3D PRINTING

SECOND EDITION

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With Best Wishes,

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THE NEXT REVOLUTION

The planet Mars is at least 54 million kilometres from the Earth. Travelling to Mars is therefore somewhat difficult, while transporting anything back from the red planet is currently impossible. It is therefore remarkable that, in April 2014, scientists at NASA's Jet Propulsion Laboratory held in their hands a meteorite named 'Block Island' that one of their robotic rovers had discovered on the surface of Mars in 2009.

The above feat was achieved using detailed measurements and panoramic images taken by NASA's rover. These were transmitted to the Earth, converted into a computer model, and turned back into a solid object by a 3D printer. The resultant plastic facsimile looked identical to the original meteorite, although admittedly it was far lighter and had not physically travelled from Mars. Even so, as illustrated in figure 1.1, its 3D form had definitely managed to traverse deep space.

The above is just one example of the groundbreaking application of 3D printing. In the last year or so, 3D printers have also been used to create functional rocket engine components, a pair of reading glasses, a full-size replica of Tutankhamun's tomb, and ten habitable houses. Almost every day I read a press release that indicates how the 3D Printing

Revolution is continuing to gather momentum, with its technology increasingly finding mainstream business or broader cultural application.

This book is your guide to the rapidly advancing world of 3D printing. The following chapters detail every 3D printing technology, as well as the key players in the 3D printing industry. We will also meet a fascinating spectrum of pioneers who are manufacturing all manner of 3D printed products ranging from jewelry to aerospace components, and toys to medical appliances. As we shall see, it is already possible to 3D print in many different plastic, metal and ceramic materials. And this is only the beginning.

3D PRINTING TECHNOLOGIES

So 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 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 manufacture objects by controlling the placement and adhesion of successive layers 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. As we shall see in chapter 5, desktop and handheld 3D scanners are now improving rapidly, with entry-level models on sale for a few hundred dollars.

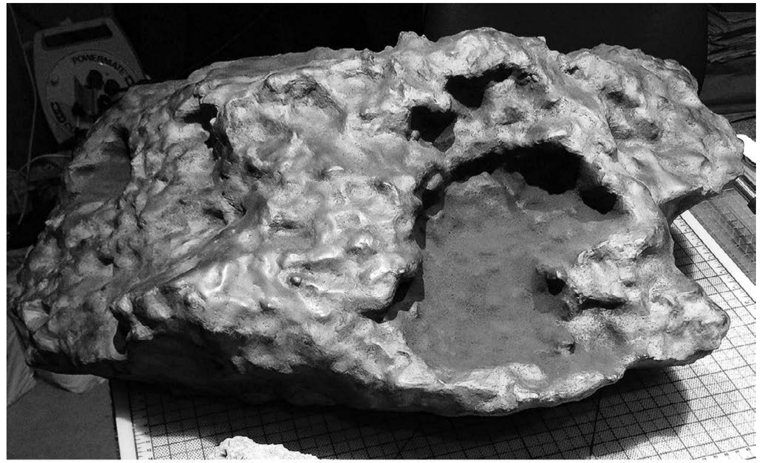

Figure 1.1: 3D Print of 'Block Island' Martian Meteorite.
Image courtesy of NASA.

Regardless of how a digital model is created, once it is ready to be fabricated it needs to be put through some 'slicing software' that will divide it up into a great many cross sectional layers only a fraction of a millimetre thick. These object layers 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. 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, all 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 even 3D printers that extrude concrete 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 out a single layer of resin 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 objects made from multiple materials. Most notably, the latest such 3D printer from market leader Stratasys – the Objet500 Connex3 – can create colour objects in several different materials including 'rubber-like' and 'digital ABS'. This amazing printer is illustrated in figure 1.2.

A third and very broad category of 3D printing hardware builds objects by selectively sticking together successive layers of a very fine powder. Such 'powder adhesion' or 'granular materials binding' can be achieved by jetting an adhesive onto each powder layer, or by fusing powder granules together using a laser or other heat source. Yet other technologies melt and then fuse the granules of a powdered build material as it is deposited onto a build surface. Various forms of powder adhesion are already commonly used to 3D print in a wide range of materials. These include nylon, bioplastics, ceramics, wax, bronze, stainless steel, cobalt chrome and titanium.

Lastly, 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.

Figure 1.2: The Stratasys Objet500 Connex3.
Photo courtesy of Stratasys.

MARKETS & APPLICATIONS

3D printing is already being used for rapid prototyping, the production of molds and other industrial tooling, the direct digital manufacture of final products, and 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

Currently 3D printing is most commonly used for rapid prototyping (RP). This is where 3D printers are used to create concept models and 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 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 hours for a fraction of the price of traditional methods. In addition to saving time and money, this allows improved final products to be brought to market, as designs can evolve through a great many iterations.

The use of 3D printing to create rapid prototypes is now common across a wide range of industries. For example, in the automotive sector, GM's Rapid Prototype Laboratory 3D prints over 20,000 prototype parts every year. Ford similarly does a great deal of 3D printing, and in December 2013 produced a prototype Mustang engine cover as its 500,000th 3D printed auto part. In Formula 1 motor racing, the 3D printing of prototype parts is also very well established. Renault, for example, has been using 3D printers to produce prototype Formula 1 car parts since 1998 in order to test different aerodynamic designs.

Producing Molds & Tooling

As well as rapid prototypes, 3D printers are also used to make molds, patterns, jigs, fixtures and other production tooling. Most traditional production processes require such

items to be created in order to fashion metals or plastics into final product parts. Like product prototypes, molds, jigs 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. It may also allow manufacturers to change their designs more rapidly, and to manufacture a wider product range.

A particularly promising application of 3D printing is in the direct production of molds. For example, as we shall see in the next chapter, 3D printers can now be used to directly produce sand cast molds into which molten metals are poured to create final components. As reported by ExOne – a pioneer in the manufacture of 3D printers for this purpose – by 3D printing sand cast molds, total production time can be reduced by 70 per cent, with a greater accuracy achieved and more intricate molds created. Using 3D printers to produce sand cast molds can also allow parts to be manufactured that would be impossible to make by packing sand around a pattern object that would need to be removed before the mold was filled with molten metal.

Several manufacturers now 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 dentistry, 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.

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 are ever likely to realize that the soles of their trainers were produced in a mold that was derived from a 3D printed pattern master. Nevertheless, the use of 3D printers to produce molds, patterns, jigs and fixtures is growing rapidly, and is a critical area of 3D printing application.

Direct Digital Manufacturing

In a few niche markets, 3D printers are already being used to manufacture end-use industrial components and final consumer products. This exciting development is usually referred to as 'direct digital manufacturing' (DDM), and is gaining traction in industries as diverse as aerospace, car manufacture, toy production and fashion. In August 2014, Mercedes revealed that it may well use 3D printing to manufacture one-piece air vents, as well as other intricate interior parts like speaker grills, for its 2018 S-Class model.

One of the amazing things about DDM is that it can be used to create objects that 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, a whistle with the pea already inside, or a ship in a bottle. At Airbus, complex metal parts have already been 3D printed that would traditionally have been welded amalgams of ten different components. Using plastic or resin build materials, many 3D printers can now even create working, multi-part 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.

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, 3D printed plastic and metal parts are already finding their way into commercial and military aircraft. Indeed, where traditional spare parts are unavailable, 3D printed replacements sometimes provide the only economic means of keeping older aircraft in service.

Because no tooling is required to initiate manufacturing, 3D printing offers great opportunities for one-off or low-run 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. As another example, a French company called Crea'Zaurus 3D now employs 3D printing to manufacture paleontological models. Just one of their amazing, full-size 3D printed dinosaur heads is illustrated in figure 1.3. In chapter 4 I will detail in depth the work of many more DDM pioneers.

Personal Fabrication

In parallel with the growth of industrial 3D printing, we are witness to the rise of personal fabrication. This refers to all situations in which individual 'makers' 3D print things for themselves, so by-passing the need for everything they own to have started life in a distant factory. For example, last week I met a 3D printing enthusiast called Elliott Viles, who is now the Design Manager at the iMakr 3D printer store in London. As a child, Elliot had always wanted a model of Han Solo's blaster from *Star Wars*. So once he had access to a 3D printer,

Figure 1.3: 3D Printed Dinosaur Head by Crea'Zaurus.

he just built the gun in a 3D modelling package and printed it out. The amazing replica he created is shown in figure 1.4, and can be freely downloaded from MyMiniFactory.com.

Two or three years ago, while personal 3D printers did exist, most were home assembled. It also took the determined efforts of a dedicated enthusiast to reliably obtain a decent printout (or sometimes any printout at all). It is therefore amazing that, by the end of 2014, there are over 100 pre-assembled personal 3D printers on the market, with reputable models that pretty much print out of the box starting from $500. The market for personal 3D printers is also now growing rapidly. As I shall explore in chapter 5, personal 3D printers – and associated hardware like personal 3D scanners – are therefore set to become an increasingly common domestic and educational technology.

Figure 1.4: 3D Print of Han Solo's Blaster by Elliot Viles.

INDUSTRY DEVELOPMENT

It is critically important to appreciate not just the existence of the 3D printing industry's four, distinct market segments, but also the fact that they are in very different stages of development. To highlight this frequently ignored reality, figure 1.5 illustrates 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.

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. Given that the curves in the figure extend several decades into the future, they are obviously not based on definitive data! This said, I would suggest that they do illustrate some pretty solid facts. 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 actually make end-use products 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 actually afford to own.

As figure 1.5 indicates, 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 this is, I would suggest, more than realistic for two reasons. Firstly, 3D printing is not the only rapid prototyping technology. And secondly, there will always be many instances where traditional methods will remain 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 and 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 the 3D printing industry very soon indeed. As I indicated in the *Preface*, by 2020 most things produced on 3D printers will no longer be prototypes and concept models, with an increasing proportion being molds, patterns, jigs and other items that will be used to help manufacture final products via traditional means. As figure 1.5 indicates, my guess is that it will take decades for this large market to saturate, with the business opportunities in this area providing a solid foundation for the increased industrial adoption of 3D printing. Talk to industrial 3D printer manufacturers, and they are all well aware of this. Right now, in most industries, the 3D printing of

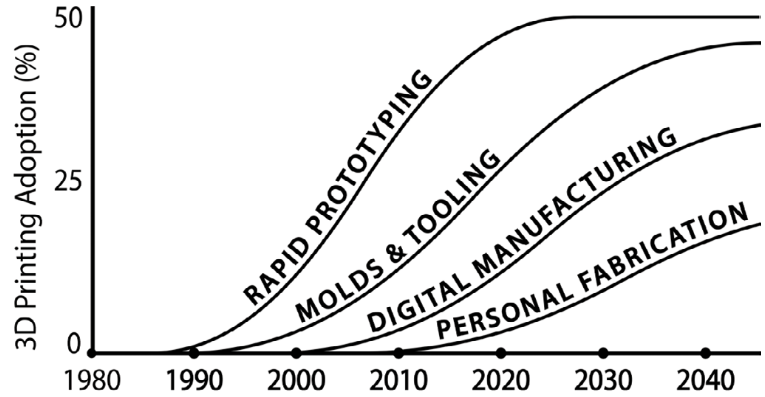

Figure 1.5: 3D Printing Adoption Curves.

molds and other tooling represents the largest market opportunity.

Moving on, the digital manufacture of end-use industrial components or final consumer products is a significantly less mature market that we should not expect to go mainstream as rapidly as many popular media pundits predict. In the next ten years or so, many industries – including healthcare, fashion, designer goods and aerospace – 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. But even so, in 10 or 20 years time, the vast majority of the objects in our lives will not be 3D printed (although many will probably be produced using a wider range of local digital manufacturing or 'LDM' technologies, as I shall outline in chapter 7).

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, maybe 10 per cent of 3D printing industry revenues come from 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. In fact, in April 2014, Juniper Research confidently predicted that the sale of consumer 3D printers will exceed 1 million units per year by 2018. It is therefore not a surprise that global consumer product manufacturers are starting to launch products into this new market space, with the first such entrants being tool manufacturer Dremel and the Taiwanese giant Kinpo Group.

The above points noted, by 2018 the average personal 3D printer will probably cost under $1,000, so making the annual sale of around 1 million units worth less than a billion dollars. This means that, by 2020, personal 3D printing will still account for no more than 10 per cent of the global 3D printing marketplace (which should turn over at least $10 billion by that time). I therefore 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.

ACHIEVING THE IMPOSSIBLE

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 8 of this book. But

before we get there, I think it is worth highlighting the key opportunities.

Customization & Personalization

For a start, 3D printing will increasingly allow products to be customized according to our tastes, or personalized according to our individual characteristics. Since the Industrial Revolution, the economies of scale associated with mass production have dominated manufacturing, with factories tooled up to make large quantities of identical, standardized products. But the economics of 3D printing are somewhat different, as every part or product that is additively manufactured on a 3D printer can be different without incurring extra cost.

As we shall see in chapter 4, a few digital manufacturing pioneers are now selling jewelry and toys that are customized via their websites and then 3D printed to unique customer specification. Some traditional manufacturers are also starting to customize their products by including one or a few 3D printed parts. Panasonic, for example, recently showcased a range of Lumix GM1 cameras with designer 3D printed bodies.

In the medical sector, 3D printing is also increasingly being employed to create personalized hearing aids, dental appliances and other prosthetics. Nobody can be certain when or if 3D printing will transform mainstream manufacturing. But a revolution in 3D printed customized and personalized goods has already begun.

Democratizing Access to Market

In addition to allowing many more people to own customized and personalized possessions, 3D printing will 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. Even more fundamentally, the development of 3D printing bureau services 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 invest in any sales infrastructure or stock. In a similar fashion, the opportunity to bring products to market with no capital or stock investment will increasingly exist for lone product designers who want to reach a global audience.

As we shall see in chapter 4, already anybody can upload an object design to a 3D printing bureau such as i.materialise or Shapeways. These companies will then market the item on their website, take orders and payment, 3D print the final goods, and despatch them to the customer. All an artist or product designer has to do after uploading their design is to wait to receive their cut of each sale.

In March 2014, Amazon took many people by surprise when it launched a pilot program to sell consumer goods that are 3D printed on demand. In ten years time, many of our possessions may be created by lone designers and small companies, but produced by 3D printing bureau services large and small. This is likely to raise a whole heap of potentially problematic issues as I shall highlight in a few pages time. Even so, I have no doubt that the democratized access to market made possible by 3D printing is going to have a significant impact on many industries.

Open Design

Possibilities will also increasingly exist for at least some products to iteratively evolve. Already there are object sharing websites – such as Thingiverse.com – that allow 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 3D design 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.

Digital Storage & Transportation

As well as enabling mass customization, democratizing market access, and opening up opportunities for open design, 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 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.

Many people now regularly share text, photos and video online, and thanks 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.

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 starting to replace 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.

Improving Human Health

Talking of health matters, 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 2015, 3D printed tissues are likely to start being 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 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 and its implications in chapter 6.

Increasing Sustainability

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 our 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. As I shall explore in chapter 7, the long-term killer advantage of 3D printing may therefore turn out to be its ability to enable local digital manufacturing (LDM).

As well as allowing us to produce things far closer to home, 3D printing will also improve sustainability by facilitating raw material savings. This is because 3D printing 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. As a consequence, when things are manufactured using 3D printers it is possible to obtain raw material savings of up to 90 per cent.

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 replacement components are simply not available. But with more and more 3D printers on hand, the opportunity will soon exist to fabricate whatever parts are needed to mend and keep operational a great many broken things.

CHALLENGES AHEAD?

Like any significant 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 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' 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, the logistics sector has 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 rise in the last-mile delivery of small packages. Specifically, the White Paper forecast that 3D printing could lead to its parcel delivery business seeing revenues increase by $486 million every year. This projection is based on the proposition that most 3D printed goods will be manufactured in commercial bureaus rather than people's homes – which is almost certainly the most realistic proposition.

Beyond the impact on employment, two other major challenges are intellectual property infringement and the use of 3D printing for criminal purposes. Already it is possible to use prosumer hardware to scan an object – for example a model of Mickey Mouse – and to 3D print one or one hundred plastic copies. 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 $500 personal 3D printer can only make a single-use plastic gun. But when it becomes possible to personally 3D print in metal, so we may have a significant problem on our hands.

A final and potentially massive minefield associated with 3D printing, and in particular with future personal fabrication, will be 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 may 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 then broke off, and this second child choked on it 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, as I shall explore in more depth in chapter 8, it is the kind of conundrum that we will very soon be unable to ignore.

IN THE WORDS OF PIONEERS

The 3D Printing Revolution is – like any other revolution – 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 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 – Head of 3D Printing Services at Industrial Plastic Fabrications – 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! Ten years ago, when I first started using Objet (3D printers), I had one material. Ten years on, 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.

Next I spoke with Jon Cobb in the United States, the Executive Vice President of Corporate Affairs for 3D printing giant Stratasys. 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.

Alongside Stratasys, the other corporate Goliath of the 3D printing industry is 3D Systems, also based in the United States. When I interviewed Andy Christensen, Vice President for Personalized Surgery and Medical Devices at 3D Systems, once again the broad ranging opportunities to use 3D printing to change workflows came to the fore. As Andy explained:

> 3D printing is advancing at an exponential rate, but we're no longer just talking about the printers. What makes this technology so revolutionary today is the ability to work across a digital thread: combining software, scanners, simulation, haptic devices and 3D printers into a seamless digital workflow. This enables never-before-possible control and precision in the most demanding applications; it is the driving force behind the groundbreaking work we're doing in personalized medical devices and virtual surgical planning, for example. When you combine these capabilities with the array of print materials now

available – ranging from biocompatible metals to edibles to ceramics – the possibilities with 3D printing are infinite.

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

> 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.

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.

Mark Fleming founded 3Dprinter.net, and focused on the disruptive potential. As he neatly summarized:

> 3D printing destroys the inefficient, 20th century manufacturing model and replaces it with a new paradigm that brings a reduction in design-to-manufacturing time, virtually eliminates storage and transportation costs, reduces resource consumption, allows us to make things that were not possible before, and democratizes the materialization of ideas so literally everyone can create. 3D printing will do to manufacturing what the Internet has done to communication.

Finally, Sylvain Preumont, founder and director of the iMakr 3D printer store and the MyMiniFactory.com 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 above quotations hopefully highlight the incredible revolutionary possibilities of 3D printing. The words of Anssi, Constantine, Gary, Jon, Andy, Miranda, David, Mark and Sylvain also I think convey 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, then 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.

Just as computers were once assumed to have no mass-market potential, so today many commentators believe that few people will ever want a 3D printer. Certainly 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 local manufacturing facilities. 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 have 3D printed for them.

As we head through 2015 and beyond, the speed and variety of the 3D Printing Revolution will continue to gather momentum. As it does so, there is also a distinct 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 the practicalities of every 3D printing technology.

— END OF SAMPLE CONTENT —

THE REST OF THE BOOK

The remaining contents of this book are as follows: