The Next Big Thing: From 3D Printing to Mining the Moon

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 CONTENTS
  Prologue: Beyond the Internet In 1995 I published a book called *Cyber Business* that predicted the birth of e-commerce and social media. Since that time I have frequently been quizzed about future online trends, and have introduced many individuals and organizations to key developments like cloud computing. Even so, when people now ask me about the world of tomorrow, I often begin by stating that the Internet Revolution has come to an end. The mainstreaming of the Internet in the closing years of the 20th century was undoubtedly a seminal moment in human history. Nevertheless, no period of revolution can go on indefinitely. Look back 375 million years, and our ancestors were dragging themselves out of the oceans and developing a technology called 'lungs' in what we could term the 'Breathing Air Revolution'. To this day, lungs remain critical to the survival of all mammals. And yet the Breathing Air Revolution has clearly long since ended. In a similar fashion, now that the Internet has become established as our collective, planetary nervous system, so the idea of the 'Internet Revolution' ought rapidly to be consigned to history. Granted, the online world will continue to incrementally evolve. But those seeking radical, future shaping innovation really need to divert their attention away from the cyber world to which we increasingly retreat. While our civilization is now reliant on the Internet, we are even more dependent on the sustainable production of physical things. We therefore need to shift our collective focus away from the digital world, and toward the innovation of radical new manufacturing methods and the attainment of fresh resource supplies. If only to ensure our civilization's long-term survival, it is now time for the human race – and the world's stock markets – to recover from Internet fever in preparation for the Next Big Thing.   The following chapters

extrapolate from bleeding-edge science and engineering to predict ten dominant technologies and related undertakings of the 2020s, 2030s, 2040s and beyond. In doing so, the four parts of this book additionally highlight four fundamental future transitions. These will take us on a journey from the reign of the microprocessor to that of the microfabricator; from a use of dumb computing devices to a cohabitation with smart synthetic citizens; from consuming less here on the Earth to finding more resources out in space; and from healthcare systems focused on medical maintenance to those which champion generational upgrades of the human form. While each of the ten Next Big Things that will underpin the above transitions could develop and be studied in isolation, it is my contention that they are all highly interrelated. Understanding these interrelations is also quite important. So, before we get to chapter 1 – and to provide some explanation of the last paragraph! – here is a brief overview of things to come. **LOCAL DIGITAL MANUFACTURING** The current model of industrial production works roughly like this. Somebody dreams up a new product, a factory thousands of miles 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. The products are then transported to a warehouse, from where they are gradually shipped to wholesalers and retailers for potential sale. In time, many products are sold, although about one-seventh of the resultant revenues are spent on transportation, warehousing and related logistics services. Unfortunately, some of the products that are manufactured are never actually bought by anybody, and need to be discarded. This highly wasteful, globalized, mass production arrangement works because there are enough relatively cheap natural resources still available for companies to be able to squander a great deal and still make a profit. But as resources become less plentiful and energy prices rise, so how most things are made will have to change. And this is when we will transition to local digital manufacturing. As detailed across Part I of this book, local digital manufacturing (LDM) uses digital technologies to make products on demand very close to where final consumers actually live. Using future LDM hardware, designs for both inorganic and organic products will be able to be stored and transported digitally, before being locally 'materialized' into a physical format one layer, cell or molecule at a time. Right now, as we shall explore in chapter 1, the most developed LDM technology is 3D printing. This builds objects in layers, and even today can fabricate items in plastics, metals, ceramics, foodstuffs and living cells. Already jewelry, car bodies, toys, aerospace components, medical devices, works of art and buildings have been 3D printed. Using an organic 3D printing variant called 'bioprinting', living human tissue has also already been manufactured one layer at a time. Of all the Next Big Things detailed in this book, 3D printing may well be the first to enter the mainstream. Though when it comes to local digital manufacturing, 3D printing will be just the tip of the iceberg. In addition to 3D printing, there is already another highly versatile technology that can turn digital designs into complex physical things in pretty much any location. This amazing technology is life itself, with the DNA of all plants and animals containing a robust digital code that can tell cells how to reproduce, rearrange and subsequently function. So what if we could turn living biology into a construction kit that could be digitally programmed as a production technology? Well, we have already started to do this with the creation of a new science called synthetic biology. As we shall see in chapter 2, synthetic biology allows living things to be created that have never existed in nature. Already synthetic biology is being applied to develop micro-organisms that can ferment organic feedstocks into biofuels, bioplastics, bioacrylics and pharmaceuticals. In time, synthetic biology even has the potential to create new plants and novel animals for specific manufacturing purposes. Consumables for 3D printers, for example, may one day be grown locally in desktop hydroponic devices or urban vertical farms. As well as relying on 3D printing and synthetic biology, LDM will be facilitated by next generation nanotechnologies. As we will investigate in chapter 4, so-termed 'atomically precise manufacturing' (APM) will permit objects to be fabricated on a molecular scale using a process called 'self-assembly'. Over the next two decades, we are also likely to witness the convergence of nanotechnology with 3D printing and synthetic biology. In turn, this will facilitate the construction of 'microfabricators' that will be able to fashion a very wide range of highly sophisticated products directly from digital designs. Even today there is an overlap between 3D printing, synthetic biology and nanotechnology, with scientists and engineers in each discipline increasingly sharing knowledge and techniques as they learn to digitally manipulate matter on a very small scale. For example, nanoscale 3D printing processes are starting to be developed that can allow material composition as well as material placement to be digitally controlled. Add in synthetic biology, and future microfabricators should be able to control the composition, placement and living behaviour of digitally manufactured things. As I said a few paragraphs back, 3D printing will be just the start of the local digital manufacturing revolution. **SYNTHETIC CITIZENS** A score or less years hence, we are very likely to be sharing our first planet with artificial entities more intelligent than ourselves. As we will discover in chapter 4, some of these will be disembodied artificial intelligences (AIs) that will help human beings with specific tasks at which machines tend to excel. Already so-termed 'narrow' forms of AI are able to pilot aeroplanes, drive automobiles, diagnose disease, manage power grids, track vehicle license plates, translate languages, and perform stock market trades. Many people are also starting to use 'virtual assistants' (VAs) like Microsoft's Cortana or Apple's Siri, with the trend to develop AI as a next-generation computing interface set to continue. Today, Cortana or Siri are novel add-ons bundled with an operating system. Yet in less than 10 years, Microsoft or Apple's primary product may well be a virtual assistant with an operating system and supportive hardware bundled on top. This means that, sometime in the 2020s, we may talk far more about VAs and far less about PCs. Indeed, if you are wondering why there is not a section of this book devoted to future computing, it is because I suspect that we will soon look back on the use of dumb computing devices as a rather quaint late-20th and early-21st century phenomenon. Exactly when and how 'artificial general intelligences' (AGIs) will be created is a point of significant contention. There are also many who believe that creating highly sophisticated AGIs is a dangerous undertaking that ought to be prevented, or at least very tightly controlled. Personally, I think that the development of AGIs is not just inevitable, but essential if we are to rollout widespread local digital manufacturing and in the process to deal with looming resource scarcity. Granted, current legal frameworks will need to be adapted to deal with very smart technology that can act autonomously and potentially do both very good and very bad things. We may even choose to give future AGIs some legal rights. Nevertheless, the real debate ahead will, I think, be far more about the role to be played in our society by non-human forms of intelligence, rather than whether or not they should be created. In practical terms, it is likely to be the mainstream rollout of autonomous vehicles in the 2020s, and humanoid robots in the 2030s and 2040s, that will bring the critical debates surrounding AI to the fore. Within 15 years, most people will either be travelling in driverless vehicles, or will be relying on the autonomous carriages occupied by others not to crash into their car or to run them over on the sidewalk. As we shall explore in chapter 5, in a few decades time it is also very likely that humanoid robots will be delivering healthcare, looking after the elderly, and transforming at least some traditional production methods. Our artificial world has been crafted for occupation and manipulation by the human form. It will therefore make sense to build mechanical beings in our own image, even if doing so may not be to everybody's taste. Robot ascendance is likely to be symbiotically associated with the rise of local digital manufacturing. On the one hand, robots will become a complimentary technology to 3D printing and synthetic biology, as they will be able to locally prepare and assemble product parts and raw materials that are fabricated on demand. The other way around, local digital manufacturing technologies will be critical in robot evolution, as they will become the dominant means of robot procreation. Even today, robot development is being driven forward not just by the availability of cheap computing power, but due to the existence of low-cost 3D printers that can rapidly and cost-effectively produce custom mechanical components. As synthetic biology and organic computing develop, it is also quite likely that parts for future robots will be able to be grown. Today, the popular vision of a humanoid robot is of a metal or plastic machine. But in three decades time, our mechanical servants and companions are just as likely to be constructed from living tissue, or else from materials produced via a synthetic organic process. Who knows, 20 or 30 years from now, you may have a warm bucket in a kitchen cupboard in which you are growing a new arm for your favourite android companion. **RESOURCES FROM SPACE** Today, a great deal of attention is starting to be focused on conducting our lives and operating our businesses in a ‘sustainable’ fashion. Usually this involves attempts to use fewer resources and to reduce our carbon footprint. Most of the time, such initiatives are a great idea. They will also be boosted by innovations in local digital manufacturing that will enable people to produce things using less energy and fewer raw materials. The above points noted, all current and future attempts to become ‘sustainable’ can at best constitute a short-term solution to the resource requirements of future generations. Like it or not, it is a physical certainty that the raw materials and energy sources available on the Earth are finite. This means that, in the long-term, the survival of our civilization has to depend on obtaining fresh energy and raw material supplies from beyond our first planet. At least some of the AIs and robots referred to in the previous section will therefore spend their lives obtaining resources from space.   Across Part III of this book we will investigate a wide range of possibilities for extraterrestrial power generation and off-world mining. Staying closest to the Earth, chapter 6 will first detail how ‘space-based solar power’ (SBSP) could be developed. Future SBSP systems would place solar power satellites in geosynchronous orbit. These would then beam energy to ‘rectennas’ on the Earth using microwaves or lasers. NASA began feasibility studies into SBSP in the 1970s. More recently, in April 2014 the Japan Aerospace Exploration Agency (JAXA) revealed a roadmap for a SBSP system to provide energy to Tokyo in the 2030s. The creation of such a system will require significant improvements in all aspects of space technology, as well as the potential development of entirely new means for getting into orbit. In addition to providing an overview of SBSP possibilities, chapter 6 will therefore examine the feasibility of future ‘space elevators’ that may help off-world energy production to become a reality. While building solar power satellites may help to meet some of our future energy needs, it will not assist with the supply of physical resources. In chapter 7, we will therefore consider the possibility of mining the asteroids – a proposition already being taken very seriously by two foresighted companies called Planetary Resources and Deep Space Industries. I would already place a fairly safe bet that many of today’s young people will one day own a consumer product manufactured at least in part from asteroid deposits.   In addition to SBSP and asteroid mining, we are at some point also likely to return to the Moon in search of new energy and raw material supplies. A potentially very valuable future nuclear fuel called helium-3 is relatively abundant in the lunar regolith, while our lonely satellite is also thought to harbour substantial deposits of cobalt, iron, gold, palladium, platinum, titanium, tungsten and uranium. Since 2009, NASA experiments have also confirmed the presence of water on the Moon. This could prove critical in supporting long-term human occupation, as well as providing a source of oxygen and hydrogen for rocket fuel. Chapter 8 will examine a range of options for lunar resource utilization, including the potential development of lunar space elevators and large-scale, Moon-based 3D printers. **TRANSHUMAN EVOLUTION** By the second half of this century, a growing proportion of the world’s population will be a mashup of legacy biology and artificial digital technologies. Such ‘transhumans’ will have had their bodies or brains augmented using technologies including bioprinting, synthetic biology, nanotechnology, cybernetics and genetic medicine. The latter is the subject of chapter 9, where we will examine how – in a new age of post-genomic healthcare – doctors and AI systems are set to become programmers of human DNA. The 21st century is likely to be remembered as the historical period in which humanity took conscious control of its own evolution, and when the line between ‘natural’ creation and ‘artificial’ technology became irrevocably blurred.   As we shall explore in chapter 10, a cybernetic synthesis of human beings and machines is an almost inevitable consequence of the development of local digital manufacturing, the creation of robots and AI, and the pursuit of resources from space. Why? Well, for a start, as we learn to digitally manufacture products one layer, cell or molecule at a time, so we will also hone the skills necessary to take digital control of human biology. Since November 2014, bioprinting pioneer Organovo has been 3D printing human liver tissue as a commercial product (if currently for drug testing purposes), while the line between synthetic biology and genetic medicine is already tantalizingly thin. In the short-term, legal and ethical constraints on the manipulation and adaptation of the human body may limit the extent to which future scientists and engineers will be able to ‘play god’. But given that local digital manufacturing will empower individuals as well as corporations to inorganically and organically fabricate anytime, anyplace and anywhere, it seems inconceivable that its technologies will not be widely applied both in healthcare and to facilitate future human augmentation. Some people may question why, later this century, anybody would want to merge with artificial technology. In part the answer is simply that the pursuit of excellence remains a common individual goal and the driving force of our evolution. More pragmatically, as AIs and humanoid robots become both more intelligent and more physically dexterous than human beings, so it is very probable that at least some people will want to 'keep up with the machines'.   Bioprinted or synthetically grown components for future humanoid robots may well be biocompatible with a genetically re-engineered human anatomy. So when somebody sees a robot strolling down the road with a cool pair of legs, they could favourite the design and have it downloaded and replicated for themselves. Some people in the future may even swap body parts as regularly as we currently change hairstyles or clothes. It may even become common to exchange limbs, eyes, memory circuits and information processing hardware with robotic co-workers or friends. The above factors noted, the biggest driver of the most extreme form of cyborg synthesis is going to be our requirement to obtain resources from space. To achieve this goal, our civilization will need to send highly adaptable and intelligent beings far from the Earth, and not all of these will be able to be entirely robotic. Unfortunately, the current human form is about as well equipped to live in space as a fish is suited to reside on dry land. Yes, humans can protect themselves in space suits and pressurized capsules, and can shelter behind radiation shielding when required. We can also take food, water and oxygen with us from the Earth – or learn to obtain such critical life support supplies off-world. Although, when it comes to large-scale space endeavours, it is going to prove far safer and far more cost effective for future space pioneers to be transhumans with bodies designed for long-term deep-space survival. By the end of this century, we are therefore likely to witness the emergence of a new cybernetic superspecies who will not be reliant on oxygen, water and food, and who will be far less easily damaged by extraterrestrial radiation than their traditional human forebears.   **TOWARD THE SINGULARITY** In 1961, science fiction author and futurist Arthur C. Clarke wrote that 'any sufficiently advanced technology is indistinguishable from magic'. Certainly, a great many of the technologies that we currently take for granted would have seemed magical only a century ago. Yet many of the innovations on the medium- and long-term horizon are destined to be even more astonishing. Microfabricators, synthetic citizens, resources from space, and our transhuman evolution, may therefore be perceived as impossible fantasies by the majority of the world's population. Hopefully, as a reader of this book, you are distinct from the majority and more open than most people to accept the incredible developments and opportunities that lie ahead. As I have detailed in this *Prologue*, four fundamental transitions now loom on the horizon, and will soon drive radical changes in how things are made, who we share the planet with, where resources come from, and the evolution of the human race. Each of these transitions is going to be an extraordinary adventure. I am therefore pleased that, by choosing to read *The Next Big Thing*, you have decided to proactively step on board to anticipate the ride. In aggregate, all of the technologies and undertakings explored in this book will lead us toward a moment in history called the 'Singularity'. This is a technological event horizon beyond which we cannot see, and that we will reach when exponential progress makes possible anything we can imagine. Looked at from one perspective, we will arrive at the Singularity when the divide between 'technology' and 'magic' blurs. Or to reduce things to a more practical level, the Singularity will be upon us when we are able to digitally program, replicate, repair and otherwise control all forms of living or inorganic matter. At the Singularity and beyond, we will also no longer face any resource constraints, as we will have learned how to turn waste products into fresh raw materials, or to access the very broad range of resources waiting for us beyond Planet Earth.   Journeying toward the Singularity is likely to require the application of mental and physical capabilities far beyond those of the current human form. The creation of artificial intelligences and very sophisticated robots will therefore be essential if we are to arrive in a new age of enlightenment and plenty. Also very likely to be required will be some transhuman upgrading of *Homo sapiens*. However magical it may sound, the Singularity is a point in future history that many of today's young people will one day experience, and which could turn out to be the greatest ever Next Big Thing. We live in extraordinary times that are going to get increasingly unbelievable. So, without further introduction, it is now time for us to explore the incredible possibilities that lie ahead . . .

PART I: LOCAL DIGITAL MANUFACTURING

1. 3D Printing

The human race has become a rather wasteful species. Billions of slightly-broken products are discarded every year, while poor market forecasts and overproduction result in manufactured items that never get sold. Most products also travel thousands of miles to reach their final customer. In fact, about one seventh of the energy reserves and raw materials consumed by humanity are devoted to transporting things around the planet. Economists may preach that this is a fantastic way to sustain an increasingly global economy. Yet, in reality, it is an intensely foolish and potentially suicidal state of affairs. To help our civilization to survive and thrive, it would be far better to locally manufacture the majority of products on-demand, and to repair rather than discard those that fail. It is therefore fortunate that a wide range of innovations in local digital manufacturing (LDM) that will allow this to happen are already being honed. As we shall see in chapter 2 and chapter 3, critical LDM technologies include synthetic biology and next generation nanotechnology. But before these enter mainstream application, the dominant form of LDM will be 3D printing. 3D printing is the popular term for 'additive manufacturing', and refers to all technologies that turn digital models into physical objects by building them up in layers. In effect, 3D printing does exactly what it says on the tin. Just as traditional 2D printers create documents or photographs by outputting one or a few layers of ink, so 3D printers create real, solid, fully-dimensional stuff by outputting hundreds or thousands of layers of a build material. As we shall see in this chapter, 3D printing has already been used to fabricate a wide range of things that include product prototypes, prosthetics, rocket engine components, and a five storey apartment block. The 3D printing industry is also growing rapidly, with Deloitte estimating the sale of 220,000 3D printers in 2015, and Gartner predicting 496,000 units to be sold in 2016. According to a June 2015 report published by Smithers Pira, the 3D printing marketplace will be worth $49.1 billion by 2025.

In the future, 3D printing has the potential to do for physical objects – or 'physibles' – what the Internet has already done for the digital creation, storage, manipulation and communication of information. What this means is that 3D printing could allow products to be designed, manipulated, stored and transported in a digital format, before being 'materialized' on demand anytime, anyplace and anywhere. The potential implications for global manufacturing, the logistics industry and personal fabrication are subsequently breathtaking.

3D printing has, in fact, already been hailed as the technology that will destroy capitalism by putting the means of production into the hands of the majority. This, I am certain, is too extreme a view. Nevertheless, with 3D printing rapidly evolving from a prototyping process into a mainstream production technology, it is easy to see why many believe that 3D printing will be the Next Big Thing.

MATERIAL EXTRUSION

Contrary to popular belief, 3D printing is not a single technology. Rather, there are already a wide range of methods for turning a digital design into a physical object by building it up in layers. In an attempt to introduce some clarity into a quite confusing marketplace, in June 2012 the American Society for Testing and Materials (ASTM) categorized all 3D printing technologies under seven generic headings. These are outlined in figure 1.1, and provide a useful taxonomy for understanding current and potential future 3D printing methods.

Right now, the most common form of 3D printing is material extrusion. This was invented by Scott Crump in 1998 following a successful attempt to build a plastic frog for his daughter using a hot glue gun. Crump subsequently founded 3D printing giant Stratasys, and patented his material extrusion process under the name 'fused deposition modelling' (FDM). In a typical material extrusion 3D printer, a thermoplastic build material known as 'filament' is fed to a print head where it is heated into a molten state and extruded onto a 'build platform' to form an object layer. The build platform then lowers a fraction, another layer of thermoplastic is extruded, and so on. 3D printers that extrude thermoplastics come in a wide variety of sizes, prices and configurations. At the time of writing, the cheapest desktop models start at about $300, with prices likely to fall to $99 well before 2020. At the other end of the spectrum, industrial '3D production systems' cost up to $900,000. Figure 1.2 illustrates two popular desktop 3D printers from Ultimaker and Printrbot, while figure 1.3 shows four Stratasys 3D production systems in a factory environment.

Although the cheapest material extrusion 3D printers can currently only build objects in a single thermoplastic, printers with dual or triple extruders that can output multiple colours of the same thermoplastic are becoming quite common. 3D printers with 'mixer extruders' that can combine several different filaments in their print head – so permitting full-colour plastic printout – have also been demonstrated. It is therefore not unreasonable to assume that, in five or ten years time, full-colour material extrusion 3D printing will be a mainstream technology. The most common build materials used for material extrusion are the petroleum-based thermoplastics acrylonitrile butadiene styrene (ABS), nylon and polycarbonate (PC), as well as a bioplastic called polylactic acid (PLA). 'Thermoplastic elastomers' are now also available that permit the material extrusion of rubber-like, flexible parts. In the past few years, a range of composite 3D printing filaments have additionally arrived on the market. These include thermoplastics mixed with wood, carbon fiber, brick, or various metals. For example, a thermoplastic composite called copperFill was launched by a filament manufacturer called Colorfabb in 2014. This contains a fine copper powder, and allows consumer 3D printers to make metal-like objects that can be polished to a shine. Pioneer Graphene 3D Lab is even working on nanocomposite filaments that combine a thermoplastic with carbon nanotubes or graphene, and which it hopes will soon allow the 3D printout of working electronic devices. As all of these developments illustrate, by the 2020s it is highly probable that the $99 hardware I predicted a few paragraphs back will be able to print in a wide range of materials. Indicating even broader future possibilities, several companies are developing material extrusion 3D printers that output thermoplastics reinforced with another material during printout. Most notably, MarkForged in the United States now market a 3D printer that combines a thermoplastic with a continuous strand of carbon fiber, fiberglass or Kevlar. This allows plastic objects to be 3D printed that are stronger than some metals. In addition to thermoplastics, or composites thereof, it is already possible to 3D print by extruding metals, concrete, clay or food. When it comes to extruding metals, some of the leading work is being done at the University of Cranfield for aircraft manufacturer BAE Systems. Here a 3D printing method called 'wire and arc additive manufacturing' (WAAM) has been created that melts a titanium strand fed to a computer-controlled arm. Already WAAM technology has been used to create a 1.2 metre spar section of an aircraft wing. Eventually it is hoped that entire aircraft frames will be 3D printed. Also 3D printing in metal using a material extrusion process 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 metal 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 titanium alloys and tantalum. Since 2004, Professor Behrokh Khoshnevis at the University of Southern California has been working to develop 3D printers capable of extruding concrete. This he labels 'contour crafting', which he in turn describes as a 'mega scale layered fabrication process' for use on building sites. Similarly working to 3D print human dwellings are the World's Advanced Savings Project (WASP), who are based in Italy. Their experimental 'Big Delta' 3D printer extrudes clay or soil mixed with resin, with the intention being to develop the technology to rapidly 3D print houses or modular building sections following natural disasters. On a less grand scale, several pioneers have managed to 3D print many different kinds of food, including chocolate, ice-cream, candy and cake frosting. My favourite team is a Spanish research group called Robots in Gastronomy, who have developed a 3D printer called FoodForm. This can extrude food onto any surface, including a hot grill or a chilled anti-griddle. Using the FoodForm, Robots in Gastronomy have already managed to 3D print by extruding bread and cookie doughs, chocolate creams, cheese, ice cream, cheesecake and various frostings. **SOLIDIFYING LIQUIDS** Alongside material extrusion, two other common 3D printing technologies are vat photopolymerization and material jetting. These are currently more accurate than material extrusion, offer fantastic surface quality, and use liquid build materials. Vat photopolymerization was invented by Charles 'Chuck' Hull in 1983, and uses a laser beam to trace out object layers on the surface or base of a vat of liquid photopolymer resin. Where it is contacted by the laser, the photopolymer cures from liquid to solid. When each layer is complete, the 3D printer's build platform then moves a fraction, so allowing the next layer to be traced out and set solid. Chuck called this 3D printing process 'stereolithography', and his 3D printer a 'StereoLithographic Apparatus' (SLA). In 1986 he also obtained patent protection for his revolutionary innovations, and started a company called 3D Systems. Three decades on, 3D Systems is still going strong, and alongside Stratasys is well established as one of the two giants of the 3D printing industry. Material jetting 3D printers spray liquid photopolymer layers from an inkjet-style, multi-nozzle print head. Each layer is then set solid with UV light before the next layer is added. Material jetting hardware has been developed by many companies including Stratasys (who term it 'PolyJet') and 3D Systems (who call it 'MultiJet Printing'). As illustrated in figure 1.4, the Objet Connex hardware from Stratasys is particularly impressive, as it can 3D print multi-material, multi-colour objects by supplying different photopolymers to the print head which are then combined as required. **ADHERING POWDERS** Our next three 3D printing technologies – binder jetting, powder bed fusion and directed energy deposition – all turn a digital file into a solid object by sticking together granules of a fine powder. In binder jetting hardware, successive layers of powder are rolled or otherwise swept across the build area. A multi-nozzle print head then sprays on a binder solution to stick the required powder granules together. In some binder jetting printers, the print head also deposits coloured inks, so allowing full-colour objects to be created. For many years binder jetting was almost entirely limited to making objects in a gypsum-based powder. This then had to be infiltrated with resin after printout if a robust object was required. However, in late 2013, 3D Systems launched a printer – the ProJet 4500 – that can 3D print full-colour, semi-rigid plastic parts that require no post-processing after their removal from the print bed. German 3D printer manufacturer voxeljet additionally now manufacture binder jetting 3D printers than can build objects from a modified acrylic glass powder, or from sand to produce casting molds. Some of the binder jetting printers manufactured by voxeljet are also very large indeed. Most notably, their VX4000 can 3D print objects as large as 4 x 2 x 1 metres in size. A few binder jetting 3D printers, such as those manufactured by a company called ExOne, can create objects out of powdered metals, including bronze and the nickel-based alloy Inconel 625. After metal parts are 3D printed using ExOne's technology, they need to be cured in an oven, and placed in a kiln for 24 hours to be infused with more metal. The result is a 3D printed object that is about 99.9 per cent solid. To 3D print really high quality metal parts, an alternative technology called powder bed fusion has to be used. This is similar to binder jetting, save that here the layers of powder are selectively fused solid using a controlled heat source. Most commonly this is a laser, with the involved process termed laser sintering or laser melting. Another variant of powder bed fusion is electron beam melting (EBM), which uses an electron beam to fuse metal powder granules in a vacuum. In addition to allowing the 3D printout of metal objects, powder bed fusion is commonly used to produce high quality parts in plastics (such as nylon), or plastic-metal composites. Powder bed fusion can, for example, 3D print using a material called alumide, which is a mix of nylon and aluminium powders. A final, powder-based 3D printing technology is directed energy deposition (DED), also known as 'laser powder forming' or 'laser engineered net shaping' (LENS). Here, a metal powder is supplied to a print head that moves in 3D space, and which jets the powder into a high-power laser beam. Because the metal powder is not laid flat for selective fusion, directed energy deposition can either create new objects, or fuse new metal onto existing parts. Most notably, the technology is already being used to repair worn or otherwise damaged jet engine turbine blades. Directed energy deposition can fabricate objects in new alloys by feeding a range of different metal powders to the print head. The powders can even be mixed in continuously variable ratios during printout. This presents the potential to 3D print components in novel metal alloys, and indeed out of alloys that have different properties in different parts of an object. **BINDING SHEETS** The last, current 3D printing technology is sheet lamination. This builds objects by sticking together layers of cut paper, plastic or metal foil. Where objects are built out of cut paper – as happens in the Iris 3D printer made by MCor in Ireland – coloured inks can be sprayed on to create stunning, full-colour output. Other variants of sheet lamination include the 'ultrasonic additive manufacturing' (UAM) process created by Fabrisonic. This uses high frequency sound waves to fuse layers of metal tape in order to produce robust metal parts. Fabrisonic's technology has the advantage of being able to fuse different metals into the same part, once again allowing the creation of items – such as metal objects with embedded sensors – that could not be created by traditional manufacturing techniques. **DIRECT DIGITAL MANUFACTURING** As we have seen, there are already a large number of 3D printing technologies that can manufacture items using an ever-broadening range of materials. It is therefore already possible to 3D print complex objects made from multiple materials, even if today this requires different components to be output on different printers based on different technologies. But in the future? Well, as local digital manufacturing takes hold, so there is a high probability that we will develop local 'microfactories' or 'distributed manufacturing facilities' (DMFs) that will combine multiple 3D printing technologies to allow small-scale custom manufacture in almost any location. The creation of multi-technology microfactories probably lies many years and even decades into the future. It is therefore worth considering what kinds of things are most likely to be 3D printed in the shorter-term using existing, single technologies. Today, most things that are 3D printed are product prototypes. But as early as 2020, the majority of industry insiders expect that this will no longer be the case. As 3D printing matures into a mainstream manufacturing method, its primary area of application will be the fabrication of production tooling. Most traditional production processes rely on dedicated tools, jigs and fixtures to make and assemble product parts, and some of these are starting to be 3D printed. This may not sound that exciting, but nevertheless offers an enormous potential to cut costs, to improve quality, and to allow a greater variety of products to be created. Volvo Trucks in Lyon, France have recently reduced the time to manufacture some production tools from 26 days to just 2 days by 3D printing them. Meanwhile, case studies published by ExOne – who make 3D printers that manufacture sand molds for use in traditional metal casting – have revealed that mold production lead times can be reduced from months or weeks to days or even hours. The 3D printout of sand cast molds can also reap cost savings as high as 85 per cent. While the 3D printing of prototypes and tooling can deliver significant cost and other advantages, sometime in the 2020s a tipping-point will be reached and the majority of 3D printed items will be final products. Using 3D printers to make such finished consumer or industrial goods is known as 'direct digital manufacturing' (DDM), which the Society of Manufacturing Engineers define as 'the process of going directly from an electronic digital representation of a part to the final product'. Although DDM is still in its infancy, in certain circumstances it already offers a wide range of advantages over traditional production methods. The first of these is the ability to reduce the cost of low-run production, and indeed to make possible the manufacture of components that would be prohibitively expensive to create using traditional machining or casting techniques. Stratasys, for example, have reported that 3D printing is already cheaper than injection molding for production runs of less than 5,000 plastic parts. This is because the cost of tooling a mold is saved. **MATERIAL SAVINGS** Another major benefit of 3D printing is the manufacture of products using fewer raw materials. In part this can be achieved because 3D printing is an additive process. This means that 3D printing starts with nothing and adds only the material that is required. This makes 3D printing more resource efficient than subtractive manufacturing processes – such as machining – which start with a lump of material and shave parts of it away. In addition to reducing the amount of material that ends up on the factory floor, 3D printers can fabricate parts with highly material-efficient geometries that would be impossible to fashion using traditional methods. When molten plastic or metal is injected or poured into a mold, the resultant component inevitably comes out solid. But when things are 3D printed, the insides of components can be made hollow or semi-solid by controlling the level of 'infill' required. All of this means that 3D printing will allow people in the future to make products that are similar to those we have today, but which consume fewer natural resources. Particularly keen to produce parts that use less material – and which are hence lighter – are the aerospace sector. It is therefore hardly surprising that aerospace companies are at the forefront of DDM. Indeed, the Airbus A350 XWB passenger aircraft already has some brackets that are 3D printed in titanium using powder bed fusion. This has allowed the bracket design to be optimized to a shape that meets structural requirements, but which uses 30 per cent less metal than a traditional milled or cast part. The quantity of metal wasted in the manufacturing process is also reduced from over 95 per cent to around 5 per cent. This improvement in the material 'buy-to-fly' ratio, coupled with the fact that tooling is no longer required, results in cost and time savings of up to 75 per cent.

Also saving time, cost and materials are Winsun Technologies in Shanghai, China. Here buildings are being fabricated using a material extrusion 3D printer that is 6.6 metres high, 10 metres wide and 150 metres long. Winsun's hardware is fed a special 'ink' comprised of cement, glass fiber and construction waste, and accrues material savings partly due to its additive process, and partly because 3D printed walls do not have to be entirely solid to meet structural requirements. In fact, by including air gaps within walls, their insulation properties can actually be improved. Winsun estimates that by 3D printing buildings, it can achieve material savings of between 30 and 60 per cent. The company also estimates that production times can be cut by as much as 70 per cent, with labour costs reduced by up to 80 per cent. Unlike many other 3D printing pioneers, Winsun has already made good on its amazing claims. For a start, in March 2014, the company 3D printed ten houses in one day. These rudimentary but functional dwellings had a floor area of 200 square metres, and cost about $5,000. Were this not impressive enough, in January 2015 Winsun showcased a five storey 3D printed apartment block, together with a 1,100 square metre 3D printed mansion. Also in January 2015, Winsun revealed that it had orders for 10 3D printed mansions, as well as 20,000 houses to be 3D printed for the Egyptian government. Winsun additionally announced plans to establish factories in at least 20 countries, including the United States, Saudi Arabia, the UAE, Qatar, Morocco and Tunisia. The company's aim is to provide cheap and efficient homes for low-income families, and I would place a fair bet that it is going to succeed. If, in 20 years time, you are living in a newly constructed building, there has to be a reasonable possibility that it will have been 3D printed. **MASS CUSTOMIZATION** While most factories need to keep costs down by specializing in mass production, a 3D printer need never make the same item more than once. As a consequence, 3D printing is likely to lead to a new age of mass customization, with more and more products personalized to individual requirement. One of the first pioneers of 3D printed mass customized products was Nervous System, based in Somerville, Massachusetts. Via the company's website at n-e-r-v-o-u-s.com, visitors can 'generate their own 3D printed jewelry' by moving sliders, dragging morph targets, and otherwise sculpting the geometry of a rotatable 3D model. When the personalized design is complete, the user can choose to have it 3D printed in plastic in a range of colours, or cast in a choice of metals from a 3D printed wax pattern. In addition to web-crafted jewelry, custom 3D printed figurines are now starting to become popular. Several companies – including Twinkind, iMakr, Shapify and the UK supermarket Asda – now offer a service where they scan a person and make a miniature copy using a colour binder jetting 3D printer. Alternatively, over at MyMakie.com, visitors can design their own 3D printed doll, with interactive, onscreen control of everything from clothing and hairstyle, down to mouth shape, ear shape and even nostril flare. The resultant 'Makie' is 3D printed in nylon using powder bed fusion. 3D printing is now also starting to be used in the manufacture of personalized medical appliances. Today, the best things to 3D print are small, customized and expensive, which makes medicine a prime sector for 3D printing application. It is therefore hardly surprising that a 2014 Morgan Stanley Blue Paper found that nearly 40 per cent of new 3D printing patent applications are already in the medical sector. The range of end-use medical products that have been 3D printed is growing rapidly, and includes dental appliances, hearing aid shells, hip implants and artificial limbs. For example, in 2012 a replacement human jaw bone was 3D printed in titanium for an elderly lady whose own jaw had been damaged by a bone infection. Meanwhile, a Japanese company called Fasotec have developed a material jetting 3D printing process called 'bio-texture modelling'. This allows models of internal organs to be derived from scan data, as illustrated by the liver model shown in figure 1.5. Such custom models are 3D printed from materials that feel organic to the touch, and allow surgeons to plan complex operations before cutting flesh. Right now, dentistry is at the forefront of medical 3D printing, and by 2025 it is probable that the majority of dental appliances will be fabricated in a few minutes using some form of photopolymerization. In the second half of the next decade, 3D printed replacement hip and other joints are also likely to become common. By the mid 2030s, it is therefore perfectly possible that a billion or more people will have plastic or metal 3D printed prosthesis inside their bodies. **LOCALIZATION & PRODUCT REPAIR** As I indicated at the start of this chapter, the most significant advantage of 3D printing will be the possibility to manufacture products on a local

basis. People sometimes tell me that this is a crazy idea, as nobody will be able to make their own furniture on a desktop 3D printer. While this may well be the case, hardware for the local printout of large items is starting to be developed. For example, BigRep in Germany now sell a material extrusion 3D printer called the BigRep ONE. This has a build volume of one cubic metre, and can therefore print a small table or a chair in one piece. The idea of future furniture stores locally 3D printing at least some of their wares is subsequently perfectly plausible. In fact, if a store really wanted to, it could start selling locally 3D printed plastic furniture right now. Further expanding the build envelope, Cincinnati Incorporated in Ohio have created the Big Area Additive Manufacturing machine (BAAM). This is a material extrusion 3D printer that makes very large items out of a variety of build materials which include ABS plastic reinforced with carbon fiber. The BAAM already comes in two sizes, the largest of which can 3D print objects up to 240 x 93 x 72 inches (6.1 x 2.36 x 1.8 metres) in size. In September 2014, the BAAM was used by Local Motors to 3D print a one-part chassis, frame and body for an electric vehicle called the Strati. In January 2015, the Oak Ridge National Laboratory (ORNL) next employed the BAAM to 3D print the body of a reproduction Shelby Cobra sports car. The printout of these large sections of both vehicles indicates the potential for the future local production of very complex products. Indeed, as Local Motors explains on its website:
Gone are the days of mega- or even giga-factories that consume tremendous amounts of time and energy to fabricate products. A more sustainable, nimble and flexible factory is on the horizon. Called microfactories, these diminutive factories drastically change how we produce large consumer goods for unique local needs. Local Motors plan to open 100 microfactories worldwide by 2025, and already have four in operation. Although these are not currently equipped with BAAM 3D printers (instead vehicles are produced via conventional means), in time it is hoped that 3D printed vehicles like the Strati will be locally produced. While the first Strati took 44 hours to print, Local Motors intends to get this down to 24 hours. It is also already taking orders for the first Stratis to go on general sale. In addition to allowing products large and small to be manufactured on demand, 3D printing will help to save resources by facilitating increased product repair. For example, if a Strati driver happens to crash their beloved vehicle, they should be able to return it to a microfactory where replacement parts will be replicated and fitted. Today, many items cannot be repaired because spares are unavailable. But in the future, spares for almost any product should be able to be 3D printed from a downloaded object file or a 3D scan. Airbus is in fact already installing 3D printed spare parts in older aircraft when original replacements are no longer available. Some future products may even come with a portable storage device that contains a complete, digital inventory of replacement parts. **PERSONAL MANUFACTURING** Eagerly awaiting the above kinds of development are a growing number of techno-savvy individuals collectively known as the ‘Maker Movement’. A ‘maker’ is simply the latest term for somebody who wants to make or mend their own stuff, and who in such pursuit becomes skilled in the ways of DIY or ‘DIWO’ (do-it-with-others). Supporting the latter are a growing number of local community ‘Fab Labs’ and ‘hackerspaces’. These allow people to learn construction and repair skills from each other, and to share specialist hardware like 3D printers. Today there are nearly 900 Fab Labs and hackerspaces worldwide, and it is not hard to imagine how they will evolve into the first generation of local microfactories. Already personal 3D printers can allow some things to be personally fabricated in people’s own homes. However, I suspect that for a few decades at least, most 3D printed products will be produced in microfactories – or in more conventionally-scaled production facilities – that will be run by single manufacturers, single retailers, local manufacturer or retailer conglomerates, or local community groups. Options for home-based digital manufacturing are likely to remain limited for some time to come. This is because most products will only be able to be 3D printed on hardware that will remain bulky and very expensive until at least the mid-2020s. 3D printers capable of outputting objects in multiple materials, including metals, are also set to remain too complex for the majority of people to operate and maintain in their own homes until at least the 2030s. Granted, by the early 2020s, a large minority of households are likely to own some kind of domestic 3D printer. But these relatively small, cheap fabricators will have limited production capabilities. School projects, plant pots, buttons, shoes,

toys and haberdashery will early next decade be liberally springing from domestic 3D printers. However, when you want a new car or washing machine, you will have to go to a microfactory run by Local Motors, Local Domestic Appliances, or a local community group. **BIOPRINTING** So far in this chapter I have focused on 3D printing technologies and applications that turn digital designs into solid but inorganic reality. There is, however, already an entirely distinct variant of 3D printing that builds objects from living cells. This quite wondrous innovation is known as 'bioprinting', and has the potential to transform not just medicine, but all future forms of local digital manufacture. One of the first bioprinting pioneers was a Japanese paediatrician called Makoto Nakamura. Back in 2002, the good doctor realised that the droplets of ink jetted out by a standard 2D photo printer were about the same size as human cells. He subsequently began experiments to modify a standard Epson photoprinter to allow it to print human tissue. This he eventually 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. Continuing his work, between April 2005 and March 2008 Nakamura led a project at the Kanagawa Science and Technology Academy that scratch-built an experimental bioprinter. This was capable of creating 'biotubing' from layers of two different types of cells. In the future, such biotubing could be used by surgeons as a living replacement for human blood vessels. Another bioprinting pioneer is Gabor Forgacs from the University of Missouri. In 1996, Forgacs recognised that cells stick together during embryonic development in a manner that could greatly assist in artificial tissue fabrication. By 2004, Forgacs had used this insight to develop a bioprinting technology that fabricates tissues not from individually jetted cells, but by building up layers of 'bio-ink spheroids' that each contain tens of thousands of cells. The cells in question are cultured in the lab from samples obtained via human biopsies. In 2007, Forgacs founded a company called Organovo, and by 2008 had developed a prototype bioprinter. As shown in figure 1.6, this injects 'bio-ink spheroids' into layer-upon-layer of a water-based 'bio-paper' support structure. Nature then takes control of the fabrication process, and over many tens of hours the cells contained in the bio-ink spheroids slowly fuse together. With the bio-paper support dissolved or otherwise removed, what eventually results is integrated, living tissue. The really amazing aspect of this kind of bioprinting is that, during the 'maturation phase', the cells contained in the bio-ink spheroids not only fuse into solid tissue, but also rearrange. For example, a blood vessel may be bioprinted from bio-ink spheroids that contain an aggregate of primary endothelial cells, smooth muscle cells and fibroblasts. After printout, these different cell types will have been randomly positioned by the bioprinter. But during maturation, the primary endothelial cells migrate to form the inner lining of the bioprinted blood vessel, while the smooth muscle cells travel to the middle, and the fibroblasts move into place to constitute the blood vessel's outer tissue. Because it outputs bio-ink tissue spheroids, Organovo's technology can be much faster than a bioprinting technique that jets individual cells. Moreover, as the cells reposition themselves after printout, it is not necessary to bioprint every last detail of the organ or tissue under construction. Rather, natural organic processes can be left to form complex, intricate structures such as the capillary networks within bioprinted kidneys. Print something in a traditional plastic or metal, and what you get is exactly what you print. But when an object is bioprinted, the fabrication process can continue after the print head has finished its activities. In 2009, Organovo developed the Novogen MMX as the world's first commercial bioprinter. In December 2010, this was subsequently used to create the first bioprinted human blood vessels, and since that time has also managed to fabricate small samples of human skeletal muscle, bone and liver tissue. In fact, in November 2014, Organovo actually started selling a bioprinted human liver product called exVive3D. This was the world's first commercial bioprinted tissue, and is fabricated for use in drug testing. As Organovo further explain:

Organovo's exVive3D Liver Models are bioprinted, living 3D human liver tissues consisting of primary human hepatocytes, stellate, and endothelial cell types, which are found in native human liver. The exVive3D Liver Models are created using Organovo's proprietary 3D bioprinting technology that builds functional living tissues containing precise and reproducible architecture. The tissues are functional and stable for at least 42 days, which enables assessment of drug effects over study durations . . . well beyond those offered by industry-standard 2D liver cell culture systems. While no company or research team has yet managed to 3D print tissues or organs for human transplantation, it is only a matter of time before this occurs. The timescale is hard to predict, but bioprinted arterial and nerve grafts, heart valves, and substitutes for 'simple' organs like kidneys, are probably a realistic possibility in the late 2020s or early 2030s. Beyond that, and as I conceptualize in figure 1.7, by the 2040s we could see bioprinters capable of fabricating complex organs like the human heart. Bioprinting large organs will not be easy, and not least due to the problems inherent in keeping sizable bioprintouts alive during fabrication. Just one researcher working on this 'thick tissue problem' is Ibrahim Ozbolat at the Biomanufacturing Laboratory in the University of Iowa. As he explained to me back in 2013:

The Next Big Thing explores future revolutions that will determine how things are made, who we share the planet with, where resources come from, and the evolution of the human species. Beyond 2030, the way we live today will no longer be sustainable. We will therefore need to develop technologies including 3D printing, synthetic biology and space travel if our civilization is to survive and thrive.

Part I reveals how *local digital manufacturing* will allow on-demand production in any location. Part II then looks at those *robots and artificial intelligences* that are destined to become our future carers, servants and companions. Part III next examines how *resources from space* will one day deliver fresh energy and raw material supplies. Finally, Part IV predicts the *transhuman evolution* that will be triggered as we learn to genetically reprogram and cybernetically upgrade our own biological hardware.

The Next Big Thing is written by futurist Christopher Barnatt of ExplainingTheFuture.com. The book will open your mind to the astonishing opportunities that lie ahead, and which will drive us toward the technological singularity . . .

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