

## 3D Printing Technology: Its principles and processes

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### Abstract

3D printing refers to processes used to synthesize a three-dimensional object in which successive layers of material are formed under computer control to create an object. In this paper, there is a detailed description on the principles of 3D printing. The objective is to understand various processes of 3D printing. The main focus is on the working of different technologies of 3D printing. When it comes to 3D printing, there are multiple materials to choose from. So the paper also highlights on different materials which are used for 3D printing. It also mentions various application areas of 3D printing significantly. Various pros and cons of 3D printing are also discussed.

**Keywords:** 3D Printing, computer

### Introduction

3D printing a process of making three dimensional solid objects from a digital file. The creation of a 3D printed object is achieved using additive processes. 3D printing, also known as additive manufacturing (AM), refers to processes used to synthesize a three-dimensional object in which successive layers of material are formed under computer control to create an object. Objects can be of almost any shape or geometry and are produced from digital model data 3D model or another electronic data source such as an Additive Manufacturing File (AMF) file.

3D Printing is an additive manufacturing process that creates a physical object from a digital design. There are different 3D printing technologies and materials we can print with, but all are based on the same principle: a digital model is turned into a solid three-dimensional physical object by adding material layer by layer.

### History

Early additive manufacturing equipment and materials were developed in the 1980s. In 1981, Hideo Kodama of Nagoya Municipal Industrial Research Institute invented two AM fabricating methods of a three-dimensional plastic model with photo-hardening polymer, where the UV exposure area is controlled by a mask pattern or the scanning fiber transmitter.

But on July 16, 1984 Alain Le Méhauté, Olivier de Witte and Jean Claude André filed their patent for the stereo lithography process. It was three weeks before Chuck Hull filed his own patent for stereo lithography. The key to stereo lithography is a kind of acrylic-based material known as photopolymer. Hit a vat of liquid photopolymer with a UV laser beam, and the light-exposed portion will instantly turn into solid piece of plastic, molded into the shape of 3D-model design.

The applications of French inventors were abandoned by the French General Electric Company and CILAS (The Laser Consortium). The claimed reason was "for lack of business perspective". Then in 1984, Chuck Hull of 3D Systems Corporation developed a prototype system based on a process known as stereo lithography, in which layers are added by curing photopolymers with ultraviolet light lasers. Hull defined

the process as a "system for generating three-dimensional objects by creating a cross-sectional pattern of the object to be formed," but this had been already invented by Kodama. Hull's contribution is the design of the STL (Stereo Lithography) file format widely accepted by 3D printing software as well as the digital slicing and infill strategies common to many processes today.

AM processes for metal sintering or melting usually went by their own individual names in the 1980s and 1990s. At the time, nearly all metal working was produced by casting, fabrication, stamping, and machining; although plenty of automation was applied to those technologies (such as by robot welding and CNC), the idea of a tool or head moving through a 3D work envelope transforming a mass of raw material into a desired shape layer by layer was associated by most people only with processes that removed metal (rather than adding it), such as CNC milling, CNC EDM, and many others. But AM-type sintering was beginning to challenge that assumption. By the mid 1990s, new techniques for material deposition were developed at Stanford and Carnegie Mellon University, including microcasting and sprayed materials. Sacrificial and support materials had also become more common, enabling new object geometries.

The umbrella term *additive manufacturing* gained wider currency in the decade of the 2000s. As the various additive processes matured, it became clear that soon metal removal would no longer be the only metalworking process done under that type of control. It was during this decade that the term *subtractive manufacturing* appeared as a retronym for the large family of machining processes with metal removal as their common theme. At this time, the term *3D printing* still referred only to the polymer technologies in most minds, and the term *AM* was likelier to be used in metalworking and end use part production contexts than among polymer/inkjet/stereo lithography enthusiasts.

By the early 2010s, the terms *3D printing* and *additive manufacturing* evolved senses in which they were alternate umbrella terms for AM technologies, one being used in popular vernacular by consumer - maker communities and the media, and the other used officially by industrial AM end

use part producers, AM machine manufacturers, and global technical standards organizations. The 2010s were the first decade in which metal end use parts such as engine brackets and large nuts would be grown in job production.

Agile tooling is a term used to describe the process of using modular means to design tooling that is produced by additive manufacturing or 3D printing methods to enable quick prototyping and responses to tooling and fixture needs. Agile tooling uses a cost effective and high quality method to quickly respond to customer and market needs. It can be used in hydro-forming, stamping, injection molding and other manufacturing processes.

### 1981–1999: The Toddlerhood of Additive Manufacturing

In 1981, Hideo Kodama of Nagoya Municipal Industrial Research Institute published his account of a functional rapid prototyping system using photopolymers. A solid, printed model was built up in layers, each of which corresponded to a cross-sectional slice in the model.

In 1992, Bill Clinton played sax on the Arsenio Hall Show—and 3D Systems created the world's first stereo lithographic apparatus (SLA) machine, which made it possible to fabricate complex parts, layer by layer, in a fraction of the time it would normally take.

### 1999–2010: 3D Printing's Adolescence

The lead-up to Y2K was thrilling—not just because, in 1999, the original *Beverly Hills 90210* entered its last season on the air, but also because the first 3D-printed organ was implanted in humans. Scientists at Wake Forest Institute for Regenerative Medicine printed synthetic scaffolds of a human bladder and then coated them with the cells of human patients. The newly generated tissue was then implanted into the patients, with little to no chance that their immune systems would reject them, as they were made of their own cells.

Medically speaking, this was a great decade for 3D printing. In just 10 short years, scientists from different institutions and startups fabricated a functional miniature kidney, built a prosthetic leg with complex component parts that were printed within the same structure, and bio printed the first blood vessels using only human cells.

This was also the decade where 3D printing met the open-source movement. In 2005, Dr. Adrian Bowyer's Rep Rap Project launched an open-source initiative to create a 3D printer that could basically build itself—or at least print most of its own parts. Its 2008 release, Darwin, is a self-replicating printer that's able to do just that. Suddenly, people everywhere had the power to create whatever stuff they could dream up on their own.

By the mid-2000s, the democratization of manufacturing had captured the public's imagination, as had the idea of mass customization. The first SLS machine became commercially viable in 2006, which opened the door to on-demand manufacturing of industrial parts. 3D-printing startup Objet built a machine that could print in multiple materials, which allowed a single part to be fabricated in different versions, with different material properties. The intensely creative innovations of the decade were topped off with the launch of collaborative co-creation services such as Shape ways, a 3D-printing marketplace where designers can get feedback from consumers and other designers and then affordably fabricate their products.

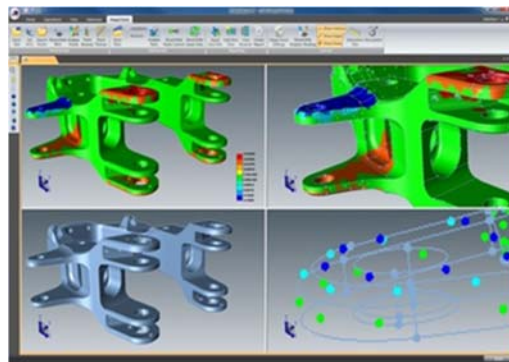
### 2011–Present Day: 3D Printing in Its Prime

Today, looking back over just the past few years, it's hard not to feel like we're living in the future. Coming soon: 3D-printed jetpacks! While the price of 3D printers has fallen rapidly and the accuracy of 3D printing has improved, innovators are pushing the envelope in ways that Charles Hull could only dream of. Designers are no longer limited to printing with plastic.

### Three Random, Cool, Unexpected Facts about 3D Printing

- NASA is a major proponent of 3D printing—from food to the first zero-gravity 3D printer in space.
- There's a 3D printer on the market (the Photonic Professional GT) that can create objects no wider than a human hair.
- This year, Louis DeRosa used a 3Doodler—the 3D-printing pen made famous by netting \$2.3 million on Kickstarter—to create a working hexacopter-framed drone.

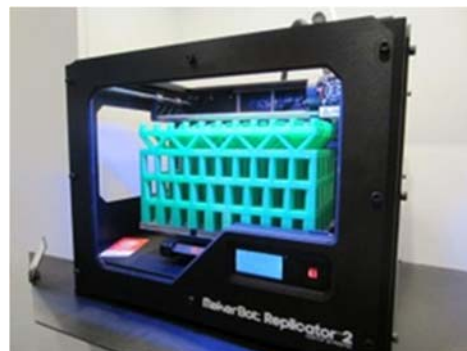
### Principles of 3D printing Modeling



Draw a three-dimensional view on CAD or "animation modeling software" and slice it into "digital cross sections", which are accepted by machine and successively used as an instruction in printing. According to the types of the machine, material is deposited on the platform until "material layering" is finished and the object is printed

Standard Tessellation Language (SLT) file format is a standard data interface connected CAD and the printer. It translates CAD files into a language understood by machines. "An STL file approximates the shape of part or assembly using triangular facets.

### Printing



To execute a print, the design instruction (an STL file) is transferred to the printer and then materials are laid down to generate successive cross sections. These cross sections, corresponding on virtual layers from CAD blueprint, are fused to fabricate the 3D model. Depending on this technique, almost geometric feature can be performed perfectly.

“Printer resolution describes layer thickness & X-Y resolution in micrometers.” Typical thickness of a layer is approximately 100 micrometers while 3D Systems ProJet series is capable of printing 16 micrometers layer. “X-Y resolution is comparable to that of laser printers”. The diameter of particles is between 50 and 100 micrometer.

**Finishing**

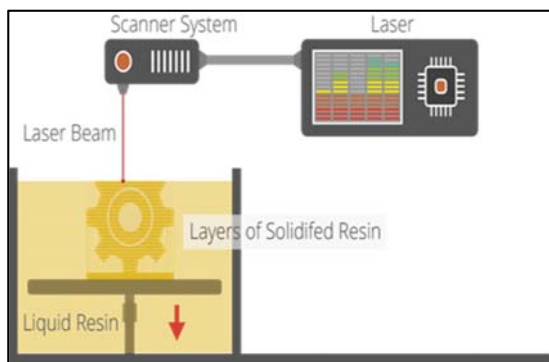


Applications; nevertheless, obtaining larger precision is possible. Choosing a faintly oversized version of the model in standard resolution, and then removing material with “higher-resolution subtractive process” can accomplish it. The printer resolution is adequate for lots of

Some additive manufacturing techniques are able to combine multiple colors and multiple materials during the course of constructing process. In addition, some utilize supports that are removed or dissolved after printing to support overhanging features when printing

**3D Printing Processes**

**Stereolithography**

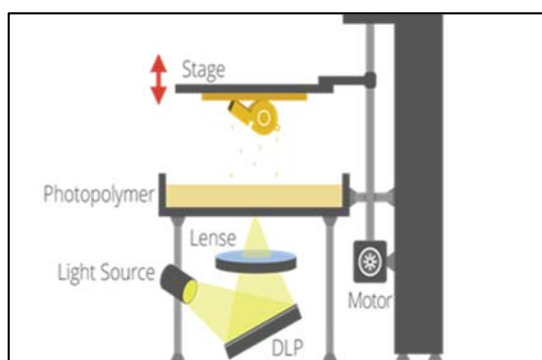


Stereo lithography (SL) is widely recognized as the first 3D printing process; it was certainly the first to be commercialised. SL is a laser-based process that works with photopolymer resins that react with the laser and cure to form a solid in a very precise way to produce very accurate parts. It is a complex process, but simply put, the photopolymer resin is held in a vat with a movable platform inside.

A laser beam is directed in the X-Y axes across the surface of the resin according to the 3D data supplied to the machine (the. stl file), whereby the resin hardens precisely where the laser hits the surface. Once the layer is completed, platform within the vat drops down by a fraction (in the Z axis) & the subsequent layer is traced out by the laser. This continues until the entire object is completed & the platform can be raised out of the vat for removal.

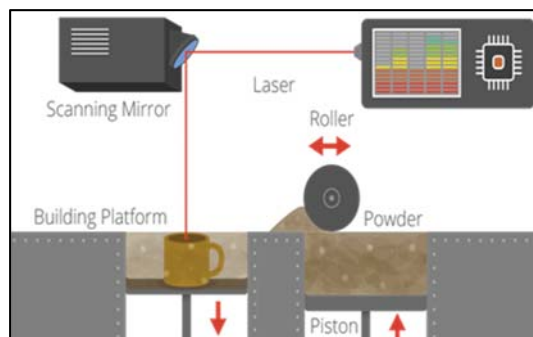
Because of the nature of the SL process, it requires support structures for some parts, specifically those with overhangs or undercuts. These structures need to be manually removed. It is generally accepted as being one of the most accurate 3D printing processes with excellent surface finish. However limiting factors include the post-processing steps required and the stability of the materials over time, which can become more brittle.

**DLP (Digital Light Processing)**



DLP is a similar process to stereolithography in that it is a 3D printing process that works with photopolymers. The major difference is the light source. DLP uses a more conventional light source, such as an arc lamp, with a liquid crystal display panel or a deformable mirror device (DMD), which is applied to the entire surface of the vat of photopolymer resin in a single pass, generally making it faster than SL. Also like SL, DLP produces highly accurate parts with excellent resolution, but its similarities also include the same requirements for support structures and post-curing.

**Laser Sintering / Laser Melting**

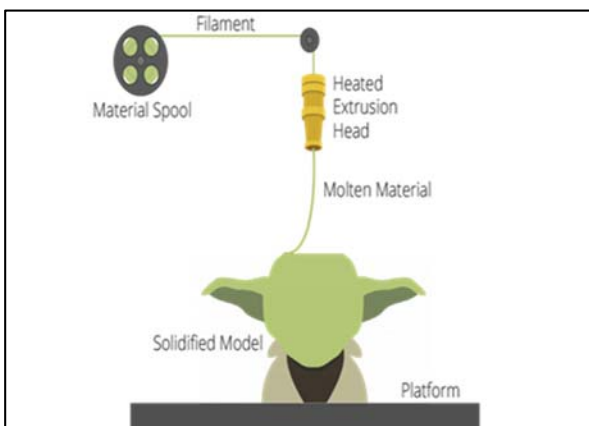


Laser sintering and laser melting are interchangeable terms that refer to a laser based 3D printing process that works with powdered materials. The laser is traced across a powder bed of tightly compacted powdered material, according to the 3D data fed to the machine, in the X-Y axes. As the laser

interacts with the surface of the powdered material it sinters, or fuses, the particles to each other forming a solid.

As each layer is completed the powder bed drops incrementally and a roller smooths the powders over the surface of the bed prior to the next pass of the laser for the subsequent layer to be formed and fused with the previous layer. The build chamber is completely sealed as it is necessary to maintain a precise temperature during the process specific to the melting point of the powdered material of choice. Once finished, the entire powder bed is removed from the machine and the excess powder can be removed to leave the 'printed' parts. One of the key advantages of this process is that the powder bed serves as an in-process support structure for overhangs and undercuts, and therefore complex shapes that could not be manufactured in any other way are possible with this process.

**Extrusion / FDM / FFF**



3D printing utilizing the extrusion of thermoplastic material is easily the most common — and recognizable — 3DP process. The most popular name for the process is Fused Deposition Modelling (FDM), due to its longevity, however this is a trade name, registered by Stratasys, the company that originally developed it. Stratasys' FDM technology has been around since the early 1990's and today is an industrial grade 3D printing process

The process works by melting plastic filament that is deposited, via a heated extruder, a layer at a time, onto a build platform according to the 3D data supplied to the printer. Each layer hardens as it is deposited and bonds to the previous layer.

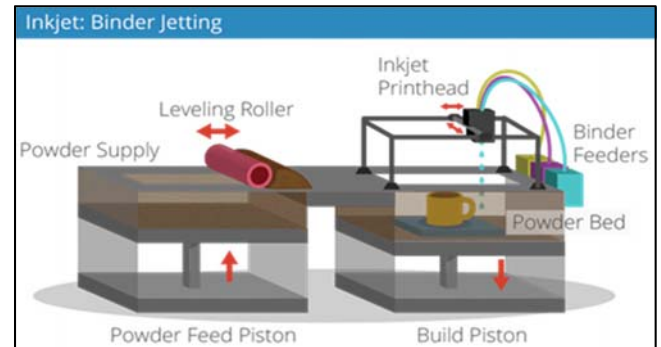
Stratasys has developed a range of proprietary industrial grade materials for its FDM process that are suitable for some production applications. At the entry-level end of the market, materials are more limited, but the range is growing. The most common materials for entry-level FFF 3D printers are ABS and PLA.

The FDM/FFF processes require support structures for any applications with overhanging geometries. For FDM, this entails a second, water-soluble material, which allows support structures to be relatively easily washed away, once the print is complete. Alternatively, breakaway support materials are also possible, which can be removed by manually snapping them off the part. Support structures, or lack thereof, have generally been a limitation of the entry level FFF 3D printers. However, as the systems have evolved and improved to incorporate dual extrusion heads, it has become less of an issue. In terms of models produced, the FDM process is an accurate and reliable

process. At the entry-level, as would be expected, the FFF process produces much less accurate models, but things are constantly improving.

**Inkjet**

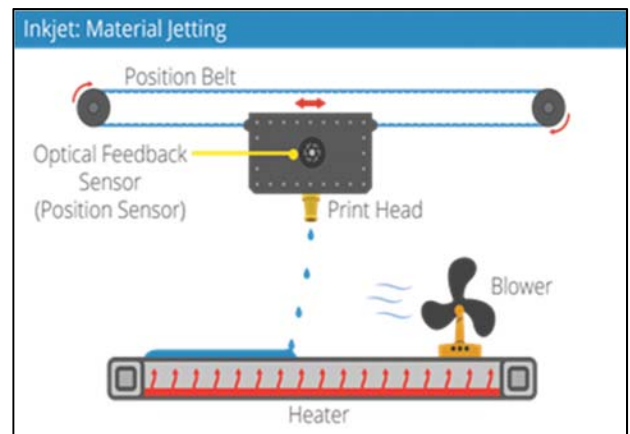
There are two 3D printing processes that utilize a jetting technique.



**Binder jetting**

Where the material being jetted is a binder, and is selectively sprayed into a powder bed of the part material to fuse it a layer at a time to create/print the required part. As is the case with other powder bed systems, once a layer is completed, the powder bed drops incrementally and a roller or blade smooths the powder over the surface of the bed, prior to the next pass of the jet heads, with the binder for the subsequent layer to be formed and fused with the previous layer

The parts resulting directly from the machine, however, are not as strong as with the sintering process and require post-processing to ensure durability.

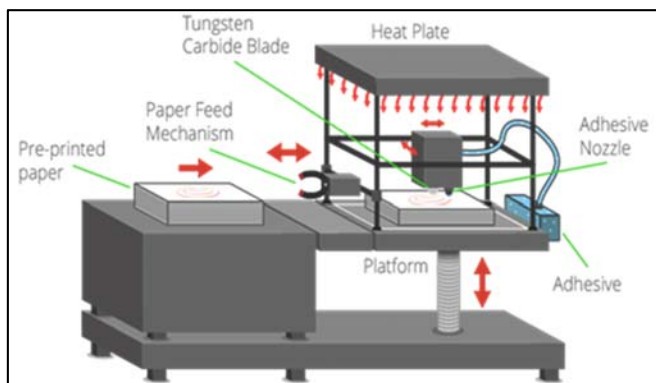


**Material jetting**

A 3D printing process whereby the actual build materials (in liquid or molten state) are selectively jetted through multiple jet heads (with others simultaneously jetting support materials). However, the materials tend to be liquid photopolymers, which are cured with a pass of UV light as each layer is deposited.

The nature of this product allows for the simultaneous deposition of a range of materials, which means that a single part can be produced from multiple materials with different characteristics and properties. Material jetting is a very precise 3D printing method, producing accurate parts with a very smooth finish

### Selective Deposition Lamination (SDL)



SDL is a proprietary 3D printing process developed and manufactured by Mcor Technologies. There is a temptation to compare this process with the Laminated Object Manufacturing (LOM) process developed by Helisys in the 1990's due to similarities in layering and shaping paper to form the final part. However, that is where any similarity ends

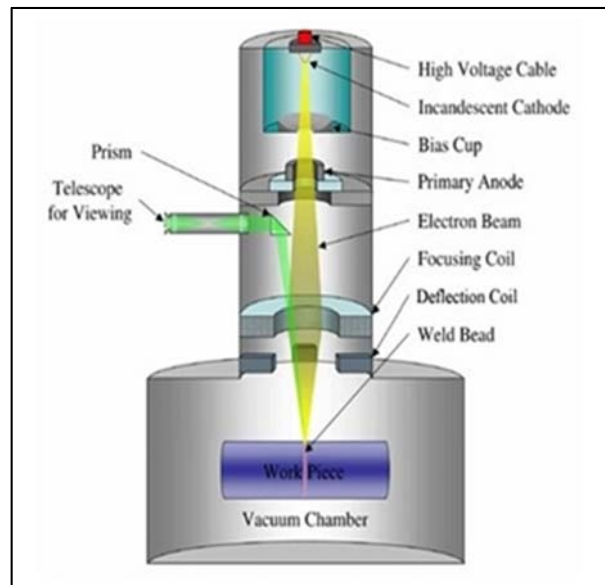
The SDL 3D printing process builds parts layer by layer using standard copier paper. Each new layer is fixed to the previous layer using an adhesive, which is applied selectively according to the 3D data supplied to the machine. This means that a much higher density of adhesive is deposited in the area that will become the part, and a much lower density of adhesive is applied in the surrounding area that will serve as the support, ensuring relatively easy "weeding," or support removal.

After a new sheet of paper is fed into the 3D printer from the paper feed mechanism and placed on top of the selectively applied adhesive on the previous layer, the build plate is moved up to a heat plate and pressure is applied. This pressure ensures a positive bond between the two sheets of paper. The build plate then returns to the build height where an adjustable Tungsten carbide blade cuts one sheet of paper at a time, tracing the object outline to create the edges of the part.

### EBM

The Electron Beam Melting 3D printing technique is a proprietary process developed by Swedish company Arcam. This metal printing method is very similar to the Direct Metal Laser Sintering (DMLS) process in terms of the formation of parts from metal powder. The key difference is the heat source, which, as the name suggests is an electron beam, rather than a

laser, which necessitates that the procedure is carried out under vacuum conditions. EBM has the capability of creating fully-dense parts in a variety of metal alloys, even to medical grade, and as a result the technique has been particularly successful for a range of production applications in the medical industry, particularly for implants. However, other hi-tech sectors such as aerospace and automotive have also looked to EBM technology for manufacturing fulfillment.



The EBM process is conducted under high temperature of about 1000°C. The materials used for EBM are Titanium, Inconel. It is used for medical implants and aerospace areas

### Working of 3D printing

There are 3 main steps in 3D printing. These are same as principles of the 3D printing.

- Preparation
- Printing process
- Finishing

The variety of materials used in 3D printing is very broad. It includes plastics, ceramics, resins, metals, sand, textiles, biomaterials, glass, food and even lunar dust! If we use Plastic or Alumide



### Fused Deposition Modeling (FDM) Technology

Is at the very entry of the market as it mainly used by individuals. It is probably the most popular printing method due to the number of printers available on the market. FDM is an affordable 3D printing process compared to other 3D printing

technologies. This process works by material being melted and extruded through a nozzle to 3D print a cross section of an object each layer at a time. The bed lowers for each new layer and this process repeats until the object is completed. Layer thickness determines the quality of the 3D print.

### SLS Technology

Laser sintering is a 3D printing technique consisting of the fabrication of an object by melting successive layers of powder together in order to form an object. The process most notably facilitates in the creation of complex and interlocking forms. It is available for Plastic and Alumide. If we use Resin or Wax



### Photopolymerisation

A technique that involves the solidification of photo-sensitive resin by means of a UV light. It is used by different 3D printing processes

### Stereolithography (SLA)

Uses a vat of curable photopolymer resin. The build plate descends in small increments and the liquid polymer is exposed to light where the UV laser draws a cross section layer by layer. The process is repeated until a model has been created. The object is 3D printed by pulling the object out of the resin (bottom up), which creates space for the uncured resin at the bottom of the container and can then form the next layer of the object. Another method is to 3D print the object by pulling it downward into the tank with the next layer being cured on the top.

Digital Light Processing (DLP) a projector is used to cure photopolymer resin. This is very similar to the SLA method except that instead of using a UV laser to cure the photopolymer resin, a safelight (light bulb) is used. Objects are created similarly to SLA with the object being either pulled out of the resin, which creates space for the uncured resin at the bottom of the container thus forming the next layer of the object, or down into the tank with the next layer being cured at the top.

Sculpteo uses DLP technology for Silver and Brass 3D printing. 3D print a wax model first then, we use a lost-wax casting technique: a mould is made around the wax before it is melted and filled with silver, creating your object.

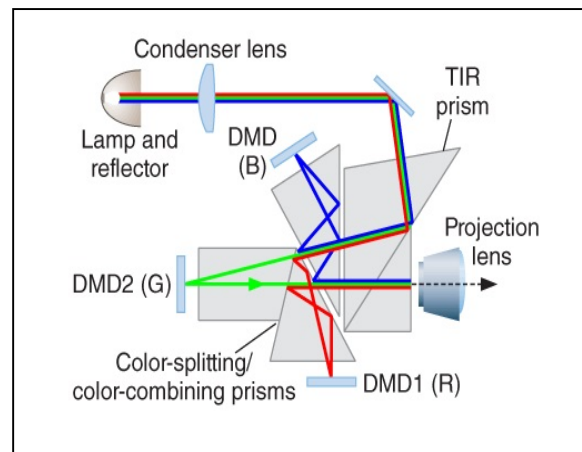
DLP technology was created in 1987 by L. Hornbeck of Texas Instruments & became very popular in Projectors production. It uses digital micro mirrors laid out on a semiconductor chip. The technology is applicable for movie projectors, cell phones & 3D printing.

Continuous Liquid Interface Production (CLIP) works by projecting a continuous sequence of UV images, generated by a digital light projector, through an oxygen-permeable, UV-transparent window below a liquid resin bath. The dead zone created above the window maintains a liquid interface below the part.

### MultiJet Printers

Similar to Stereolithography, the high-quality PolyJet and MultiJet 3D printing processes use a UV light to crosslink a photopolymer. Instead of scanning a laser to cure layers, a printer jet sprays tiny droplets of the photopolymer in the shape of the first layer. The UV lamp attached to the printer head crosslinks the polymer and locks the shape of the layer in place. If we use Metal

DLP combined with the lost-wax casting technique allows objects to be printed in 3D. Sculpteo uses DLP technology for Silver and Brass 3D prints. First, we 3D print a wax model. Then, we use a lost-wax casting technique: a mould is made around the wax before it is melted and filled with silver, thus create the object



The results of such printing are robust and have excellent resolution. Big advantage of DLP over SL is much less materials to be used for detail production that results in lower cost and less waste. Examples of DLP rinses are the Envision Tec Ultra, MiiCraft High Resolution 3D printer, and Lunavast XG2.

### Direct Metal Laser Sintering (DMLS)

Uses a laser as a power source in order to sinter metal powder by aiming a laser and tracing a cross section of the object layer by layer. Direct Metal Laser Sintering is similar to the selective laser sintering process.

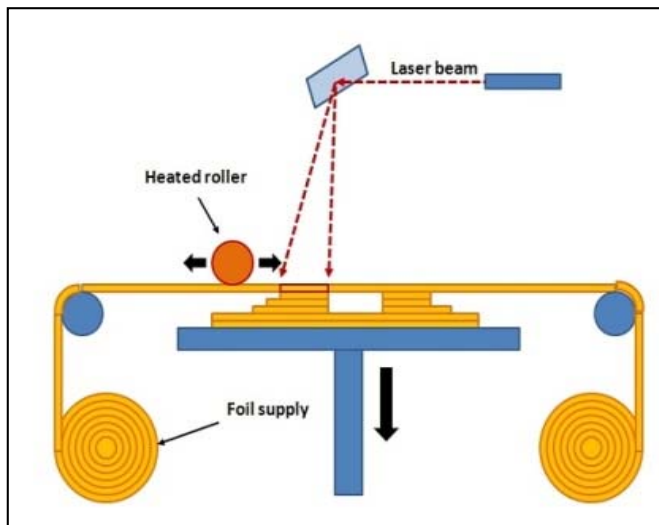
### EBM

Uses an electron beam as the power source instead of a laser to 3D print metal. An electron beam melts metal powder layer by layer within a high vacuum and can achieve full melting of the metal powder. If we use Multicolor



Binder Jetting is popular since you can create detailed 3D prints with colour. An automated roller is used to spread a layer of powder onto the build platform. Excess powder is pushed to the sides and ensures that the bed is filled with a layer of packed powder.

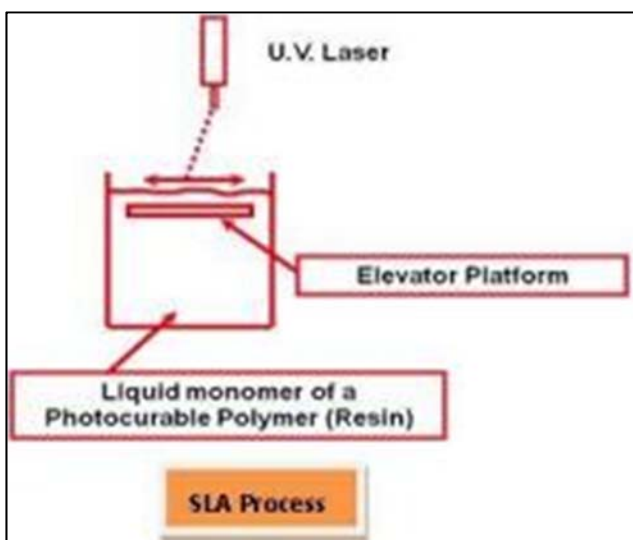
Selective Deposition Lamination is a 3D printing process using paper. This process is similar to Laminated Object Manufacturing (LOM) rapid prototyping method. The process involves layers of adhesive coated paper that are successively glued together with a heated roller and cut to shape with a laser cutter layer by layer. A roller with the material moves each new sheet of material over the last and repeats the process until the object is completed.



Triple-jetting technology (PolyJet) used in Stratasys Objet500 Connex3, is the most advanced method of PolyJet 3D printing. This technology performs precise printing with three materials and thus makes three-colour mixing possible.

**Technologies used in 3D printing**

**i) Stereolithography (SLA) – Liquid Based 3D Printing**



The first commercial 3D printer was based on Stereolithography, invented by Charles Hull in 1986. It is also called as SLA. In these printers, successive layers of fluid resin are hardened using UV rays or lasers. After each layer is fused, the perforated platform is lowered very slightly and another slice is traced out and hardened by the UV / laser. This process is repeated until a complete object has been printed.

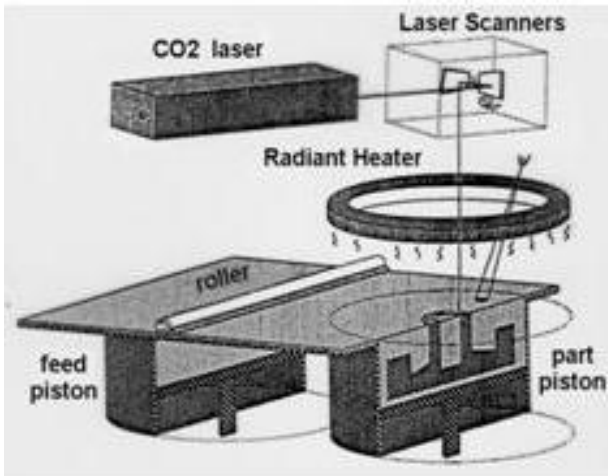
It converts liquid plastic into 3D objects. This technology is widely used in jewellery industry due to its fine surface finish and accuracy. It is one of the most expensive technologies to use. Objects printed cannot be used directly as it needs post-curing operation to strengthen the parts. It requires CAD file to process the object. This file contains information about 3D representation of object. CAD file is converted to printing machine understandable format. There is STL (Standard Tessellation Language) format used by stereolithography & other additive manufacturing processes. The whole process consists of consequent printing of layer by layer. Hence STL file that printing machine uses should have the information for each layer. SLA printing machines don't work as usual desktop printers which extrude some amount of ink to the surface. SLA 3D printers work with excess of liquid plastic that after some time hardens and forms into solid object.

The process of printing includes several steps. It starts from creation of 3D model in CAD program, special piece of software processes the CAD model and generates STL file that contains information for each layer. There could be up to ten layers per each millimeter. Then SLA machine exposes the liquid plastic and laser starts to form the layer of the item



After plastic hardens a platform of the printer drops down in the tank a fraction of a millimeter and laser forms the next layer until printing is completed. Once all layers are printed the object needs to be rinsed with a solvent and then placed in an ultraviolet oven to finish processing. The time required to print an object depends on size of SLA 3d printers used. Small items can be printed within 6-8 hours with small printing machine, big items can be several meters in three dimensions and printing time can be up to several days long. Stereolithography is widely used in prototyping as it doesn't require too much time to produce an object and cost is relatively cheap comparing to other means of prototyping. Although this 3d printing method is rarely used for printing of the final product.

**ii) Selective Layer Sintering (SLS) – Powder Based 3D Printing**



Selective Laser Sintering (SLS) was developed and patented by Dr. Carl Deckard and academic adviser, Dr. Joe Beaman at the University of Texas at Austin in the mid-1980s, under sponsorship of DARPA

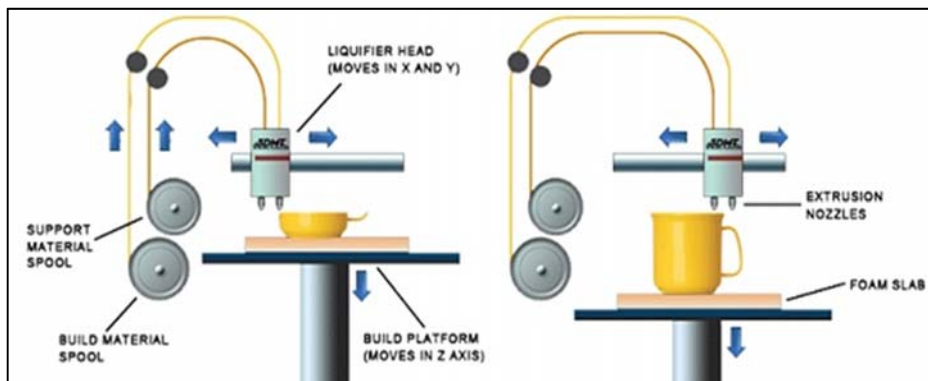
In SLS, a computer controlled laser pulses down on the platform, tracing a cross-section of the object onto tiny particles of plastic, ceramic or glass. The laser heats the powder either to

just below its boiling point (sintering) or above its boiling point (melting), which fuses the particles in the powder together into a solid form. This process continues until the entire object has been printed. SLS parts are widely used for snap-fit applications. As powder is used for printing the parts; special care needs to be taken while handling these machines. These machines can't be used in office environment & needs a special environment

**iii) Fused Deposition Modeling (FDM): Plastic Filament Extrusion Based technology**

Fused Deposition Modeling (FDM) developed & implemented at first time by Scott Crump, Stratasys Ltd. founder, in 1980s. It creates 3D prototypes by heating & extruding a filament of plastic material. In a typical FDM system, the extrusion nozzle moves over the build platform in X and Y directions. This “draws” a cross section of an object onto the platform.

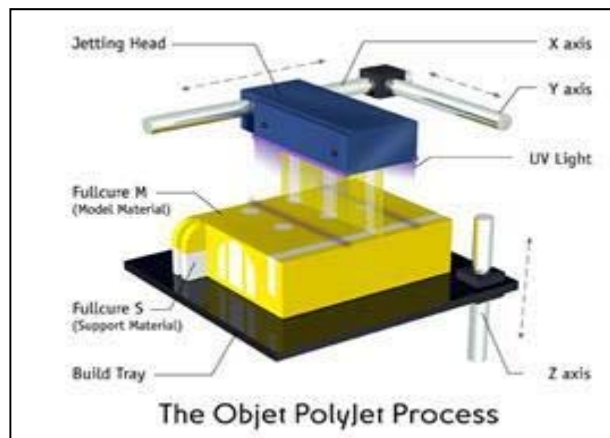
A well-known nowadays company Maker Bot coined a nearly identical technology known as Fused Filament Fabrication (FFF). With help of FDM we can print not only functional prototypes, but also concept models and final end-use products. What is good about this technology that all parts printed with FDM is the only 3D printing technology that builds parts with production-grade thermoplastics, so things printed are of excellent mechanical, thermal & chemical qualities



When this thin layer of plastic cools and hardens, it immediately binds to the layer beneath it. Once a layer is completed, the base is lowered slightly, making way to add the

next layer of plastic. It uses real engineering grade thermoplastics, parts built are stronger, durable and widely used for functional testing applications in Design office.

**iv) PolyJet / InkJet 3D Printing**



PolyJet inkjet technology works by jetting state of the art photopolymer materials in ultra-thin layers (16µ) onto a build tray layer by layer until the part is completed. Each photopolymer layer is cured by UV light immediately after it is jetted, producing fully cured models that can be handled and used immediately, without post-curing. The gel-like support material, which is specially designed to support complicated geometries, is easily removed by hand and water jetting

This technology helps us in printing rigid parts, Transparent Parts, Rubber like / Flexible parts required for prototyping applications. This is the only technology which can print multi-materials and multi-colors in a single build. FDM technology is simple-to-use and environment-friendly. With use of this 3D printing method it became possible to build objects with complex geometries and cavities

### 3D Printing Materials

The materials available for 3D printing have come a long way since the early days of the technology. There is now a wide variety of different material types, which are supplied in different states (powder, filament, pellets, granules, resin etc). These materials are:

#### Plastics

Nylon, or Polyamide, is commonly used in powder form with the sintering process or in filament form with the FDM process. It is a strong, flexible and durable plastic material that has proved reliable for 3D printing. It is naturally white in colour but it can be coloured — pre- or post printing. This material can also be combined (in powder form) with powdered aluminium to produce another common 3D printing material for sintering — Alumide

LayWood is a specially developed 3D printing material for entry-level extrusion 3D printers. It comes in filament form and is a wood/polymer composite. It is also referred to as WPC.

Currently, plastics are the most widely used materials in additive manufacturing, and the important ones are listed below

- ABS - acrylonitrile butadiene styrene or 'lego' plastic – a very common choice for 3D printing
- PLA - polylactic acid – Is available in soft and hard grades, is becoming very popular and may overtake ABS in the near future. It is bio- degradable material.
- PVA - polyvinyl alcohol – This is used as a dissolvable support material or for special applications.
- PC – polycarbonate – Polycarbonate requires high-temperature nozzle design and is in the proof-of-concept stage.
- SOFT PLA - polylactic acid – Is rubbery and flexible, available in limited colors and sources. As 3D printing spreads, may get easy to find

#### Metals

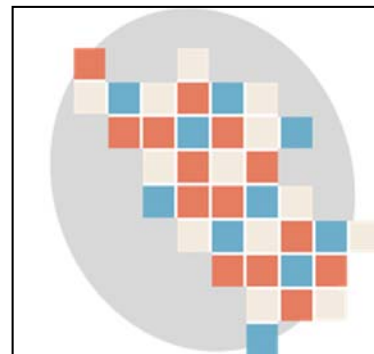
A growing number of metals and metal composites are used for industrial grade 3D printing. Two of the most common are aluminium and cobalt derivatives. 3D printing also uses Stainless Steel in powder form for the sintering/melting/EBM processes. It is naturally silver, but can be plated with other materials to give a gold or bronze effect.

Gold and Silver have been added to the range of metal materials that can be 3D printed directly, with applications across the jewellery sector. These are both very strong materials and are processed in powder form. Titanium is one of the strongest

possible metal materials and has been used for 3D printing industrial applications for some time. Supplied in powder form, it can be used for the sintering/melting/EBM processes. The Materials Science fraternity will also be very interested in 3-D printing for the range of possibilities involving metals. Some of the metals used in 3D printing include the following: Steel, Stainless steel, Titanium, Bronze, Brass.

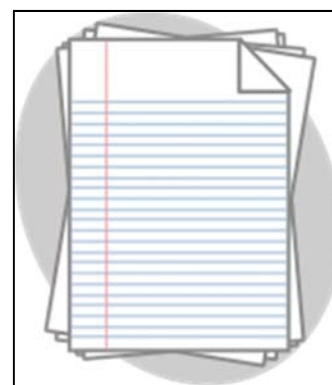
#### Ceramics

Ceramics are a relatively new group of materials that can be used for 3D printing with various levels of success. The particular thing to note with these materials is that, post printing, the ceramic parts need to undergo the same processes as any ceramic part made using traditional methods of production — namely firing and glazing.



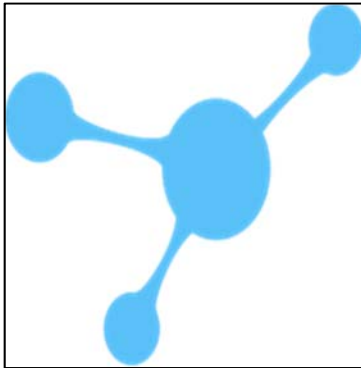
#### Paper

Standard A4 copier paper is a 3D printing material employed by the proprietary SDL process supplied by Mcor Technologies. The company operates a notably different business model to other 3D printing vendors, whereby the capital outlay for the machine is in the mid-range, but the emphasis is very much on an easily obtainable, cost-effective material supply, that can be bought locally. 3D printed models made with paper are safe, easily recyclable and require no post-processing



#### Bio Materials

There is a huge amount of research being conducted into the potential of 3D printing bio materials for a host of medical applications. Living tissue is being investigated at a number of leading institutions with a view to developing applications that include printing human organs for transplant, as well as external tissues for replacement body parts. Other research in this area is focused on developing food stuffs — meat being the prime example.



### Chocolate

Material engineers have devised a way to use chocolate in 3D printers to obtain some delicious treats. With the help of computer-aided manufacturing systems found in 3D printers innovative designs can be developed with this delicious material.

### Bio-Ink

Biomedical professionals such as Anthony Atala are researching the use of materials such as bio-ink. Bio-ink comprises stem cells and cells from a patient, which can be laid down, layer by layer to form a tissue. Human organs such as blood vessels, bladders and kidney portions have been replicated using this technology.

### Bone Material

A research team at Washington State University printed a bone-like material comprising silicon, calcium phosphate and zinc. This bone-like material was integrated with a section of undeveloped human bone cells.

- **Objet Digital Material** - Objet has transformed the 3D printing world by introducing printers that can make use of several materials at the same time. These multi-jet printers can create fine models offering a range of textures, colors and attributes. These mixtures are referred to by Objet as digital material.
- **Objet Tango Family** - Objet has also introduced a rubber-like material that is probably the only one of its kind in 3D printing. Although it is not exactly rubber, it shows a lot of similarity to rubber.
- **Hot Glue** - A common hot glue gun was hooked up by designers to their CAM system and although hot glue may not be significant, the results if any obtained by hobbyists will truly be fascinating.
- **Full Color Sandstone** - This material enables the production of 3D printed creations with almost any color. Fine designs for action figures, architecture and character models are becoming highly popular with this material.
- **Glass** - Ground up glass powder is spread layer by layer, bonded with adhesive spray then baked resulting in 3D printed glass product.
- **Medication** - Engineers and doctors are working together to create 3D-printed medication. Medication need not be always purchased from pharmacies, the days are not far away when they can be printed!!
- **Skin** - Similar to bio-ink, 3D printers can help in skin regeneration. This could bring about a change in how patients receive treatment.

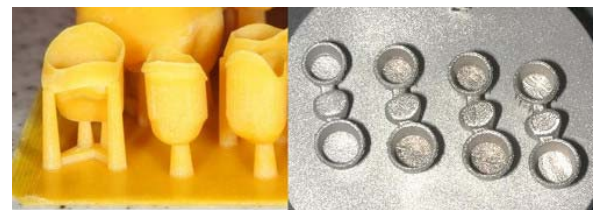
### Applications of 3D Printing

The origins of 3D printing in 'Rapid Prototyping' were founded on the principles of industrial prototyping as a means of speeding up the earliest stages of product development with a quick and straightforward way of producing prototypes that allows for multiple iterations of a product to arrive more quickly and efficiently at an optimum solution. This saves time and money at the outset of the entire product development process and ensures confidence ahead of production tooling.

The developments and improvements of the process and the materials, since the emergence of 3D printing for prototyping, saw the processes being taken up for applications further down the product development process chain. Tooling and casting applications were developed utilizing the advantages of the different processes.

### Medical and Dental

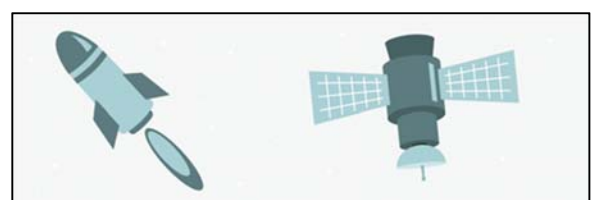
The medical sector is viewed as being one that was an early adopter of 3D printing, but also a sector with huge potential for growth, due to the customization and personalization capabilities of the technologies and the ability to improve people's lives as the processes improve and materials are developed that meet medical grade standards.



Wax implant for indirect manufacturing (left), Co-Cr implant, SLM direct manufacturing (right)

3D printing technologies are being used for a host of different applications. In addition to making prototypes to support new product development for the medical and dental industries, the technologies are also utilized to make patterns for the downstream metal casting of dental crowns and in the manufacture of tools over which plastic is being vacuum formed to make dental aligners. The technology is taking advantage of directly to manufacture both stock items, such as hip and knee implants, and bespoke patient-specific products, such as hearing aids, orthotic insoles for shoes, personalized prosthetics and one-off implants for patients suffering from diseases such as osteoarthritis, osteoporosis and cancer, along with accident & trauma victims. 3D printed surgical guides for specific operations are also an emerging application that is aiding surgeons in their work & patients in their recovery. It is also being developed for the 3D printing of skin, bone, tissue, pharmaceuticals and human organs.

### Aerospace



Like the medical sector, the aerospace sector was an early adopter of 3D printing technologies in their earliest forms for product development and prototyping. These companies, typically working in partnership with academic and research institutes, have been at the sharp end in terms of pushing the boundaries of the technologies for manufacturing applications. Because of critical nature of aircraft development, the R&D is demanding and strenuous, standards are critical and industrial grade 3D printing systems are put through their paces. Process and materials development have seen a number of key applications developed for the aerospace sector — some non-critical parts are all-ready flying on aircraft.

### Automotive

Another general early adopter of Rapid Prototyping technologies — the earliest incarnation of 3D printing — was the automotive sector. Many automotive companies — particularly at the cutting edge of motor sport and F1 — have followed a similar trajectory to the aerospace companies. First using the technologies for prototyping applications, but developing and adapting their manufacturing processes to incorporate the benefits of improved materials and end results for automotive parts.

Many automotive companies are also looking at the potential of 3D printing to fulfill after sales functions in terms of production of spare/replacement parts, on demand, rather than holding huge inventories.

### Jewellery

Traditionally, the design and manufacturing process for jewellery has always required high levels of expertise and knowledge involving specific disciplines that include fabrication, mould-making, casting, electroplating, forging, silver/gold smithing, stone-cutting, engraving and polishing. Each of these disciplines has evolved over many years and each requires technical knowledge when applied to jewellery manufacture. Just one example is investment casting — the origins of which can be traced back more than 4000 years.

For the jewellery sector, 3D printing has proved to be particularly disruptive. There is a great deal of interest — and uptake — based on how 3D printing can, and will, contribute to the further development of this industry. From new design freedoms enabled by 3D CAD and 3D printing, through improving traditional processes for jewellery production all the way to direct 3D printed production eliminating many of the traditional steps, 3D printing has had — and continues to have — a tremendous impact in this sector.

### Art / Design / Sculpture

Artists and Sculptors are engaging with 3D printing in myriad of different ways to explore form and function in ways previously impossible. Whether purely to find new original expression or to learn from old masters this is a highly charged sector that is increasingly finding new ways of working with 3D printing and introducing the results to the world. There are numerous artists that have now made a name for themselves by working specifically with 3D modeling, 3D scanning and 3D printing technologies.

### Architecture

Architectural models have long been a staple application of 3D printing processes, for producing accurate demonstration

models of an architect's vision. 3D printing offers a relatively fast, easy and economically viable method of producing detailed models directly from 3D CAD, BIM or other digital data that architects use.

3D printing processes have improved in terms of resolution and more flexible materials, one industry, renowned for experimentation and outrageous statements. 3D printed accessories including shoes, head-pieces, hats and bags have all made their way on to global catwalks. And some even more visionary fashion designers have demonstrated the capabilities of the tech for haute couture — dresses, capes, full-length gowns etc.

### Food

Food is one of fundamental ingredients of life which is at the base of the pyramid of human needs. Bringing the food industry to the digital age is one of the essential and revolutionary applications of 3D printing. Applying this technology enables fast automated & repeatable processes, freedom in design, as well as allowing large and easy variability of the cooking process which can be customized for each region or individual



### 3D printing of chocolate

Using robotic layer based food printing systems allows the recipe of the food to be digitized and saved in order to prepare very repeatable and high quality dishes without any margin for operator error. Shape and decoration of the food can be individualized.

### Shelter

Shelter is another basic human necessity which can be an interesting application for 3D printing. The building industry is one of the last remaining fields where human labor and skills are the norm & mass manufacturing techniques. Robots are considered science fiction. Conventional building methods are hazardous, time consuming, & expensive; 3D printing of buildings can enable automated creation of variety of buildings quickly.

The technology can be used for a variety of housing projects with application in custom luxury designer homes, large scale development projects, to temporary housing projects. This technology could enable engineers to design & build stiffer & safer geometries for houses i.e. Dom geometries which are typically very labor intensive and difficult to be constructed. It can also help engineers to rebuild and restore old heritage designs quickly.

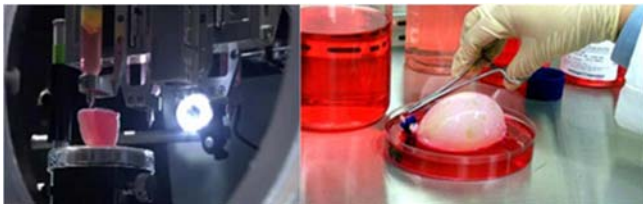
### Health

While much effort is put forth by individuals, societies, and businesses to improve our physical health, an ideal health is very subjective and could depend on location and vary over time. However, it can be said that the absence of sickness, specially, chronic illnesses is a requisite for good health.

Illnesses, accidents, and aging deteriorate the body's or a specific organ's condition. Organ transplants have been successfully conducted in the past.

### Bio-Organ printing

Organ and body tissue regeneration is an incredible ability observed in plants, vertebrates, and mammals. However, this ability is naturally very limited in humans. Regenerative science is expected to provide replacement tissue and entire organs by applying tissue engineering which begins with living cells that are multiplied. The cells are seeded into a 3D containment structure that facilitates the directed 3D growth and proliferation while also providing nutrients to the cells.

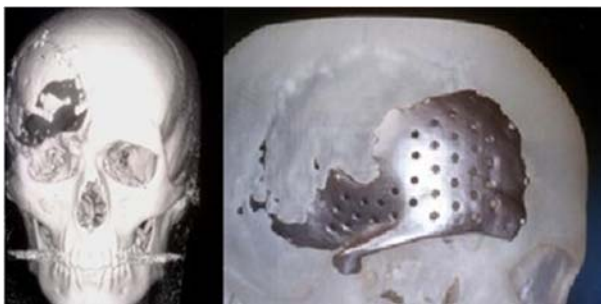


Bio printing machine (left), Bio-printed model of Kidney (right)

3D printing of human tissue & organs revolutionize the healthcare industry by extending the average life expectancy and greatly improving the quality of life. Organ recipients will no longer have to wait months or years for a donor with the correct blood type, organ transplant rejection will be abolished, illegal human trafficking for organ harvesting can be minimized, and war and accident amputees can once again gain full mobility

### Skull and jaw implants

Researchers have shown that 3D printed parts can be used as bone replacement for people whom lost part of their skull or jaw in an accident.



CAD model of skull, installed 3D printed skull implant

### Security and integration

Becoming more integrated and secured implies improving life chances and providing people with equal opportunities. These opportunities may include the ability of human communication or mobility which is considerably difficult for people with various disabilities and illnesses such as considerable in disabilities cases like Arthrogryposis. Regarding this, 3D printing as an advanced technology can compensate the individual's disability or deficiency by manufacturing complex composite 3D objects using 3D scanned data. It can help people regain mobility, improve their employment and social opportunities and possibly help self-reliance and alleviate self-confidence issues.

### Self-actualization

Self-actualization stands at the top of Maslow's hierarchy of needs. The basis form of the perceived need for self-actualization can be defined in a sentence, "What a man can be, he must be". This level of need refers to a person's potential and realizing that potential. Education and creativity as two important branches of self-actualization.

### Education

The education system plays an important role in aiding people achieve their full potential. 3D printing can revolutionize the learning experience by helping students interact with the subject. Affordable 3D printers in schools may be used for a variety of applications which can aid students in finding their field of interest easier and faster. Currently there are different types of educational projects to attract students to the various fields by giving them the opportunity to create & fabricate their own designs using 3D printing technology. The ability to develop & present ideas is one of the most important needs in the society and human development.

### Pros and cons

#### Advantages

- 1. Ability to customize products:** Customization is the norm when it comes to 3D printing. With the desired raw material, a 3D printer, and the required blueprint, we can "manufacture" any object we want, with the specifications and design of our choice. It can make any shape.
- 2. No assembly required:** 3D printing forms interlocked parts. Mass manufacturing is built on the backbone of assembly line. 3D printer could print a door and attached interlocking hinges at the same time, no assembly required. Less assembly will shorten supply chains, save money on labour and transportation. It is less polluting.
- 3. Rapid production of prototypes:** 3D printing enables quick production of prototypes or small-scale versions of the real object. This helps researchers and engineers plan the actual object and catch any design flaws that may affect quality and functionality.
- 4. Low cost of production:** Although the initial cost of setting up a 3D printing facility may be high, the overall savings in the form of labor costs, time saved, and equal effort for small-scale and mass manufacturing ensures that the cost of production is relatively low.
- 5. Increased employment opportunities:** Widespread use of 3D printing technology will increase the demand for designers and technicians to operate 3D printers and create blueprints for products.
- 6. Quick availability of organs:** The long and often traumatic wait for an organ donor could come to an end with advances in bioprinting or manufacture of 3D printed organs. Research is on to create bioprinters that can create living organs along with the structural lattice for the organ using the patient's own cells and tissues.
- 7. Manufacturing Speed and skills:** Just like the previous advantage, the manufacturing speed for a large number of final products is equally fast. There is no complexity in manufacturing. Unskilled manufacturers can also offer mode of production for people in remote environments or extreme circumstances.

8. **Reduced Costs:** Even though the initial setup costs are higher, 3D printing has become cheaper than cheap labor in third world countries. Additionally, the costs of 3D printing are still decreasing, with the potential of 3D printers in homes in the near future. Furthermore, the costs of customized products are the same for mass production products.
9. **Medical:** One of the innovative products that 3D printing may provide is the manufacturing of customizable human body parts or organs. While these usages are still experimental, the potential advantages are huge. Imagine doctors quickly building and replacing critical organs, such as the heart, lungs, or liver that will have almost no chance of donor rejection, since the organs will be built using the patients' unique characters and DNA.

#### Disadvantages

1. **Intellectual property issues:** The ease with which replicas can be created using 3D technology raises issues over intellectual property rights. The availability of blueprints online free of cost may change with for-profit organizations wanting to generate profits from this new technology.
2. **Limitations of size:** 3D printing technology is currently limited by size constraints. Very large objects are still not feasible when built using 3D printers.
3. **Limitations of raw material:** At present, 3D printers can work with approximately 100 different raw materials. This is insignificant when compared with the enormous range of raw materials used in traditional manufacturing. More research is required to devise methods to enable 3D printed products to be more durable and robust.
4. **Cost of printers:** The cost of buying a 3D printer still does not make its purchase by the average householder feasible. Also, different 3D printers are required in order to print different types of objects. Also, printers that can manufacture in color are costlier than those that print monochrome objects.
5. **Limited Materials:** Currently, 3D printers only manufacture products out of plastic, resin, certain metals, and ceramics. 3D printing of products in mixed materials and technology, such as circuit boards, are still under development.
6. **Dangerous Items:** 3D printers can create dangerous items, such as guns and knives, with very little or no oversight.

#### Conclusion

3D Printing technology could revolutionize and re-shape the world. Advances in 3D printing technology can significantly change and improve the way we manufacture products and produce goods worldwide. An object is scanned or designed with Computer Aided Design software, then sliced up into thin layers, which can then be printed out to form a solid three-dimensional product. 3D printing can have an application in almost all of the categories of human needs. While it may not fill an empty unloved heart, it will provide companies and individuals fast and easy manufacturing in any size or scale limited only by their imagination. One of the main advantages of the industrialization revolution was that parts could be made nearly identically which meant they could be easily replaced without individual tailoring. 3D printing, on the other hand, can enable fast, reliable, and repeatable means of producing tailor-made products which can still be made inexpensively due to

automation of processes and distribution of manufacturing needs. If the last industrial revolution brought us mass production and the advent of economies of scale - the digital 3D printing revolution could bring mass manufacturing back a full circle - to an era of mass personalization, and a return to individual craftsmanship.

The 3D printing industry continues to innovate its hardware as well as the materials and processes to create objects or parts. Depending on many factors such as budget, design or function, choosing the appropriate 3D printing process as well as the right material is important. 3D printing can create many different 3D printed objects that were previously only fabricated through mass manufacturing methods.

#### Future Aspects

3D printers have many promising areas of potential future application. They may be used to output spare parts for all products, and which could not possibly be stocked as part of the inventory of even the best physical or even online store. Hence, rather than throwing away a broken item, faulty goods will be able to be taken to a local facility that will call up the appropriate spare parts and simply print them out. 3D printers may also be used to make future buildings.

Another future application is the use of 3D printers to create replacement organs, and even to directly repair the human body in situ. This is known as bio-printing, and is an area of rapid development.

#### References

1. Gebhardt A. Understanding Additive Manufacturing, Hanser Publications Cincinnati, 2011.
2. Maslow AH. A Theory of Human Motivation, Psychological Review 1943; 50(4):370-96.
3. <http://www.chocedge.com>
4. Lipton J. Multi-Material food printing with complex internal structure suitable for conventional post processing, utexas 2010, 809-8015.
5. Khoshnevis B. Experimental investigation of contour crafting using ceramic materials, Rapid Prototyping Journal. 2001; 7(1):32-42,
6. <http://www.rael-sanfratello.com/?p=916>
7. Anthony Atala, Institute for Regenerative Medicine, TED conference
8. Fachhochschule Aachen university, Silber fuer Zukunft project
9. Jo-hayes award, <http://www.johayes.com>
10. Jain RA. Biomaterials 2000; 21:2475.
11. Lindenfeld Eric. Strict Liability and 3D-Printed Medical Devices. Yale Journal of Law and Technology, 2015.