The complete book is available from most Amazon sites as a 276 page paperback or as a Kindle e-book.

ISBN: 978-1484181768

Paperback RRP: $14.99 / US £9.99 UK / €11.50 EU

Amazon.com: Paperback or Kindle

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With Best Wishes,

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THE NEXT REVOLUTION

As I emerged from Moorgate underground station it was starting to rain quite hard. Most of the area outside the station was also boarded up for building work, making it difficult to orientate myself with the crumpled Google Map hardcopy in my hand. Even so, I stepped out into the dull, damp early afternoon of 19th October 2012 with a spring in my step. I was on a mission. And it was going to be rather interesting.

Arriving anywhere in a city around 1:00pm is never ideal, and especially so when it is raining and those on their lunch break are intent on using umbrellas to stop non-locals finding their way. Nevertheless I persisted, and was soon arriving at a venue called The Brewery.

As I crossed its cobbled courtyard I realized that The Brewery was a very upmarket place indeed. Well before the main entrance I was intercepted by an immaculately dressed young man with an extremely large umbrella. For a second I thought my clothing choice of a leather jacket had let me down and I was about to be turned away. But no, the now soggy ticket I was clutching along with my Google Map was enough to assure him I was legit, and I was let through.

On the door I was asked whether I was 'trade or press?' My answer of 'both really' did not phase an equally immacu-

lately attired doorman, and I joined a short queue at a registration desk. A moment later my bedraggled ticket was exchanged for a glossy programme, and a plastic purple bracelet had been secured around my left wrist.

The strap line on the programme proclaimed that the Internet had changed the world in the 1990s, and that the world was about to change again. With this statement I also agreed. I had just arrived at the 2012 3D Printshow – the first major 3D printing event to be held in the United Kingdom, and one of the first in the world.

I was there in part to shoot a video, and so before I left the registration desk I asked if there were any restrictions on the use of cameras. They knew of none, and suggested that I visit their gallery of 3D printed works of art as the main exhibition halls were yet to open.

The gallery was down several flights of red-carpeted stairs, and entering it was a bit like stepping into another world. The room was already heaving with people, and most were looking at its 3D printed exhibits through the cameras on their smartphones or iPads. Clearly my question about what could be photographed had been irrelevant! The room was also liberally festooned with things worth committing to flash memory.

3D printers turn digital computer models into solid, physical objects by building them up in a great many very thin layers. As the exhibits in the art gallery demonstrated, already objects can be 3D printed in a wide range of materials including plastics, metals and ceramics. At the centre of the room were a pair of white, high-fashion 3D printed shoes that their designer told me would be worn on the catwalk that evening. Only one plinth away was a display of very colourful 3D printed vases. Next to them were some intricate 3D printed metal sculptures, including one in the shape of a teapot. Elsewhere in the room were a 3D printed iPhone

case, all kinds of jewelry, a fragmented human head 3D printed in black plastic, and a computer keyboard with raised 3D printed keys in the shape of a city skyline.

Many of those milling around in the gallery were clearly amazed that everything on display had been 3D printed. Yet this was just the beginning of a very eye-opening three day event. Upstairs in the main exhibition halls we were all soon to see scores of functioning 3D printers, as well as a plethora of their creations. These included coffee cups, several lampshades, two guitars, a bikini, a range of customized dolls, a fabulous model of a concept car, two prosthetic limbs, a hoard of plastic robots, and an Egyptian mummy 3D printed from a digital scan. Figure 1.1 illustrates some of the many 3D printed objects that were on display.

In addition to hundreds of fascinating exhibits, the 3D Printshow also harboured a very noticeable buzz. As I toured the exhibition halls and talked to both exhibitors and fellow attendees, it was incredibly obvious that something very significant was starting to happen and that we were all part of a watershed event. From the conversations taking place it was also clear that many visitors were in attendance because they planned to become the entrepreneurs, scientists, artists or investors who would help shape the Next Industrial Revolution.

SO HOW DOES 3D PRINTING WORK?

OK, I have hopefully now captured your attention! But how, you may be wondering, does the apparent magic of 3D printing actually work? Well, to a large extent, the processes involved are no more than a logical evolution of the 2D printing technologies currently 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 manufacture objects by controlling the placement and adhesion of a 'build material' in 3D space.

To 3D print an object, a digital model first needs to exist in a computer. This may be fashioned by hand using a computer aided design (CAD) application, or some other variety of 3D modelling software. Alternatively, a digital model may be created by scanning a real object with a 3D scanner, or perhaps by taking a scan of something and then tweaking it with software tools.

However the digital model is created, once it is ready to be fabricated some additional computer software needs to slice it up into a great many cross sectional layers only a fraction of a millimetre thick. These object layers can then be sent to a 3D printer that will print them out, one on top of the other, until they are built up into a complete 3D printed object.

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 we shall see in chapter 2, already there are more than a dozen viable 3D printing technologies. This said, almost all of them work in one of three 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 continuous stream of hot thermoplastic that very rapidly sets after it has left the print head. Other extrusion-based 3D printers manufacture objects by outputting a molten metal, or by extruding chocolate, cheese or cake frosting (icing sugar) to 3D print culinary creations. There are even experimental 3D printers that output a computer-controlled flow of liquid concrete, and which may in the future allow whole buildings to be 3D printed.

Figure 1.1: Exhibits at the 3D Printshow, London 2012.
'Ula Miami' car by Josh Henry and Materialise. 'Digital Natives' vases by Matthew Plummer Fernandez. 'N12' bikini by Continuum Fashion. 'Exoskeleton' shoes by Janina Alleyne. Tiny robot by 3D Systems.

A second category of 3D printer creates object layers by selectively solidifying a liquid – 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 photopolymer. Meanwhile others jet out a single layer of liquid and then use an ultraviolet light to set it solid before the next layer is printed. A few of the 3D printers that are based on the latter technology are able to mix and solidify many different photopolymers at the same time, so allowing them to print out multi-material objects made of parts with different material properties. For example, the latest Connex printers from a company called Stratasys can build objects in up to 14 different materials at the same time. These range from hard plastics in a range of transparencies and colours, to softer, rubber-like compounds.

A final category of 3D printing hardware creates objects by selectively sticking together successive layers of a very fine powder. Such 'granular materials binding' can be achieved either by jetting a liquid glue or 'binder' onto each powder layer, or by fusing powder granules together using a laser or other heat source. Already granular materials binding can be used to 3D print objects in a very wide range of materials. These include nylon, ceramics, wax, bronze, stainless steel, cobalt chrome and titanium.

WHY 3D PRINT?

Like any new development, 3D printing will only drive a revolution if it can offer clear and significant benefits over existing technologies and industrial practices. Before we proceed any further, it is therefore worth outlining how 3D printing may help us to usefully achieve new things, or else to achieve old things in more effective ways.

IMPROVING PRODUCT DESIGN

Already 3D printing is starting to be used to improve product design. It does this by facilitating the rapid creation of 'concept models', so allowing physical manifestations of in-progress designs to be viewed and handled early in the design process.

While computer graphic renderings of new products are now highly sophisticated, still nothing compares to holding a 3D model of a potential new product in your hand. Often potential design flaws that are not obvious when a design is viewed on a computer screen or tablet become very evident when a physical concept model can be seen and touched. By allowing concept models to be rapidly created – sometimes in full colour – 3D printers are therefore already improving the communication flow between designers and their clients. In turn this often helps to speed up the design process, as well as allowing better products to be created.

Beyond the concept design stage, 3D printers are also already being used to create 'verification models' or 'functional prototypes'. For this reason, in some industrial circles 3D printing has subsequently become known as 'rapid prototyping' or 'RP'. This is also a little sad, as in my experience the use of the 'rapid prototyping' label is blinding some people to the wider application of 3D printing technology.

Functional prototypes need to be created during most design processes to check the form, fit and function of a product's different parts. Traditionally such prototypes could only be created by skilled craftspeople using labour-intensive workshop techniques. It was therefore not uncommon for many product prototypes to take many weeks to produce and to cost thousands or tens of thousands of dollars, pounds euro or yen. In contrast, 3D printers can now often produce functional prototypes in a few hours for a tiny fraction of the price of traditional methods. The use of 3D printing is there-

fore already making prototyping quicker and cheaper, and in turn allowing new products to cycle through more iterations. As just one example, since 1998 the Renault Formula 1 racing team has been using 3D printers to produce prototype car parts to test the aerodynamic properties of its new designs. This allows the team to test hundreds of possible aerodynamic changes to its Formula 1 cars every year.

Over the past couple of decades, several 3D printing pioneers have set up successful businesses that specialize in producing concept models and functional prototypes. Many such companies are today continuing to thrive. But the falling cost of 3D printer hardware is also starting to allow many of their clients to move concept model and prototype production in-house, and even onto the desktop. Some Ford engineers, for example, were recently reported to be using 'MakerBot' desktop 3D printers that cost a few thousand dollars. These allow the creation of plastic components that can be assembled to check fit and function. The use of 3D printers by Ford engineers is hence helping to 'bridge the gap between the abstract and the practical' in new engine development.

TRANSFORMING TRADITIONAL PRODUCTION

Beyond concept model and prototype fabrication, 3D printers are also starting to be used in industrial pre-production. Most traditional production processes require the creation of bespoke jigs, tools, patterns and molds that are then used during manufacturing to shape metals and plastics into appropriate forms. Like product prototypes, such items have traditionally been crafted by hand in a manner that has proven both time consuming and expensive. The use of 3D printers to help tool-up factories for traditional production may therefore save a great deal of time and money.

A particularly promising application of 3D printing is in the direct production of molds, or else of master 'patterns' from which final molds can be taken. For example, as we shall see in the next chapter, '3D sand casting' is increasingly being used to print molds into which molten metals are then directly poured to create final components. As explained by ExOne – a pioneer in the manufacture of 3D printers for this purpose – by 3D printing sand casting molds, total production time can be reduced by 70 per cent, with a greater accuracy achieved and more intricate molds created. In fact, using 3D sand casting, single part molds can be formed that would be impossible to make by packing sand around a pattern object that would then need to be removed before the mold was filled with molten metal.

Some 3D printer models are created exclusively for the production of molds or patterns. For example, the range of Solidscape printers sold by a company called Stratasys print in wax-like plastics that are used to produce small molds or patterns in dental labs or for jewelry making. Like sand casts, these molds or patterns are 'sacrificial', as the process of producing a final object using them results in their destruction.

The use of 3D printers to create molds, patterns and other production tooling may rarely if ever be seen let alone appreciated by the consumers of most final products. For example, few people today are ever likely to realize that the soles of their trainers were probably produced in a mold that was derived from a 3D printed pattern master. Nevertheless, even though it will remain a behind-the-scenes development, the use of 3D printers in industrial pre-production is likely to prove a key facet of the 3D Printing Revolution.

DIRECT DIGITAL MANUFACTURING

While 3D printing is already an established part of some design and pre-production processes, the ultimate applica-

tion of the technology will be in the development of 'direct digital manufacturing' (DDM). This does what it says on the tin, with DDM using 3D printers to create final products, or more usually parts thereof. As we shall see in chapter 4, DDM is already gaining traction in industries as diverse as aerospace, jewelry making, dentistry, toy production, and the manufacture of fashion items like designer homewares and customized sunglasses.

One of the amazing things about 3D printing is that it can be used to create objects which cannot be directly produced using traditional manufacturing techniques. For example, a 3D printer can print a necklace made up of links that do not have a break in them, not to mention a whistle with the pea already inside, or a ship in a bottle. Some 3D printers can also directly print working, multi-part mechanisms like gearboxes. Traditionally, the manufacture of multi-component products has always involved a final assembly stage. But when things are made using 3D printers this no longer has to remain the case.

In the future it is possible that almost anything could be manufactured using 3D printing technology, including entire aeroplanes. While this may sound crazy, a small team at Airbus is already designing a revolutionary airliner that would be 65 per cent lighter than a conventional aircraft because it would be 3D printed from a plastic resin. While such an aircraft – and the 3D printer required to make it – may not be ready until 2050, in 2011 Airbus parent company EADS opened a £2.6 million Centre for Additive Manufacturing at the University of Exeter. The goal of this research facility is to develop 3D printed parts for aircraft, including the current Airbus A380.

MASS CUSTOMIZATION

One of the key benefits of DDM is the ability to achieve mass customization, as no two objects produced on a 3D

printer ever have to be the same. Some 3D printing pioneers have also begun to spot niche markets in which mass customization can allow totally novel products to be created. For example, visit Cubify.com, and you can create a custom iPhone case that will be 3D printed with a raised design on the back based on a digital image that you supply. In a similar fashion, ThatsMyFace.com invites visitors to upload a front and side photograph of their face, from which it then generates a coloured 3D model. ThatsMyFace customers can then have a 3D printed version of their head added to a selection of plastic action figures or a Lego model. Alternatively, they can purchase their face as a 3D printed portrait or mask.

The way in which ThatsMyFace.com purchases standard figurines, discards their heads, and replaces them with custom 3D printed parts, really is very clever indeed. The service not only allows anybody to own themselves in miniature super hero format, but more significantly demonstrates the potential to easily mass customize standard products using relatively low-cost 3D printing technology. For those seeking to create a new 3D printing business, similar opportunities across a great many other market sectors have to be considerable.

SMALL PRODUCTION RUNS

In addition to mass customization, DDM already allows one-off products or small batches of components to be produced at low cost, as no tooling is required to initiate production. For example, when the producers of the 2012 James Bond film *Skyfall* needed three 1/3rd scale models of an Aston Martin DB5, they had them 3D printed using a Voxeljet VX4000 3D printer. The replica cars were 3D printed in 18 parts that were then assembled and painted to be intensely accurate replicas of the real and far more expensive vehicle. Sadly the models were blown to smithereens

during filming – although this was the reason that they were created in the first place.

As another example, a custom motorcycle manufacturer called Klock Werks Kustom Cycles has adopted 3D printing technologies to allow it to rapidly create one-off components. For one build, the company had just five days to produce a custom motorcycle to take part in a TV programme. To achieve this timescale, Klock Werk's engineers designed the bike's gauge pod, fork tube covers, headlight bezel, floorboard mounts, floorboard undercovers and wheel spacer cover in a 3D modelling package called SolidWorks. They then 3D printed the parts, rather than machining them from aluminium or injecting molding them in plastic. Their finished bike even went on to set an American Motorcyclist Association land speed record.

As the above high profile examples demonstrate, 3D printing is already being used to allow things to be created that simply could not be made as quickly or cheaply using traditional production methods. For companies – or indeed individuals – who wish to manufacture a single product or a small batch thereof, 3D printing is therefore already a technology that is making the impossible possible.

DIGITAL STORAGE & TRANSPORTATION

As well as enabling mass customization and small-scale manufacturing, 3D printing is set to facilitate digital object storage and digital object transportation. What this means is that, if you want to send something to somebody far away, in the future you will have two options available. 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.

While the above may sound like pure science fiction, already an object-sharing website called Thingiverse allows designers to upload digital creations that others can download for printout. Many people now regularly share text, photos and video online, and – due to 3D printing – digital objects are soon likely to 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.

OPEN DESIGN

Possibilities will also increasingly exist for digital objects to iteratively evolve. Even today it is not uncommon for 3D printing enthusiasts to download a digital object, make an alteration or few, print the object out, and also re-upload their amended design so that others can benefit from the modifications they have made. So termed 'open design' is therefore starting to take hold, with more and more people having access to CAD software and 3D printer hardware that is democratizing the design process out of the hands of a privileged few.

While many firms fear the consequences of open design, others are strongly embracing the trend. For example, on 18th January 2013, Nokia launched a 3D printing community project. This included the release of a '3D printing development kit' to help people design and personally fabricate their own cases for its Lumia 820 phones. As explained by John Kneeland, a Community & Developer Marketing Manager at Nokia:

> Our Lumia 820 has a removable shell that users can replace with Nokia-made shells in different colors, special ruggedized shells with extra shock and dust protection, and shells that add wireless charging capabilities found in the high-end Lumia 920 to the mid-range 820.

> Those are fantastic cases, and a great option for the vast majority of Nokia's Lumia 820 customers. But in addition to that, we are going to release 3D templates, case specs, recommended materials and best practices – everything someone versed in 3D printing needs to print their own custom Lumia 820 case.

Only a few days after Nokia make the above announcement it launched the Nokia Lumia 820 3D Printing Challenge to encourage people to design and share 3D printable replacement phone shells. By January 24th – only six days after the 3D printing development kit had been released – 3D printed Nokia 820 shells (including some with functional buttons) were being showcased on the web.

The above kind of practice may raise all sorts of intellectual property concerns. There are indeed already people who fear that 3D printing could wreak havoc with the functioning of capitalism itself by moving the means of production into individual hands.

Today 3D printing enthusiasts tend to share and iterate designs for objects such as smartphone cases, photographic accessories, toys and model vehicles. But there is no reason why parts and designs for pretty much anything could not be freely shared and iterated online. To the dismay of many, already people have managed to 3D print guns and share their designs. I will return to the wide-ranging issues that surround digital object replication, personal fabrication and open design in chapters 5 and 8.

TRANSFORMING RETAIL

While those who choose to own a 3D printer may increasingly fabricate their own objects at home, the mainstream impact of the 3D Printing Revolution is more likely to be felt

in traditional retail locations. Today, all physical stores only have the space to stock a relatively small range of largely non-customized goods. They are also dependent on suppliers getting goods to them on time. However, by the end of the decade, at least some retailers may have installed high-end 3D printers that will allow them to print-on-demand customized goods from a potentially unbounded digital object inventory that will never go out of stock. It also clearly makes sense both environmentally and financially for most people to 'share' large 3D printers that reside in retail locations, rather than for everybody to own the latest personal fabrication hardware.

To serve the needs of those who want to design their own products, but who do not want or cannot afford to own a personal 3D printer, 3D printing bureaus are additionally likely to become big business. As already mentioned, companies that offer industrial rapid prototyping services have existed for many years. But alongside them we are now starting to see the rise of both online services and physical stores that are intent on bringing 3D printing to the masses.

For example, if you happen to be in Los Angeles, you can call in to The Buildshop at 201 North Westmoreland Avenue to design and 3D print your own stuff. Or regardless of where you live, browse-on-over to i.materialise.com and you can upload your own designs and get them 3D printed in a choice of over 20 materials. Via the i.materialise gallery, you can also make your designs available for online sale to others. Already this kind of service is removing the barriers to entry in some industries, as anybody can now design and sell physical things without having to invest in any stock or tooling whatsoever, as every item sold is 3D printed on demand. Right now, freelance artists and jewelry makers are some of the largest users of online 3D printing services. But

they are not going to remain the majority customers in the print-on-demand marketspace for very long.

IMPROVING HUMAN HEALTH

Today, while most things that are 3D printed are made from plastics or metals, already there are specialist 3D printers that can build up living tissue by laying down layer-after-layer of living cells. Such 'bioprinters' have the potential to transform many areas of medicine by allowing replacement skin and human organs to be 3D printed from a culture of a patient's own cells. If this happens – and bioprinting pioneers expect that it will within two decades – then the development of 3D printing may cut organ donor waiting lists to zero, as well as making skin grafts a thing of the past. In as little as five years, 3D printed tissues may also start to be used in drug testing, so lessening the requirement for animal experimentation.

In addition to 3D printing replacement human tissues outside of the body, *in vivo* bioprinting is already 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. While such hypothesis may sound fantastical, some medical practitioners and 3D printing pioneers are already taking them very seriously indeed. I will discuss bioprinting in depth in chapter 7.

SAVING THE PLANET

The final and potentially the most significant benefits of 3D printing may turn out to be environmental. Today, vast

quantities of oil and other resources are used to move products around the planet, with a great many things travelling hundreds or thousands of miles before they come into our possession. Given the increasing pressure on natural resource supplies – not to mention probable measures to try and combat climate change – within a decade or two such mass transportation may be neither feasible nor culturally acceptable. Local fabrication-on-demand could therefore turn out to be 3D printing's long-term killer advantage.

In addition to facilitating digital object transportation, 3D printing is also potentially far more environmentally friendly than many forms of traditional industrial production. This is simply because it is based on 'additive manufacturing'. In other words, while many traditional production techniques start with a block of material and cut, lathe, file, drill or otherwise remove bits from it in a subtractive fashion, 3D printing starts with nothing and adds only the material that the final object requires. Digital manufacturing using 3D printers can therefore result in substantial raw material savings.

When final product parts are 3D printed, manufacturers can also optimise their designs so that each part consumes the minimum of materials. 3D printed plastic or metal parts can, for example, be designed with internal air gaps or open lattice work that cannot be fabricated inside an object produced using traditional production techniques. Such a design approach also allows lighter parts to be created – a manufacturing opportunity that the aerospace industry is very keen to take forward.

As a final environmental benefit, 3D printers may find significant application in the production of spare parts. Today, when most things break they cannot be mended as spares are simply not available. But with more and more 3D printers on hand, the opportunity will soon exist to fab-

ricate whatever parts are needed to mend a great many broken things.

Today, most of us still embrace a culture of mass disposability that favours the consignment of broken possessions to landfill rather than regular product repair. Yet as natural resources dwindle, over the next few decades attitudes and practices will have to change. At least in part, it may also turn out to be 3D printing that facilitates our return to a society in which we increasingly opt to repair rather than replace. I will explore the actual and potential links between 3D printing and sustainability in chapter 6.

CATALYSTS FOR A REVOLUTION

So far in this chapter I have provided a brief overview of what 3D printing is, a quick run-through of how it works, and a summary of its current and potential future advantages. In doing so I have hopefully convinced you that a 3D Printing Revolution really is now on the cards. This said, given that 3D printing has been around for several decades, you may reasonably be asking why the 3D Printing Revolution has not happened in the past, and just why it is about to take off right now.

The answer to the above key question is inevitably multifaceted. For a start, 3D printing has had to wait for the substantial improvements in computer processing power, storage and network infrastructure that now potentially allow almost anybody to create, exchange and generally work with digital 3D objects. When first generation 3D printers came onto the market in the late 1980s and early 1990s, the industrial PC workstations used for 3D object design were expensive, and the idea of exchanging large quantities of data over the Internet was ludicrous. Yet today, many smartphones and tablets – let alone desktop PCs and laptops – are powerful enough to be used to design and store

complex 3D objects. A high speed Internet is now also a reality, in turn meaning that the online storage and communication of 3D objects no longer presents a technical challenge. As if to demonstrate how far we have come, some of the personal 3D printers being showcased at the 2012 3D Printshow were wirelessly connected to iPads.

Technological advances made in the world of 2D printing have also helped to build the foundations of the 3D Printing Revolution. While 3D printers are by no means the same as their 2D ancestors, most do rely on somewhat similar servo motors and feed mechanisms, lasers, inkjet print heads, and electronic controllers. The advancement of such hardware over the past two decades was hence a necessary prerequisite to a printing revolution of the 3D kind.

In a bizarre kind of way, the development of 3D printing has also had to wait for the development of 3D printing itself. Here I am referring to the fact that some developments in low-cost 3D printer hardware have relied on the efforts of enthusiasts who have used early 3D printers to help innovate and build better models. Open source 3D printers called 'RepRaps' were in fact always intended to be 'replicating rapid prototypers' capable of partially reproducing themselves in order to facilitate the creation of next generation machines. In a sense, and as we shall see in chapter 5, at a grassroots level 3D printing is therefore quite literally a technology that has taken some time to almost organically evolve.

A fourth factor that is catalyzing the 3D Printing Revolution right now is the increasing digitization of human activity. Even ten years ago, most people rarely if ever went online, with very few of us communicating digitally or harbouring digital possessions. In stark contrast, today billions of people use the Internet, while owning a digital music, photo or video collection is hardly unusual. The idea

of using 3D printers to fabricate physical objects from online digital data is therefore far more likely to be enthusiastically embraced right now than it was when 3D printers were first invented.

Finally, some of the patents on 3D printing technology that were taken out in the late 1980s and early 1990s have either run out, or will soon expire. Some of the potential legal barriers that may until now have slowed the 3D Printing Revolution are therefore starting to fall.

IN THE WORDS OF PIONEERS

The 3D Printing Revolution is – like any other – the product of the actions, energies and visions of those pioneers who are brave enough to make it happen. Throughout this book I will report on what such pioneers are doing, and will also include extracts of my original interviews with some of those who are driving things forward. Right now, in this chapter, my goal is to capture your imagination rather than to focus on details and practicalities (we do, after all, have the rest of the book for that). So, as we head toward the end of this introduction, I thought I would report the responses of a few 3D printing pioneers when I asked them the fundamental question 'why 3D print?'

One of the first people I spoke to was Alex Schmid, who runs the 3D printing search engine Fabforall.com. As he enthused:

> We think that 3D printing matters in the same way that the Internet matters to people and businesses. It means an amazing explosion of creativity, personal enabling, global connectivity [and] disruptive innovation in the material world [to match what] the Internet did in the digital realm.

Reuben Menezes works for Proto3000, a company that provides 3D printing and related product development services in North America. As he argued:

> From my perspective, there are really two parts to this 3D printing journey. The first being the consumer. I believe that 3D printers in the hands of consumers will mean the end of standardization, and the beginning of products personalized to every individual. The second portion of this 3D printing paradigm is its effect on manufacturing and production. Already, 3D printed parts are being used as end-products, achieving new levels of cost-reduction. Not to mention, on the horizon are new 3D printing materials with properties that rival existing elements. [For example] in a few years plastics could rival the strength of metals through the use of nanotechnology in 3D printing.

Miranda Bastijns is Director of the Belgium-based 3D printing services i.materialise and .MGX. 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.

Anssi Mustonen, who runs AMD-TEC, a 3D printing and design company in Finland, focused on the customer service angle:

> 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 [using] traditional methods.

David Blundell, the writer and editor of *Replicator World*, brought a range of arguments together in signalling the truly revolutionary potential of 3D printing. As he enthused:

> The 3D Printing Revolution marries the rapid production of the Industrial Revolution with the global distribution of the Digital Revolution. For two hundred years, mass production has shackled the individualization of products. As Ford once said of his Model T, 'you can have any color you want, as long as it's black!' But with the ascension of 3D printing the means of production have begun to move to the desktop. You can truly now have any color you want. Or shape. Or function. All over the world millions of tiny personal factories creating personal products are springing up. Objects designed for the people by the people. Welcome to the future.

I could go on to cite a great many more pioneers who believe that the 3D Printing Revolution is both about to happen and will yield great benefits. Though hopefully from the above five quotations you have garnered the impression that I am far from alone in proposing that a step-change is now set to occur in how we manufacture quite a few things. The words of Alex, Reuben, Miranda, Anssi and David have also I trust served to demonstrate the sheer energy and passion of those who are driving our next wave of radical change.

THE PC OF CENTURY 21

In 1943 Thomas Watson, the founder of IBM, reputedly stated that there would be 'a world market for about five computers'. If this is what he actually said, then to date he has been caught out by a factor of at least a billion. And even if it is not exactly what he said, the belief of so many in the 1950s, 60s and 70s that computers would always be a minority, industrial technology has clearly been proved plain wrong.

Today, a great many commentators seem to be of the opinion that very few people will ever want a 3D printer, and hence that the demand for them will remain very limited. As I have argued in this chapter, it is quite possible that only a minority of us will ever have a personal 3D printer at home purely because the most useful and sophisticated models will be shared online or in retail outlets. Even so, I would speculate that within 20 years, and perhaps in less than 10, most people in developed nations will regularly make use of a 3D printer to 'materialize' a digital design, or will be regularly purchasing products or spare parts that others materialize for them. It may also turn out that most people will have at least a little 3D printer at home, if only as a hobbyist tool or educational device. When a 3D printer can be purchased as a

smartphone or tablet accessory for $99 or less (and this will happen well before the end of this decade), would you really never purchase one for yourself or your child?

Over the next decade or two, the 3D Printing Revolution has the potential to mirror the PC Revolution of the 1980s and 1990s. In fact, as I wandered around the 3D Printshow in October 2012, I was reminded of how it felt when I visited an early personal computing expo way back in 1987. At that time, PCs were only just starting to take hold and had touched very few people's lives. Even so, as I explored the 1987 PC expo it was very obvious that the foundations of a revolution were being laid. In a similar fashion, as I toured the 2012 3D Printshow it was clear that the metaphorical concrete required to support another radical technological transition was once again being poured. Granted, we do not currently have 3D printers that can easily manufacture most products in our homes. Nor does the hardware even exist for factories and retail outlets to offer widespread fabrication-on-demand. Yet it is increasingly obvious that within five to ten years, such technology is going to be possible.

Beyond the arguments presented in this chapter, there is increasingly strong practical evidence that the 3D Printing Revolution is revving up a gear. Not least, 2012 was undoubtedly the first year in which 3D printing started to capture mainstream media attention and the public's imagination. For example, in January 2012 the first real consumer 3D printer – the Cube from 3D Systems – was launched at the Consumer Electronics Show in Los Angeles. This offered out-of-the-box 3D printing to anybody with $1,199, and came with a USB key of 25 objects all ready for printout.

In addition to seeing the launch of the Cube, 2012 was also the first year in which people could purchase personalized, 3D printed chocolates (from ChocEdge.com), buy a 3D printer kit for under $400 (from Printrbot.com), and

download a free app to turn a Microsoft Kinect games controller into a 3D scanner. In December 2012, Staples even announced the roll-out of a 3D printing service in its European stores in 2013. And as 2013 got underway, in his State of the Union address President Obama advocated the continued development of 3D printing as a technology with 'the potential to revolutionize how we make almost everything'.

All of the above were signature developments that may serve to bring the 3D Printing Revolution just one baby step closer. Yet for me, the most memorable 3D printing innovation of the last year or so was the launch of a $1,200 service called 'Form of Angels' from the Japanese pioneer Fasotec. Here an MRI scan is taken of a pregnant woman, and then used to produce a 3D printed model of her unborn baby. The plastic foetus can even be supplied embedded in a resin model of its mother's midriff for presentation on the expectant parent's mantelpiece.

As we head through 2013, 2014 and beyond, the speed and variety of the 3D Printing Revolution will continue to gather momentum. As it does so, there is also a danger that reality and fantasy will become blurred, and that really important developments will get lost in the hype. For all of those seeking a serious understanding of how 3D printing is likely to transform both manufacturing and our personal lives, some knowledge of what current and likely-future 3D printing methods can and cannot achieve is subsequently paramount. In our next chapter I will therefore detail every known 3D printing technology.