4-2015

3D Printing

Jackson B. Stone

3D Printing

WILLIAM & MARY

CHARTERED 1693

Jackson Stone

May 4, 2015

Dedication

This thesis is dedicated to my mom, my dad, and my sisters Madeleine and Claire for their endless love and support.

Acknowledgements

I would like to thank my mentor and advisor, Carey Bagdassarian, for his massive voluntary effort to help me during this project, his mentorship, and the immeasurable help throughout my collegiate career.

I would like to thank the Charles Center for the continued support of my thesis. In particular, I would like to extend my appreciation to Joel Schwartz, Lisa Grimes, and the rest of the helpful staff of the Charles Center for all of the underappreciated work that they do. I would also like to thank all of the donors that make the summer research fellowships possible.

I would like to thank my honors committee members: Professor Bagdassarian, Professor Davies, and Professor Erlich for for their time and energy in conducting my thesis defense.

I would like to thank Professor Erlich, Professor Deconinck, and everyone else that helps run the makerspace for allowing Jacob Lisi and me to build a 3D printer on campus.

I would like to thank Cory Chapman for being an inspiration throughout this project, and providing me with countless resources along the way.

I would like to thank Jacob Lisi for introducing me to 3D printing, for his work building the RepRap Prusa i2, and for being a sounding board throughout my writing process.

Contents

Chapter 1

Introduction

This thesis, while providing a scholarly review of historical and contemporary developments alike, communicates to the lay reader the historical, current, and future impacts of 3D printing on society in the United States.

1.1 Correcting a Misconception: Challenges of 3D-Printing

Because of the foreign and novel concepts of 3D printing, also called additive manufacturing, this technology receives more than its fair share of media attention. In fact, the only time that many individuals ever hear of 3D printing occurs in a context that Laurie Segall elaborates on a CNN special:

> *It used to be that the average person couldn't own one because 3D printers are really, really expensive. We're talking like half a million bucks. But now a couple different companies came and they said, 'You know what? We want to make this so average people could have this.' You can probably get one for about a thousand bucks. So let's say I had a jacket and I lost my button. Instead of going and trying to go to a store and find a new button, I could actually download the blueprint, connect it with my 3D printer and I could print out a new button.[23]*

While Segall does a great job of explaining how much the price of an at-home 3D printer has changed as companies recognized the potential for a new market, she fails to point out how involved the process truly is for most printers. A more accurate depiction of the current state of printing technology might read something like this:

> *So let's say I had a jacket and I lost my button. Instead of going to a store to find a new button, I could actually download the blueprint, connect it with my 3D printer and I could print out a new button. And then I would wait 6 hours for the small plastic part, sand off the excess plastic material, and affix my off-color printed button to my shirt and hope that none of my possessions larger than a pencap break anytime soon. Oh, and if anything breaks, we better hope that it is made out of a very specific kind of plastic.*

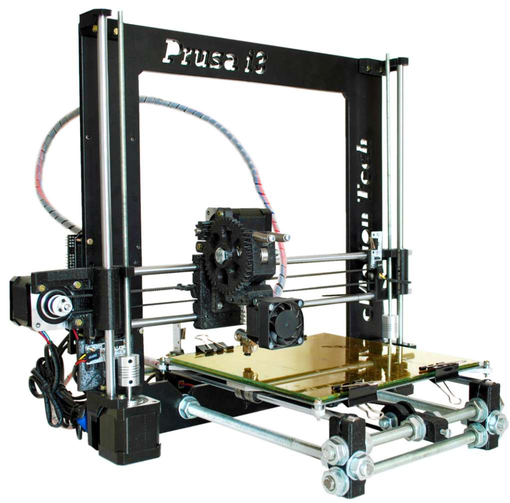
The point of this example is to demonstrate that at-home printing is not as simple as:

$$\text{Download Button} \longrightarrow \text{Print Button} \longrightarrow \text{Wear Button}$$

Ten years ago, the first difficulty that might have been encountered in printing a button for a shirt would have been that an engineer had to be hired to create it. But as the speed of information transfer between individuals across the planet has increased, this initial barrier has been broken down. As at-home printers have become more popular, an online community of enthusiasts has been met by a host of websites that store computer automated design, or CAD, files. These files can now be shared as fast as the upload speed of one's local internet connection. This opportunity to share designs is enhanced by websites that host their creations. Thingiverse, which is owned by a DIY (do-it-yourself) 3D printing company called Makerbot, is likely the most prominent example of such a website. Thingiverse currently houses over 100,000 designs for CAD files that encode printable three-dimensional objects [32].

The increasing role of the internet in 3D printing illustrates a significant theme present in the development of 3D printing: the democratization of information. By creating a network where individual 'makers' can share and

Figure 1.1: The Prusa i3, a common printer from the RepRap series [2].
.



develop projects with others across the globe, a part of the barrier to innovation has broken down. The value is obvious: Laurie Segall's fictional button-losing character is now able to immediately find a button design that probably is the right size and shape to fit his shirt and style. But what might not be so obvious is what happens when a network of these individuals emerges. When a potential design can be stored, tested, and iterated, projects that once required individual research teams to focus on a single problem for a long time may now be passed along at each stage, garnering slight improvements along the way.

What stands in the way of making a button to replace the one that fell off a shirt? Once the file is found online, it might seem that it would be as easy as just pressing 'go' and *voila button*. The biggest and most obvious barrier to printing a button is having something that can print it. The cheapest commonly available printer right now costs $500 to purchase in kit form. While this may seem affordable in a society where many spend $600 every two years just to update their mobile phone, it is expensive enough that it would be very difficult to earn a return just by replacing lost shirt buttons.

Therefore, to replace a lost shirt button, even a thrifty American consumer would have to pay $500 plus the cost of the plastic the button is made of. There is no clear advantage in printing something that might be given away for free by a nearby tailor.

But even after obtaining the printer and setting it up, it is not completely trivial to pop out the button and head out to work. Two other problems need to be solved before we can finish the task at hand. First, downloading and configuring a program that can use the CAD file downloaded from the internet takes more than a few hours. The second problem is that printers do not necessarily work perfectly right out of the box. To ensure that the button prints, there is a significant amount of work involved in configuring the actual hardware of the 3D printer so that it makes the object without defects.

Given $500 to spare, a computer, the appropriate file for the button that we want, and finally, the technical expertise and patience necessary to solve the little problems that the printer is liable to have, then an 'average' consumer can print the button. Unfortunately, with the cheapest printers this may take more than an hour for each print.

Routine 3D printing to replace worn and broken household items is a long way away. However, while there are clear barriers that will prevent an impending influx of a printers into every household, there are still influential roles for additive manufacturing to play in the near future.

Chapter 2

History of 3D Printing

2.1 Introduction

The history of additive manufacturing is nonlinear. The beginnings were slow. Over the course of the 1970s, 1980s, and 1990s, there were a series of relevant innovations that enabled the modern technology, but it truly did not take the shape that it holds today until the inception of the RepRap (replicating rapid prototyper) movement in 2005. So it makes sense, then, to break up the history of the 3D printer into two sections: first, an explanation of a few developments in the manufacturing industry that set the stage for the RepRap, and second, an ex planation of the origins of the RepRap and the rapidly developing ecosphere that has evolved since.

2.2 Pre-RepRap

2.2.1 Technology

Prior to the late 1970s, the idea that objects could be built by adding material instead of subtracting it or making a mold received relatively little attention. Aside from use in the electronics industry for the manufacture of computer chips, the technique was rarely used. But in 1974, a column in New Scientist was written by a man named David Jones that proposed a new method of manufacturing plastic objects by shining a laser through a container of liquid plastic monomer [15]. While his article was intitially taken as a joke, in 1977 a patent was granted to Wyn Kelly Swainson for what appears to be that very same concept [30].

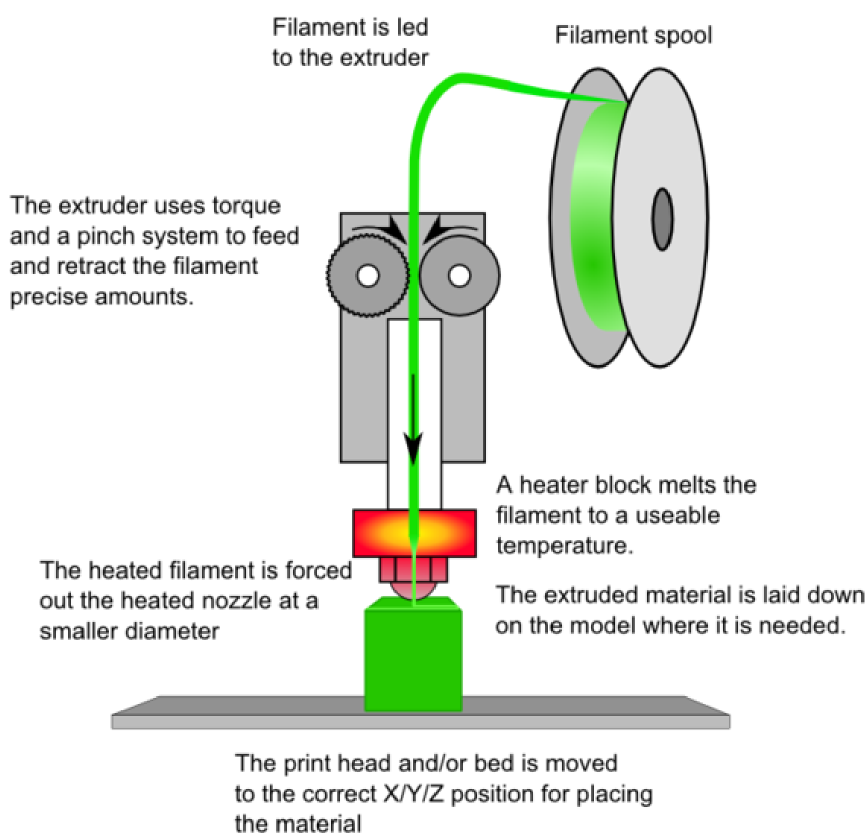
This innovation marked the conception of a technology that would eventually evolve into the modern technique of additive manufacturing. In an article by Adrian Bowyer, Simon Bradshaw, and Patrick Haufe, the advantages of the new technology are outlined as immediately apparent:

> *The primary reason that 3D printing technology was (and is) so easy to use was that it completely eliminated the tool-path calculation problems of numerically-controlled cutting machines. Because parts are built up layer by layer, there is always a flat-topped surface with unrestricted access for the laser (or other solidifying or depositing device) to gain access to build upon. This makes it very simple to write a computer programme to control the machine from a computer model of the shape required.*
>
> *Although it is typically slightly less accurate than cutting, 3D printing is capable of manufacturing more complicated and intricate shapes than any other primary manufacturing technology. Most 3D printing technologies work using plastics but technologies such as selective sintering of metal granules have allowed the printing of metal shapes and there are systems that can work with ceramics [3].*

Though the selective laser sintering model was one of the earliest patents in the additive manufacturing field, the RepRap ultimately was designed with a different modality named fused-filament fabrication, or FFF. It is worth noting here that FFF is just a different name that was created by Adrian Bowyer and the other founders of the RepRap project to differentiate it from fused deposition modeling, or FDM, which was invented by S. Scott Crump in the 1980s. Scott Crump ultimately founded Statys, which, has grown into one of the largest manufacturers of 3D printers today. The term FDM is a trademark of Stratys, Ltd, which is why Bowyer and his cofounders had to create a new term to describe the technology behind their open source project. [27] [3].

FFF works by leading a filament of the printable material into an extruder, which heats the material as it is being pushed out onto the surface of the printer bed, where it solidifies and ultimately forms additional layers until the entire object has been printed. A graphic found on the RepRap website is particularly helpful in understanding this mechanism, and is reproduced

Figure 2.1: A demonstration of fused filament fabrication [2].



here for clarity.

2.3 The RepRap Era

The Theory of Self-Reproducting Automata, by John von Neumann, was edited posthumously and published by John Burks in 1966. It is a work of massive historical significance. It exhibits an exploration of von Neumann's theory of automata, which explores the essence of natural mechanisms and, of particular import to the RepRap project, a mechanism that von Neumann dubbed a universal constructor. The universal constructor, as outlined by von Neumann, was a proposed machine that could create any structure from an input tape [22]. While this philosophical exposition explored similarities between artificial mechanisms and natural life ultimately was seminal in the development of the original computers, it also inspired what was to be named the RepRap Project [2].

2.3.1 RepRap Inception and *Wealth Without Money*

On February 2, 2004, a man named Adrian Bowyer unveiled an idea online titled text *Wealth Without Money*. Bowyer used the model of a universal constructor to introduce his goal to create a self-replicating machine that would do no less than enable a new way of life for modern humans. He described his initial goal of creating, "a rapid-prototyping machine that can make all its components other than self-tapping steel screws, brass brushes, lubricating grease, standard electronic chips such as microcontrollers and optical sensors, a standard plug-in low-voltage power brick, and stepper motors" [2]. This vision was intentioanlly within the range of technological capability at the time [2].

The very first paragraph of his thesis grounds it in a philosophical argument, using a seed of Marxist theory that permanently sets the tone for the community-based project:

> *Karl Marx and Frederick Engels wrote in the Communist Manifesto that, 'By proletariat is meant the class of modern wage labourers who, having no means of production of their own, are reduced to selling their labour power in order to live.' This diagnosis is essentially correct; it is a commonplace that people with*

resources can quite easily use them to acquire more, but people without have to try exceptionally hard to get anywhere, and most of them never do [2].

Bowyer then asserts that while he believes Karl Marx' diagnosis of the proletariat's struggle is correct, the reason communism has failed is because the treatment never addressed the problem appropriately. According to Bowyer, a more elegant solution than the failed revolutions of the past is something much more physical and inventive: a universal constructor. By providing those without resources with the necessary tools to produce tangible assets, Bowyer imagines a world with massively increased social mobility.

The overly peachy futuristic understanding 3D printing that we examined in the introduction is actually quite well-married to Bowyer's original vision:

> *I have no need to buy a spare part for my broken vacuum cleaner when I can download one from the Web; indeed, I can download the entire vacuum cleaner. Nor do I need a shop or an Internet mail-order warehouse to supply me with these things. I just need to be able to buy standard parts and materials at the supermarket alongside my weekly groceries.*
>
> *The self-copying rapid-prototyping machine will allow people to manufacture for themselves many of the things they want, including the machine that does the manufacturing. It is the first technology that we can have that will simultaneously make people more wealthy whilst reducing the need for industrial production [2].*

By setting forth his vision of of allowing the proletariat to directly control a means of industrial production, Bowyer spawned the RepRap Project.

2.3.2 Building a Critical Mass

Bowyer's call to action was not instantaneously adopted by a revolution of tens of millions of people ready to rise up and develop 3D printers. At first, there were very few people working on the projects, and it took over a year to build the very first replicator [2].

Within one year, though, the project won over a highly relevant audience. By June 2006, when Adrian Bowyer made a keynote speech at the *Seventh National Conference on Rapid Design, Prototyping and Manufacturing* at the Centre for Rapid Design and Manufacture in Buckinghamshire, UK, the RepRap project had garnered support in the form of grants and donations from the Nuffield Foundation, a 20,000 GBP grant from the EPSRC (Engineering and Physical Sciences Research Council of the United Kingdom), the University of Bath Innovative Manufacturing Research Centre, and a number of individuals who chose to donate to the project online. In addition to thanking those who gave monetary support, Bowyer also acknowledged the research team:

> *I would also like to thank my research student, Ed Sells for his excellent work on the project. In addition to Ed and me there are five other RepRap researchers: two from New Zealand: Vik Olliver and Simon McAuliffe, and three from the USA: Forrest Higgs, Brett Bellmore, and Zach Smith. These people are working tirelessly on the project for no reward, simply because they are interested in it and believe in it. I would like to end by thanking them for their selflessness and dedication.*

It is notable that only seven people were working on the RepRap at this time. From the initial date of the first blog post by Bowyer in February, 2004, to the first production of the RepRap Darwin in the spring of 2007, the development of the first printer took three full years [2].

Over the next few years the project steadily gained momentum, and the number of RepRaps eventually increased rapidly. The RepRap wiki provides a graphic that illustrates the exponential expansion of the RepRaps made for as long as it was reasonable to track them.

As troubleshooting problems and continual experimentation led to new designs, the original leaders of the RepRap project curated an online resource to ensure that each design would be replicable for new users. Since then, the RepRap movement has taken off and become a self-supported community. In an longitudinal survey sent out to hackerspaces, end users, and developers of 3D printing designs, the RepRap was found to be the most commonly used printer by 2012, making it a crucial cornerstone of the Maker Movement [18].

Figure 2.2: Working RepRaps from 2006 to 2011 [2].

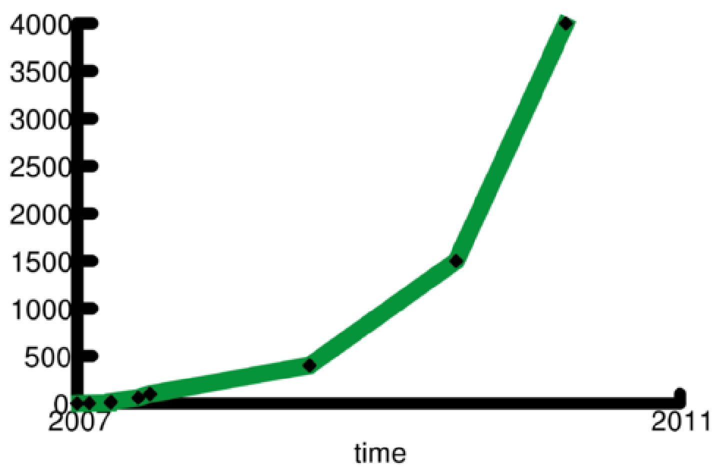
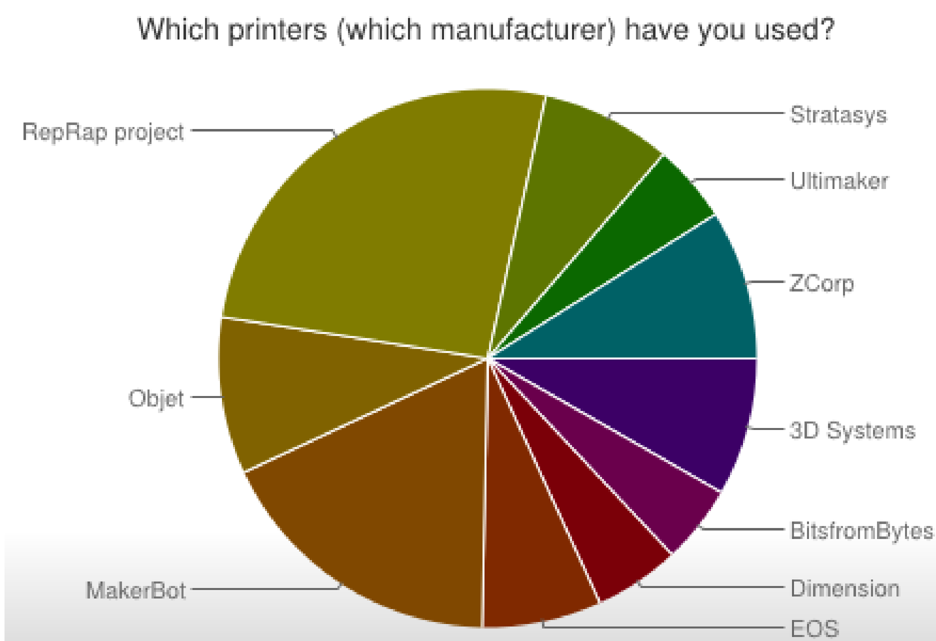


Figure 2.3: 3D printers in use by various hobbyists [18].



Chapter 3

Maker Movement

3.1 Introduction

The current home of the 3D printer is in makerspaces, with makers. We will define a maker, in this context and in all future uses, as an individual or artisan who uses their creative talents in craft activities or otherwise produces functional or artistic home-made items.

Makers are worth studying. According to the Atmel, a semiconductor manufacturer and heavy financial backer of the Maker Movement, there are 135 million Americans who can be described as makers, by our definition [25].

To put that in perspective, that comprises 57% of the adult American population. It forms such a large faction that any major change in the way these individuals work may serve as relevant barometer for changes in the economy at large.

The second reason this is a relevant consideration is philosophical. The current era is defined by the recent adoption of widespread internet usage across the world. In the case of additive manufacturing, the internet revolution is particularly influential. Ideas that once had to slowly diffuse across geographic and personal networks to effect change in crafts and workmanship now have links that connect nodes from Hong Kong to Boston as effortlessly and as quickly as typesetting an email and pressing send. The internet as it is understood today has only been around for about 25 years [29].

It is reasonable to expect that secondary effects of these relatively new capabilities may define the next 50 years. As we find new ways to create and shape a new world, technology, as always, will play a pivotal role. It is always difficult to predict the future, but by focusing on the areas that have the largest involvement in terms of human participation, we will be likely to find areas that are also ripe for the greatest change.

Now that we have defined makers and explained why they are important, it is prudent to explain the so-called Maker Movement. The Maker Movement is a social trend that orients and motivates individuals to create things on their own. The fundamental principles of the movement, in many ways, complement the culture present in Silicon Valley and other hotbeds for new startups in the United States. The movement encourages sharing ideas, making things and breaking things, and encourages creative endeavors for their own sake.

3D printing forms the foundation of this movement. The ability to create any object that can be made enables organizations and individuals to explore creative opportunities in new ways. The communities that have formed around this movement, and around 3D printing in particular, are worth exploring because they form a crucial example of how self-organized communities can develop new technologies organically. Because of this, these communities serve as a demonstrative complement to modern corporate research and development model used by large corporations.

3.2 Making, Innovation, and the Internet

The internet has revolutionized the way we communicate, and for many of us it may be easy to forget that there was a time before one could pick up a smartphone and send a message to a friend on the other side of the world.

But while the novelty of our technological advancement fades quickly, the impact on innovation as we use new tools to our advantage snowballs. The ability to collaborate with people without actually being in their presence is transformative for innovation. Additive manufacturing is no exception to this trend. Thingiverse, which is an online warehouse of computer aided design files hosted by Makerbot, is a hallmark example. Clay Shirky, an early board member of Makerbot, explained the new nature of development in designs in an interview with Mckinsey in 2014:

> *And you could see these things happening where somebody uploaded a little model for a radio-controlled, 3-D printed shell for*

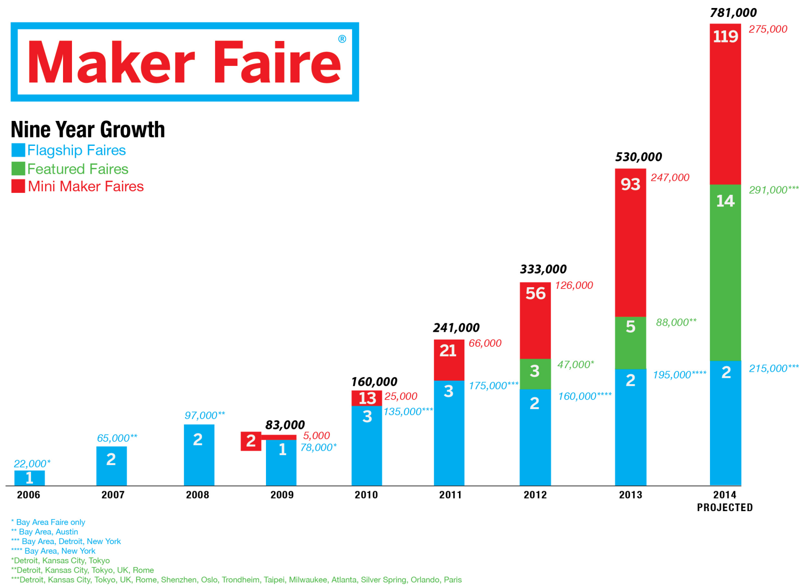
> *a little radio-controlled car. And they said, 'Here's this thing. It looks great. There's only one problem: It doesn't work, because it's too heavy. But I'm uploading it anyway.' And then other people who were good at figuring out, 'Well, you can take the weight out here and there,' turned it into something workable. No one person made that radio-controlled shell. So the collaborative penumbra around 3D printing is a place where you don't have to have someone who can do everything - from having the idea to making the mesh to printing it. You can start having division of labor. So you've got all of these small groups that are just working together like studios and still able to play on a world stage [24].*

3D printing, when paired with a large network of individuals that share their projects, allows the iteration process to occur almost in the background, letting designs evolve and 'learn' from a plethora of people that come with different creative and technical capabilities. Specifically, the massive online warehouse of CAD, or computer automated design files on Thingiverse has allowed an online community to flourish and catalyze its own growth, as more innovators are brought in to see projects that others have already made.

This is just as evident in the business behind making as it is in the movement itself. Autodesk, which is the company that makes the most prevelent CAD program used for 3D printing, AutoCAD, purchased a company called Instructables, which hosts a community of individuals focused on DIY projects on an online platform [37]. In an interview with *Wired* magazine, the CEO of Autodesk was quoted as saying, "One of the things that we're seeing is that technology is increasingly starting with consumers, and then moving up into business [14]." The creation of new ideas outside of a corporate setting is getting noticed from the top-down, and with that attention comes potential for new models for profitization by the firms that have a stake in the industry.

The ability to collaborate across barriers of time and space expands the community of potential contributors to any project at all, though, not just those that can be uploaded on the internet. The modernization of collaboration is a key contributing factor to why we can see the Maker Movement rising in popularity across the country. People have begun to gather around the spirit and community of making for the purpose of making - enjoying collaboration on DIY projects solely for the sake of seeing what can be hacked

Figure 3.1: Occurences of Maker Faire from 2006 to 2014 [11].



and made into something interesting. If current trends continue, we will see that the number of self-identified ‘’Makers’ will increase in size for years to come [11].

3.3 Maker Faire

Events called Maker Faires have been popping up around the nation since their launch by *Maker Magazine* in 2006 near San Francisco [11]. Sponsored by Make magazine, these faires are a promotional embodiment of the Maker Movement. Over the course of the last year, over 50 events have been put on by Maker Faire globally [10]. During this same year, Google and Make magazine teamed up to hold a maker camp, where over 1 million children participated in an online camp that taught them how to, “build, hack, make, and explore [4].”

3.4 Maker Spaces

As defined by Makerspace.com, an online community affiliated with Maker Faire, a makerspace

> *...combine[s] manufacturing equipment, community, and education for the purposes of enabling community members to design, prototype and create manufactured works that wouldn't be possible to create with the resources available to individuals working alone. These spaces can take the form of loosely-organized individuals sharing space and tools, for-profit companies, non-profit corporations, organizations affiliated with or hosted within schools, universities or libraries, and more.*

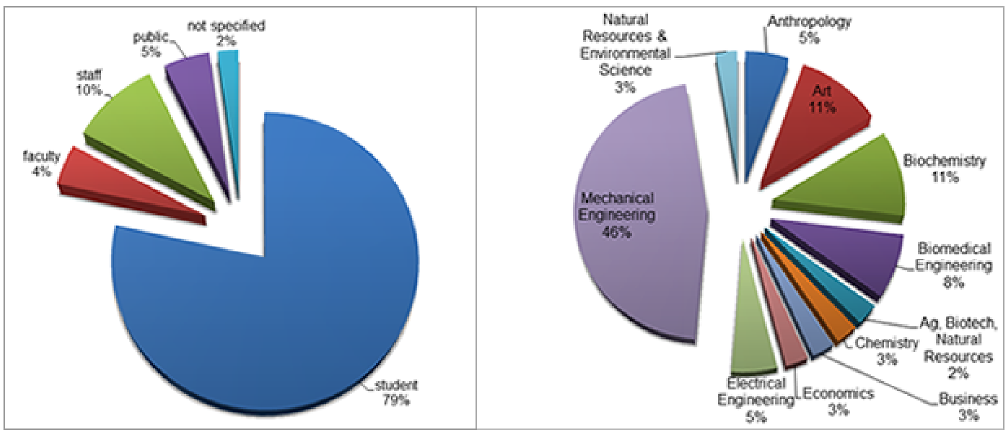
By their definition, a makerspace is any location dedicated to providing a workspace to create. Makerspaces have popped up across the country. The development of shared spaces where individuals can explore and create whatever they want to is not a new concept, but the inclusion of tools with a diverse range of uses has allowed for a change in the way the spaces are viewed and used. And while the actual items included in such a space vary, the core concept of encouraging individuals to collaborate and pursue creative projects with modern tools is prolific.

3.5 Makerspaces in Educational and Public Use Settings

The draw of incorporating printers into libraries and pubic use settings is compelling. Enabling individuals to explore different avenues of production and providing an outlet to enhance their lives through creativity meshes well with the mission of most libraries.

In July, 2012, University of Nevade, Reno library became the first in the nation to provide a 3D printer as part of its services [34]. The decision to install this printer was surely not one without questions, for maintaining a 3D printer is not a cost-free or maintenance-free endeavor. Sources of funding and local expertise for publicly installed printers remain a question for all settings that intend to provide a printer free of cost. Soon after, though, many other libraries followed suit. According to the American Library Association,

Figure 3.2: Left: A distribution of 3D print jobs by self- identified customer category. Right: A distribution of 3D print jobs by self- identified discipline of customers. [5].



by 2015 there were 250 printers in public libraries nationwide [36].

Regardless of whether other libraries follow this model in the future, the idea of access to a 3D printer as a public service now has a proven model. While the nascent state of the field gives this development an air of experimentalism, enabling individuals to use additive manufacturing as a shared resource makes sense in light of the high cost and technical expertise required to set up a 3D printer. The popularity of makerspaces on college campuses and 3D printers in public libraries serves as a reasonable metric for widespread acceptance of the Maker Movement; as more people embrace the movement, tools that let people engage in it will rise in popularity.

Chapter 4

3D Printing in the Biomedical Industry

4.1 Introduction

Companion diagnostics, precision medicine, stem cells and 3D printing are poised to push the biopharmaceutical industry towards individualized care. This new model of selecting patient groups can provide clear advantages over "shotgun pharmaceuticals," which are given to patients grouped by their symptoms instead of by the root cause of their afflictions. In particular, research into genetic variance within diseased populations is making a huge impact on the way patients are prescribed medication [13]. In some cases, this has allowed pharmaceutical companies to demonstrate therapeutic value more effectively. The most recent example of this came on March 20, 2015, as Biogen released compelling data for a new Alzheimer's drug, *aducanumab*. By pre-selecting its trial group for a population that was most likely to benefit, Biogen was able to fast-track *aducanumab*, pushing it directly from Phase Ib trials to Phase III trials [6]. If the results hold through the third stage of trials, this could ultimately shave as much as 2 years off the clinical trial process [31] [6]. This sets a precedent of targeted treatment that promises to both benefit those afflicted by a wide range of diseases and make research and development cost more palatable for large pharmaceutical companies that, according to research published in November of 2014 by the Tufts Center for the Study of Drug Development, spend an average of $ 2.6 billion for each drug they bring to market. [7]

As the value for innovations in the field of personalized medical treatments becomes more obvious, investors will be more likely to invest in companies in that field. If this model of development continues to gain clout, both academic research and early stage for-profit ventures may find it easier to support their innovations with funding. This is particularly salient in the field of bioprinting, which is the three dimensional printing of biological tissue for either clinical or research purposes. This field has faced a myriad of challenges since its inception, but has also seen recent success. In an article from August, 2014 in Nature: Biotechnology, it is remarked that "3D bioprinting has already been used for the generation and transplantation of several tissues, including multilayered skin, bone, vascular grafts, tracheal splints, heart tissue and cartilaginous structures. Other applications include developing high-throughput 3D-bioprinted tissue models for research, drug discovery and toxicology" [19].

3D printing in the biomedical field has a few proven use-cases, but a number of others may be enabled by advances in associated technologies. It could enhance customized care, which ranges from developing cheaper prosthetics to printing tissues that may allow accelerated drug discovery [17]. To gain insight into some of the challenges that the future may hold for innovations in 3D printing, it is worth investigating some of the current uses and challenges today.

4.2 Modalities

There are a number of different modalities in which additive manufacturing technology can be utilized in the healthcare space. In particular, the creation of external low cost external devices has been the first wave of additive manufacturing making a splash in a day-to-day healthcare setting. Some other potential uses for additive manufacturing technology could prove to be valuable in organ replacement and tissue production in the years to come, but are very research intensive and commercially expensive to develop.

4.2.1 Prosthetics, Casts and Orthodontics

There are many possible uses for 3D printing in a biomedical setting. Simple, customizable, externally-worn biomedical devices may be the most straightforward innovations to implement and develop using 3D printing. In this section I will examine three main use-cases for externally worn orthopedic medical devices created using additive manufacturing.

Casts

History and Development: Those who have ever broken a wrist and needed to stabilize it with a conventional cast probably remember jamming a butterknife up it to scratch an itch. For those who have not experienced it, suffice it to say that a new technology would be welcome. Multiple versions of webbed, lightweight 3D printed casts have been designed, and one called The Osteoid won a research grant from the A' Design Competition [26] [16]. If clinical studies show that they protect and stabilize the bone at least as effectively as their predecessor, 3D printed casts have some clear advantages that could pave their way to market.

The process for creating such a cast, however, would likely be slightly more involved than simply wrapping wet plaster around the affected limb and waiting until it dries. In order to 3D print anything the size of a cast, not only would a patient need to have their affected limbs X-rayed and scanned by a 3D scanner, which would extend the length of care needed in an emergency room or orthopedist's office for patients.

Prosthetics

History and Development: The 3D printing of prosthetic devices was born out of the maker movement. A number of individuals created fully-functional mechanical hands as personal projects and out of the necessity of prohibitively expensive current commercially offered prosthetic options [20]. This undercurrent was eventually noticed by the NIH, which has created a 3D Print Exchange to curate and, "support the Maker Movement in mechanical hands by bringing together designers, engineers, physicians, 3D print enthusiasts, families and amputees, to create, innovate, re-design and share 3D-printable prosthetics" [20]. In doing so, the NIH has encouraged a space outside of the intellectual property grasps of online warehouses of 3D printing CAD files and allowed engineers and hobbyists to innovate and source designs that are free to share and use for whoever would like to make them.

Orthodontic Consumables

History and Development: Invisalign braces, manufactured by the company Align Technology, were approved by the FDA in 1998, which makes them one of the oldest uses of 3D printing for individual use medical devices.

Current Use: Invisalign braces are worn by individuals that have a need for orthodontic corrective braces to straighten their teeth. They have lay claim to significant space in the field since their inception; a proxy filing from 2014 shows that their revenue was up to $660 million [12], which comprises a significant share of the global orthodontics market. This represents a growth in revenue of over 400% since 2003. Such strong financial growth comes even with mixed results in clinical studies; a retrospective cohort study from as early as 2004 found that Invisalign braces have success rates 27% lower than standard braces in treating orthodontic malocclusions [8]. This likely points to value for patients in categories outside of medical treatment, which could include ease of use and improved perception of aesthetic appearance for the end consumer.

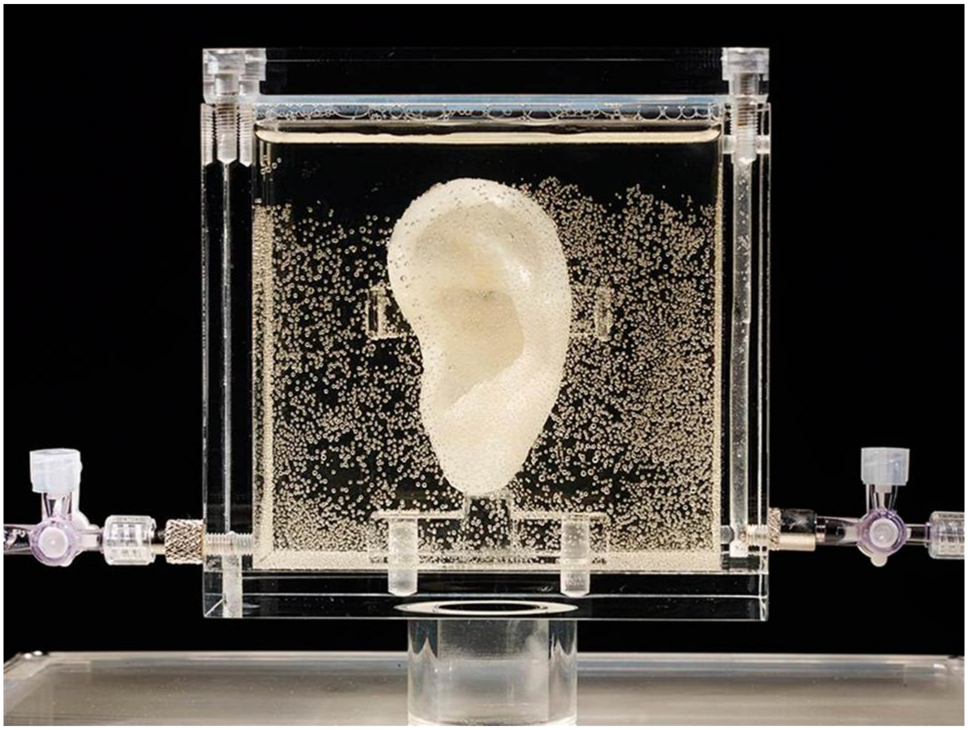
Technology: The process of creating Invisalign braces begins with an x-ray, pictures, and dental impression at a patient's orthodontal or dental office. After diagnosis and confirmation by the dental professional, the dental impressions sent to Align Technologies, where the Invisalign braces are printed using stereolithography [33] [1].

Costs/economics: Conventional braces generally cost around $4,500 per treatment, and Invisalign braces generally cost around $1000 more. Given the significant cost difference and lack of proven evidence that it provides superior medical results, it is unlikely that the major payers in dental insurance will augment coverage for Invisalign treatment, which leaves patients bearing the difference. The augmented market share of Invisalign coupled with its increased price as compared to conventional braces together demonstrate a significant consumer preference for the Invisalign product.

4.2.2 Tissue Printing and Bioprinting

While 3D-printed hearts and livers have been in the news for years , many research groups argue that the technology is still in its earliest stages [23] [35] [19] So called tissue engineering is married with molecular biology, stem cell research, and our understanding of how to program cells to develop *in vitro* just as as they would naturally form in the human body.

Figure 4.1: Diemut Strebe's peculiar artistic exhibit [28].



Though the production of fully formed implantable 3D-printed organs may be far off, successful demonstration of certain applications has been achieved and a proof of concept illustrates that a critical mass of knowledge may be closer than we think. Diemut Strebe may have strayed from the beaten path in attempting to regenerate living tissue from an envelope she believed that Vincent Van Gogh may have licked years ago, but the production of a functional cyborg human ear was no joke. Though she was not ultimately able to obtain Van Gogh's actual DNA, a three dimensional 'living' model of Van Gogh's once-chopped off ear was on display at the VKM museum in Germany this summer, bathed in a a nutrient solution nourishing all of its cells. The source for the genetic material was one of Van Gogh's male descendants [28].

Challenges

The long term opportunity for a futuristic model of 3D printing organs as they are needed remains. In order to effectively print out organs that are ready for use by humans in a clinical setting, three major technological innovations have to emerge and integrate. The first barrier is cell technology. While advances in molecular cell biology have enabled contemporary researchers to use targeted gene therapy for over a decade, procuring cells that can organize to form a functional tissue structure is a challenge that has yet to be fully overcome [9].The second barrier to bioprinting organs will be the creation of a device that can print cells effectively. After cell biology has advanced to a point where cells can be effectively integrated into the organ, it will be a challenge to create a printer that can effectively integrate the living cells and biomaterials into a functional organ. The last major barrier is one where many novel biological therapies have significant difficulty: *in vivo* integration. The main challenge is to incorporate organs in the body in a way that is safe and efficacious [21] [19].

4.3 The Future of 3D Printing in Medicine

The best current use-cases for additive manufacturing in a biomedical setting are not the most complicated. Newly affordable 3D printing technology has enabled promising developments in externally printed parts to take shape. In the near future, it is reasonable to expect that developments in prosthetics, casts, splints, and other solid form medical devices will be pushed forward by innovations developed using additive manufacturing.

Just like the imagined world of ubiquitous household 3D printers, the idea that organ printing will be as simple as:

$$\text{Print Heart} \longrightarrow \text{Install Heart} \longrightarrow \text{Use Heart}$$

is not a reasonable expectation in the immediate future. However, working models of 3D printed tissues, like van Gogh's ear, gives reason to believe that printing hearts will, in fact, be possible as auxiliary technologies progress.

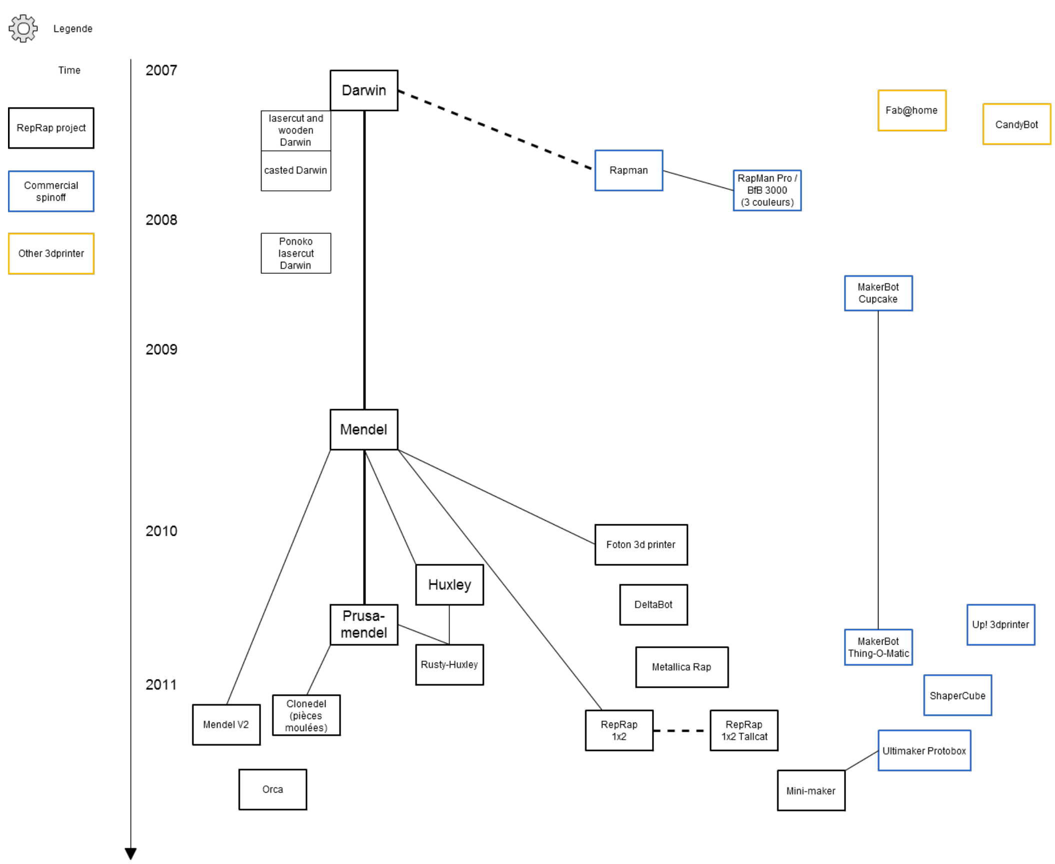
Chapter 5

Conclusion

Inherent in the RepRap movement is the capability for the printer to reproduce itself and ultimately be accessible to anyone who has the resources to make one. But what might not be immediate in my brief history of the movement is the biomimetic nature of the lines of printer. By creating an adjustable genetic code for the printer, in the form of modifiable CAD files that encode its parts, paired with the capability of reproducing those parts, Bowyer and the other creators of RepRap Darwin created a technology that evolved in a similar fashion to that by which evolution occurs in the natural world.

Though far from totally ubiquitous, RepRaps have been steadily gaining in population since their inception. And crucial to their history is the idea that open source projects are more likely to lead to a public good than protection by restrictive patents. By allowing the RepRap to be freely reproduced by anyone who could access it, the founders set forth a trend that left a stamp on the nature of making forever. The balance of allowing inventors to profit off of their creations and not letting great ideas be sequestered by large corporations is a difficult one. In the case of 3D printers, however, it seems clear that the culture created by allowing for a totally reproducible mode of production has been beneficial both in perpetuating the movement and in creating opportunities for translational innovations. So while it may be tempting to fixate on the foreign and novel innovations that seem impossible, like bioprinting organs to be transplanted into the human body, I posit that something as simple as creating a self-replicable printer may have more of an impact on the long term history of innovation.

Figure 5.1: The RepRap family tree [2].



Bibliography

[1] A Bishop, R Womack, and M. Derakhshan. “An esthetic and removable orthodontic treatment option for patients: Invisalign”. In: *The Dental Assistant* 14 (Oct. 2002).

[2] Adrian Bowyer. *RepRap.org*.

[3] S. Bradshaw, A. Bowyer, and P. Haufe. “The intellecutal property implications of low-cost 3D printing”. In: *ScriptEd* 7.1 (2010), pp. 5–31.

[4] Maker Camp. *Maker Camp Season 2014*. URL: `http://makercamp.com/summer-2014/`.

[5] Patrick Colegrove. “Making It Real: 3D Printing as a Library Service”. In: *Educause Review* (Oct. 2014).

[6] Emily Cukier-Meisner. “Ready for Prime Time”. In: *Biocentury* (Mar. 2015), pp. 1–6.

[7] Joseph DiMasi, Henry G. Grabowski, and Ronald W. Hansen. “Cost of Developing a New Drug”. In: *Tufts Center for the Study of Disease Development* (Nov. 2014).

[8] G Djeu, C Shelton, and A Maganzini. “Outcome assessment of Invisalign and traditional orthodontic treatment compared with the American Board of Orthodontics objective grading system”. In: *American Journal of Orthodontics and Dentofacial Orthopedics* 128.3 (Sept. 2005), pp. 292–298.

[9] Michael Edelstein and Mohammad R. Abedi. “Gene therapy clinical trials worldwide to 2007 - an update”. In: *The Journal of Gene Medicine* 9.10 (Oct. 2007), pp. 833–842.

[10] Maker Faire. *Maker Faire: A Bit of History*. 2015. URL: `http://makerfaire.com/bay-area-2015/media-kit-press-resources/`.

[11] Maker Faire. *Maker Kit Press Resources*. 2015. URL: `http://makerfaire.com/bay-area-2015/media-kit-press-resources/`.

[12] "Financial Results Financial Results Q1 2015". In: *Align Technology, Inc.* (2015).

[13] *From Genes to Personalized Medicines*. Tech. rep. NIH, Oct. 2010.

[14] Sam Gustin. "Democratizing Design: Autodesk's CEO Carl Bass Announces 123D". In: *Wired Magazine* (May 2011).

[15] David Jones. "Adriadne Column". In: *New Scientist* (Oct. 1974).

[16] Deniz Karasahin. "Osteoid Medical cast, attachable bone stimulator". In: *A'Design Award and Competition* (Mar. 2014).

[17] Shelby M. King, Sharon C. Presnell, and Deborah G. Nguyen. "Development of 3D bioprinted human breast cancer for in vitro drug screening". In: *American Association for Cancer Research* (Apr. 2014).

[18] Jarkko Moilanen and Tere Vaden. "Manufacturing in motion: first survey on 3D printing community". In: *Statistical Studies of Peer Production* (2012).

[19] Sean V. Murphy and Anthony Atala. "3D bioprinting of tissues and organs". In: *Nature biotechnology* 32 (Aug. 2014), pp. 773–785.

[20] *NIH 3D Print Exchange*. 2015. URL: `http://3dprint.nih.gov/collections/prosthetics`.

[21] Ibrahim T. Ozbolat and Yin Yu. "Bioprinting Toward Organ Fabrication: Challenges and Future Trends". In: *IEE Transactions on Biomedical Engineering* 60.3 (Mar. 2013), pp. 691–699.

[22] Hiroki Sayama. "Von Neumann's Machine in the Shell: Enhancing the Robustness of Self-Replication Processes". In: *Artificial Life VIII* (2002).

[23] Lauren Segall. *CNN Explains: 3-D printing.*

[24] Clay Shirky and Michael Chui. "The disruptive power of collaboration: An interview with Clay Shirky". In: *Mckinsey Insights Publications* (Mar. 2014).

[25] Martha Stewart. "Martha Stewart. Meet USA's New Entrepreneurs". In: *USA Today* (2013).

[26] Liz Stinson. "Is this case the future of healing broken bones?" In: *Wired Magazine* (July 2013).

[27] *Stratys Legal Information*. Apr. 2015. URL: http://www.stratasys.com/legal/legal-information.

[28] Diemut Strebe. Sugababe. 2014.

[29] Ph. D Susan R. Harris and Elise Gerich. "Retiring the NSFNET Backbone Service: Chronicling the End of an Era". In: *ConneXions* (1996).

[30] W.K. Swainson. *Method, medium and apparatus for producing three-dimensional figure product*. US Patent 4,041,476. 1977. URL: http://www.google.com/patents/US4041476.

[31] *The Drug Development Process*. Tech. rep. The Food and Drug Administration, Mar. 2015. URL: http://www.fda.gov/ForPatients/Approvals/Drugs/ucm405622.htm.

[32] *Thingiverse*. Apr. 2015. URL: https://www.thingiverse.com/about.

[33] Orhan Tuncay. "The Invisalign System". In: *Quintessence Publishing Company* (2006).

[34] *University of Nevada, Reno library first in nation to offer 3D printing campuswide*. University of Nevada, Reno. University of Nevada, Reno/108 Reno, NV 89557, July 2012.

[35] J Visser et al. "[Tissue printing; the potential application of 3D printing in medicine] translated from Dutch". In: *Ned Tijdschr Geneeskd* 157.52 (2013).

[36] Charlie Wapner. "Progress in the Making Progress in the Making: 3D Printing Policy Considerations through the Library Lens". In: *OITP Perspectives* 3 (Jan. 2015).

[37] Robin Wauters. "Autodesk Acquires DIY Community Instructables". In: *TechCrunch* (Aug. 2011).