stronger than diamond [and] more conductive than copper'.

By creating graphene nanocomposite filaments, Graphene 3D Lab hopes to further revolutionize 3D printing. As it explains in its investor presentation:

> Our goal is to bring to market cutting-edge 3D printing technology that exploits graphene, a material with incredible properties. Our proprietary method has [the] potential to enable a 'one-touch' capability that can print working electronic devices. This as of yet unrealized advancement may become the manufacturing process of choice in nearly every industry.

The above is a bold claim, if one that has already allowed Graphene 3D Lab to successfully float on the US stock market. On 23rd October 2014, the company announced that it had managed to 3D print all of the components required for a working graphene battery.

Also using nanomaterials as a 3D printing consumable are XJet with their new nanoparticle jetting (NJP) technology. As you may remember from chapter 2, this forms object layers from nanoparticles of metal that are held in a liquid suspension and sprayed from an inkjet-style print head. High temperatures are then used to evaporate each nanoparticle's liquid coating and to sinter the particles together. The NJP process could transform how some direct metal 3D printouts are created, and has clearly come to market as a result of a close convergence of developments in material jetting 3D printing technology and nanoparticle chemistry.

In addition to 3D printing materials, we will also see the development of a range of nanoscale 3D printing processes. A photopolymerization 3D printing method called two-photon polymerization (2PP) has already been created that can achieve an X-Y resolution down to 100 nanometres, so technically classifying it as nanotechnology. This is being developed by several teams, including the Additive Manufacturing Technologies group at the Technical University of Vienna, as well as Nanoscribe in Germany.

In addition to the 2PP process based on photopolymerization, opportunities may exist to achieve nanoscale resolutions with other 3D printing methods. Already German pioneers EOS e-Manufacturing Solutions and 3D-Micromac have increased the resolution of 'traditional' powder bed fusion with their micro laser sintering (MLS) technology. Here the minimum feature resolution is currently 1 μm (0.001 mm), or in other words 1,000 nanometres. MLS is therefore not currently a nanoscale process. I would, however, be very surprised if we do not see MLS, or at least one other 3D printing technology aside from 2PP, achieving the generally-accepted nanoscale resolution of 100 nanometres by the early 2020s. Not least the aforementioned nanoparticle jetting process developed by XJet has to be a prime candidate.

TOWARD THE MICROFABRICATOR

The term ‘nanotechnology’ entered the public lexicon following the publication of a groundbreaking book called *Engines of Creation* in 1984. Authored by nanotechnology guru Eric Drexler – who is often credited with creating the field – this foresaw ‘bottom-up’ manufacturing processes that will build products one molecule and even one atom at a time. To date, all commercial nanotechnologies have been based on a so-termed ‘top-down’ approach that creates nanoscale structures and nanocomposites using conventional-scale production tools. But according to Drexler’s vision, the true revolution of nanotechnology will involve the bottom-up, ‘atomically-precise manufacture’ (APM) of future products by ‘nanomachines’.

Already we manufacture hundreds of millions of nanomachines every year. We just happen to call them ‘microprocessors’, and use them to move around bits of information. But in the future, our nanomachines may be ‘microfabricators’ that will manipulate physical matter. Or as Drexler explains in his 2014 book *Radical Abundance*:

> Where digital electronics deals with patterns of bits, APM deals with patterns of atoms. Where digital electronics relies on nanoscale circuits, APM relies on nanoscale machinery. Where the digital revolution opened the door to a radical abundance of information products, the APM revolution will open the door to a radical abundance of physical products.

In the research lab it is already possible to move around individual atoms using a machine called a scanning tunnelling microscope (STM). But given that most products contain quintillions of atoms, using such ‘positional assembly’ methods to achieve APM is never going to be practical. The future of the microfabricator will therefore have to rely on a process of ‘self-assembly’. This is quite literally where molecules (clumps of atoms) construct themselves into final products. Or as I explained in *The Next Big Thing*:

> Self-assembly refers to manufacturing processes in which nanoscale parts fit themselves together without the intervention of production tools. This becomes possible when each individual part has a distinct set of bumps and hollows that can catch and lock-on to other components when they are mixed together. The whole idea is akin to putting all of the parts required to make a smartphone into a cocktail shaker, giving it a really good workout, and opening the container to find the latest, fully-assembled Samsung or Apple device.

Before you dismiss the above idea as ridiculous, just remember that every living thing on the planet was put together via the self-assembly processes championed by Mother Nature. Further, as we have explored in this chapter and the last one, bioprinting *already* relies on self-assembly to re-position and fuse together layers of a cell aggregate in its post-printout maturation phase. In addition, researchers are today learning how to self-assemble complex structures like viruses by mixing-and-matching the right proteins. Molecular self-assembly is indeed exactly the process relied upon by SGI-DNA’s BioXp

3200 when it prints out custom DNA.

Amazing as it may sound, for billions of years self-assembly has been the dominant production technology on Planet Earth. It is therefore not a surprise that it has become the foundation of both synthetic biology and bioprinting. And if you wonder why I am telling you all of this, it is because the fusion of nanotechnology and 3D printing could result in self-assembly being used to manufacture not just living, organic tissues, but all kinds of inorganic things.

The precise science of self-assembly is mind-bending, incredibly complex, and clearly beyond the scope of this chapter. Suffice it to say that its pioneers are now learning how to create programmable, artificial polymers – called ‘foldamers’ – that are like complex Lego pieces that lock into precise configurations when mixed. Meanwhile other researchers are studying how enzymes cut-and-paste molecules, and how such functionality may be introduced into artificial self-assembly systems.

One pioneer in the field is Martin D. Burke, who heads a team at the University of Illinois. Here they have developed the first ‘molecular 3D printer’ that can fabricate carbon-based small molecules ‘at the click of a mouse’. Their incredible hardware self-assembles the molecules in an additive fashion from simple chemical building blocks. The team have already managed to build 14 different classes of small molecules, with possible initial applications including the development of new materials for LEDs, solar cells and medications. Figure 7.4 illustrates the team’s prototype molecule-making machine. I would imagine that you were not expecting to discover that such a 3D printer has already been built.

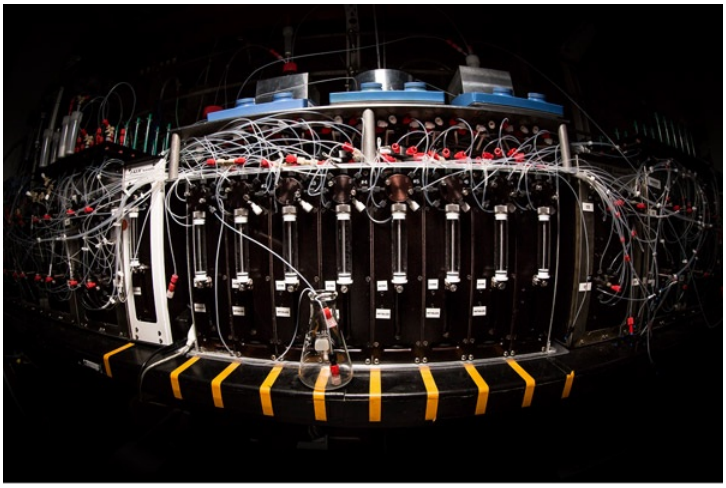

Figure 7.4: The First Molecular 3D Printer. Created by a team lead by Martin D. Burke at the University of Illinois. Photo: L. Brian Stauffer. Image courtesy of BurkeScience / University of Illinois.

In his book *Fabricated*, 3D printing guru Hod Lipson describes multiple potential ‘episodes’ of 3D printing development. Here the first involves mastery of the shape of objects, while the second adds precise control of their composition, and the third involves control of the material's post-printout behaviour (or self-assembly). The development of Martin D. Burke's molecular 3D printer is very much an indication that the third episode of 3D printing will arrive sooner rather than later. It is also a very good indication of the triple convergence of 3D printing, synthetic biology and nanotechnology.

As you have hopefully clocked, we *already* have 3D printers that can fabricate all kinds of things from inorganic materials, living tissue, synthetic DNA, and nanoscale chemical components. With this in mind, the convergence of 3D printing, synthetic biology and nanotechnology that I encapsulated back in figure 7.3 seems almost inevitable. When it comes to developing future forms of additive manufacturing, laying down or mixing synthetic materials that then self-assemble really has to be the way to go. Evolution has, after all, already signalled this pretty strongly. As the microfabricator emerges, it is unlikely to be constructed entirely or at all from the 3D printing technologies detailed earlier in this book.

THE INEVITABLE DOWNSIDE

The convergence of 3D printing, synthetic biology and nanotechnology, and the emergence of related new microfabrication technologies, lies decades into the future. In the meantime, today's first-generation 3D printing processes are just starting to be used for direct digital manufacturing and personal fabrication. In almost all instances, the results empower the companies and individuals involved. Though inevitably, there will also be some downsides. No new technology has ever managed to invade our lives without wreaking a little havoc, and 3D printing will be no different.

For a start, there are very real concerns that 3D printing will allow the personal fabrication of items that society may not want everybody to own. Most obviously, personal 3D printers could be used to duplicate keys or to print all kinds of weapons or parts thereof. Indeed, as the YouTube user 'Ilovewinter' commented after watching one of my 3D printing videos:

> What I really like is the brand new application to allow anyone anywhere to print a firearm, or parts to a firearm. Most pistols are composite, and aside from the barrel that can be made quickly on CNC, the rest can be produced from a 3D printer, and parts purchased at any hardware store. I even hear it is even possible to make a single fire all plastic gun :) Nonetheless it will help us Americans hold on to ours :) Since we can now print magazines with no trace as to when they were made.

To many people's alarm, the claims stated in the above comment are absolutely true. Back in the first week of May 2013, a 25-year-old law student called Cody Wilson successfully fired a bullet from a 3D printed plastic gun. Adding further to his world-wide notoriety, he also made the 3D files for his single-use 'Liberator' weapon freely available online. They were then rapidly downloaded over 100,000 times.

Fairly soon the US State Department insisted that the Liberator plans were removed from the web and they were. Legal wrangles ensued, and it took until September 2016 for the 5th Circuit Court of Appeals to rule that the hosting of files for printing a gun is not protected under the 1st Amendment, and is subsequently illegal. This, according to the court's judgement, is due to the risks to national defence and national security posed by not 'preventing foreign nationals – including all manner of enemies of this country – from obtaining technical data on how to produce weapons and weapon parts'.

While at the time of writing the above court ruling is the close of the matter in the United States, the files necessary for 3D printing weapons and weapon parts remain in circulation. The manufacture of firearms on any desktop is hence causing concern in many quarters. Not only may 3D printed plastic (or plastic composite) firearms get into the wrong hands, but they can also evade a metal detector (although an X-ray scan will pick them out).

Aware of the issue, authorities around the world have taken what action they can. For example, in December 2013 the US House of Representatives voted to extend the Undetectable Firearms Act, so banning any weapon – like a 3D printed plastic gun – that can evade a metal detector. The European Union has also noted that 3D printed guns are illegal, while in May 2014 a Japanese man called Yoshitomo Imura became the first person to be arrested for the possession of a potentially lethal 3D printed weapon. Thingiverse also has a clause in its Terms of Use that bans users from uploading anything that 'promotes illegal activities or contributes to the creation of weapons'. This has, however, not stopped the site hosting designs for keys to high-security handcuffs, as well as realistic toy guns.

THE END OF INTELLECTUAL PROPERTY?

The exchange of 3D object designs online additionally raises the broader question of how intellectual property (IP) may be controlled as the 3D Printing Revolution takes hold. Undoubtedly, 3D printing is a unique technology in terms of the range of IP variants that it may one day be able to infringe. Often people compare the potential, unauthorized 3D printout of commercial products to the digital duplication and sharing of music files. But whereas an illegal copy of a music track only infringes copyright, an elicit 3D print may potentially infringe not just a copyright, but also the design rights in an entire product, patents relating to key parts of its design, and any trademarks (such as product logos) included in the print.

Due to 3D printing and 3D scanning, protecting IP in physical things will in the longer term prove very difficult indeed. This said, today we are not even close to the creation of personal technology that can easily duplicate multi-part objects, let alone things made out of multiple materials or with integrated electronics or other complex internal mechanisms. To be clear, we are decades away from microfabricator hardware that will be able to scan a smartphone, television or other complex item and print out a copy. On the other hand, the technology to make a reasonable copy of a plastic coat hanger, a pair of flip-flops, a bicycle helmet, a lunchbox, or a plastic figurine, is increasingly going to be in public hands.

Major 3D printing pioneers are obviously aware of the potential to use their hardware to copy stuff, though generally they appear to harbour few concerns. For example, when Stratasys subsidiary MakerBot launched their Digitizer 3D scanner in August 2013, they were more at pains to point out that 'when you scan an object, you give it a whole new life in the digital world'. Which is just great, unless you happen to make your living from designing and selling the object in the first place. And yet this is not quite how MakerBot appeared to view the situation. For as initial marketing copy for the Digitizer further explained:

> Sharing is central to the Next Industrial Revolution, so we built it directly into the MakerBot Digitizer experience. Send your 3D design files to friends, family, and colleagues, or easily upload them to Thingiverse.com, the largest community for sharing 3D designs.

But, I hear you cry, surely Stratasys/MakerBot must have provided some kind of legal advice on the IP issues associated with scanning things? Well yes, if you downloaded the FAQ for the Digitizer 3D scanner, you soon found that they addressed the issue head on. Specifically, in response to the questions 'What about intellectual property and copyrights? Does scanning something violate those?', they provided the following answer:

> The MakerBot Digitizer is a new technology in a new frontier. If you're interested in reading more about copyright and other IP topics, check out writings from the public interest group Public Knowledge.

In late 2016 the MakerBot Digitizer is far less widely available than it once was, and I really do not want to pick too heavily on Stratasys and MakerBot here. Both are 3D printing pioneers that continue to do great things. They have also at least acknowledged the IP issue, which is more than some other personal 3D scanner manufacturers have bothered to do in their materials.

In a world in which most governments are desperate for their citizens to learn new technology skills, I strongly suspect that no more than lip service will be paid to 3D printing and IP for quite some time. Right now, industrial 3D printers and 3D scanners are certainly powerful new weapons in the armoury of professional counterfeiting operations. There is, however, no serious IP risk that can be sensibly associated with current and near-future personal 3D hardware. I therefore imagine that, for some time to come, those with the most interest in this area will be IP lawyers and academics with time on their hands.

The potential future illegal copying of physical objects – or 'physibles' – is indeed now attracting the attention of some in the legal profession, and a few associated inventors. Most notably, in October 2012 the US Patent Office issued a patent to an organization called The Invention Science Fund for a 'method for secure manufacturing to control object production rights'. In effect, this is a patent for a digital rights management (DRM) system for physical objects that would prevent a 3D printer from fabricating something that its owner did not have the right to print.

In recent years DRM systems have had some success in curtailing the piracy of digital content such as music or videos. It is, nevertheless, difficult to understand how any form of DRM will be able to prevent copies of objects being made. Not least, open source 3D printers are already a reality. So unless all open source designers and makers choose to incorporate a globally implemented DRM system into their hardware, the cat is already well and truly out of the bag.

Pragmatically, the IP issues that surround 3D printing are likely to lie low until consumer and prosumer technology dramatically improve. This said, if you do want to know more, an attorney called Michael Weinberg has written some very detailed articles on the subject. The latest is called *What's the Deal with Copyright and 3D Printing?*, and can be downloaded as a pdf from publicknowledge.org/Copyright-3DPrinting.

BROADER CONCERNS

In addition to the fabrication of undesirable things and intellectual property infringements, the 3D Printing Revolution may raise even wider concerns. One of these is health and safety, as objects produced at home or in a 3D printing bureau may not be as safe as those mass-manufactured in a factory and subject to rigorous checks. Even a simple item like a mug could prove dangerous if the handle came away when it was full of a boiling beverage. 3D printing new parts to fix domestic appliances could also prove highly unsafe if they turn out to be structurally unfit for purpose, and yet this is not necessarily the first thing that a domestic maker may take into account. Quite how this matter will in the future be accounted for is again unclear. I therefore strongly suspect that we will hear far more about liability issues arising from faulty and dangerous 3D printed goods in the relatively near future.

A final major concern relates to the potential impact of the 3D Printing Revolution on employment. Today, almost everything we own is made in a factory at least in part by a fellow human being who is financially rewarded for their labours. But if domestic and local print-on-demand become common, what then? Will 3D printing prove the final nail in the coffin that forces many struggling businesses under and puts millions of out of work?

My first response to the above common worry is that, for a very long time to come, domestic fabrication and local manufacture-on-demand are going to be limited to high-value, customized objects and the production of industrial tooling and spare parts. As I have stated several times in this book, in the next 20 years 3D printing is likely to transform how about 20 per cent of things are directly or indirectly manufactured, and this will leave 80 per cent of manufacturing practice and employment untouched.

The above point noted, given those traditional production methods that it will in part replace, 3D printing will almost inevitably trigger job losses in some companies, sectors and nations. Yet in tandem it will also create new employment. As every technology-led revolution up until the last one of the Internet ought to remind us, industrial transition only really occurs when people start doing new things in new ways, and those new things have typically been good for economic prosperity. I therefore suspect that 3D printing will prove far more of a springboard for industrial rejuvenation and economic recovery than a catalyst for unemployment.

We must also again remember that the 3D Printing Revolution will arrive in a very specific environmental and economic context. Many – including Barack Obama – have claimed that 3D printing will result in the 'repatriation' of jobs from China, India and other developing nations to the more stagnant economies of Europe and the United States. I have no doubt that over the next two decades such a migration of manufacturing employment will occur, and that 3D printing and broader digital manufacturing will play their part in allowing it to happen. However, I strongly suspect that the decline of globalized industrial production and the rise of localization will be driven almost entirely by looming resource shortages, rising energy prices, and measures put in place to try and lessen the impact of climate change.

THE ROAD AHEAD

So here we are, nearing the end of *3D Printing: Third Edition*, and I hope that you have enjoyed the ride. I also hope that reading this book has convinced and informed you of the extraordinary potential of 3D printing. There can be little doubt that, earlier this decade, 3D printing became mired in hype. But today, realism has returned and a very solid foundation continues to be laid for a radical manufacturing transformation. To draw matters to a close, I therefore thought I would end with some predictions for where 3D printing is headed in both the short- and the long-term.

In terms of the next few years, those companies operating in industrial 3D printing will I think have to focus more intently on those things they can currently do best. As in the past, this will include making better and better prototypes. But increasingly, the business of the 3D printing industry will be delivering hardware that is used to fabricate molds and other production tooling, as well as final product parts. In turn this will require industrial 3D printer manufacturers to behave far more like traditional machine tool makers, and in particular to seek avenues for integrating additive manufacturing processes with other computer-controlled technologies.

We already know the kinds of organizations that will be using 3D printers to make final product components in the short-term. Most notably, they will be companies in the aviation and wider aerospace sector, those in the business of making medical prosthesis, quite probably vehicle manufacturers and high-end spare parts suppliers, and almost certainly the producers of expensive designer goods including jewelry and specialist footwear. Other businesses are also, of course, destined to join this pioneering clan, and look set to include companies that make expensive one-off or low-run products where a premium can be charged for customization, personalization, radically optimized product geometries, or significant material savings.

To meet the demands of such clients, the industrial 3D printing sector is going to undergo a significant transformation. Specifically, in ten years time, and maybe in as little as five, I suspect that the majority of industrial additive manufacturing systems will be made by diversified, traditional manufacturers with a very wide range of non-3D-printing activities. In other words, I predict that the 3D printing industry's 30 years of being dominated by pure play startups – however large they are today – is destined to come to an end. For many years Stratasys and in particular 3D Systems went on their own purchasing sprees to bring a great many smaller 3D printing companies under their corporate wings. But increasingly, the purchasing is going to be done by those with far deeper pockets.

As I write these words, the current intention of GE to purchase Arcam and Concept Laser indicates the start of this trend. When I started working on this book, there were six publicly-traded, pure play industrial 3D printer manufacturers (Stratasys, 3D Systems, Arcam, ExOne, SLM Solutions and voxeljet). Fairly soon this is likely to be cut down to five. And it would be very surprising if, by the time that a fourth edition of this book is in the offing in 2018, the number has not been further reduced.

In parallel, internal investment in the development of 3D printers by diversified manufacturing organizations is rising. As we saw in chapter 3, already such players include Renishaw, Prodways (part of Groupe Gorgé), HP Inc, Canon and Ricoh, with Toshiba also working on direct metal 3D printing hardware, and GE set to join the club as and if it adopts Concept Laser and Arcam.

Turning to the personal side of the market, by end-of-decade I expect around half a million desktop material extrusion 3D printers to be sold every year, with most models priced at under $1,000, and many selling for no more than $200. I also suspect that practically all 3D printers costing $1,000 or less will be made by large Asian manufacturers, many of whom will not be 3D printing pure plays. Such manufacturers are extremely likely to include Kinpo’s XYZprinting, and most probably Tiertime and Flashforge (or their new owners). As the exit of 3D Systems from the consumer market in December 2015 clearly illustrated, Western companies are unable to profitably manufacture mass-market, consumer-grade 3D printers at a realistic price. In 2016 Polaroid did bravely start selling consumer hardware. But Polaroid’s 3D printers and their proprietary-chipped consumables cost 3-4 times as much as comparable products from Kinpo, Tiertime and Flashforge. So it really does not take a genius to work out what it going to happen.

The above noted, I also anticipate that there will be a growing if niche market for desktop, material extrusion hardware in the $1,000 to $5,000 price bracket. This demand I expect will be served by a score or more of small, pure play manufacturers that understand what enthusiasts want and small businesses require. Current players in this sector, including Ultimaker, Zotrax and Lulzbot, I think will continue to do well.

By the early 2020s, I additionally anticipate that we will start to see many more sub-$5,000 desktop 3D printers based on technologies other than material extrusion. Specifically, vat photopolymerization, powder bed fusion and possibly material jetting look set to become fairly widespread desktop-scale and desktop-priced technologies, if not the kinds of processes that will be safe or pleasant to operate on a kitchen table. The lower-cost availability of such 3D printing technologies will offer great opportunities for serious makers to fabricate a far wider range of things than they can today, as well as for very small companies to engage in cost-effective, niche-market manufacturing. This said, most individuals and small companies that adopt 3D printing to allow them to bring niche products to market will continue to use service providers to manufacture their wares, rather than their own, personal hardware.

THE NEXT REVOLUTION?

Looking deeper into the future, I firmly believe that we stand on the brink of revolution in digital fabrication that will determine how many, but by no means all, future products are made. Right now, this revolution is being driven by advancements in 3D printing as detailed in the previous six chapters of this book. It will also be taken further forward by the development of hybrid technologies including 3D Systems' Figure 4 vat photopolymerization and industrial robot hardware, as well as those 3D-printing-plus-CNC-milling systems now hitting the market from several manufacturers. However, as I noted earlier in this chapter, in the decades ahead I predict that 3D printing will more radically converge with a host of other organic and inorganic technologies in order to allow a very wide range of digital designs to be turned into physical things pretty much on-demand and in pretty much any location.

We really need to remember that 'manufacturing additively' (rather than subtractively) encompasses a far wider range of processes than building up objects in layers using computer-controlled machine tools. Not least, all biological systems fabricate in an additive manner. When did you last hear of a micro-organism, plant or animal increasing the size of itself or its offspring by sawing parts off?

In tandem with its convergence with synthetic biological technologies, I expect that by the late 2020s and into the 2030s, 3D printing will be adopted by the majority of manufacturers as one of their core production technologies. As I will state here for a final time, my signature prediction is that, in 20 years time, about 20 per cent of products will include at least some parts that are produced directly or indirectly using a 3D printer. I also think that many, many people really do not appreciate how significant this will be. In part this is because the United States and most European countries have ceased to be manufacturing nations. The consequences of being able to 3D print a few custom, material-optimized or otherwise geometrically-challenging components for an otherwise traditionally-produced product are therefore not widely understood. In particular they are not appreciated in most business schools where it has been forgotten that 'business' is actually about making and delivering products and services, rather than devising 'strategies', practising 'human resource management', or running marketing campaigns.

The very dramatic implications of future bioprinting – or more probably some bioprinting and synthetic biology hybrid – are I think similarly and significantly underestimated at the present time. For a start, the technology should have a major impact in healthcare, as it ought to allow organ donor waiting lists to become a thing of the past, as well as easing the repair of major burns and other wounds, and allowing the routine replacement of body parts damaged by cancers and infection. Cosmetic bioprinting may also become an enormous business. And even more significantly, the bioprintout of new synthetic-organic materials has to offer us a very wide range of opportunities for making old and new things in new ways.

Decades hence, and in a resource-challenged world in which we will have to achieve more with less, the 3D Printing Revolution even has the potential to transform our relationship with our possessions and the physical world. During the Internet Revolution millions of people learnt new things. In contrast, the 3D printing Revolution is more likely to be characterised by millions of people rediscovering old ways. For example, 20 years from now, it may become routine for companies (and their robots) to use 3D printers to make spares to facilitate the repair of broken items, while many private citizens will routinely use domestic 3D printers to fabricate some of their own stuff.

Ten years from now the 3D Printing Revolution will be just picking up speed. Yet even by that time it will probably be old news, with the revolution's true pioneers long since crowned, and mainstream attention shifting to broader and more radical developments in local digital manufacturing. If you really want to be part of the 3D Printing Revolution, you therefore need to act sooner rather than later.

Never in history have the opportunities been so great for so many organizations and individuals to start manufacturing things in new ways. If you are a potential pioneer in waiting, I therefore hope that the end of this book is actually a beginning. The future is always forged by those who are prepared to act rather than just think. So if you are up for the challenge, it is now time to 3D print.

Glossary

2PP — *see* two-photon polymerization

3D MANUFACTURING FORMAT

The 3D manufacturing format (3MF) is a standard for 3D files that is being developed by the 3MF Consortium. 3MF improves on the older STL format by including information on materials as well as geometry.

3MF — *see* 3D manufacturing format

3SP — *see* scan, spin and selectively photocure

ABS — *see* acrylonitrile butadiene styrene

ACRYLONITRILE BUTADIENE STYRENE

Acrylonitrile butadiene styrene (ABS) is a common thermoplastic that is often used as the build material or 'filament' in material extrusion.

ACRYLONITRILE STYRENE ACRYLATE

Acrylonitrile styrene acrylate (ASA) is a thermoplastic that can be 3D printed via material extrusion.

ADDITIVE LAYER MANUFACTURING

Additive layer manufacturing (ALM) is another term for additive manufacturing (AM) or 3D printing.

ADDITIVE MANUFACTURING

Additive manufacturing (AM) is the process of building objects by depositing material in layers. 3D printing is therefore an additive manufacturing process. Engineers often refer to 3D printing as additive manufacturing, although increasingly the two terms are used interchangeably.

ADDITIVE METAL MANUFACTURING

Additive metal manufacturing (AMM) refers to any 3D printing technology that builds up metal objects in layers. Such technologies include those based on powder bed fusion, such as direct metal laser sintering (DMLS), laserCUSING and electron beam melting (EBM). However, AMM can also encompass any form of directed energy deposition (DED), the fused deposition modelling of metals (FDMm), electron beam additive manufacturing (EBAM), wire and arc additive manufacturing (WAAM) and nanoparticle jetting (NPJ).

ALM — *see* additive layer manufacturing

ALUMIDE

Alumide is a 3D printing material that is a two-part mix of nylon and aluminum powders. It is used in powder bed fusion 3D printers to produce objects with a metal feel and sparkle at relatively low cost.

AM — *see* additive manufacturing

American Society for Testing and Materials

The American Society for Testing and Materials (ASTM) is a standards development organization that has worked with the International Standards Organization (ISO) to develop ISO/ASTM 52900.

AMM — *see* additive metal manufacturing

APD — *see* augmented polymer deposition

APM — *see* atomically precise manufacturing

ASA — *see* acrylonitrile styrene acrylate

ASTM — *see* American Society for Testing and Materials

ATOMICALLY PRECISE MANUFACTURE

Atomically precise manufacture refers to 'bottom-up' nanotechnological processes, such as self-assembly, that allow items to be created without the intervention of conventional-scale production tools.

AUGMENTED POLYMER DEPOSITION

Augmented polymer deposition (APD) is material extrusion technology invented by Rise Inc. It jets a ‘repelling ink’ between an object and its support structures in order to facilitate the latter’s easy removal.

BINDER JETTING

Binder jetting is the generic term for all 3D printing technologies that spray a binder from an inkjet-style print head onto successive layers of powder. Binder jetting hardware from different manufacturers can currently build objects from a range of materials that include plastics, ceramics, gypsum-based powders, sand, and even metal nanoparticles held in liquid suspension.

BIO-INK

Bio-ink is a culture of living cells that is used as a build material in a bioprinter.

BIO-PAPER

Bio-paper is a support material used in bioprinting, and is usually a hydrogel, such as a water-collagen mix.

BIOPRINTER

A bioprinter is a 3D printer that outputs objects made of living cells, rather than plastics, metals or other inorganic materials.

BREAKAWAY SUPPORT TECHNOLOGY

Breakaway support technology (BST) is featured on 3D printers that add extra build material to an object during printout to hold in place upward sloping or orphan parts that would otherwise fall away.

BST — *see* breakaway support technology

CFF — *see* composite filament fabrication

CLIP — *see* continuous liquid interface production

CNC

CNC stands for ‘computer numerical control’, and is used in reference to automated production tools such as CNC milling machines.

COLORJET PRINTING

ColorJet printing is 3D System’s implementation of binder jetting that can create full-colour 3D prints.

COMPOSITE FILAMENT FABRICATION

Composite filament fabrication is a term coined by Markforged to refer to their technology which adds continuous reinforcement strands to 3D printed objects during the process of material extrusion.

CONCEPT MODEL

A concept model is a representation of a final product that approximates its form, but which lacks its functionality.

CONTINUOUS LIQUID INTERFACE PRODUCTION

Continuous liquid interface production (CLIP) is an inverted vat photopolymerization 3D printing process created by Carbon3D.

CONTOUR CRAFTING

Contour crafting is another name for the material extrusion of concrete. The term was coined by Behrokh Khoshnevis, who describes it as a ‘mega scale layered fabrication process which builds large scale three-dimensional parts by depositing paste materials’.

DAYLIGHT POLYMER PRINTING

Daylight polymer printing (DPP) is a vat photopolymerization process created by PhotoCentric. It solidifies photopolymer layers using natural light wavelengths projected through an LCD panel.

DDM — *see* direct digital manufacturing

DIRECT DIGITAL MANUFACTURING

Direct digital manufacturing (DDM) refers to the production of final products, or parts thereof, using a 3D printer.

DIRECT METAL LASER SINTERING

Direct metal laser sintering (DMLS) is a form of powder bed fusion that uses a laser to selectively heat and so fuse together metal powders.

DIRECTED ENERGY DEPOSITION

Directed energy deposition is the generic name for any 3D printing technology that deposits metal powders that are fused into object layers using a laser or electron beam.

DLP PROJECTION

DLP projection is a vat photopolymerization technology in which a DLP or 'digital light processing' projector is used to solidify layers of a photopolymer, typically on the base of a UV-transparent vat.

DMLS — *see* direct metal laser sintering

DMP — *see* direct metal printing

DPP — *see* daylight polymer printing

DROP-ON-DEMAND — *see* wax deposition modelling

EBAM — *see* electron beam additive manufacturing

EBF3 — *see* electron beam melting

EBM — *see* electron beam melting

ELECTRON BEAM ADDITIVE MANUFACTURING

Electron beam additive manufacturing is a 3D printing technology developed by Sciaky. It feeds two solid metal wire feedstocks into an electron beam that fuses them into potentially very large industrial parts.

ELECTRON BEAM FREEFORM FABRICATION

Electron beam freeform fabrication is another term for electron beam melting.

ELECTRON BEAM MELTING

Electron beam melting (EBM) is a powder bed fusion technology that builds up metal objects in a vacuum by using an electron beam to selectively melt and so fuse together successive layers of a metal powder.

FAB@HOME

Fab@Home was an open source 3D printer project started in 2006 by Hod Lipson & Evan Malone. Deemed a success, it was closed in 2012.

FDC — *see* fused deposition of ceramics

FDM — *see* fused deposition modelling

FDMm — *see* fused deposition modelling of metals

FFF — *see* fused filament fabrication

FFM — *see* fused filament modelling

FIGURE 4

Figure 4 is a developmental vat photopolymerization and robotic 3D printing process created by 3D Systems. It employs modularization and new hybrid resins to offer high-speed industrial part production.

FILAMENT

Filament is used to 3D print objects via material extrusion, also commonly referred to as 'fused deposition modelling' (FDM). Filament is typically a thermoplastic (such as ABS or PLA) that is fed to a print head as a solid, and then heated for extrusion from a nozzle. Filament is typically 1.75 mm or about 3 mm in diameter.

FUNCTIONAL PROTOTYPE

A functional prototype is a representation of a final product created to test its form, fit and function before committing to production.

FUSED DEPOSITION MODELLING

Fused deposition modelling (FDM) is a material extrusion 3D printing process that creates objects in layers by depositing a heated thermoplastic from a computer-controlled print head nozzle. FDM was invented by a company called Stratasys, which has trademarked the term. Other companies subsequently refer to this kind of material extrusion technology as 'plastic jet printing' (PJP), 'fused filament modelling' (FFM), 'fused filament fabrication' (FFF), the 'fused deposition method' and 'melted and extruded modelling' (MEM).

FUSED DEPOSITION MODELLING OF METALS

The fused deposition modelling of metals (FDMm) is a form of material extrusion that deposits a molten metal to 3D print objects in successive layers. *See also* wire and arc additive manufacturing (WAAM) and electron beam additive manufacturing (EBAM).

FUSED DEPOSITION OF CERAMICS

The fused deposition of ceramics (FDC) refers to the 3D printing of ceramic objects using multiphase jet solidification (MJS).

FUSED FILAMENT FABRICATION

Fused filament fabrication (FFF) is another term for material extrusion, also commonly referred to as fused deposition modelling (FDM).

FUSED FILAMENT MODELLING

Fused filament modelling (FFM) is another term for material extrusion, also commonly referred to as fused deposition modelling (FDM).

GRANULAR MATERIALS BINDING

Granular materials binding is a generic term for all forms of 3D printing that create objects by selectively sticking together the granules of a powder. Granular materials binding therefore encompasses binder jetting, powder bed fusion and directed energy deposition.

HIPS

HIPS stands for high impact polystyrene, and is a thermoplastic that can be used by some material extrusion 3D printers.

HTPLA

HTPLA stands for ‘high temperature PLA’, and is a stronger and more durable form of the traditional thermoplastic PLA.

ISO/ASTM 52900

ISO/ASTM 52900 categorizes most additive manufacturing (3D printing) technologies under the seven generic headings of material extrusion, vat photopolymerization, material jetting, binder jetting, powder bed fusion, directed energy deposition and sheet lamination

LAMINATED OBJECT MANUFACTURE

Laminated object manufacture (LOM) is a sheet lamination technology that builds up objects by adhering successive sheets of cut paper.

LAMP — *see* large area maskless photopolymerization

LARGE AREA MASKLESS PHOTOPOLYMERIZATION

Large area maskless photopolymerization (LAMP) is a 3D printing technology developed by DDM Systems. It uses a moving DLP projector to solidify layers of a liquid and ceramic powder composite.

LASER BEAM MELTING

Laser beam melting (LBM) refers to all powder-bed fusion 3D printing technologies that use a laser beam to fuse together successive layers of a powdered build material. This distinguishes such technologies from those that use another heat source, such as an electron beam.

LASER DIRECT-WRITING

Laser direct-writing (LDR) uses laser energy to 3D print on the microscale or nanoscale. LDR includes techniques such as two-photon polymerization (2PP), as well as an experimental bioprinting technique that creates precise biological patterns using laser energy to transfer individual cells from a ‘donor slide’ to a ‘collector slide’.

LASER ENGINEERED NET SHAPING

Laser engineered net shaping (LENS) is a directed energy deposition 3D printing technology pioneered and trademarked by Optomec.

LASER METAL DEPOSITION

Laser metal deposition (LMD) is a form of directed energy deposition independently developed by BeAM, Toshiba and TRUMPF.

LASER POWDER FORMING

Laser powder forming is another term for directed energy deposition

LASERCUSING

LaserCUSING is a powder bed fusion technology that uses high power lasers to fuse together the granules of a metal build material.

LBM — *see* laser beam melting

LCM — *see* lithography-based ceramic manufacturing

LDM — *see* local digital manufacturing

LDR — *see* direct laser writing

LENS — *see* laser engineered net shaping

LITHOGRAPHY-BASED CERAMIC MANUFACTURING

Lithography-based ceramic manufacturing (LCM) is a vat photopolymerization technology developed by Lithoz in Austria. The process selectively cures a photosensitive resin that contains ceramic particles.

LMD — *see* laser metal deposition

LOCAL DIGITAL MANUFACTURING

Local digital manufacturing (LDM) uses digital technologies to make products on demand very close to the location of their final consumer.

LOM — *see* laminated object manufacture

LOW-TEMPERATURE DEPOSITION MODELLING

Low-temperature deposition modelling is a form of material extrusion that works at low temperatures, and which has particular potential application in tissue engineering.

LS — *see* selective laser sintering

MATERIAL EXTRUSION

Material extrusion is the generic term for all 3D printing technologies that build objects in layers by extruding a material – such as a molten thermoplastic – from a computer-controlled print head nozzle. Many people refer to material extrusion as fused deposition modelling (FDM), although this label is trademarked by Stratasys. Other terms for material extrusion include fused filament modelling (FFM), fused filament fabrication (FFF), thermoplastic extrusion, melted and extruded modelling (MEM), and plastic jet printing (PJP).

MATERIAL JETTING

Material jetting is the name for any 3D printing technology that emits a liquid from a print head. In most material jetting processes, the build material is a photopolymer that is set solid with UV light before the next layer is printed on top of it. Such 'photopolymer material jetting' is known via a variety of other names, including 'PolyJet' (short for 'photopolymer jet', the term used by Stratasys), 'MultiJet Printing' (MJP, the term used by 3D Systems), and 'inkjet photopolymer printing'. *See also* wax deposition modelling and nanoparticle jetting.

MELTED AND EXTRUDED MODELLING

Melted and extruded modelling (MEM) is another term for those 3D printing technologies generically known as material extrusion.

MEM — *see* melted and extruded modelling

MICRO LASER SINTERING

Micro laser sintering (MLS) is a powder bed fusion 3D printing technology that can achieve a minimum feature resolution of 1 μm (0.001 mm). It was developed by EOS e-Manufacturing Solutions and 3DMicromac in Germany.

MICROFABRICATOR

A microfabricator is the equivalent in manufacturing of a microprocessor in computing. Theoretically, 3D printing and related LDM technologies will one day allow the creation of such microscale and nanoscale machines that will use self-assembly techniques to manipulate physical matter, rather than bits of information.

MJF — *see* multi jet fusion

MJP — *see* multijet printing

MJS — *see* multiphase jet solidification

MLS — *see* micro laser sintering

MOVINGLIGHT

MOVINGLight is a DLP vat photopolymerization technology created by Prodways. It works like standard DLP projection, but achieves a greater resolution by physically moving a top-mounted projector, rather than statically projecting each object layer onto the base of the photopolymer vat. *See also* DLP projection.

MULTI JET FUSION

Multi Jet Fusion is a 3D printing technology unique to HP. It lays down a layer of powder from one print carriage, before a second print head selectively sprays droplets of ‘fusing and detailing agents’ that are then fused solid using a heat source.

MULTIJET PRINTING

MultiJet Printing (MJP) is the name used by 3D Systems to refer to its material jetting 3D printers.

MULTIPHASE JET SOLIDIFICATION

Multiphase jet solidification (MJS) is a 3D printing process where a ceramic or metal powder is mixed with a binder so that it can be heated and extruded through a nozzle.

NANOPARTICLE JETTING

NanoParticle Jetting (NJP) is a material jetting 3D printing technology developed by XJet. It fabricates metal objects by jetting nanoparticles of metal that are initially held in a liquid suspension, before being fused with heat.

NANOTECHNOLOGY

Nanotechnology refers to measuring and manufacturing at a level of precision of between 1 and 100 nanometres. Specific technologies include nanolithography, the production of nanocomposites, and forms of organic and inorganic self-assembly.

NPJ — *see* NanoParticle Jetting

PA12

PA12 is a polyamide that is commonly used for making plastic objects via powder bed fusion.

PATTERN

A pattern is a master version of an object that is created for the purposes of taking a mold.

PC — *see* polycarbonate

PC-ISO — *see* polycarbonate-ISO

PETG — *see* polyethylene terephthalate glycol-modified

PHA — *see* polyhydroxyalkanoate

PHOTOPOLYMER

Photopolymers are liquid plastic resins that solidify when exposed to light, and which are used as the build materials in vat photopolymerization and most material jetting 3D printers.

PJP — *see* plastic jet printing

PLA — *see* polylactic acid

PLASTIC JET PRINTING

Plastic jet printing (PJP) is the name used by 3D Systems for their 3D printing process that extrudes a molten thermoplastic. It is what Stratasys call fused deposition modelling (FDM). *See also* material extrusion.

PMMA — *see* polymethylmethacrylate

POLYAMIDE

Polyamides, such as nylon, are semi-crystalline thermoplastic polymers, and may be used as both thermoplastic extrusion and powder bed fusion 3D printing build materials.

POLYCARBONATE

Polycarbonate (PC) is a thermoplastic that is sometimes used as the build material in material extrusion 3D printers.

POLYCARBONATE-ISO

Polycarbonate-ISO is a polycarbonate thermoplastic that can be sterilized with gamma radiation or ethylene oxide, and which offers good biocompatibility for the fabrication of 3D printed medical devices.

POLYETHYLENE TEREPHTHALATE GLYCOL-MODIFIED

Polyethylene terephthalate glycol-modified (PETG) is a thermoplastic that can be used as the build material in some material extrusion 3D printers.

POLYHYDROXYALKANOATE

Polyhydroxyalkanoate (PHA) is a bioplastic that is sometimes used as the build material in material extrusion 3D printing.

POLYJET

PolyJet – or PolyJet Matrix – is a Stratasys material jetting technology that can fabricate full-colour, multiple material objects.

POLYLACTIC ACID

Polylactic acid (PLA) is a bioplastic that can be used as the build material or ‘filament’ in many material extrusion 3D printers.

POLYMETHYLMETHACRYLATE

Polymethylmethacrylate (PMMA) is a clear thermoplastic that can be used as the filament in some material extrusion 3D printers.

POLYPHENYLSULFONE

Polyphenylsulfone is a thermoplastic that can be used to 3D print objects that require very high temperature and chemical resistance.

POLYVINYL ACETATE

Polyvinyl acetate (PVA) is a synthetic polymer that is sometimes used by material extrusion 3D printers to create soluble support structures.

POWDER BED FUSION

Powder bed fusion is the generic term for all 3D printing technologies that build objects in layers by using a heat source to selectively stick together successive layers of powder. It therefore encompasses laser sintering (LS), selective laser sintering (SLS), selective laser melting (SLM), selective heat sintering (SHS), direct metal laser sintering (DMLS), electron beam melting (EBM) and laserCUSING.

PPSF — *see* polyphenylsulfone

PRINTOPTICAL

Printoptical is a material jetting technology created by LUXeXceL. It can 3D print functional lenses and other optical components.

PVA — *see* polyvinyl acetate

RAPID PLASMA DEPOSITION

Rapid plasma deposition (RPD) is a direct-metal 3D printing process created by Norsk Titanium.

RAPID PROTOTYPING

Rapid prototyping (RP) refers to any technology used to create a prototype object from digital data using computer-controlled hardware. Rapid prototypers include, but are not limited to, 3D printers. ‘Rapid prototyping’ and ‘3D printing’ are hence not interchangeable terms.

REPRAP

RepRaps – or ‘replicating rapid prototypers’ – are open source 3D printers capable of making many of their own parts.

RP — *see* rapid prototyping

RPD — *see* rapid plasma deposition

SACRIFICIAL MOLD

A sacrificial mold is a single-use mold, such as a sand cast mold, that is destroyed during the production process that utilizes it.

SCAN, SPIN AND SELECTIVELY PHOTOCURE

Scan, spin and selectively photocure (3SP) is a vat photopolymerization 3D printing technology pioneered by EnvisionTEC.

SDL — *see* selective deposition lamination

SELECTIVE DEPOSITION LAMINATION

Selective deposition lamination' (SDL) is the name used by Mcor Technologies for its sheet lamination 3D printing process.

SELECTIVE HEAT SINTERING

Selective heat sintering (SHS) is a powder bed fusion technology created by a company called BluePrinter. The process is similar to selective laser sintering (SLS), but uses a thermal print head rather than a laser to selectively fuse together successive layers of a plastic powder.

SELECTIVE LASER MELTING

Selective laser melting (SLM) is a powder bed fusion 3D printing technology that uses a very high power laser to entirely melt metal powder granules in order to form object layers.

SELECTIVE LASER SINTERING

Selective laser sintering (SLS) is a powder bed fusion 3D printing technology that uses a laser to selectively fuse or 'sinter' together the granules of successive layers of powder.

SELF-ASSEMBLY

Self-assembly is the process that allows living things, synthetic biological constructs, and bleeding-edge nanotechnologies, to assemble cells, inorganic polymers and potentially other nanoscale materials without the aid of production tools.

SHEET LAMINATION

Sheet lamination is the generic term for all 3D printing processes that build objects by adhering sheets of cut paper, plastic or metal foil.

SHS — *see* selective heat sintering

SLA — *see* stereolithography

SLM — *see* selective laser melting

SLS — *see* selective laser sintering

SOLUBLE SUPPORT TECHNOLOGY

Soluble support technology (SST) is featured on 3D printers that output a dissolvable material (such as PVA) to hold in place the upward sloping or potentially 'orphan' parts of an object that would otherwise fall away. As the name suggests, soluble supports are removed after printout using a liquid solvent, such as a water-based detergent.

SST — *see* soluble support technology

STEREOLITHOGRAPHY

Stereolithography is a vat photopolymerization process that builds objects in layers using a StereoLithographic Apparatus (SLA). Objects are created by a laser beam that traces out and solidifies each successive layer on the surface or base of a vat of liquid photopolymer.

STL

STL is a computer file format widely used in 3D printing. Exactly what STL is an acronym for is debated, though most commonly it is taken to be short for 'standard tessellation language'.

SUPPORT STRUCTURE

Support structures are additional parts that are added to objects during 3D printing to prevent overhanging or orphan parts falling away.

SYNTHETIC BIOLOGY

Synthetic biology (SynBio) is a digital manufacturing technology that breaks DNA into modular building blocks than can be re-arranged in a computer and chemically rendered as living matter.

THERMOPLASTIC

A thermoplastic is a plastic whose shape can be changed by heating it into a molten form and then allowing it to cool back into a solid. Thermoplastics are widely used as the build material in material extrusion and powder bed fusion 3D printers.

THERMOPLASTIC ELASTOMER

A thermoplastic elastomer (TPE) is a material that can be used to create highly flexible parts in some material extrusion 3D printers. Examples include thermoplastic polyurethanes (TPUs, also known as TPE-Us).

THERMOPLASTIC POLYURETHANE

Thermoplastic polyurethane (TPU or TPE-U) is a thermoplastic elastomer that can be used in some material extrusion 3D printers to create rubber-like parts.

TISSUE ENGINEERING

Tissue engineering refers to the creation or alteration of living matter, as may be achieved using a bioprinter.

TPE — *see* thermoplastic elastomer

TPU — *see* thermoplastic polyurethane

TWO-PHOTON POLYMERIZATION

Two-photon polymerization (2PP) is a vat photopolymerization 3D printing technology that uses a femtosecond pulsed laser to selectively solidify successive layers of a specially developed liquid photopolymer. This build material includes ‘initiator’ molecules that trigger monomer solidification when stuck by two photons. Two-photon polymerization can currently achieve a layer thickness and an X-Y axes accuracy down to 100 nanometres (0.0001 mm).

UAM — *see* ultrasonic additive manufacturing

ULTEM 9085

ULTEM 9085 is a specialist thermoplastic 3D printing material from Stratasys that is certified for use in aviation.

ULTRASONIC ADDITIVE MANUFACTURING

Ultrasonic additive manufacturing (UAM) is a sheet lamination 3D printing technology developed by Fabrisonic. It create objects by ultrasonically welding together layers of metal tape.

VAT PHOTOPOLYMERIZATION

Vat photopolymerization is the generic term for all 3D printing technologies in which a vat or tank of liquid photopolymer is selectively solidified using a laser beam or other light source. Vat photopolymerization processes currently include stereolithography, DLP projection, MOVINGLight, daylight polymer printing (DPP), scan, spin and selectively photocure (3SP), lithography-based ceramic manufacturing (LCM), continuous liquid interface production (CLIP), Figure 4, and two-photon polymerization (2PP).

WAAM — *see* wire and arc additive manufacturing

WAX DEPOSITION MODELLING

Wax deposition modelling (WDM) is a Stratasys material jetting technology that creates sacrificial casting patterns by depositing layers of a special thermoplastic called TrueWax. WDM is also known as drop on demand (DOD).

WDM — *see* wax deposition modelling

WIRE AND ARC ADDITIVE MANUFACTURING

Wire and arc additive manufacturing (WAAM) is a 3D printing technology that feeds a thin titanium wire to the tip of an adapted arc fusion welding robot, where it is heated to a molten state for deposition into object layers.

WOOD/POLYMER COMPOSITE

A wood/polymer composite (WPC) is a filament used in material extrusion 3D printing that is made from a traditional thermoplastic (such as PLA) mixed with sawdust or other wood fibers.

WPC — *see* wood/polymer composite

3D Printing Directory

Note that a constantly-updated, online version of this directory can be accessed from **explainingthefuture.com/3Dprinting**

INDUSTRIAL 3D PRINTER MANUFACTURERS

3D SYSTEMS — 3dsystems.com

3D Systems makes hardware based on a wide range of technologies, including vat photopolymerization (stereolithography), powder bed fusion (laser sintering and DMLS), binder jetting (ColorJet Printing), material jetting (MultiJet Printing) and material extrusion (PlasticJet Printing).

3GEOMETRY — 3geometry.com

3Geometry in India produces 3D printers for making sand cast molds and cores.

ADDITIVE INDUSTRIES — additiveindustries.com

Additive industries produces the MetalFab1 powder bed fusion 3D printer for making final components in metal.

ADMATEC — admatec.nl/nl/

ADMATEC produces 3D printers that fabricate highly detailed ceramic parts.

AGILISTA — agilista.jp

Agilista are a Japanese manufacturer of material jetting 3D printers.

ARCAM — arcam.com

Arcam produces 3D printers based on a powder bed fusion technology called electron beam melting.

ASIGA — asiga.com

Asiga produces desktop vat photopolymerization (stereolithographic) 3D printers.

ASPECT — aspect.jpn.com

Aspect are based in Japan and produce powder-bed fusion 3D printers.

BEAM — beam-machines.fr

BeAM is a French manufacturer of 3D printers based on the directed energy deposition process.

BIGREP — bigrep.com

BigRep produce a material extrusion 3D printer called the BigRep ONE that features a 1.3 cubic metre build volume.

BLUEPRINTER — blueprinter.dk

Blueprinter produces a desktop 3D printer that uses a powder bed fusion technology called selective heat sintering (SHS).

CARMINA — carima.co.kr

Carmina are a South Korean manufacturer of vat photopolymerization (DLP projection) 3D printing hardware.

CMET — cmet.co.jp/eng

CMET produce vat photopolymerization (stereolithographic) 3D printers in Japan.

CONCEPT LASER — concept-laser.de

Concept Laser produce 3D printers based on a powder bed fusion technology called laserCUSING.

DWS SYSTEMS — dwssystems.com

DWS Systems in Italy produce vat photopolymerization 3D printers for producing waxups.

ENVISIONTEC — envisiontec.de

EnvisionTEC produce a range of vat photopolymerization 3D printers based on DLP projection and 3SP (scan, spin and selectively photocure). The company also sells a 3D-Bioplotter for tissue engineering (bioprinting).

EOS — eos.info

EOS manufactures a range of powder bed fusion 3D printers based on selective laser sintering. Different models are dedicated to making things in metals, plastics or sand (for sand casting).

EXONE — exone.com

ExOne sells industrial 3D printers that use binder jetting to build objects in sand (to enable sand casting), as well as stainless steel, bronze, Inconel and glass.

FABRISONIC — fabrisonic.com

Fabrisonic produce sheet lamination 3D printers that create objects by ultrasonically welding together layers of metal tape using what they term ‘ultrasonic additive manufacturing (UAM).

FARSOON — farsoon.com/english

Farsoon is a Chinese manufacturer of powder bed fusion (laser sintering) 3D printers.

HP INC. — http://www8.hp.com/us/en/printers/3d-printers.html

HP Inc. manufacture industrial 3D printers based on their own, unique technology called multijet fusion (MJF).

ILIOS — ilios3d.com/en/

Ilios produce two photopolymerization-based 3D printers.

INSSTEK — insstek.yehkwang.com

InssTek is a Korean manufacturer of directed energy deposition 3D printers.

LITHOZ — lithoz.com/en

Lithoz is an Austrian manufacturer of 3D printers that are based on a process called lithography-based ceramic manufacturing (LCM).

LUXEXCEL — luxexcel.com

LUXeXceL have developed a material jetting technology called Printoptical that enables the 3D printing of functional lenses.

MARKFORGED — markforged.com

Markforged make material extrusion 3D printers called the Mark Two, the Mark X and the Mark X Enterprise that embed continuous strands of carbon fiber, fiberglass or Kevlar into their printouts.

MATSURRA — lumex-matsuura.com/english/

Matsurra produces a hybrid, direct metal 3D printer that incorporates both powder bed fusion and CNC milling technologies.

MCOR TECHNOLOGIES — mcortechnologies.com

Mcor Technologies makes 3D printers that use a sheet lamination process called selective deposition lamination (SDL) to produce full-colour printouts out of paper.

NANOSCRIBE — nanoscribe.de/en

Nanoscribe produce a nanolithograhic 3D printer that uses two photon polymerization (2PP) to create 3D objects on a nanoscale.

OPTOMEC — optomec.com

Optomec produces 3D printers based on a directed energy deposition technology called ‘laser engineered net shaping’, as well as ‘Aerosol Jet’ hardware that can print working electronics onto 3D surfaces.

PRODWAYS — prodways.com/en

Prodways are a Groupe Gorgé company who produce 3D printers based on a vat photopolymerization process called MOVINGLight.

REALIZER — realizer.com/en

Realizer produce powder bed fusion 3D printers based on selective laser melting.

RENISHAW — renishaw.com

Renishaw produce powder bed fusion 3D printers than additively manufacture metal objects.

SLM SOLUTIONS — slm-solutions.com

SLM Solutions produce a range of 3D printers based on a powder bed fusion technology called selective laser melting.

SCIAKY — sciaky.com

Sciaky produce 3D printers based on a direct-metal proccess that they term ‘electron beam additive manufacturing’ (EBAM).

SHAANXI HENGTONG — china-rpm.com/en

Shaanxi Hengtong produce vat photopolymerization (stereolithographic) 3D printers.

SHANGHAI UNION TECHNOLOGY — union-tek.com/en

Shanghai Union Technology produce vat photopolymerization (stereolithographic) 3D printers.

SINTERIT — sinterit.com

Sinterit make a desktop laser sintering 3D printer called the Lisa.

SINTRATEC — sintratec.com

Sintratec produce low-cost desktop laser sintering 3D printers.

STRATASYS — stratasys.com

Stratasys makes 3D printers based on material extrusion (FDM) and material jetting (Polyjet and WDM) technologies.

TIERTIME — tiertime.com/products/industrial_3d_printer

Tiertime produces industrial 3D printers based on material extrusion, or what it terms ‘melted extrusion modeling’.

TPM — trumpsystem.com/E_index.asp

TPM in China produce powder bed fusion 3D printers.

TRUMPF — trumpf-laser.com/en/products.html

TRUMPF is a German manufacturer of powder bed fusion and directed energy desposition direct-metal 3D printers.

VOXELJET — voxeljet.de/en

voxeljet produces 3D printers that use binder jetting to produce plastic objects or 3D sand cast molds from powders. The company’s largest model, the VX4000, has a build volume of 4 x 2 x 1 metres.

WUHAN BINHU MECHANICAL & ELECTRICAL CO — **binhurp.com/en**

Wuhan Binhu Mechanical & Electrical Co makes 3D printers based on powder bed fusion and vat photopolymerization.

PERSONAL 3D PRINTER MANUFACTURERS

AFINIA — afinia.com

Afinia sell rebranded Tiertime desktop material extrusion 3D printers in the United States.

AIO ROBOTICS — zeus.aiorobotics.com

AIO Robotics sell an all-in-one 3D printer and 3D scanner called the Zeus, which includes an integrated STL model editor.

BEEVERYCREATIVE — beeverycreative.com

BeeVeryCreative make a range of very stylish and easily portable material extrusion 3D printers.

BOOTS INDUSTRIES — bootsindustries.com

Boots Industries produce low-cost material extrusion 3D printers under the name Rostock.

BUILDER — 3dprinter4u.com

BUILDER make material extrusion 3D printers, including a model with a dual extruder that can mix two thermoplastics in the same build.

BY FLOW — 3dbyflow.com

By Flow produce a foldable, material extrusion 3D printer with interchangeable print heads, and which can 3D print food.

CEL — robox.cel-uk.com

CEL produce a material extrusion 3D printer called the Robox.

DWS LAB — dwslab.com

DWS Lab produce a desktop vat photopolymerization (stereolithographic) 3D printer called the XFAB.

ECKERTECH — eckertech.com

Ekertech makes a material extrusion 3D printer called the eksbot.

EDISON — 3disonprinter.nl

Edison sell material extrusion 3D printers that can print not just in thermoplastics, but also in chocolate, as well as a metal-clay paste.

FLASHFORGE — flashforge.com

FlashForge is a highly-regarded Chinese manufacturer of material extrusion 3D printers called the Finder, Dreamer and CreatorPro.

FORMLABS — formlabs.com

Formlabs produces desktop vat photopolymerization 3D printers called the Form 1+ and Form 2.

FUSION3 DESIGN — fusion3design.com

Fusion3 Design make desktop material extrusion 3D printers called the F400 and F306.

GERMANREPRAP — germanreprap.com/en

German RepRap produce material extrusion 3D printers called the Neo and X400.

IONCORELTD — ioncoretechnology.com

IonCoreLtd produce two material extrusion 3D printers called the Zinter and Zinter PRO.

LEAPFROG 3D PRINTERS — lpfrg.com

Leapfrog produces a range of material extrusion 3D printers, with several of its models offering the ability to extrude multiple materials.

LEWIHE — lewihe.com/store

Lewihe produce thermoplastic extrusion 3D printers called the Play, Sneaker and Sneaker XL.

LULZBOT — lulzbot.com

Lulzbot produce three highly regarded thermoplastic extrusion 3D printers called the Taz 5, the Taz 6 and the Taz Mini.

M3D — printm3d.com/themicro/

M3D produce a small, low cost thermoplastic extrusion 3D printer called the M3D Micro, and a bigger printer called the Micro Pro.

MAKERBOT INDUSTRIES — makerbot.com

MakerBot produce a range of MakerBot material extrusion 3D printers including the Replicator 2X and Replicator Fifth Generation.

MAKEGEAR — makergear.com

MakerGear sells its own M Series material extrusion 3D printers, as well as some RepRap open source hardware.

PHOTOCENTRIC — photocentric3d.com

Photocentic make low-cost vat photopolymerization 3D printers based on a process called daylight photopolymer printing (DPP).

PORTABEE — portabee3dprinter.com

The Portabee make a small, foldable material extrusion 3D printer called the Portabee Go.

PRINTRBOT — printrbot.com

PrintrBot produce low-cost material extrusion 3D printers called the Play, the Simple and the PrintrBot Plus.

REPRAPUNIVERSE.COM — reprappro.com

ReprapUniverse.com sell kits for MendleMax and Prussa open source, material extrusion RepRap 3D printers.

TIERTIME — tiertime.com/en

Tiertime Corporation is a Chinese manufacturer of material extrusion 3D printers including the UP Mini, Up Plus 2 and the UP BOX.

TINKERINE — tinkerine.com

Tinkerine is a Canadian manufacturer of material extrusion 3D printers called the Litto, Ditto+ and Ditto Pro.

ULTIMAKER — ultimaker.com

Ultimaker produces very well respected material extrusion 3D printers called the Ultimaker 3, Ultimaker 3 Extended, Ultimaker2+, Ultimaker 2+ Extended, and the Ultimaker 2 Go.

VSHAPER — vshaper.com/en/

VShaper sell a range of material extrusion 3D printers.

WEISTEK — ideawerk3dprinter.com

Weistek produce the IdeaWerk and X-Master material extrusion 3D printers.

ZMORPH — zmorph3d.com/3d-printers

Zmorph sell a material extrusion 3D printer called the Zmorph 2.0.

ZORTRAX — zortrax.com

Zortrax produce a range of material extrusion 3D printers that include the M200, M300 and Inventure.

XYZPRINTING — xyzprinting.com

XYZprinting sell a range of low-cost material extrusion 3D printers under their Da Vinci brand, as well as a vat photopolymerization model called the Nobel 1.0.

BIOPRINTING PIONEERS

3D BIOPRINTING SOLUTIONS — bioprinting.ru/en/

3D Bioprinting Solutions are a Russion bioprinting pioneer who have developed a bioprinter called the FABION.

3DISON — en.3disonprinter.com/product-invivo.php

3Dison sell a ‘hybrid bio 3D printer’ called the Rokit Invivo.

BIOBOTS — biobots.io

Biobots have developed a ‘fun to use’ bioprinter called the BioBots 1.

CELLINK — cellink.eu

Cyfuse have developed a bioprinter called the Inkredible.

CYFUSE — cyfusebio.com/en/regenova.html

Cyfuse have developed a bioprinter called the Regenova.

ENVISIONTEC — envisiontec.com/3d-printers/3d-bioplotter/

EnvisionTEC have developed a bioprinter system called the 3D-Bioplotter.

ORGANOVO — organovo.com

Organovo are a leading, publicly-traded bioprinting pioneer who have developed a bioprinter called the Novogen MMX.

OZBOLAT LAB — personal.psu.edu/ito1/

The Ozbolat Lab at the Penn State University focuses on developing cutting-edge bioprinting science and technology.

REGENHU — regenhu.com

RegenHU have developed bioprinters called the BioFactory and the 3DDiscovery.

REGENOVO — regenovo.com/english/

Regenovo in China has developed three bioprinters called the Bio-Printer-Lite, Bio-Printer-Pro and Bio-Printer-WS.

WAKE FOREST INSTITUTE —wakehealth.edu/WFIRM/

The Wake Forest Institute for Regenerative Medicine is a leading pioneer of bioprinting and tissue engineering.

3D PRINTING SOFTWARE

3D TRANSFORM — 3dtransform.com

3D Transform is a free, online 3D object file converter.

AUTOCAD — usa.autodesk.com/autocad-products

AutoCAD is an industry leading CAD package from Autodesk.

AUTODESK 123D — 123dapp.com

Autodesk 123D is a range of free 3D printing design applications.

BLENDER — blender.org

Blender is a free, open-source 3D design package that includes modelling tools for 3D print.

LEOPOLY — leopoly.com

Leopoly is a sculpting package for creating models for 3D print. The free Leopoly.com runs in a web browser, while the more feature-rich LeopolyNEXT is downloadable via subscription.

LIMITSTATE — print.limitstate.com

LimitState is an application for fixing STL files prior to 3D printing.

RHINO — rhino3d.com

Rhino is an excellent mid-range CAD package for 3D modelling.

SCULPTRIS — pixologic.com/sculptris

Sculptris is a free-version of the ZBrush 3D sculpting package.

SKETCHUP — sketchup.com

SketchUp (formerly Google Sketchup) is a 3D modelling application from Trimble Navigation. There are two versions: SketchUp Make, which is free to download, and a paid professional edition.

SOLIDWORKS — solidworks.com

SolidWorks is a professional CAD package from Dassault Systèmes.

TINKERCAD — tinkercad.com

Tinkercad is free, browser-based 3D design package.

TURBOCAD — turbocad.com

TurboCAD is a popular, low-cost design package that can be used to create objects for 3D printout.

Z BRUSH — pixologic.com/zbrush

Z Brush is a really cool, high-end 3D sculpting package.

3D PRINTING SERVICE BUREAU

3BIGGG.com (France) — 3biggg.com/professionnels/en

3D Creation Lab (UK) — **3dcreationlab.co.uk**

3D Hubs (whole planet network) — **3dhubs.com**

3D Material Technologies (US) — **3dmaterialtechnologies.com**

3D Print Bureau (UK) — **3dprintbureau.co.uk**

3DPhacktory (Canada) — **3dphacktory.com**

3D Print UK (UK) — **3dprint-uk.co.uk**

3DPrintus (Russia) — **3dprintus.ru**

3D ProParts (US) — **3dproparts.com**

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Axis Prototypes (Canada) — axisproto.com

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Formwurx (UK) — formwurx.co.uk

GROWit (US) — growit3d.com

Halo Technologies (US) — halotechnologiesllc.com

i.materialise (Belgium) — i.materialise.com

IDC Models (UK) — idcmodels.com/services/sla

Inition (UK) — inition.co.uk/3d-printing-and-scanning-services

Industrial Plastic Fabrications Limited (UK) — ipfl.co.uk

KAIAO Rapid Manfacturing (China) — kaiao-rprt.com

Laser Prototypes Europe Limited (Ireland) — laserproto.com

LGM Architectural Visualization (US) — lgmmodel.com

Made For Me (US, Austrailia & New Zealand) — madefor.me

Make Mode (US) — makemode.co

Materialise OnSite (Belgium) — materialise-onsite.com

Midwest Prototyping (US) — midwestproto.com

Objex (Canada) — objexunlimited.com

Ponoko (New Zealand, US, Germany, UK & Italy) — ponoko.com

Print To 3D (US) — printo3d.com

Proto3000 (Canada) — proto3000.com

Purple Porcupine (US) — purpleporcupine.com

Quickparts (US) — quickparts.com

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Rapido3D (UK) — rapido3d.co.uk

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Shapelize (France) — shapelize.com

Shapeways (US & The Netherlands) — shapeways.com

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Tri Axis Art (US) — triaxisart.com

Vivid 3D (Northen Ireland) — vivid3d.co.uk

x3D Print (France) — x3d-print.com/en/

Xometry (US) — xometry.com

3D OBJECT REPOSITORIES

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CGTrader — cgtrader.com

Cuboyo — cuboyo.com

Cults3d — **cults3d.com**

df3d — **store.df3d.com/index.php/store.html**

Humster — **humster3d.com/3d-printing-ready/**

Kraftwurx — **kraftwurx.com**

MyMiniFactory — **myminifactory.com**

Pinshape — **pinshape.com**

Redpah — **redpah.com**

Repables — **repables.com**

Thingiverse — **thingiverse.com**

Treatstock — **treatstock.com**

YouMagine — **youmagine.com**

XYZprinting Artist Collection — **us.gallery.xyzprinting.com**

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