In the 1914 H.G. Wells novel “The World Set Free”, Wells describes a uranium based continuously combusting explosive. Years later the remarkable similarities discovered between Wells’ fictional device and the atomic bombs invented and deployed during World War II were added to the ever growing list of instances where life imitates art. 3D printing had much the same backstory. In 1945 American author William Fitzgerald Jenkins published his short story “Things Pass By” under the nom de plume Murray Leinster. This story describes a machine that builds things, like houses and ships, using filaments that harden as they set. This is the first documentation of 3D printing as a concept. New developments didn’t occur until decades later. But first, what is 3D printing, and how does it work?

3D printing, also referred to as additive manufacturing, as a premise is quite simple. According to the United States Department of Energy, it is “the process of making an object by depositing material, one tiny layer at a time” (Greene and Matulka 2014). Greene and Matulka made a very apt comparison likening 3D printing to the formation of stalagmites and stalactites. Stalactites and stalagmites are formed overtime when dripping water deposits minerals that build up, layer by layer. Another example can be found in construction. When building with cinder blocks or large slabs of stone, the material is stacked on top of each other to form a larger component, much like building with legos. 3D printing is the precise layering of material to create a larger component or a complete structure. The most common type of manufacturing and the contrast to additive manufacturing is subtractive manufacturing. As the name implies, subtractive manufacturing is manufacturing that involves the removal of material to create the desired structure. An easily visualized example of this is sculpting, specifically marble sculpting. When creating masterpieces such as *David* and *Moses*, Michealangelo didn’t combine parts to create a whole, but chipped and cut away at a large block of marble to create shapes, curves, and angles to form the desired visage. While this type of manufacturing is still in practice, advancements in technology allowed for new methods to emerge.

Many inventions inspired modern technology and methods of 3D printing. One of the oldest can be linked back to 1892 when inventor Joseph E. Blanther patented his method of creating the first 3D topographical maps. These maps showed elevation using scale models built layer by layer. The concept of printing objects in layers used in 3D printing today can be traced back to this method. Another predecessor to 3D printing that played an integral role in its development is inkjet printing. Inkjet printing was first achieved in the 1950s by Ichiro Endo, a worker at Canon in Japan, who created the first successful inkjet printer. This printing method involves pressing small droplets of ink from a nozzle to paper to create an image.This concept inspired inventors like Johannes F. Gottwald who, in 1971, patented a machine, dubbed the Liquid Metal Recorder, that used a continuous "liquid bridge of an electrically conductive ink is propelled under pressure against a carrier for marking thereon" (Gottwald). This left a removable symbol made of metal. This technology of printing using a "3D" ink that dries solid, combined with Blanther's idea of layering material to create three-dimensional models is the basis for modern 3D printing technology.

All of these inventions and discoveries lead to breakthroughs in the 1980s. In April of 1980 Dr Hideo Kodama of the Nagoya Municipal Industrial Research Institute invented two methods of additive manufacturing and by 1981 had published the first account of a 3D printed solid in 1981. Although this technology is considered revolutionary and a great success now, lack of interest by Kodama's superiors leading to a poor research budget led his project and patents to be abandoned. Despite this unfortunate turn of events, Kodama wasn't the only one working on this type of technology, The next development came in 1984 when American entrepreneur Bill

Masters filed a patent for a process called Computer Automated Manufacturing Process and System. This patent coined the term “3D printing” for the first time. The Computer Automated Manufacturing Process and System gave devices instructions on creating a product using computer software and is considered the basis for modern 3D printing systems.

All of these advances culminated in 1986 when Chuck Hull patented Stereolithography or as the patent states the “Apparatus for Production of Three-Dimensional Objects of Stereolithography” and founded 3D Systems, Inc. Shortly after the patenting Hull’s company released the world’s first stereolithography machine, dubbed SLA-1. Stereolithography as defined in “A Review of Stereolithography: Processes and Systems” by Jijang Huag, Qin Qin, and Jie Wang of Sichuan University, is “the earliest form of additive manufacturing, stereolithography (SLA) fabricates 3D objects by selectively solidifying the liquid resin through a photopolymerization reaction” (Huag et al. 2020). Following the success of Hull’s machine, American inventor Carl R. Deckard came up with his own interpretation of 3D printing technology called Selective Laser Sintering, or SLS. As an undergraduate at the University of Texas, Austin, Deckard invented and patented the first SLS machine he named Betsy. Betsyvaried from previous printers because instead of using UV rays, they use high-powered lasers to fuse small particles of plastic, metal, ceramic or glass powders into 3D objects.

Thanks to these brilliant scientists, 3D printing became not only possible, but accessible, leading to a variety of different uses. When Hull and Deckard patented their machine and methods, 3D printing was an interesting, yet impractical as a side from 3D printing small objects there weren’t very many uses for the technology. This began to change in 1989 when Masaki Fujihata became the first known artist to work with 3D printing. According to the Museum of Arts and Design in New York in his computer generated work titled *Forbidden Fruits* Fujihata features “a golden orange, {and a} semi-translucent group of organic forms arranged in a sculptural cluster”. This not only brought attention to the relatively new science of 3D printing but also opened the door for more recreational and practical uses for 3D printing. That same year S. Scott Crump patented Fused Deposition Modeling (FDM), founded Stratasys, a 3D printing and production company, and Drs. Hans J. Langer and Hans Steinbichler founded EOS GmbH Electro Optical Systems, a company that used 3D printing and SLS technology generated by computer-aided design (CAD) software. CAD software allows for 3D rendering of an object or design in a digital space. Then the digital 3D model is sent to the 3D printer allowing the machine access to specific dimensions making the science of additive manufacturing more accurate. Crump’s FDM technology was more precise than previous machines and started making waves in the field of medical science.

The first 3D printed organ was created in 1999. Scientists at the Wake Forrest Institute for Regenerative Medicine successfully manufactured the first 3D printed, lab-grown organ, a bladder. This bladder was formed from the patient's own cells, reducing the chance of rejection significantly. Since then, leaps and bounds have been made in 3D printing necessary medical devices and supplies. These successes not only paved the way for advances in medical science, but in various other fields as well.

From this point forward, advances were made at a steady pace, finding new applications and methods of additive manufacturing. One often overlooked field making developments in 3D printing is construction. As predicted by Murray Leister there has been success 3D printing things as large as houses and boats, but it didn’t start out that way. Primarily referred to as additive manufacturing in the construction world, 3D printing has impacted everything from the roofs to foundations. Incorporating additive manufacturing into construction can and is helping to solve many problems that the construction industry faces including economic competitiveness, efficiency, and predominantly sustainability. Attempts at 3D Concrete printing began decades ago and in 1997 Joseph Pegna combined 3D printing technology with cementitious material. This technology advanced further by various companies eventually leading to the Freeform Construction method, a method developed by Joseph Pegna and analyzed by Buswell *et al.* The Freeform Construction method is " approaches that deliver large scale components for construction without the necessity of formworks using additive manufacturing" (Suntharalingam *et al*. 2019). Joseph Pegna (1997) theorized that this would allow entire buildings to be made using additive manufacturing as opposed to the smaller objects that 3D printing had been used for thus far. Buswell *et al.* (2018) expanded on this in their study *3D printing using concrete extrusion: A roadmap for research*. They found that the Freeform Construction method could reduce construction costs and manufacturing times as well as offer more freedom than conventional building methods.

Concrete Printing has two primary forms extrusion-based and powder-based. Extrusion based printing has the most commonalities with traditional 3D printing in that extrusion based printing "is a method that extrudes cementitious material from a nozzle" (Suntharalingam *et al*. 2019). This aligns with traditional 3D printing as that typically involves the layering of filaments fed through a nozzle to create a solid three-dimensional object. There are two forms of extrusion based printing, concrete printing and contour crafting.

There are two major obstacles to overcome regarding concrete printing: machinery and material selection. Similar to biology, in machinery and construction, typically form follows function. As one would imagine, the machines used in concrete printing can be quite large, but the size varies based on the purpose, or what the printer will be used to build. The second, and arguably more complex issue, is material selection. Many qualifications must be met for a good concrete mixture not only for quality purposes but for safety. Qualities often looked for in a good concrete are as follows, compressive strength, workability, moisture resistance, setting time, and good plasticity amongst others. Given these additional obstacles, why would one choose 3D concrete printing over traditional building methods? New materials for 3D printing concrete are being created yearly, constantly improving, and as with traditional construction, additive construction begins with a strong foundation.

From Joseph Pegna's initial theories grew an entire industry of additive manufacturing in construction, or additive construction. Still, the practice has yet to grow to its desired scale as many predict in the future skyscrapers and entire developments could be 3D printed, saving time, money, and resources. As of yet, there are five different types of 3D printing in the construction industry and each of the following paragraphs corresponds to a type: stereolithography, fused deposition modeling, inkjet powder printing, selective laser sintering and selective heating sintering, and contour crafting.

Stereolithography as discussed on page one, uses UV lasers to solidify liquid polymer as the base of the machine lowers the printing object to create multiple layers. An everyday example of this could be filling a frozen yogurt cup. When filling the container one moves the cup ("base") away from the nozzle while the nozzle stays at the same elevation, creating layers. According to Wu et al. the main obstacle to stereolithography in the construction industry is the price of the material used, coming to approximately $80 to $210 per liter. This puts stereolithography among the most expensive of the types of additive construction.

Fused deposition modeling (FDM) shares many similarities with stereolithography. FDM has three components, the printer head, material, and the supporting structure or material. Like stereolithography, the base in fused deposition modeling lowers allowing for the stacking of layers. Once the object or structure is completed, the supporting material is removed. Similarly to how once a cake is cooked, it can be removed from the pan that was helping it to keep its form. The main drawback associated with FDM printing is the low-temperature and low-strength alloy as well as the potential for oxidation of materials (Mireles et al., 2012). University of Southern Carolina Professor Behrokh Khonshnevis built the first 3D printed concrete wall in 2004 and created a fused deposition model 3D printer that weighed less than 800 pounds, making it easier to transport. Instead of lab printing the structural parts then transporting them to their permanent location, the machine could be moved to the location printing the structures on site, revolutionizing construction 3D printing.

Inkjet powder printing uses a printer head similar to fused deposition modeling as well as a printing material. As the name would imply, the printing material used is in powder form. Additionally inkjet powder printing requires a binder and an oven (heat source). After printing the structure must be heated, often oven-dried to solidify the object. Materials used can range from silica sand to metal powders and even food-safe powders. The inkjet precisely deposits droplets of the liquid binder in the powder. The binder acts as a glue, binding the powder together. Like fused deposition modeling and stereolithography, the base in inkjet powder printing lowers to create layers (Wu et al., 2016).

Selective laser sintering (SLS) or selective laser melting (SLM) uses powdered printing material like inkjet powder printing. These two methods differ in that instead of a binder and an oven as used in inkjet powder printing, selective laser sintering uses a laser to melt the layers of material. This method of printing needs a focused laser beam and the powder printing material.

Things printed using SLS are typically small but precise and can be made of many materials including metal, glass, plastic, and ceramic.

Finally, the most common type of 3D printing in the construction industry is contour crafting. Contour crafting is the most recent technological development in additive manufacturing in construction. This method requires a gantry system, trowels, printing material, and a nozzle. A gantry system is a part of the printer's frame that allows movement on a horizontal pane. Although many different materials can be used in contour crafting, typically this method is used to construct with ceramic or concrete materials (Wu et al., 2016).

These are the current methods of additive manufacturing in construction posing a new question, what is it used for? In its infancy, 3D printing was used to construct parts. This included things like sidewalks, foundations, and walls. In January of 2015 Skanska, a Swedish construction company revealed a five-story tower made partially from 3D printed parts. By May of that same year, the Russian company SPECAVIA announced their plan to sell 3D printers capable of printing entire three-story buildings. Beginning as small parts, the technology advanced to allow printing on a much larger scale. The potential of this industry spans even beyond our atmosphere to the International Space Station (ISS) and even the other planets and orbiting bodies.

NASA and various other companies are developing full-scale additive construction structures for Earth’s moon. These structures would be printed using a material primarily consisting of Lunar soil. With the current level of technological advancement, one of these Lunar structures could potentially be printed in a week, without human aid. The main setback to this project is the printing polymer. The material must be able to withstand the Moon’s atmosphere, or lack thereof. NASA and the ESA are working with various private companies to develop a polymer combining various sustainable additives and lunar soil.

Various prototypes have been created of potential Lunar and Martian habitats that would be 3D printed on site. In 2019 Nasa launched their “3D-printed Habitat Challenge”, incentivising scientists young and old with a total prize pool of $1,100,000. The competition required contestants to submit their affordable, practical, and sustainable ideas for habitat on Earth and beyond. The winning project aptly named “Marsha” was developed by AI Spacefactory. These habitats would be made from a recycled polymer stronger than concrete. This polymer, consisting of Martian rock and renewable bioplastic, helps to solve many issues with Maritan settlement. The prominent ingredient in the material would be sourced on site allowing for lighter travel loads. Additionally, these habitats could be built without human assistance. This saves time and resources as well as eliminates several safety concerns for astronauts and Lunar settlers.

3D printing began as a concept in a science fiction novel and blossomed into a technological innovation that is taking the world by storm. From words on a page to reaching out among the stars this technology is impacting not only the lives of humans, but the entire planet and beyond. There are an abundance of benefits associated with additive manufacturing that contribute to its rapid rise to fame. These range from manufacture and consumer to environmental and worker benefits.

For example, 3D printing construction results in less waste than traditional construction. According to Construction Dive, an organization dedicated to the construction related news, analysis, and trends, there is more than 1 billion tons of construction related waste per year. With the precision of additive construction, estimations or materials needed become more accurate leading to less waste. This benefits contractors, manufacturers, and the environment as a whole. The precise measuring and reduced waste have applications outside of Earth in the future Lunar and Martian colonies as covered in preceding paragraphs.

Additive manufacturing is also significantly faster than traditional construction. An entire building can be potentially manufactured in a matter of days. This increases efficiency and frees up not only time, but resources. Other potential benefits including increased sustainability and decreased worker risk are in the process of being realized.

Although 3D printing appears to be the solution to many issues, it poses a few negative consequences. Among these are increased cost, increased energy consumption, increased worker qualifications, harmful emissions, and job losses. That being said, 3D printing is not on a path to replace traditional manufacturing, but instead to simply aid it. 3D printing in construction is not a successor to traditional manufacturing, but a complement, a tool.

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