Additive Manufacturing
Module-1

Presented by:

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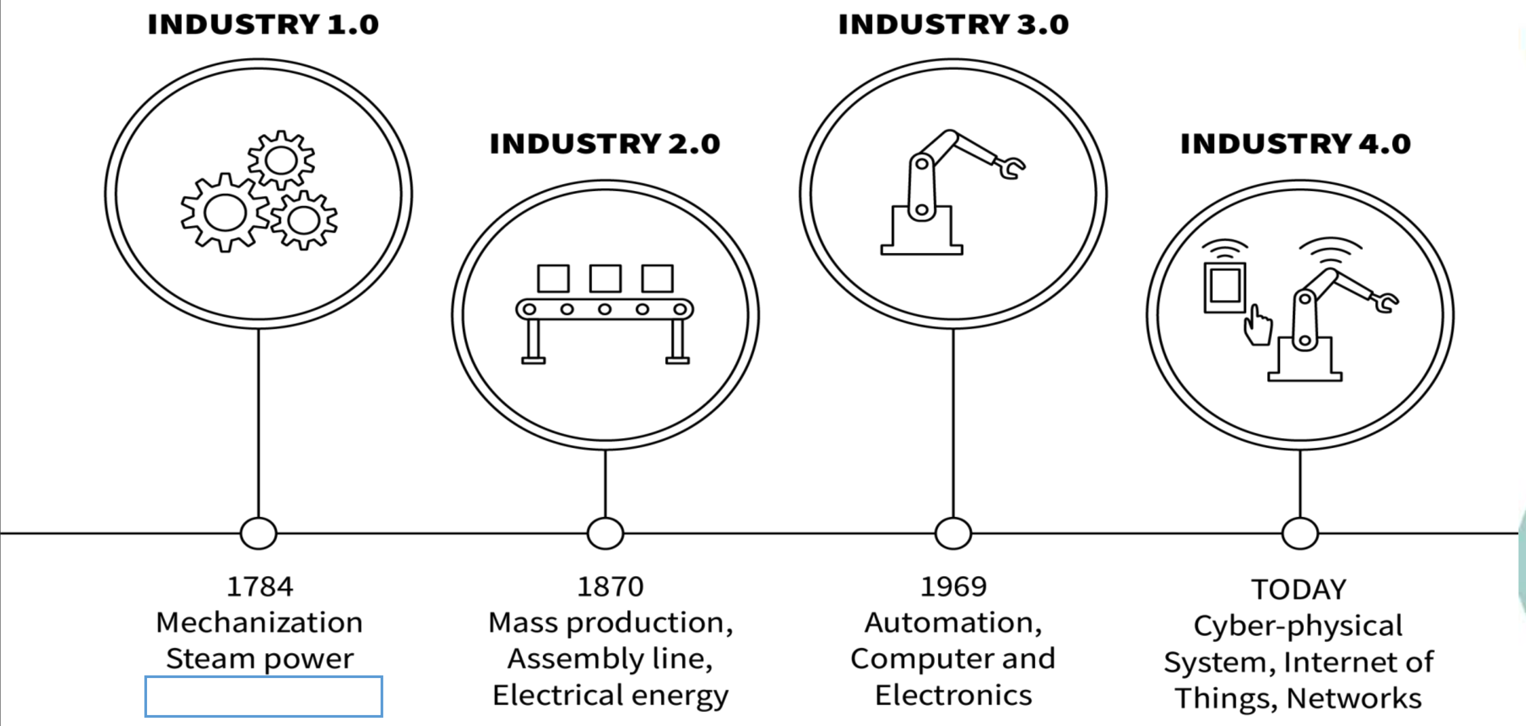
Declaration

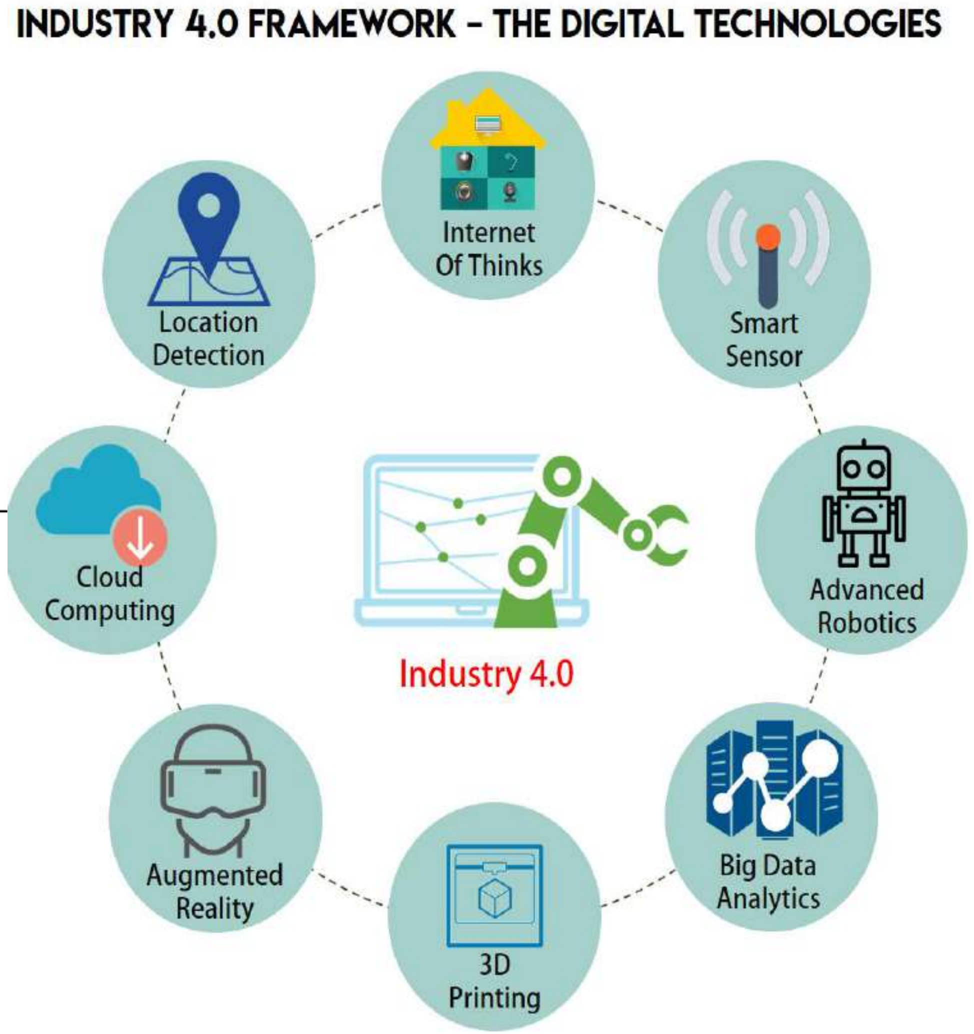
This is Prepared for the Education Purpose only

Source: https://www.theguardian.com/education/2014/oct/31/education-traditional-teaching-versus-progressive

Module-I: (10 Hours)

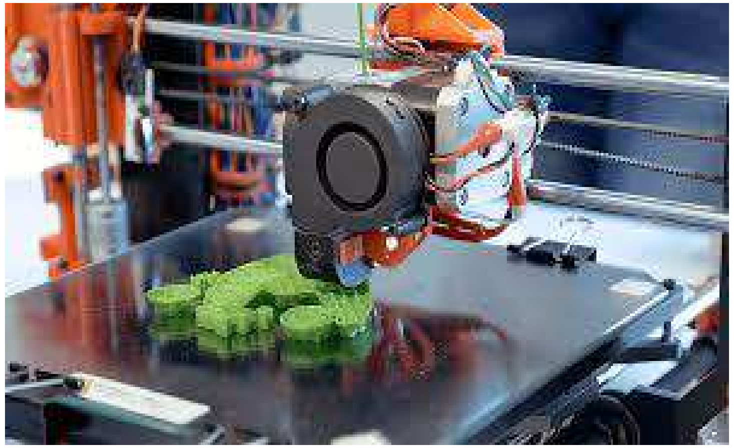
Introduction, Prototyping fundamentals, Historical development, Advantages of AMT, Commonly used terms, process chain, 3D modeling, Data Conversion, and transmission, Checking and preparing, Building, Post processing, RP data formats, Classification of AMT process, Applications to various fields

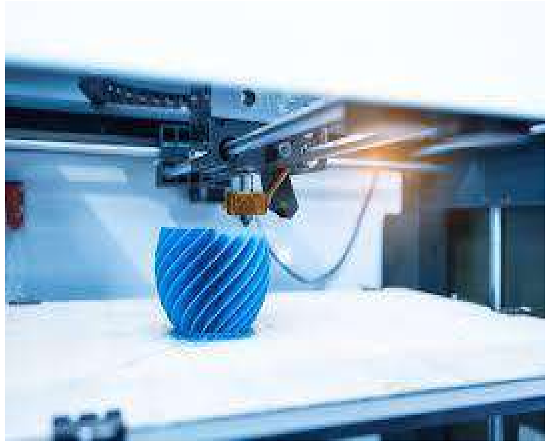

INDUSTRY 1.0
INDUSTRY 2.0
INDUSTRY 3.0
INDUSTRY 4.0
1784
Mechanization
Steam power
1870
Mass production,
Assembly line,
Electrical energy
1969
Automation,
Computer and
Electronics
TODAY
Cyber-physical
System, Internet of
Things, Networks

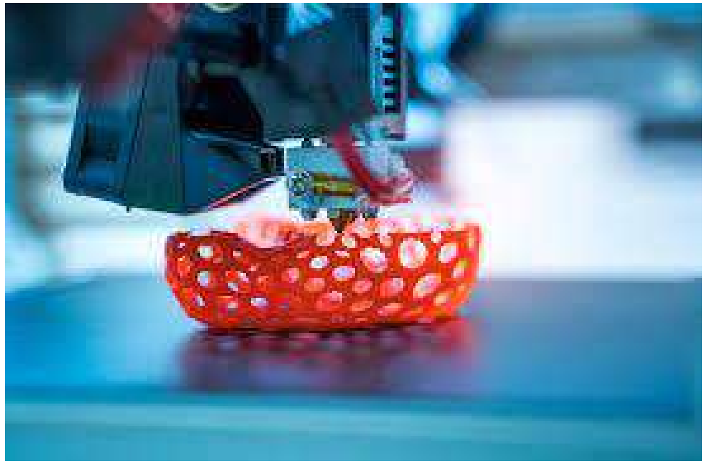

INDUSTRY 4.0 FRAMEWORK – THE DIGITAL TECHNOLOGIES
Internet
Of Thinks
Location
Detection
Smart
Sensor
Cloud
Computing
Industry 4.0
Advanced
Robotics
Augmented
Reality
3D
Printing
Big Data
Analytics

Introduction

- Additive manufacturing (AM) or additive layer manufacturing (ALM) is the industrial term for 3D printing.
- 3D printing is the technique of creating physical items from a digital model. It is a computer-controlled technique that includes depositing materials such as metal, plastic, and ceramic in solid/liquid/powder form in thin two-dimensional layers to create a three- dimensional item.







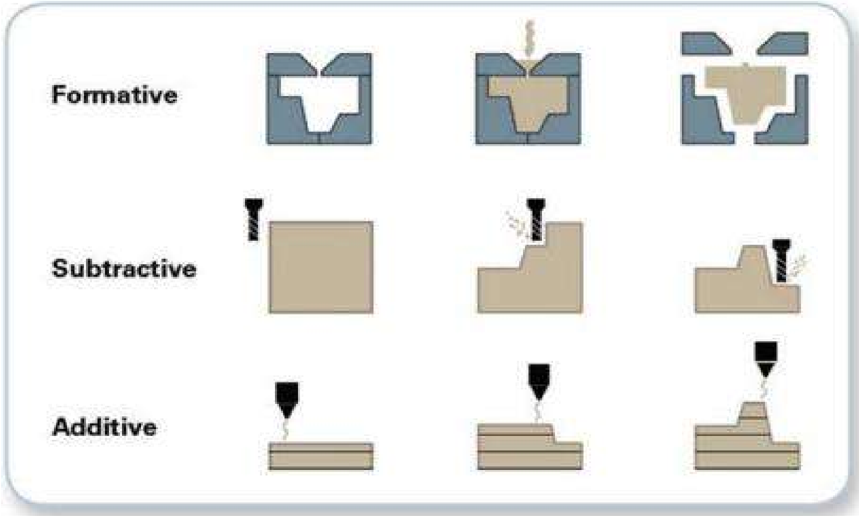
Definition of Additive Manufacturing

- ISO/ASTM 52900 defines Additive Manufacturing (AM) as the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies.

Mandatory conditions for a process to qualify as AM:

- It should be a process of joining of materials.
- It should be starting from three-dimensional (3D) model data.
- It should have preferably layer-by-layer build up approach for manufacturing
- It should not follow subtractive manufacturing methodologies.
- It should not follow formative manufacturing methodologies.

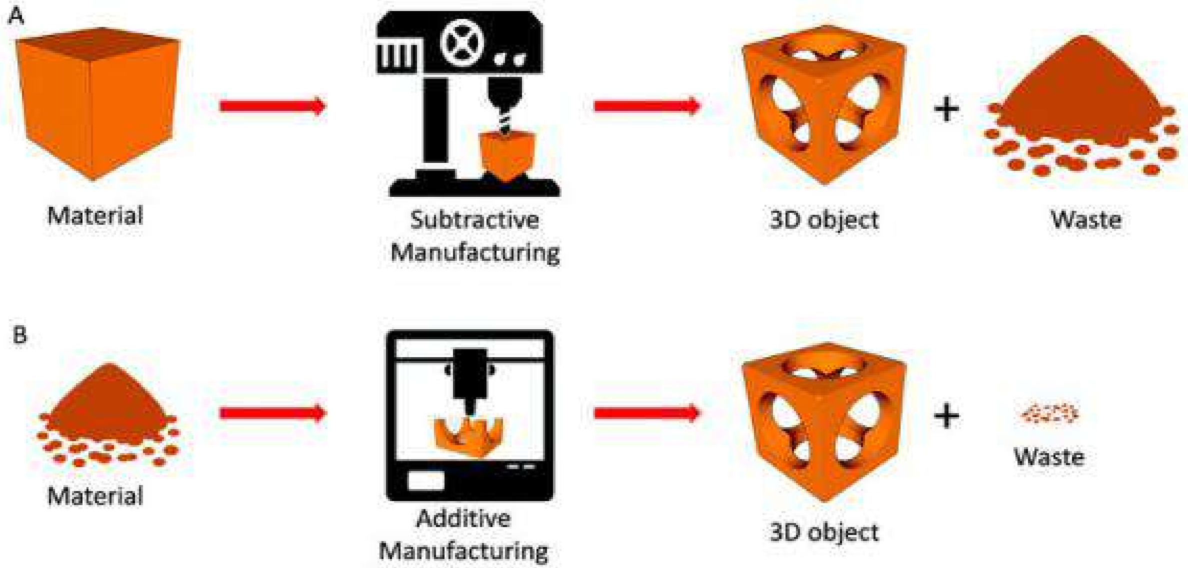
ADDITIVE VS SUBTRACTIVE MANUFACTURING PROCESSES

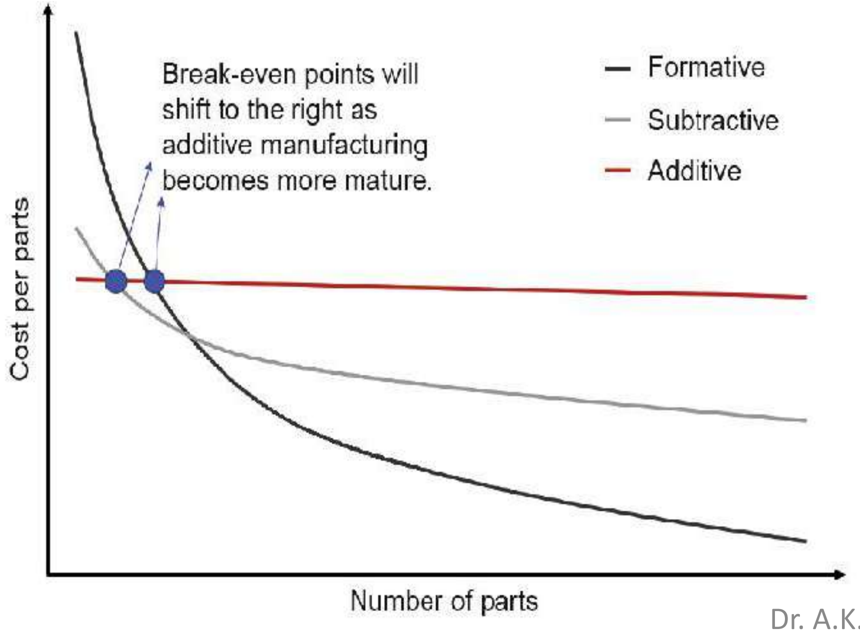


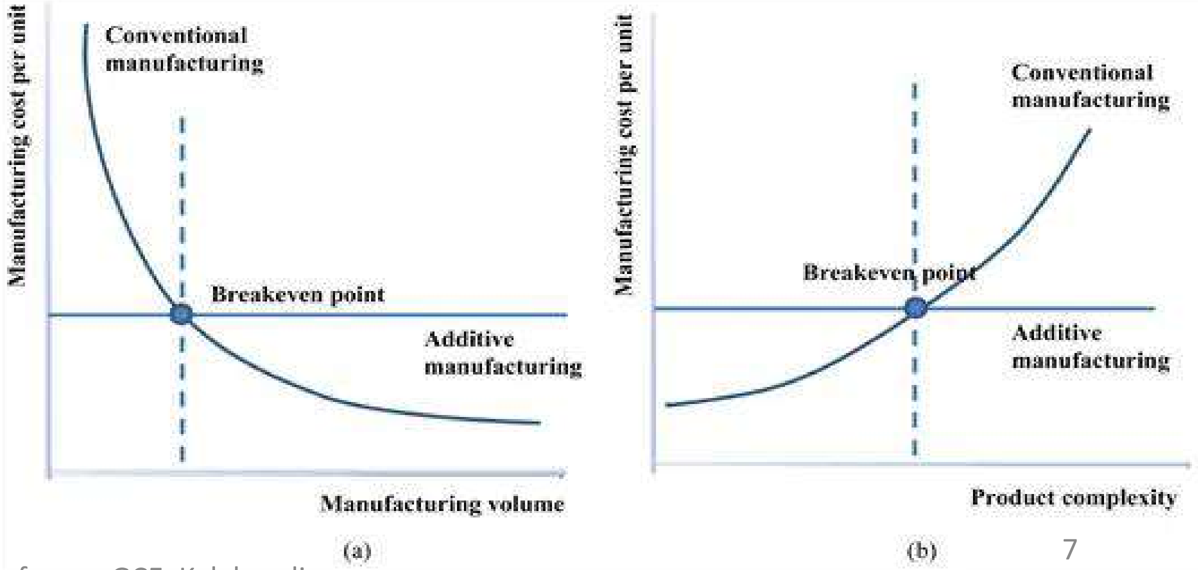
Casting, Forming, Welding

Machining

3D Printing Processes



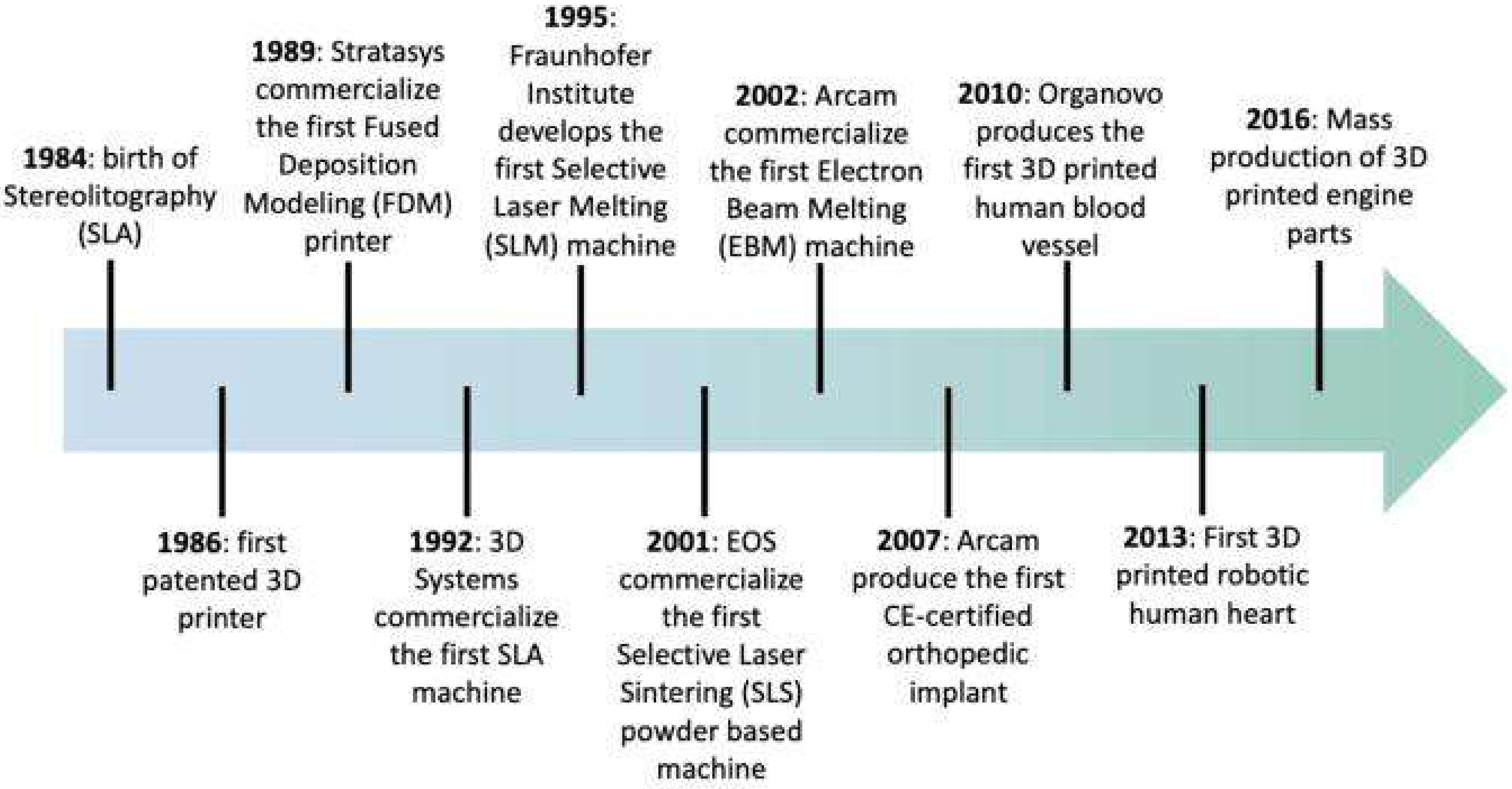




History of 3D Printing process

Key Milestones in 3D Printing History

Year	Innovation/Inventor	Technology/Process
1981	Hideo Kodama	Layer-by-layer UV resin prototyping
1984	Chuck Hull	Stereolithography (SLA), STL files
1988	Carl Deckard (University of Texas)	Selective Laser Sintering (SLS)
1989	Scott Crump	Fused Deposition Modeling (FDM)
1990	Commercial expansion	Prototyping in industry
2000	Patent expirations	Consumer and open-source printers
2010	Material and application boom	Metals, bioprinting, large-scale


1984: birth of Stereolitography (SLA)
1986: first patented 3D printer
1989: Stratasys commercialize the first Fused Deposition Modeling (FDM) printer
1992: 3D Systems commercialize the first SLA machine
1995: Fraunhofer Institute develops the first Selective Laser Melting (SLM) machine
2001: EOS commercialize the first Selective Laser Sintering (SLS) powder based machine
2002: Arcam commercialize the first Electron Beam Melting (EBM) machine
2007: Arcam produce the first CE-certified orthopedic implant
2010: Organovo produces the first 3D printed human blood vessel
2013: First 3D printed robotic human heart
2016: Mass production of 3D printed engine parts

ADDITIVE VS SUBTRACTIVE MANUFACTURING PROCESSES

Features	Additive Manufacturing	Subtractive Manufacturing
Process	It involves adding material in a layered manner, with each layer being placed on top of the previous one. This process is similar to constructing a house by stacking bricks.	Subtracting (removing) material from a bulk material piece can be understood as a process similar to carving a cave.
Equipment	This process encompasses digital manufacturing techniques like 3D printing and additive fabrication, which include methods such as material jetting, material extrusion, binder jetting, directed energy deposition, powder bed fusion, and sheet lamination.	This process involves traditional and advanced metal cutting techniques, such as CNC machining, laser cutting, EDM, plasma cutting, waterjet cutting, and abrasive processes. These methods encompass operations like turning, milling, drilling, grinding, cutting, and boring.
Production	These processes are suitable for creating prototypes and small batch production, making them ideal for testing designs and producing limited quantities of products.	These methods are best suited for mass production, allowing for the efficient and cost-effective manufacturing of large quantities of products.
Accuracy	Tolerance as small as 0.004′′	Tolerance as small as 0.001′′

ADDITIVE VS SUBTRACTIVE MANUFACTURING PROCESSES

Features	Additive Manufacturing	Subtractive Manufacturing
Additional Equipment	Post-processing systems are essential for certain printers to ensure the final product meets desired quality and appearance standards. These systems typically involve curing, finishing, and cleaning processes, which help to enhance the strength, durability, and aesthetics of the printed parts.	Different tooling, fixtures, robots, material handling systems, coolant systems, tool changers, and waste removal equipment may be required.
Complexity	Complex designs containing natural geometry can easily be realized using 3D printing.	It is suitable for mechanical designed parts. For nature-inspired or natural designs (bone etc.) it may not be suitable.
Materials	The majority of the materials are plastic. Metals, ceramics, plasters, graphite, carbon fibre, polymers, and paper are among the other materials used.	Metals, ceramics, plasters, graphite, carbon fiber, polymers, and paper are some of the other materials.

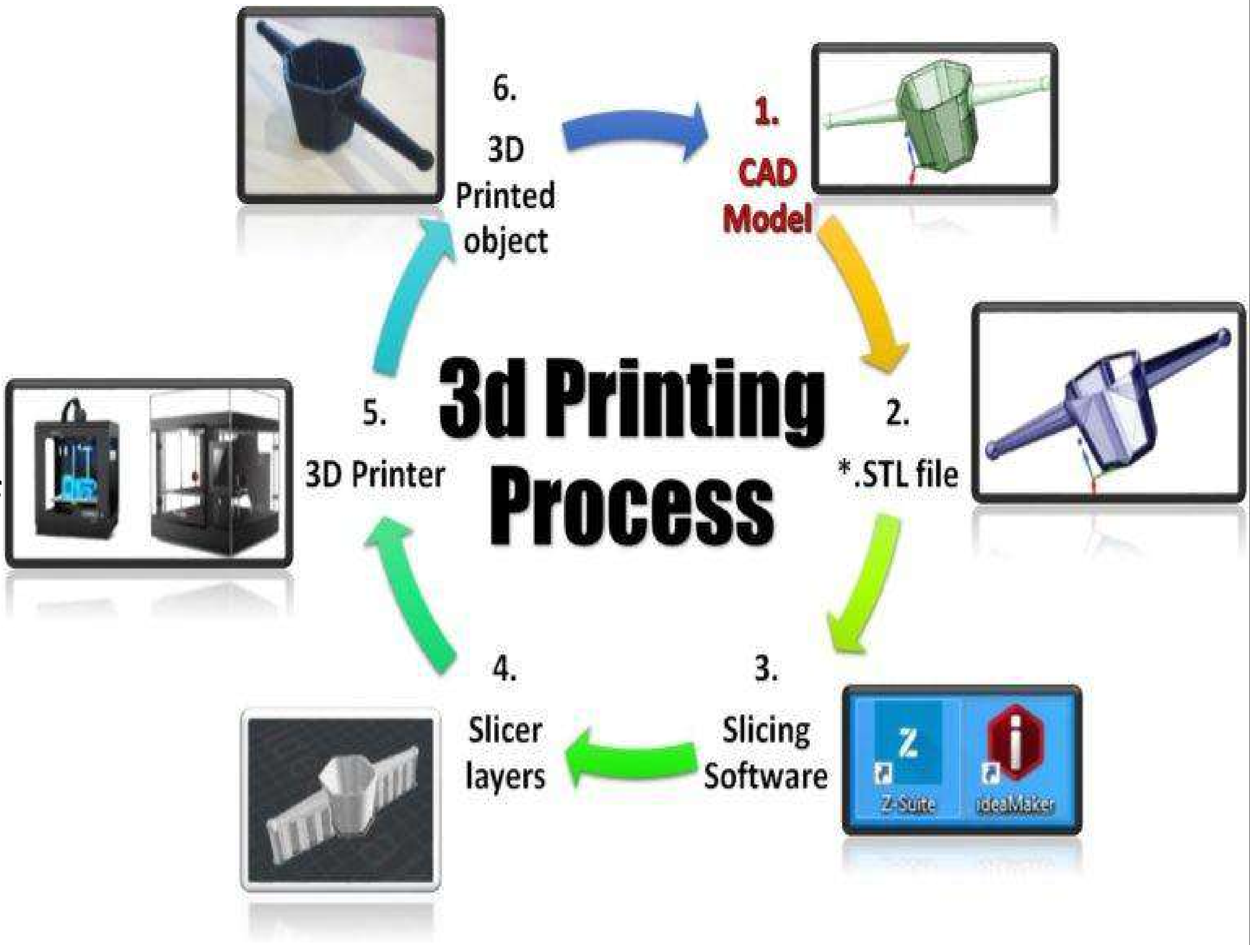
Points to Remember:

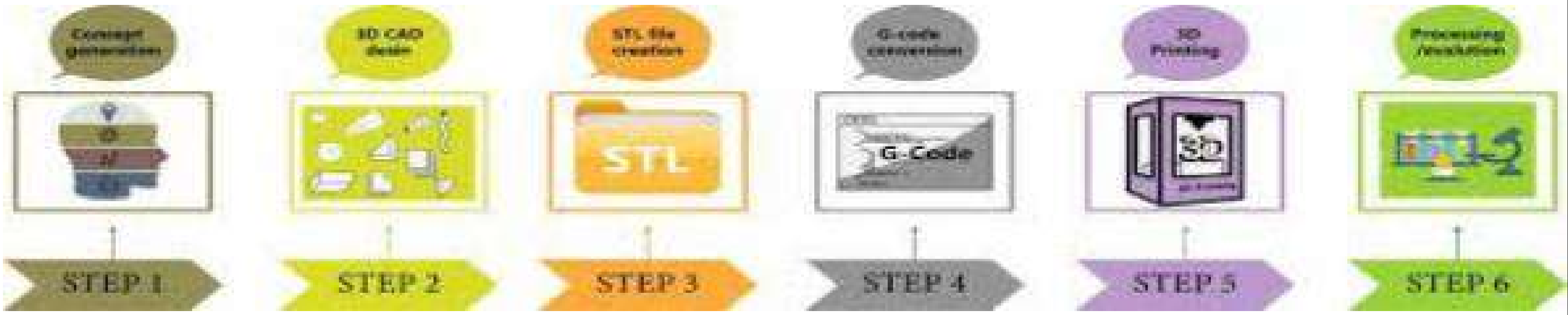
- **Prototype:** It is the original form or the formulation of the intended product, which is similar enough and has enough functionality to check the function of the intended product.
- **Model:** It is a representation and the major aim is to show the appearance of something, which can be a product, style or design or an abstract scientific theory. It may not have full functionality and is often built at a reduced scale than the planned product.
- **Rapid Prototyping:** The technology to rapidly build a scaled model/Prototype of a physical component using 3D digital model data in a layer-by-layer fashion. Later it is termed as Additive Manufacturing.
- **Rapid Tooling:** It is the technology that uses rapid prototyping to build a tool quickly in a direct or indirect manner.
- **Rapid Manufacturing:** It is defined as the process of manufacturing end-use products from 3D model data using layer-by-layer build-up approach.

3D Printing Process

Producing a 3D file

- Digital model making through CAD or Reverse Engineering
- STL creation (STL/OBJ/3DS)
- File manipulation: Slicing into layers, generation of G-Code
- Printing and Removal of supports
- Post processing: UV curing, Sintering, support material removal, Abrasive polishing, Grinding, Chemical/electrochemical etching, EDM, WEDM, AWJM, Surface melting using laser beam/plasma/TIG etc.





Application of 3D Printing/Additive Manufacturing

Manufacturing: Enables rapid prototyping and production of complex, custom parts.

Dental: Used for creating dental prosthetics and orthodontic devices.

Healthcare: Facilitates the creation of medical devices and patient-specific surgical guides.

Jewelry: Allows for intricate, customized designs and production.

Biomedical Implants: Offers the ability to produce patient-specific, complex implants.

Pharmaceuticals: Enables personalized drug dosages and unique drug delivery systems.

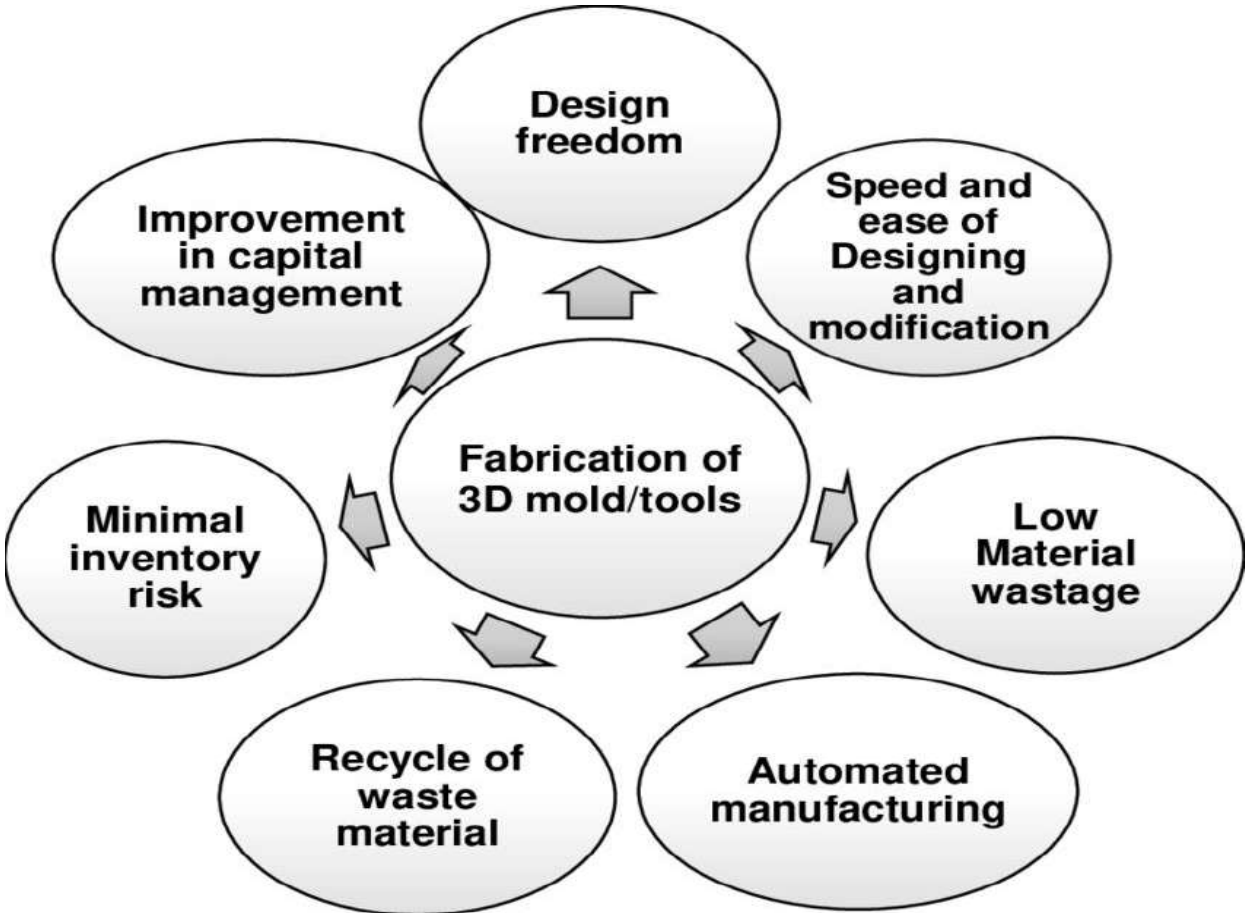
Custom-Fitted Personal Products: Allows for tailored products, such as footwear and eyewear.

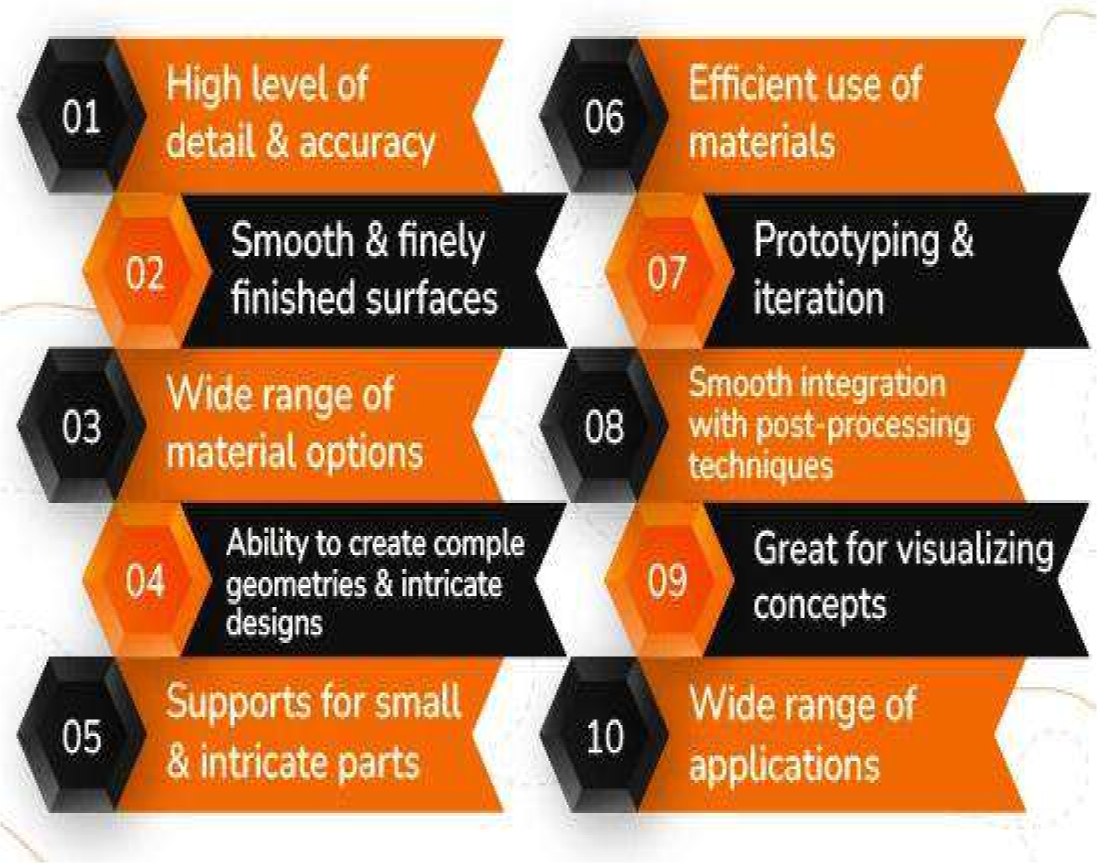
Educational Materials: Enhances learning experiences with hands-on models and visual aids.

Replacement Parts: Provides on-demand production of spare parts for household items.

Civil Construction: Showcases potential for sustainable, efficient buildings and infrastructure.

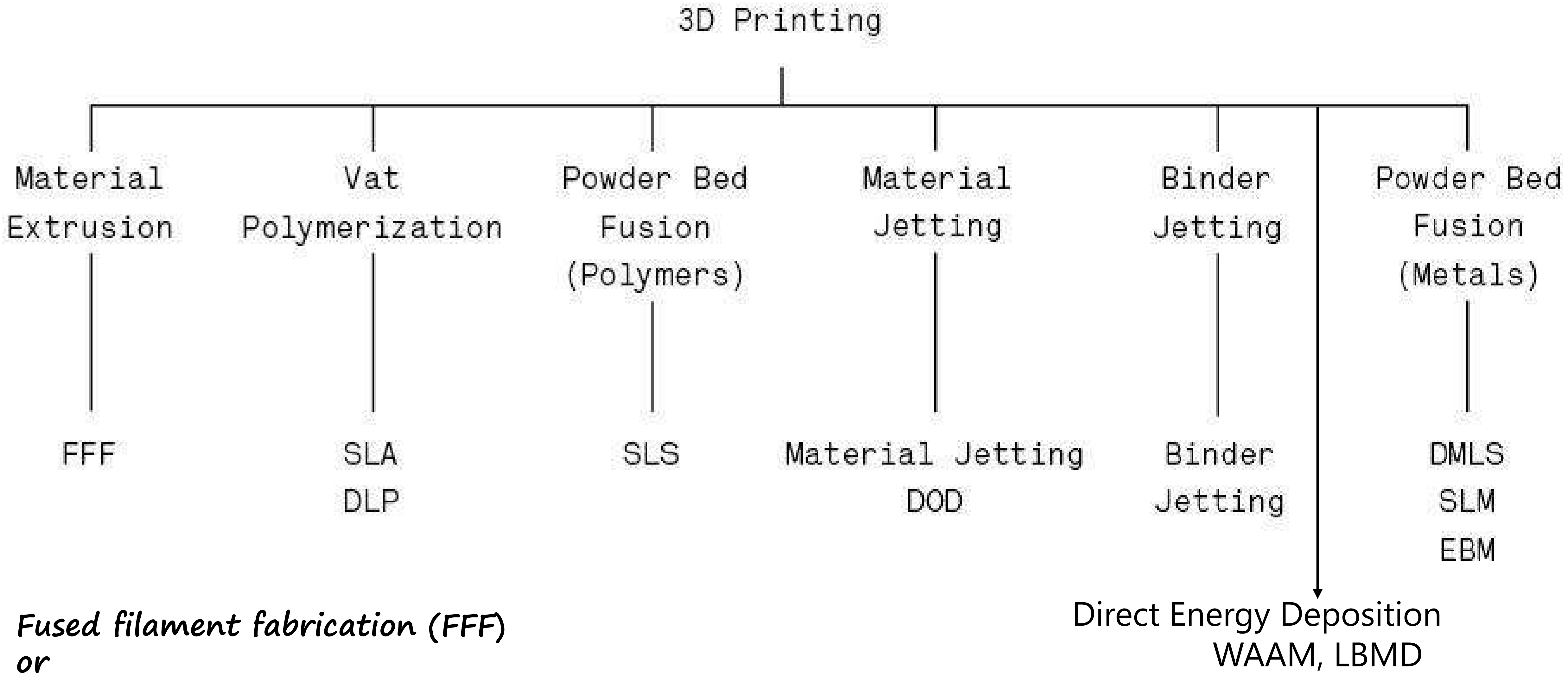
Advantages of Additive Manufacturing





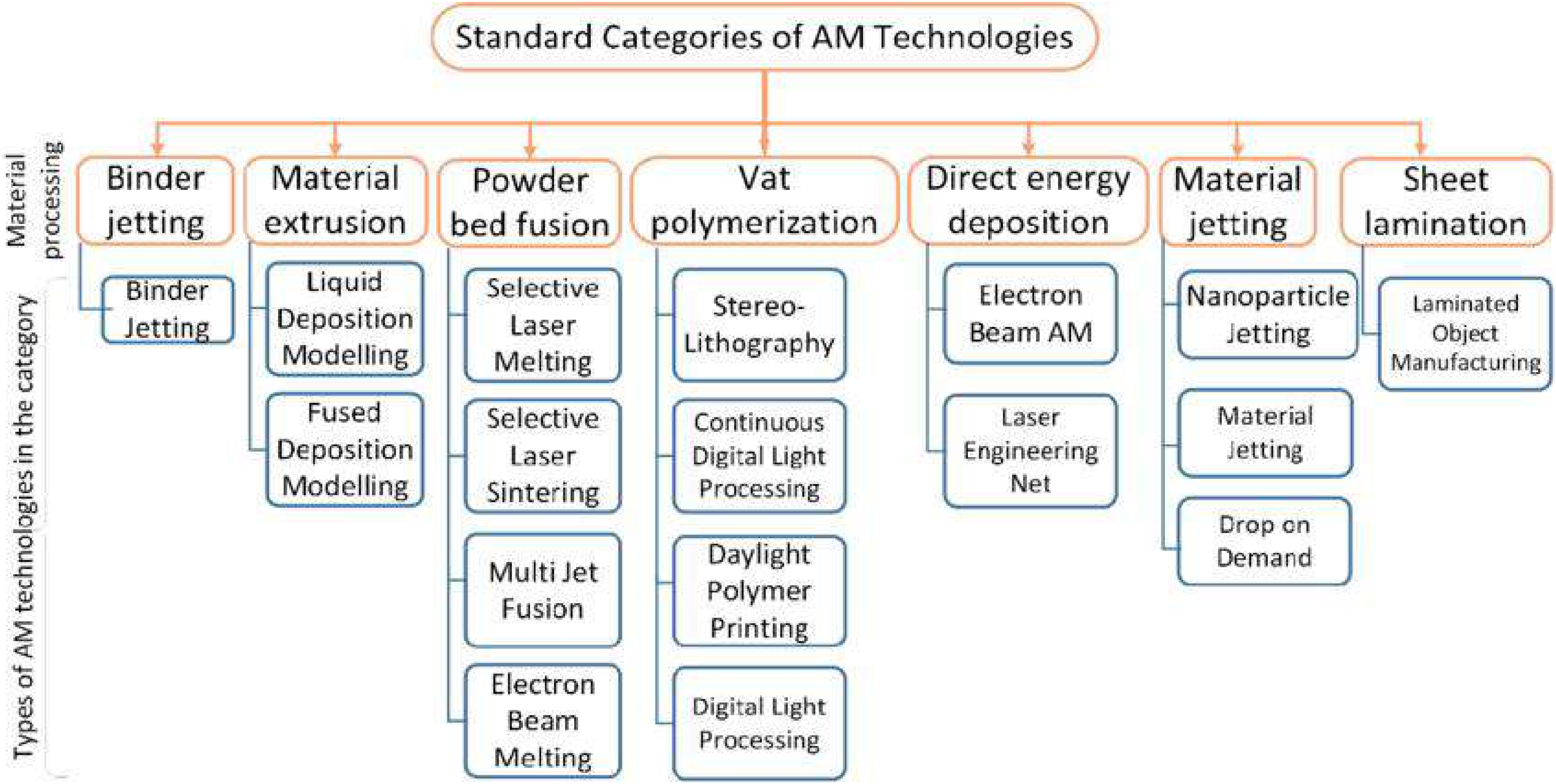
Classification of 3D printing technologies

ISO/ASTM 52900: Created in 2015



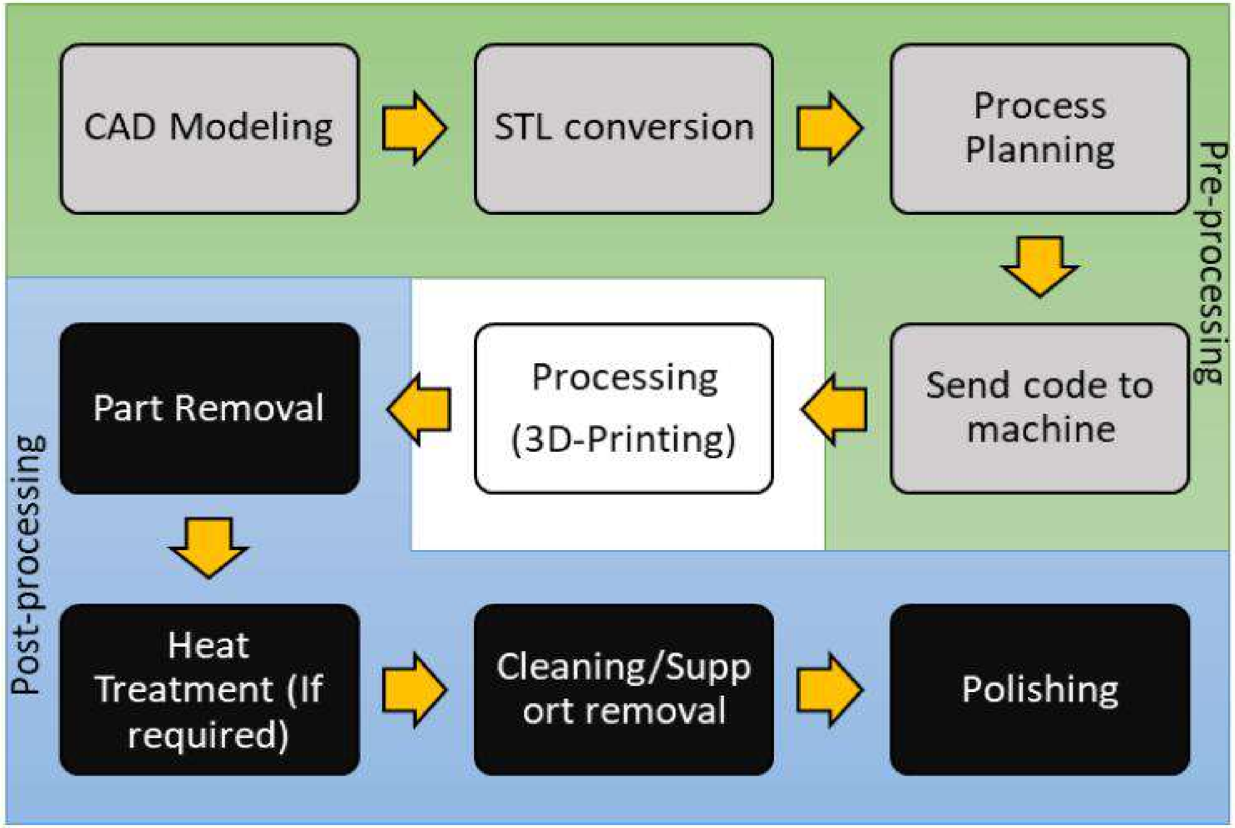
Fused filament fabrication (FFF)
or
Fused Deposition Modeling (FDM)

ASTM: American Society for Testing and Materials
ISO: International Organization for Standardization



Standard Categories of AM Technologies
Material processing
Types of AM technologies in the category
Binder jetting
Binder Jetting
Material extrusion
Liquid Deposition Modelling
Fused Deposition Modelling
Powder bed fusion
Selective Laser Melting
Selective Laser Sintering
Multi Jet Fusion
Electron Beam Melting
Vat polymerization
Stereo-Lithography
Continuous Digital Light Processing
Daylight Polymer Printing
Digital Light Processing
Direct energy deposition
Electron Beam AM
Laser Engineering Net
Material jetting
Nanoparticle Jetting
Material Jetting
Drop on Demand
Sheet lamination
Laminated Object Manufacturing

Process Chain for 3D Printing



The entire process of 3D printing is categorized into 3 parts i.e. preprocessing, processing, and post-processing.

Step 1 Modeling : CAD modelling is the initial task for 3D printing. The design in digital format needs to be supplied to any process planning software.

Step 2 STL File : To convert the CAD file that majorly in native file format into Natural file format.

- STL, or STereoLithography, is the most widely used file format for 3D printing.
- STL can be substituted with.OBJ and.3MF files. There is no color information in these file formats.
- File formats like as.X3D,.WRL,.DAE, and.PLY are required for full color 3D printing.

❖ The native file formats are essentially dictated by the specific CAD (Computer-Aided Design)

❖ To facilitate the exchange of files between individuals utilizing different CAD software, neutral file formats have been developed.

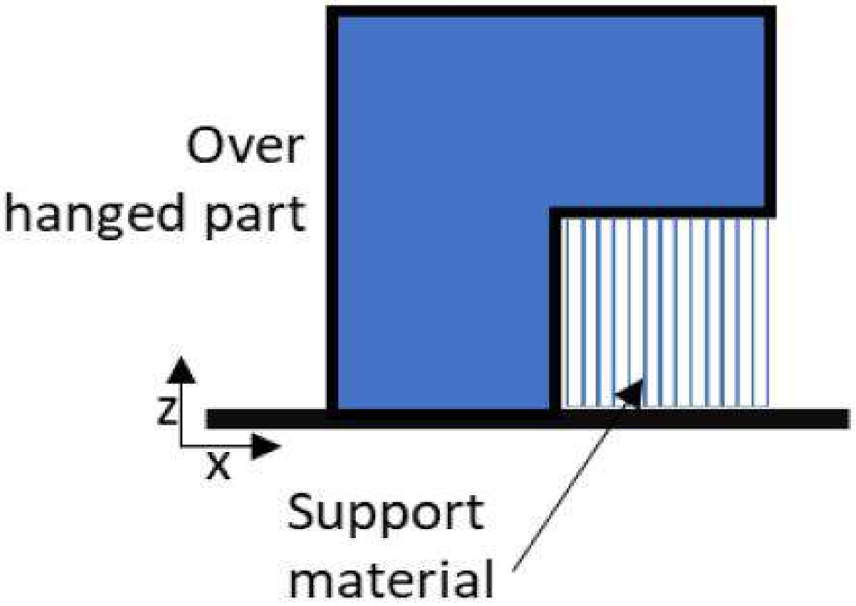
Format	*Extensions*
AutoCAD	.dwg
CATIA V4	.model
CATIA V5, V6	CATPart, CATProduct, CGR
Creo	.prt, .asm
NX, Unigraphics	.prt, .jt, .j_t
Pro/E	.prt, .asm
Inventor	ipt, iam
MicroStation	dgn
SolidWorks	.sldprt, .sldasm
Solid Edge	.par, .asm, .psm

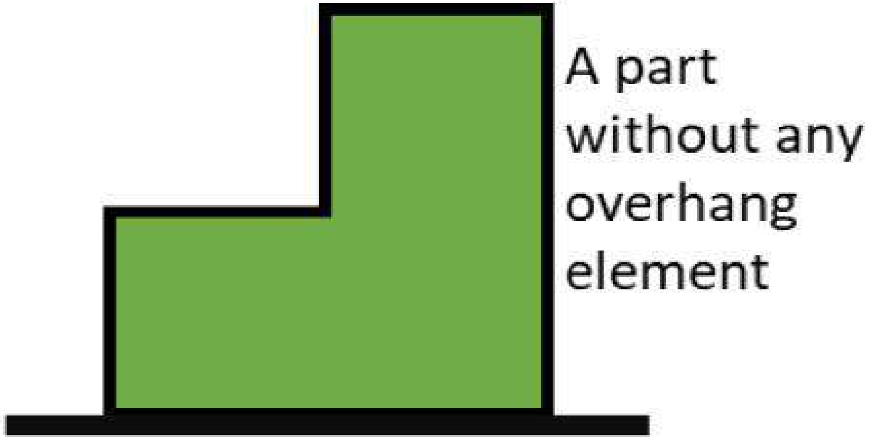
Format	Extensions
STEP	.stp, .step
STL	**.stl**
IGES	.igs, .iges
3D PDF	.pdf
Parasolid	.x_t, .x_b
VRML	.vrml
X3D	.x3d
COLLADA	.dae
DXF	.dxf

Process Chain for 3D Printing

Step 3: The STL file is sent to the process planning software. The software initially checks the quality of the STL file and repairs it if any errors are present.

- It also allows for the placement of the part on the build platform. The process planning software enables printing multiple copies of the same part simultaneously on the platform.
- Other settings, such as part orientation, size scaling, support generation, and color (in some machines), can also be defined at this stage.

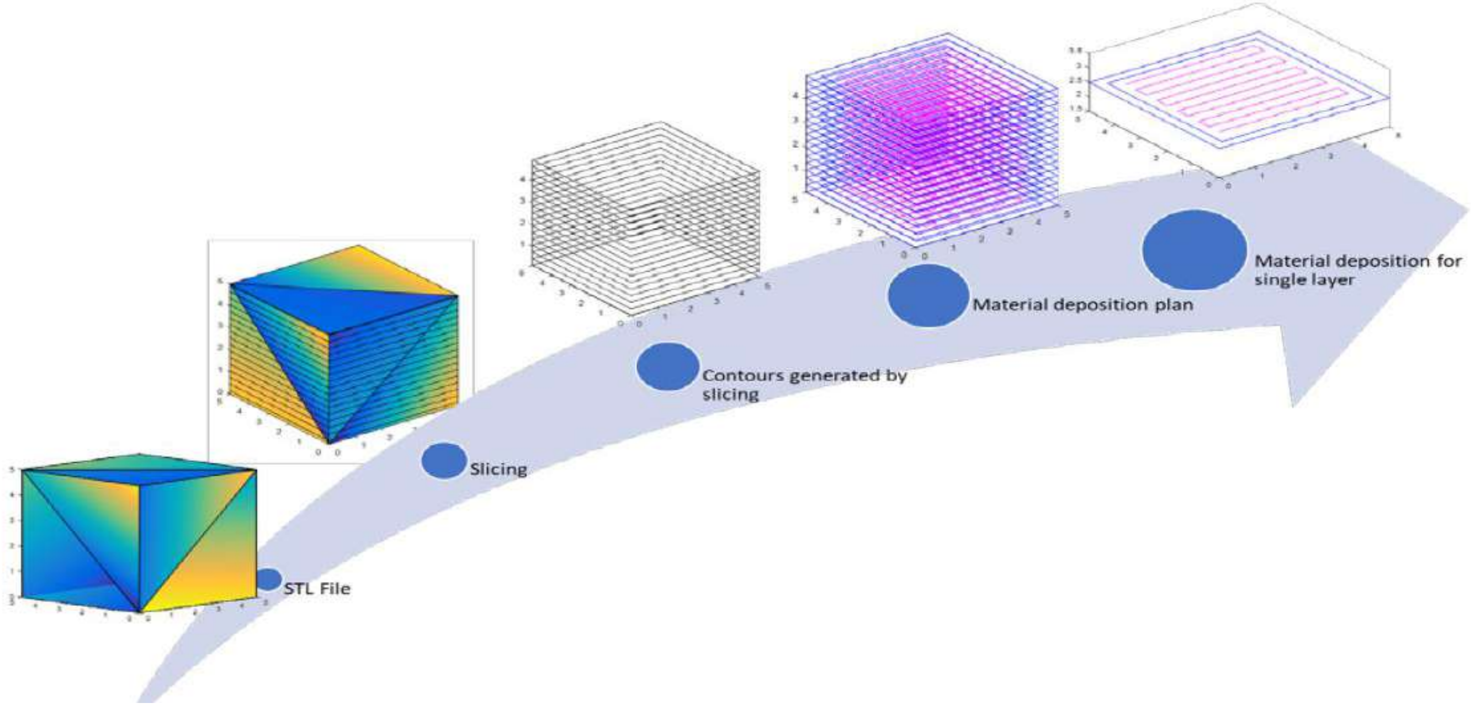




Process Chain for 3D Printing

Step 4 – Slicing

- Convert 3D files into instructions for the printer.
- Slicing refers to the method of dividing a 3D model into horizontal layers, guiding the computer to execute particular tasks.
- Upon completing the slicing process, a new file format known as G-code is generated, possessing the extension .gcode.



Process Chain for 3D Printing

Step 5 – Printing

- The 3D printer interprets the instructions in G-code format and initiates the printing process.

1.Motion of **the** axes: Confirm that the printer's X, Y, and Z axes can move smoothly and accurately without any obstructions or misalignments.

2. Material availability: Check that the printing material, often in the form of a filament or resin, is loaded correctly and sufficiently for the printing job.

3. Support material: In some cases, support structures may be necessary for overhanging parts of the object. Ensure that the support material is available and properly loaded into the printer.

4. Build platform adhesion: Verify that the build platform is clean and level, ensuring proper adhesion of the printed object. Some printers may require the use of adhesion aids like glue, hairspray, or painter's tape to help the object stick to the build platform.

5. Filament feed: Ensure that the filament is not entangled and is fed appropriately to the nozzle without any undue stress. This will help avoid issues like wire breakage or uneven cuts during the EDM process.

Step 6– Removal

Removing a printed part from the build platform tends to be simpler with desktop printers compared to industrial printers, which may necessitate specialized training.

Process Chain for 3D Printing

Step 7 – Post-Processing

- Depending on the technology and material utilized, the post-processing of 3D printed objects may differ.
- For some machines, parts can be used directly without any post-processing, while other 3D printing processes necessitate post-processing.

  Furthermore, the need for post-processing depends on the part's design, pre-processing, and intended use.
- A 3D printed part often requires post-processing such as removing supports and cleaning.
- For the Fused Filament Fabrication (FFF) process, soluble materials can be used to create support structures, which can easily dissolve in water or a specific solvent without harming the main part.
- Conversely, parts printed with powder-based 3D printing may only require removing any unused powdered material from the surface.
- Some processes required heat treatment or other specific post-processing of the part.
- Post-processing of 3D-printed parts is based on the method of 3D printing.
- Metal 3D printing requires some special surface treatment processes to manage the residual stress and heat treatment to strengthen the part.
- Additional wire EDM is used to detach the part from the built platform in case of metal additive manufacturing.

Computer Aided Design and File Formats

- Computer-aided design (CAD) is the process of creating precise and accurate representations of objects on a computer screen, free from errors and ambiguities. These representations, called solid models, are essential for inspecting and verifying the design before 3D printing, as well as for developing a fabrication process plan.

Format	*Extensions*
AutoCAD	.dwg
CATIA V4	.model
CATIA V5, V6	CATPart, CATProduct, CGR
Creo	.prt, .asm
NX, Unigraphics	.prt, .jt, .j_t
Pro/E	.prt, .asm
Inventor	ipt, iam
MicroStation	dgn
SolidWorks	.sldprt, .sldasm
Solid Edge	.par, .asm, .psm

Format	**Extensions**
STEP	.stp, .step
STL	**.stl**
IGES	.igs, .iges
3D PDF	.pdf
Parasolid	.x_t, .x_b
VRML	.vrml
X3D	.x3d
COLLADA	.dae
DXF	.dxf

Solid Modeling

•Solid models are known to be complete, valid and unambiguous representation of the objects.

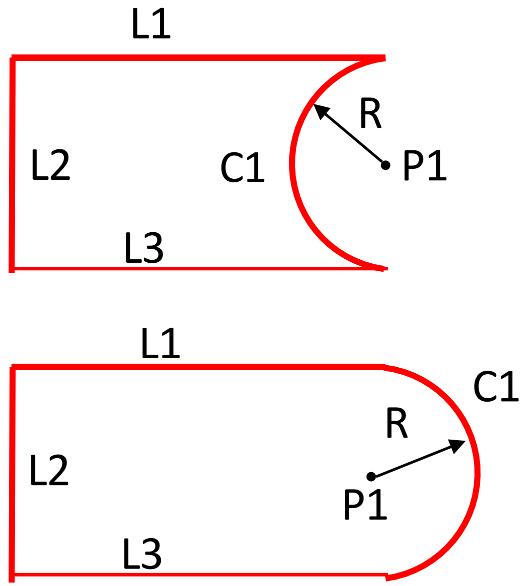
•**A complete solid** is one which enables a point in space to be classified relative to the object, if it is inside, outside or on the object.

•**A valid solid** is one that does not have dangling edges or faces.

•**An unambiguous solid** has one only one interpretation.

The completeness and unambiguity of a solid model are attribute to the fact that its database stores both, its geometry and its topology.

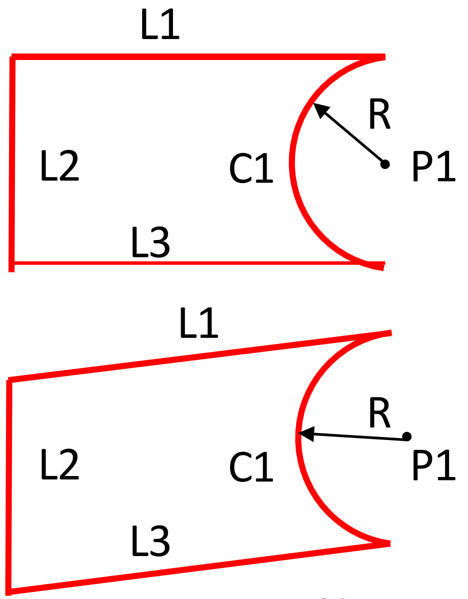
Same **Geometry** but different **Topology**

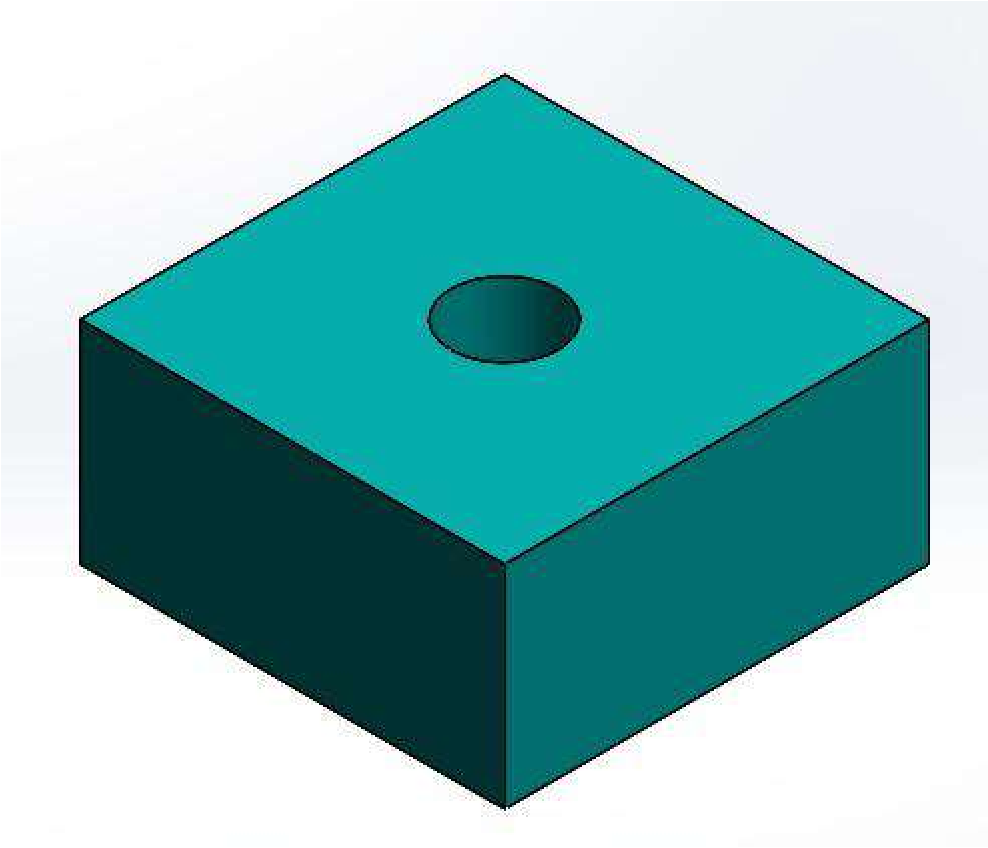


Following are the four popular methods of representing a solid:

- Constructive Solid Geometry (CSG)
- Boundary Representation (B-Rep)
- Feature Based Modeling (FBM)
- Space Decomposition (SD)
- Hybrid Modeling

Same **Topology** but different **Geometry**

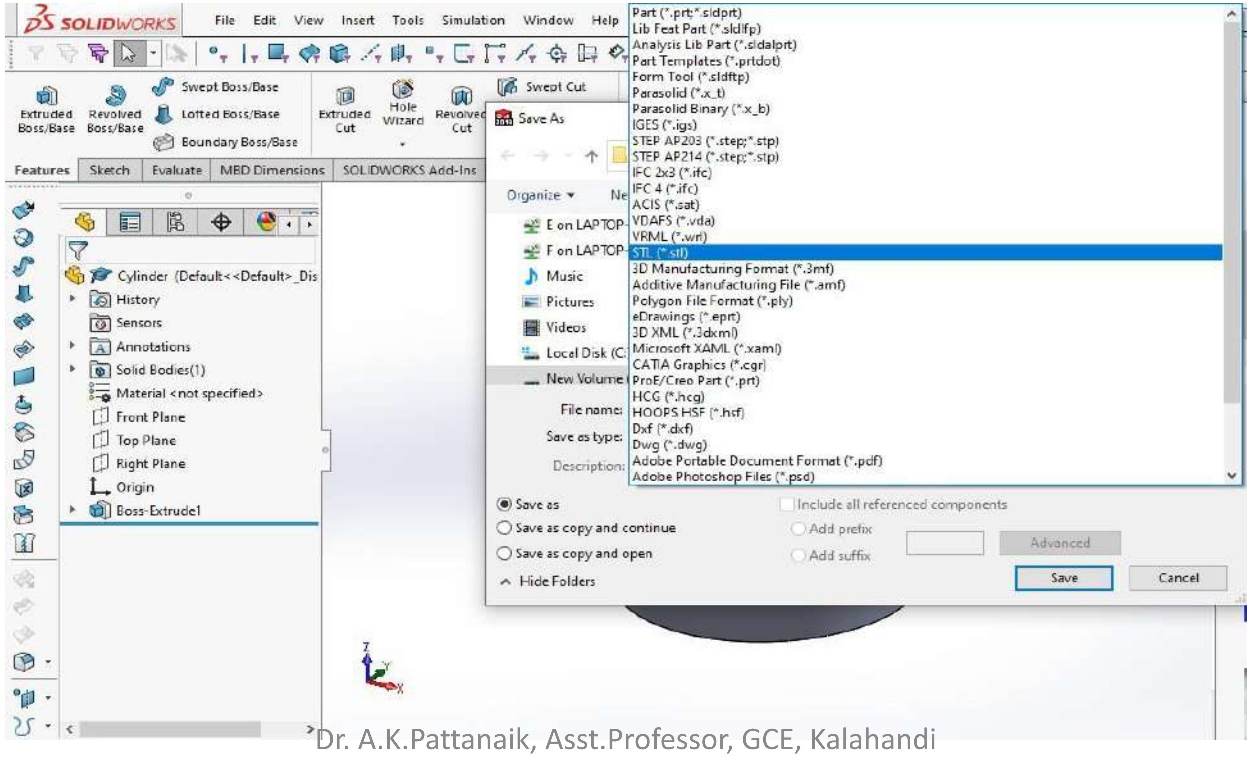




Solid Modeling

Different CAD packages uses different scheme (CSG, B-rep, FBM, SD or hybrid) for solid representation. Theoretically any commercial package (or any scheme) can be used to create the solid model of the object.

However most of the CAPP platform of AM require the solid model of the object in a format called as “**STL**”.



STL File…

The STL file is derived from the word **STereoLithography**, which was the first commercial AM process, produced by the US company 3D Systems in the early 1980s*. Over the period of time the STL is also known as:

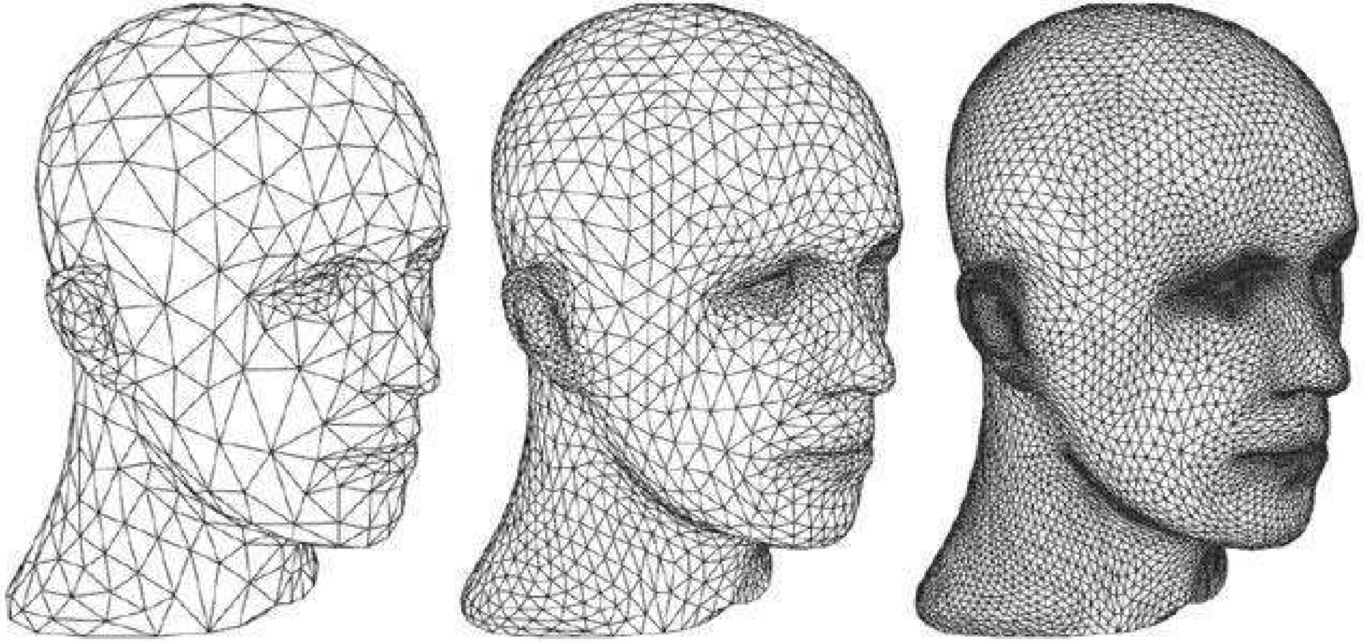
- **Standard Triangle Language**
- **Standard <u>Tessellation</u> Language**

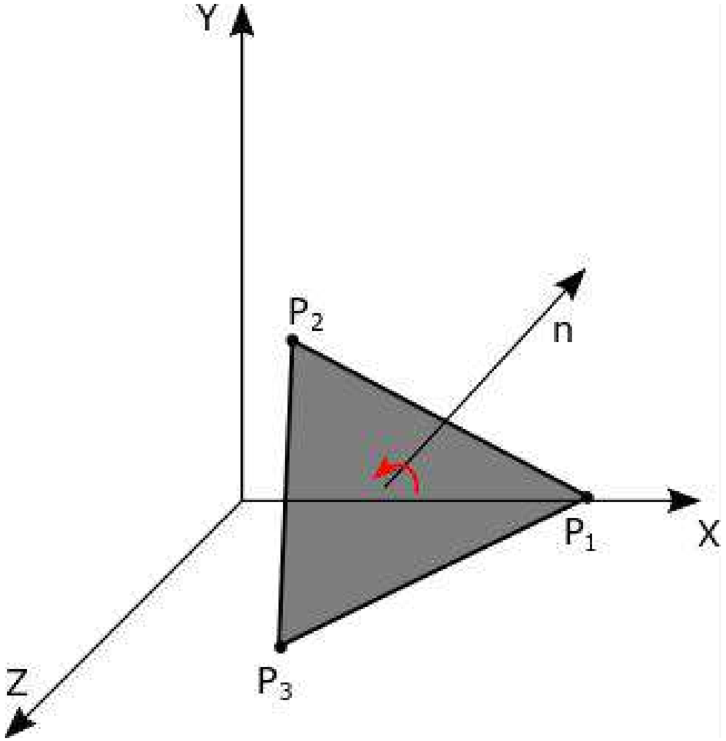
The STL file format encodes a surface geometry of a 3D object using a simple concept called "**<u>tessellation</u>**".

Tessellation is the process of tiling a surface with one or more geometric shapes such that there are no overlaps or gaps. A tiled floor or wall is a good real life example of tessellation.

STL File…

"**STL** is a faceted **Boundary Representation (B-Rep)** model of an object that approximate the model surfaces by connected series of triangles (Tessellation). It does not contain any information related to color, texture, and density etc."



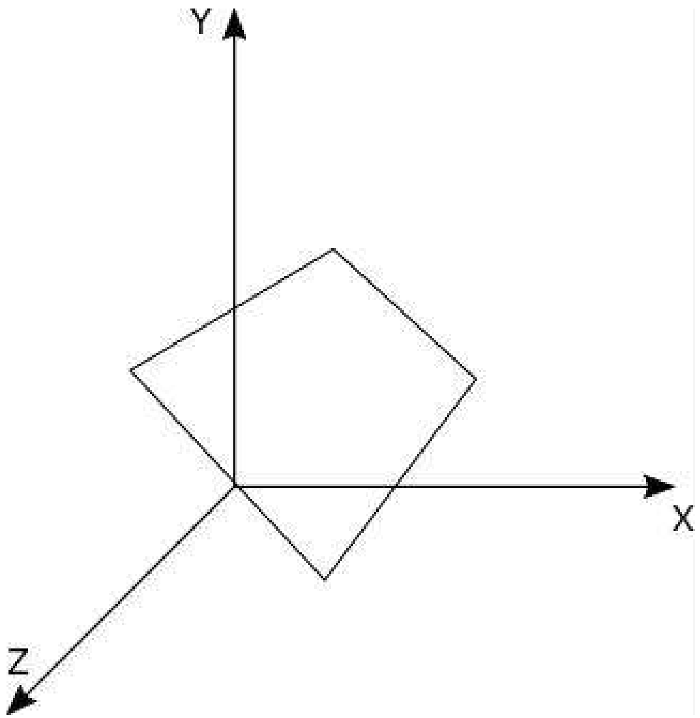


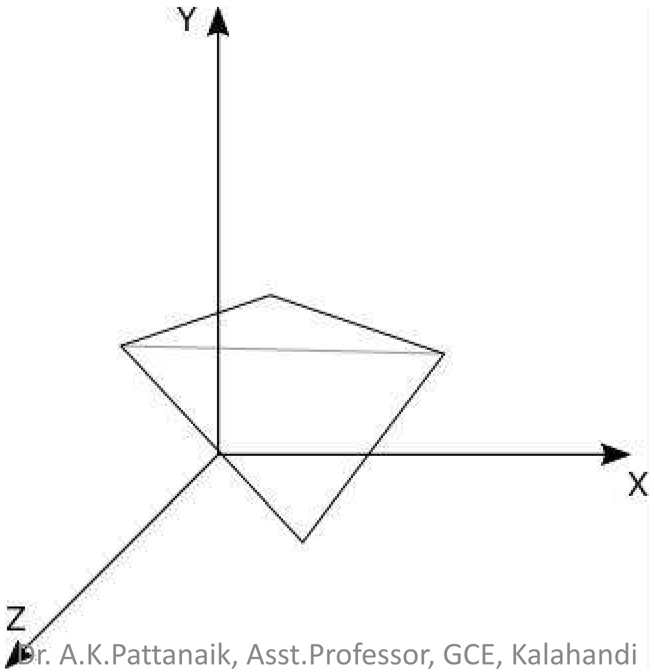
An **STL** file describes a raw, unstructured triangulated surface by representing each triangle by a unit normal and three vertices (in a 3D Cartesian coordinate system) ordered by the right-hand rule. There is no material available in the direction of normal.

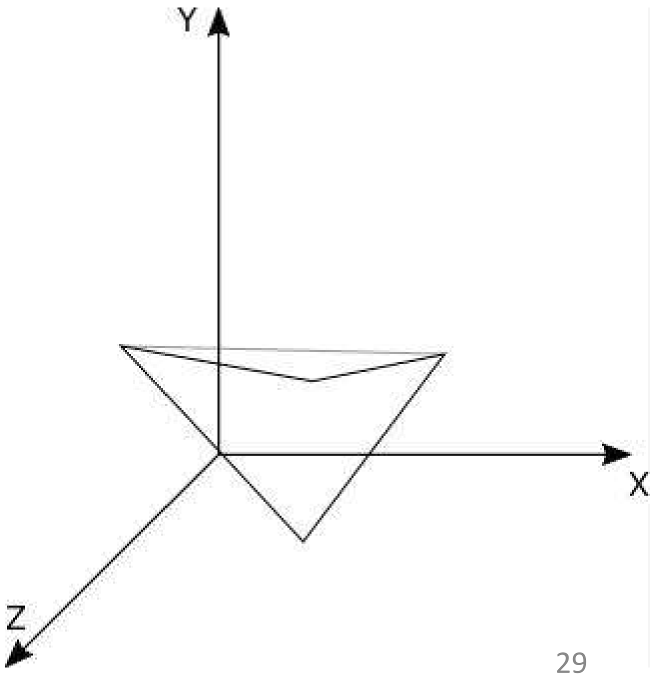
Why triangles ?

There are **certain characteristics** in the triangle that makes working with it **simpler** and **faster**:

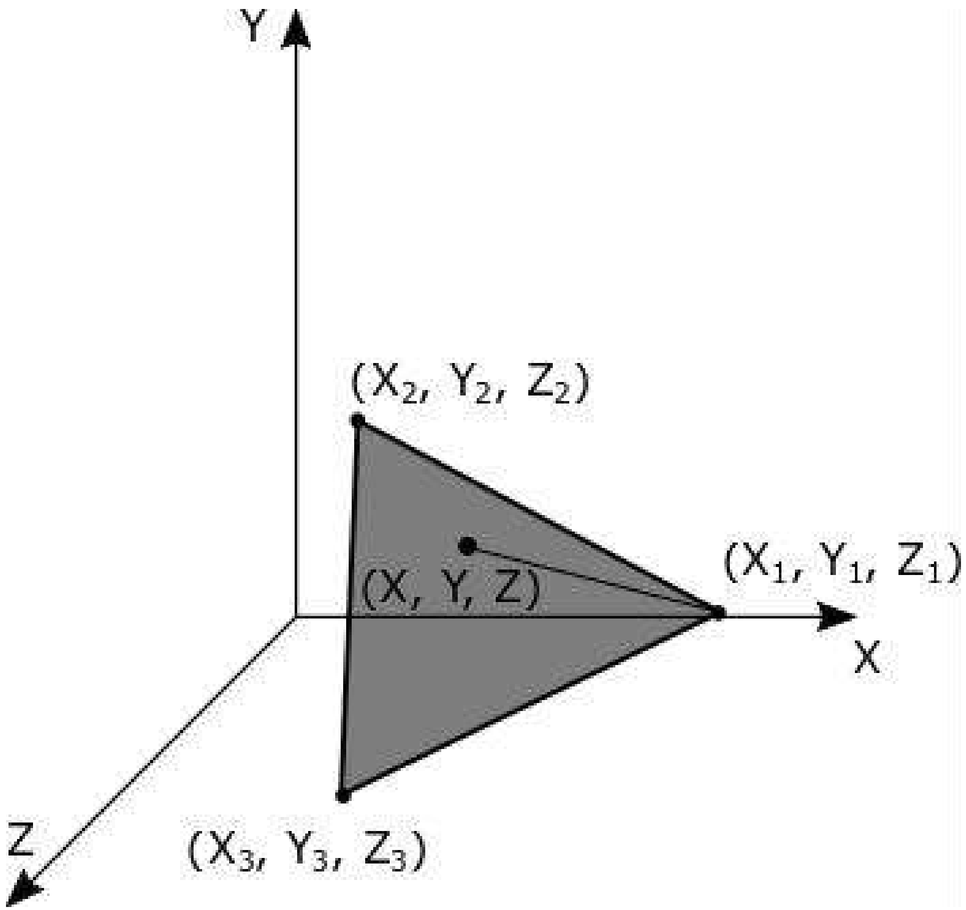
- Any three non collinear points form a triangle.
- **Every triangle forms a unique plane.** Triangle points cannot be part of two planes which save us from the trouble from dealing with multiple solutions.
- Any surface can be broken down into triangles, and triangles can only be broken down into triangles.







Mathematical Equation of a Triangular Surface



$$\begin{vmatrix} x - x_1 & y - y_1 & z - z_1 \\ x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\ x_3 - x_1 & y_3 - y_1 & z_3 - z_1 \end{vmatrix} = 0$$

Example: Find the equation of the plane in Vector form that passes through the points (1, 1, 0), (1, 2, 1) and (-2, 2, -1).

$$\begin{vmatrix} 1 & 1 & 0 \\ 1 & 2 & 1 \\ -2 & 2 & -1 \end{vmatrix} = -8$$ (Hence the three points are not collinear)

$$\begin{vmatrix} x - 1 & y - 1_1 & z \\ 0 & 1 & 1 \\ -3 & 1 & -1 \end{vmatrix} = 0$$

2x + 3y - 3z = 5

STL: Data Stucture

The content of an STL file is a set of oriented triangles, each described by the following numerical data:

$$\begin{matrix} n_x^i & n_y^i & n_z^i \\ p_{1x}^i & p_{1y}^i & p_{1z}^i \\ p_{2x}^i & p_{2y}^i & p_{2z}^i \\ p_{3x}^i & p_{3y}^i & p_{3z}^i \end{matrix}$$

where (n_x^i, n_y^i, n_z^i) are the coordinates of the outward normal of the i^{th} facet and $(p_{kx}^i, p_{ky}^j, p_{kz}^k)$ are the coordinates of the k^{th} $(k = 1,2,3)$ vertex of the i^{th} triangle, $i = 1, 2, 3 \dots N$ (N is the number of triangles).

- The file **does not contain any topological information** like links, pointers to another element, or proximity.
- Each vertex is written by its coordinates in the file as many times as it occurs in the mesh. This fact may cause **problems with** vertex identification depending on the numerical **representation of real numbers**.
- **Does not store the dimension unit**

STL files can be either in the binary or ASCII (text) format. **The ASCII format is more user friendly** while **binary is more system friendly**.

STL: ASCII

```
solid Sphere
  facet normal -6.291947e-02 -9.980186e-01 -0.000000e+00
    outer loop
      vertex 8.749243e+01 7.885322e-01 1.008030e+02
      vertex 8.749243e+01 7.885322e-01 9.919699e+01
      vertex 1.000000e+02 0.000000e+00 1.000000e+02
    endloop
  endfacet
  facet normal 5.971409e-02 -9.980186e-01 1.982642e-02
    outer loop
      vertex 1.121234e+02 7.885322e-01 1.031791e+02
      vertex 1.116173e+02 7.885322e-01 1.047033e+02
      vertex 1.000000e+02 0.000000e+00 1.000000e+02
    endloop
  endfacet
endsolid
```

Name of the file (Object) (solid Sphere)

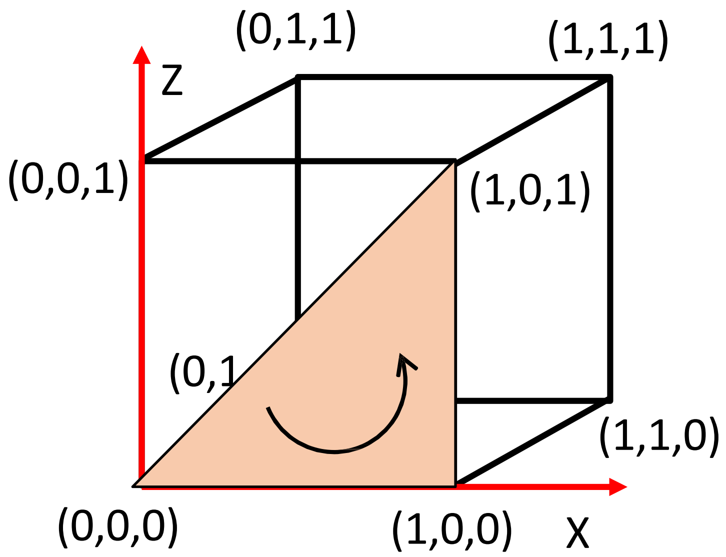
Unit vector in the direction of facet normal (facet normal)

The group of three vertices defining the triangle is delimited by the terms “outer loop” and “endloop.”

The vertices of the triangle are listed in CCW manner so that by using the right hand rule one can find the direction o the facet normal. With this proper structure of the vertices even the data corresponding to the triangle normal is redundant.

STL: ASCII

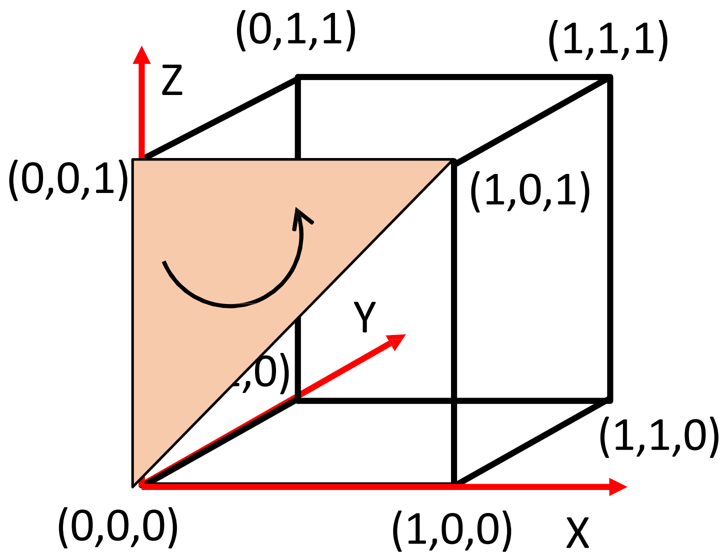
Write a ASCII code for representing the Cube of side 1 unit in STL format




```
facet normal 0.0 -1.0 0.0
  outer loop
    vertex 0.0 0.0 0.0
    vertex 1.0 0.0 0.0
    vertex 1.0 0.0 1.0
  endloop
endfacet
```

STL: ASCII

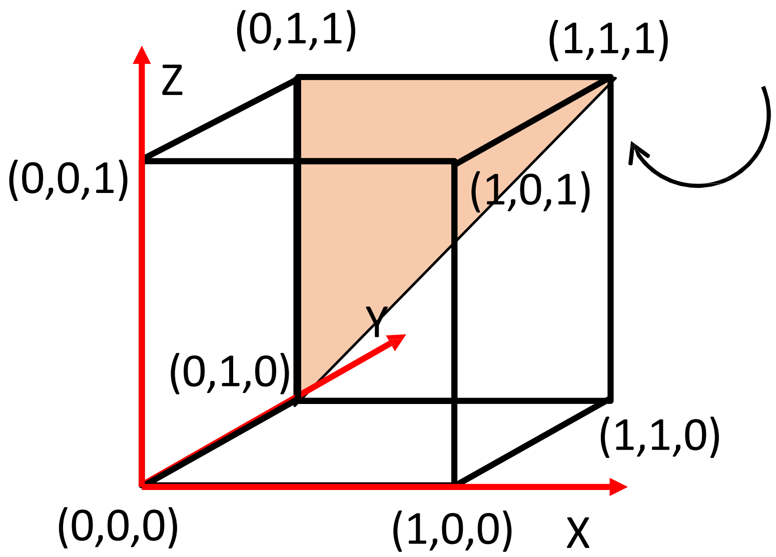
Write a ASCII code for representing the Cube of side 1 unit in STL format




```
facet normal 0.0 -1.0 0.0
    outer loop
      vertex 0.0 0.0 0.0
      vertex 1.0 0.0 1.0
      vertex 0.0 0.0 1.0
    endloop
  endfacet
```

STL: ASCII

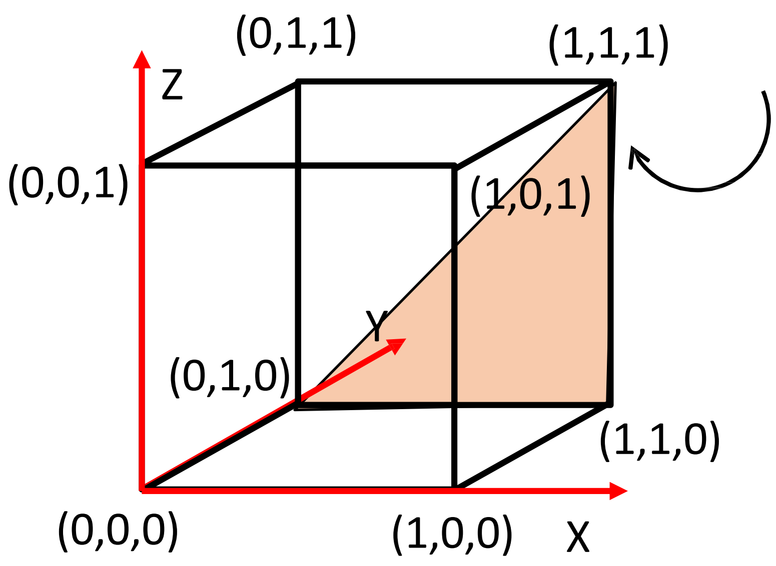
Write a ASCII code for representing the Cube of side 1 unit in STL format




```
facet normal 0.0 1.0 0.0
    outer loop
      vertex 0.0 1.0 0.0
      vertex 0.0 1.0 1.0
      vertex 1.0 1.0 1.0
    endloop
  endfacet
```

STL: ASCII

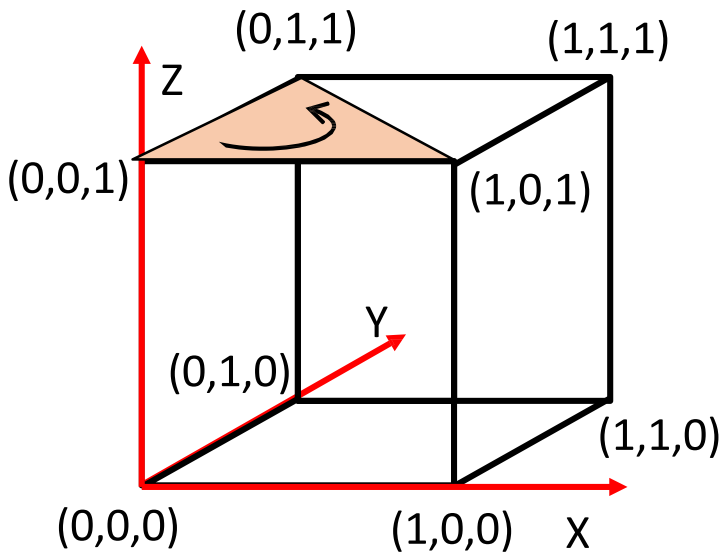
Write a ASCII code for representing the Cube of side 1 unit in STL format




```
facet normal 0.0 1.0 0.0
    outer loop
      vertex 1.0 1.0 0.0
      vertex 0.0 1.0 0.0
      vertex 1.0 1.0 1.0
    endloop
  endfacet
```

STL: ASCII

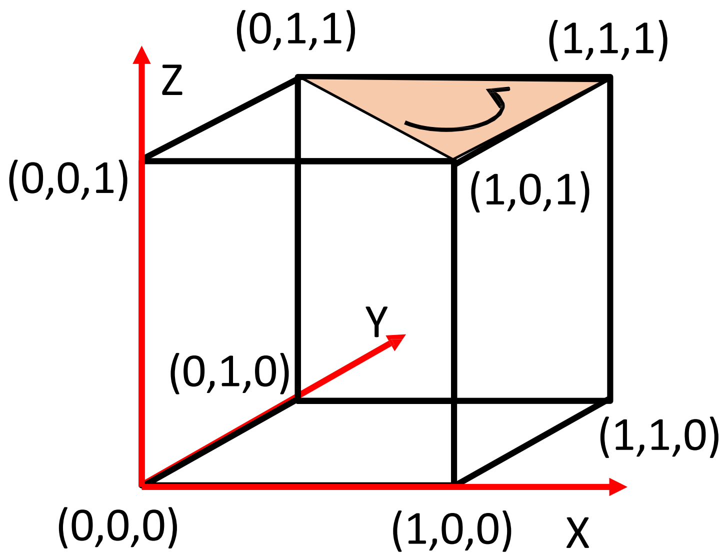
Write a ASCII code for representing the Cube of side 1 unit in STL format




```
facet normal 0.0 0.0 1.0
    outer loop
      vertex 0.0 0.0 1.0
      vertex 1.0 0.0 1.0
      vertex 0.0 1.0 1.0
    endloop
  endfacet
```

STL: ASCII

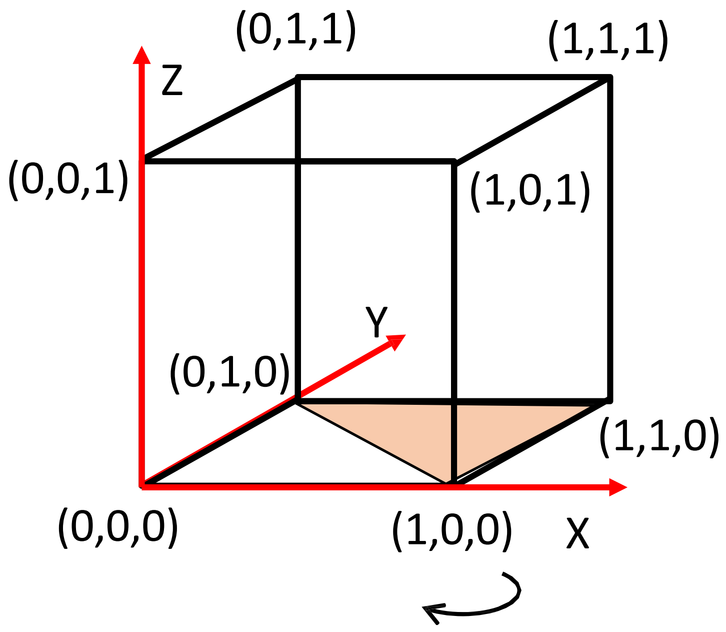
Write a ASCII code for representing the Cube of side 100 mm in STL format




```
facet normal 0.0 0.0 1.0
    outer loop
      vertex 0.0 1.0 1.0
      vertex 1.0 0.0 1.0
      vertex 1.0 1.0 1.0
    endloop
  endfacet
```

STL: ASCII

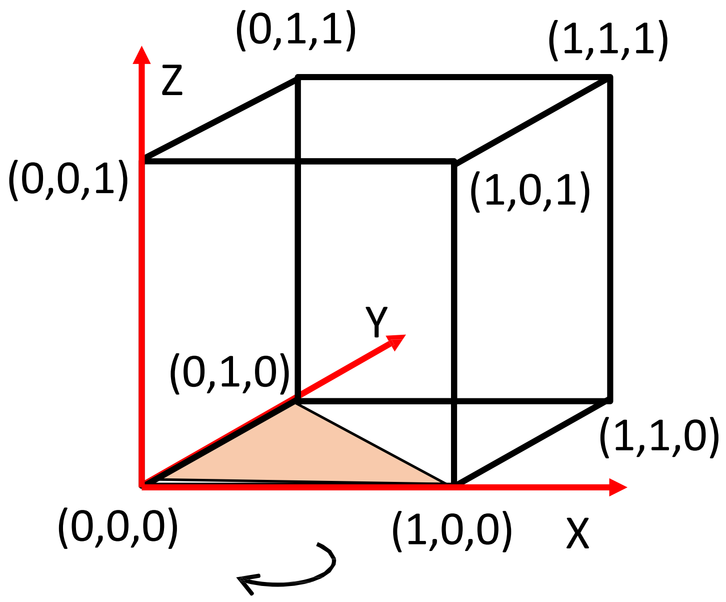
Write a ASCII code for representing the Cube of side 1 unit in STL format




```
facet normal 0.0 0.0 -1.0
    outer loop
      vertex 1.0 1.0 0.0
      vertex 1.0 0.0 0.0
      vertex 0.0 1.0 0.0
    endloop
  endfacet
```

STL: ASCII

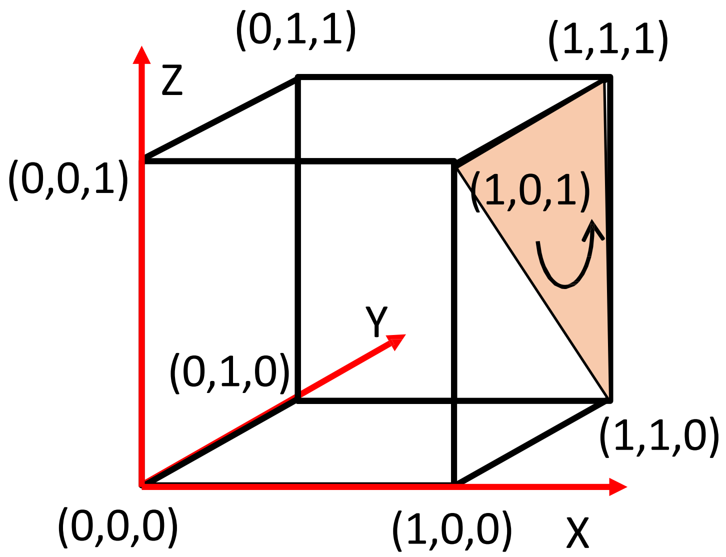
Write a ASCII code for representing the Cube of side 1 unit in STL format




```
facet normal 0.0 0.0 -1.0
    outer loop
      vertex 1.0 0.0 0.0
      vertex 0.0 0.0 0.0
      vertex 0.0 1.0 0.0
    endloop
  endfacet
```

STL: ASCII

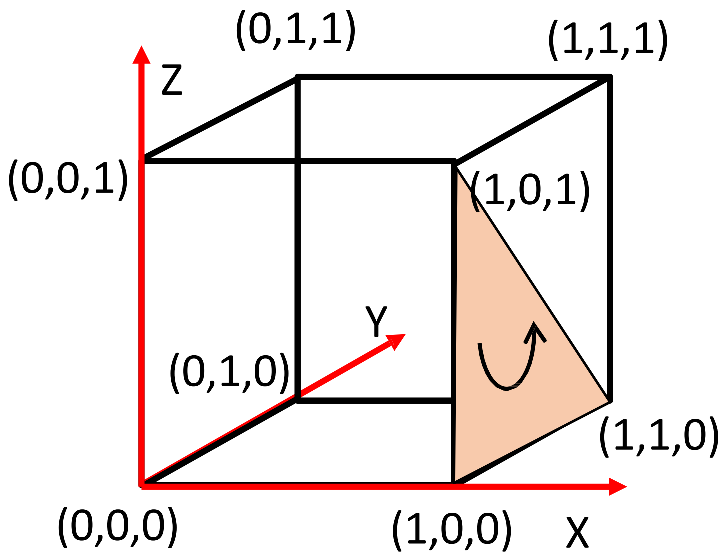
Write a ASCII code for representing the Cube of side 1 unit in STL format




```
facet normal 1.0 0.0 0.0
    outer loop
      vertex 1.0 0.0 1.0
      vertex 1.0 1.0 0.0
      vertex 1.0 1.0 1.0
    endloop
  endfacet
```

STL: ASCII

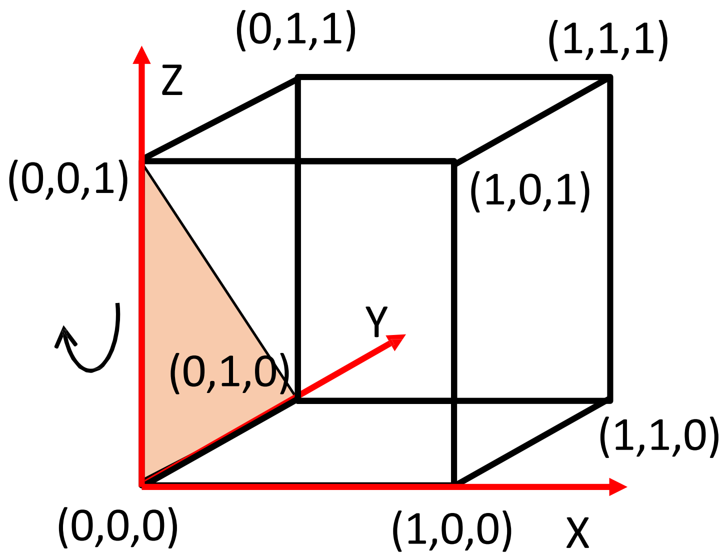
Write a ASCII code for representing the Cube of side 1 unit in STL format




```
facet normal 1.0 0.0 0.0
    outer loop
      vertex 1.0 0.0 0.0
      vertex 1.0 1.0 0.0
      vertex 1.0 0.0 1.0
    endloop
  endfacet
```

STL: ASCII

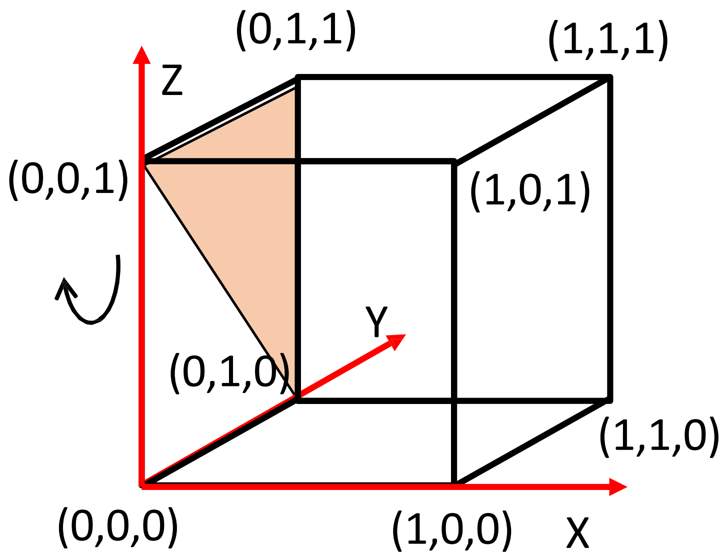
Write a ASCII code for representing the Cube of side 1 unit in STL format




```
facet normal -1.0 0.0 0.0
    outer loop
      vertex 0.0 1.0 0.0
      vertex 0.0 0.0 0.0
      vertex 0.0 0.0 1.0
    endloop
  endfacet
```

STL: ASCII

Write a ASCII code for representing the Cube of side 1 unit in STL format




```
facet normal -1.0 0.0 0.0
    outer loop
      vertex 0.0 0.0 1.0
      vertex 0.0 1.0 1.0
      vertex 0.0 1.0 0.0
    endloop
  endfacet
```

STL: ASCII

Write a ASCII code for representing the Cube of side 1 unit in STL format

```
solid CubeA
facet normal 0.0 -1.0 0.0
    outer loop
      vertex 0.0 0.0 0.0
      vertex 1.0 0.0 0.0
      vertex 1.0 0.0 1.0
    endloop
  endfacet
facet normal 0.0 -1.0 0.0
    outer loop
      vertex 0.0 0.0 0.0
      vertex 1.0 0.0 1.0
      vertex 0.0 0.0 1.0
    endloop
  endfacet
facet normal 0.0 1.0 0.0
    outer loop
      vertex 0.0 1.0 0.0
      vertex 0.0 1.0 1.0
      vertex 1.0 1.0 1.0
    endloop
  endfacet
facet normal 0.0 1.0 0.0
    outer loop
      vertex 1.0 1.0 0.0
      vertex 0.0 1.0 0.0
      vertex 1.0 1.0 1.0
    endloop
  endfacet
facet normal 0.0 0.0 1.0
    outer loop
      vertex 0.0 0.0 1.0
      vertex 1.0 0.0 1.0
      vertex 0.0 1.0 1.0
    endloop
  endfacet
facet normal 0.0 0.0 1.0
    outer loop
      vertex 0.0 1.0 1.0
      vertex 1.0 0.0 1.0
      vertex 1.0 1.0 1.0
    endloop
  endfacet
facet normal 0.0 0.0 -1.0
    outer loop
      vertex 1.0 1.0 0.0
      vertex 1.0 0.0 0.0
      vertex 0.0 1.0 0.0
    endloop
  endfacet
facet normal 0.0 0.0 -1.0
    outer loop
      vertex 1.0 0.0 0.0
      vertex 0.0 0.0 0.0
      vertex 0.0 1.0 0.0
    endloop
  endfacet
facet normal 1.0 0.0 0.0
    outer loop
      vertex 1.0 0.0 1.0
      vertex 1.0 1.0 0.0
      vertex 1.0 1.0 1.0
    endloop
  endfacet
facet normal 1.0 0.0 0.0
    outer loop
      vertex 1.0 0.0 0.0
      vertex 1.0 1.0 0.0
      vertex 1.0 0.0 1.0
    endloop
  endfacet
facet normal -1.0 0.0 0.0
    outer loop
      vertex 0.0 1.0 0.0
      vertex 0.0 0.0 0.0
      vertex 0.0 0.0 1.0
    endloop
  endfacet
facet normal -1.0 0.0 0.0
    outer loop
      vertex 0.0 0.0 1.0
      vertex 0.0 1.0 1.0
      vertex 0.0 1.0 0.0
    endloop
  endfacet
endsolid
```

Materials used by 3D Printers:

3D printers use a variety of materials including **plastics** (thermoplastics and resins), **metals**, **ceramics**, and **composites**, with the most common types for consumer FDM printers being PLA, ABS, and PETG.

The ideal material depends on the desired properties of the final object, such as strength, flexibility, or heat resistance.

Common Thermoplastics (Filaments)

- Thermoplastics, used in Fused Deposition Modeling (FDM) printers, are the most common and come in a wide variety for different applications.
- **PLA (Polylactic Acid)**:
  - **Features:** Biodegradable, easy to print, minimal warping, and odorless during printing.
  - **Applications:** Ideal for beginners, used for prototypes, models, and decorative items.

Materials used by 3D Printers:

- **ABS (Acrylonitrile Butadiene Styrene)**:
  - **Features:** Strong, durable, and resistant to heat and impact. Requires a heated print bed and ventilation due to fumes.
  - **Applications:** Functional prototypes, electronic housings, and mechanical parts.
- **PETG (Polyethylene Terephthalate Glycol)**:
  - **Features:** Balances the strength of ABS with the easy printability of PLA. Offers good chemical and water resistance, and some flexibility.
  - **Applications:** Functional parts, containers, outdoor use components, and snap-fit items.
- **Nylon (Polyamide)**:
  - **Features:** Very high strength and durability, flexible, and wear-resistant. It is hygroscopic, meaning it absorbs moisture and must be stored properly.
  - **Applications:** Gears, living hinges, and industrial functional parts.

Materials used by 3D Printers:

- **TPU (Thermoplastic Polyurethane)**:
  - **Features:** Extremely flexible and elastic, with properties similar to rubber. Excellent impact and abrasion resistance.
  - **Applications:** Phone cases, gaskets, seals, and wearable items.
- **Specialty/Composite Filaments**:
  - **Features:** These blend base plastics (often PLA or Nylon) with additives like **carbon fiber**, **glass fiber**, or metal powder to enhance specific properties like stiffness, strength, or aesthetics.
  - **Applications:** High-strength structural components, aesthetic metal-look jewelry, or wood-like architectural models.

Materials used by 3D Printers:

Resins (SLA/DLP/LCD)

Liquid resins are used in stereolithography (SLA) and Digital Light Processing (DLP) printers to create highly detailed objects with a very smooth surface finish.

- **Standard Resins:**
  - **Features:** Offer the highest resolution and finest details of plastic 3D printing methods. Generally rigid and can be brittle.
  - **Applications:** Detailed visual prototypes, figurines, and artistic models.
- **Engineering Resins:**
  - **Features:** Formulated with specific properties like high temperature resistance, toughness, or rigidity to mimic industrial thermoplastics.
  - **Applications:** Functional prototypes requiring specific mechanical performance, jigs, fixtures, and challenging snap-fit parts.
- **Medical & Dental Resins:**

  Features: Biocompatible materials designed for specific healthcare applications.

  Applications: Surgical guides, dental models, and prosthetic components.

Materials used by 3D Printers:

Industrial Materials (SLS/SLM)

- These materials are used in industrial processes like Selective Laser Sintering (SLS) for powders and Selective Laser Melting (SLM) for metals, producing strong, functional, and end-use parts.
- **Nylon Powder (PA 11/PA 12):**
  - **Features:** Lightweight, strong, and durable with high stability against impact, chemicals, and heat.
  - **Applications:** Functional end-use parts, durable mechanical components, and medical devices.
- **Metals (Powders):**
  - **Features:** Metals such as **titanium** (high strength-to-weight ratio, biocompatible), **stainless steel** (corrosion resistant), and **aluminum** (lightweight, good thermal properties) are used for strong parts.
  - **Applications:** Aerospace components, medical implants, automotive parts, and industrial tooling.

Additive Manufacturing
Module-2

Presented by:

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Asst. Professor(ME)

Govt. College of Engineering, Kalahandi, Odisha

Subject Code: MFPE3011
Semester: 6th
University: BPUT, Odisha

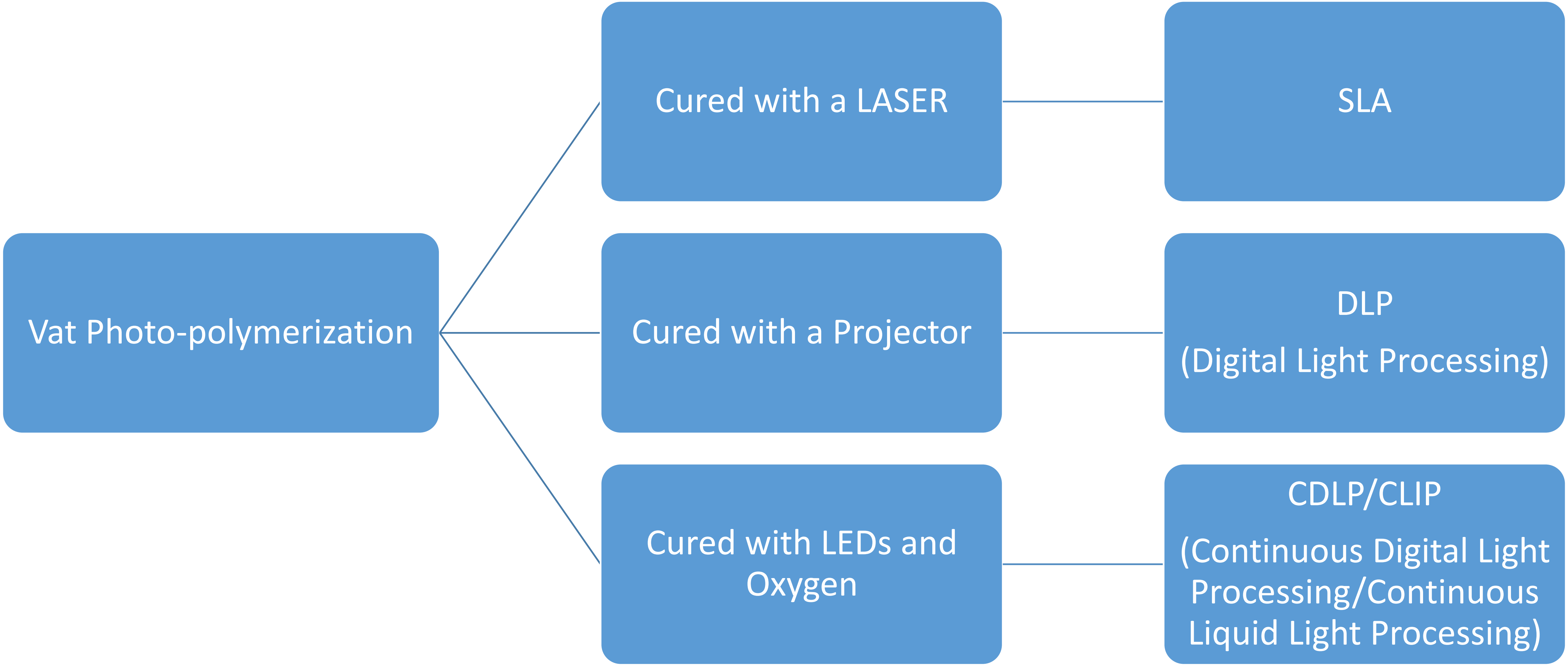
Declaration

This is Prepared for the Education Purpose only

Source: https://www.theguardian.com/education/2014/oct/31/education-traditional-teaching-versus-progressive

Module-II: (10 Hours)

- Liquid based systems: Stereo lithography apparatus (SLA): Models and specifications, process, working principle, photopolymers, photo polymerization, layering technology, laser and laser scanning, applications, advantages and disadvantages, case studies. Solid ground curing (SGC): Models and specifications, process, working principle, applications, advantages and disadvantages, case studies.


Vat Photo-polymerization
Cured with a LASER
Cured with a Projector
Cured with LEDs and Oxygen
SLA
DLP
(Digital Light Processing)
CDLP/CLIP
(Continuous Digital Light Processing/Continuous Liquid Light Processing)

Liquid based systems: Stereolithography apparatus (SLA):

- Vat Photo-polymerisation is most commonly known as *Stereolithography* process.
- It is the first commercial AM Technique which was commercialized by Charles Chuck Hull through 3D Systems.
- Vat Photo-polymerisation is defined as an additive manufacturing process in which liquid photo-polymer in a vat is selectively cured by light activated polymerisation.

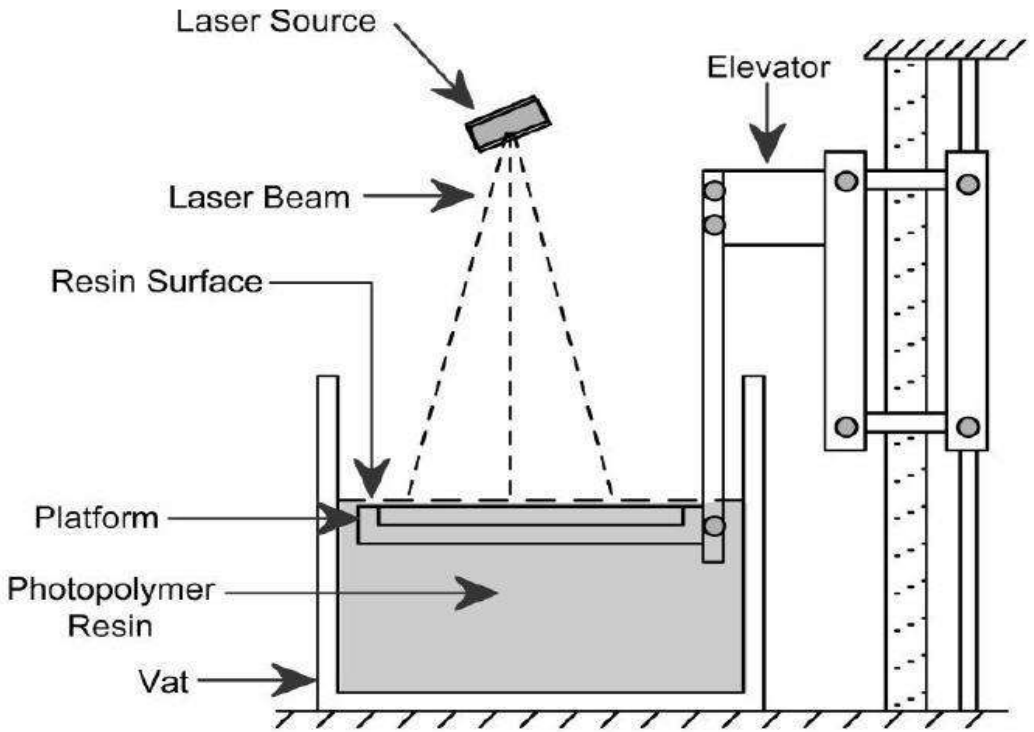


Diagram of SLA printing process

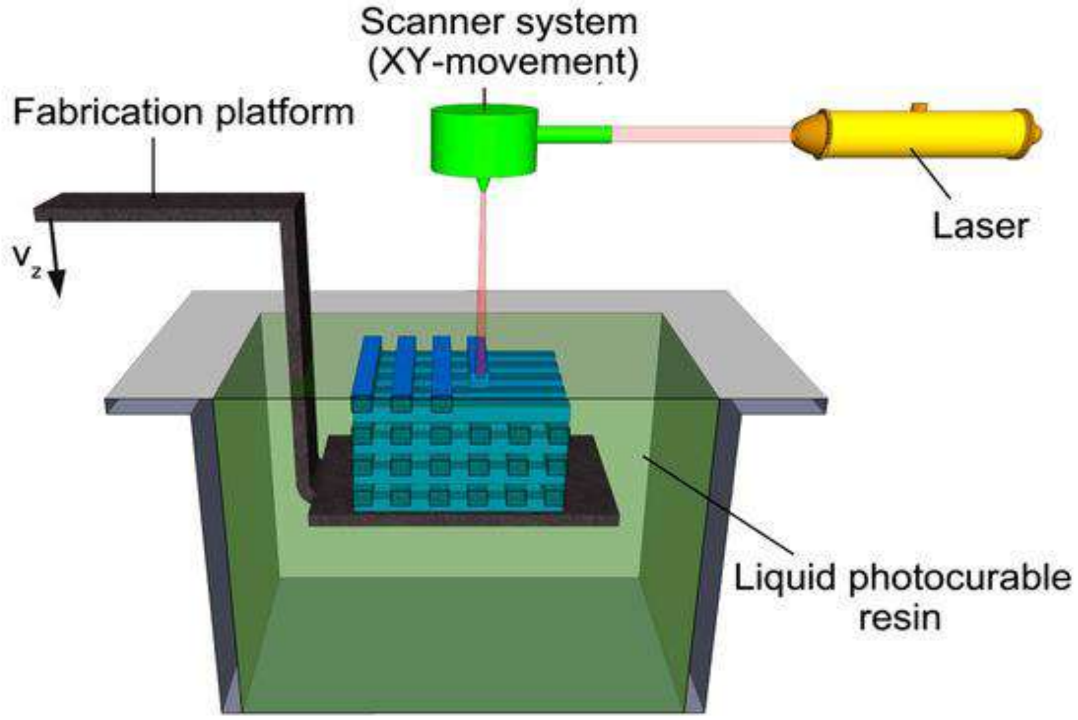
Source: https://www.whiteclouds.com/3dpedia/vat-polymerization/

SLA Process Mechanism:

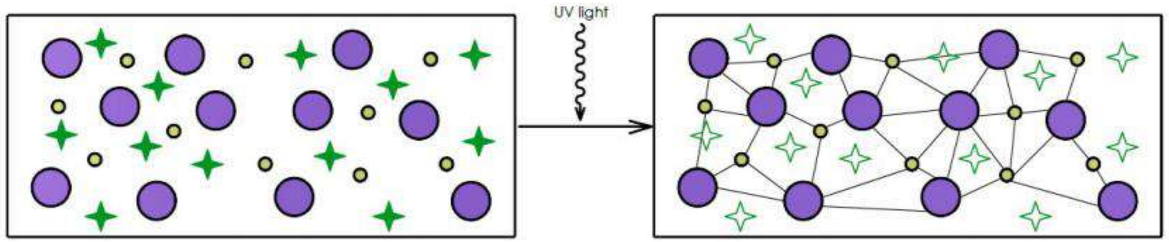
- Photo- polymerisation is the major mechanism that governs the whole process.
- A **resin** is a solid or highly viscous liquid that can be converted into a polymer.
- The resin essentially consists of precursor and photo-initiator.
- In some cases, fillers are also used to build metallic, ceramic or composite parts.

Photo-initiator + Photon → Reactive Species

Reactive Species + Monomer → Insoluble Polymer



Source: https://www.mdpi.com/1996-1944/18/7/1556



Liquid photopolymer (on the left), induced polymerization by light (small circle- monomer, large circle—oligomer, star—photo initiator)

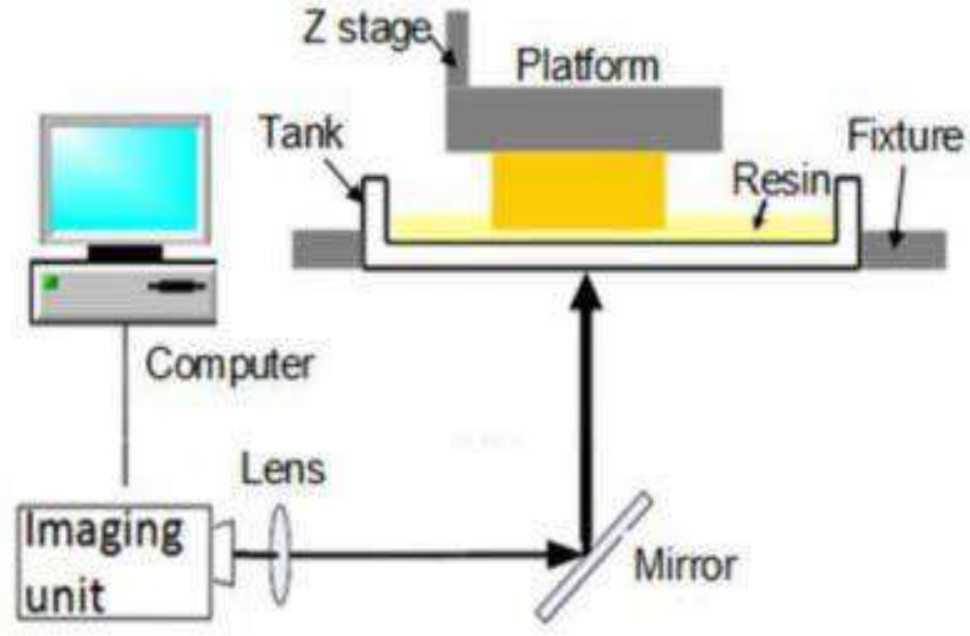
SLA Process Mechanism:

- *Photo- initiator* is the component which reacts with light and get excited to initiate the curing process.
- *Curing* in 3D printing is the chemical process of hardening liquid resin into a solid, durable plastic using light (usually UV) or heat.
- It produces *free radicals or cations* and induces the polymerization reaction.
- *Precursor* is the primary component of the resin, which is required to built the actual components.
- The Precursor is either *acrylic or epoxy* based or a combination of the both.
- The acrylic based resin cures faster than epoxy based resins because epoxy resins are cured using *cationic polymerization* ,whereas acrylic based resins use *radical polymerization* for curing.

COMPONENTS OF SLA/DLP 3D PRINTING MACHINE

- **Light Source**: The heart of SLA printer is the laser source and controlled mirrors while in case of the DLP printing process it is the light source, typically a high-intensity projector or an array of UV LEDs. This light source emits a specific wavelength of light (often ultraviolet) that triggers the photo polymerization reaction in the liquid resin.
- **Build Platform**: The build platform is a flat surface where the printed object gradually forms layer by layer. It moves up/down (Z-axis) to control the height of each layer and ensure precise printing.
- **Resin Vat**: The resin vat contains photopolymer resin. It's transparent, enabling light to pass through and selectively focus on specific areas to solidify each layer during the curing process. The bottom of the vat is typically coated with a transparent film or layer to facilitate adhesion of each layer to the build platform.
- **Optical System**: The optical system consists of mirrors, lenses, and other optical components that focus and direct the light from the light source/laser onto the surface of the liquid resin in the vat. This system ensures that the light is projected with high precision to cure the resin according to the desired pattern of each layer.

- **Control System**: The control system of the 3D printing machine manages the entire printing process. It interprets the digital 3D model of the object to be printed and generates the corresponding layer-by-layer instructions for the SLA/DLP printer. It also monitors and adjusts various parameters such as exposure time, layer thickness, and build platform movement to ensure accurate and consistent printing.
- **Cooling System**: Some SLA/DLP printers may incorporate a cooling system to regulate the temperature of the resin during printing. This helps prevent overheating and ensures optimal curing and layer adhesion.
- **Post-Processing Station**: Once the 3D printing is complete, the printed object require additional post-processing steps such as washing, curing (additional UV exposure to fully harden the resin), and support removal. Some DLP printers may include integrated post processing capabilities, while others may require manual post-processing steps.



Main components of SLA 3d printing machine

Printing Procedure in SLA Machine

- **Step 1:** prepare the 3D model -start by designing or obtaining a 3d model of the object you want to print using CAD software such as NX-CAD, Solid works etc. . This 3D model converted in to compatible file format such as .STL or .OBJ , 3MF
- **Step 2:** Slice the model use slicer software to divide the 3d model into thin horizontal layers. This process is called slicing, and it determines the path the printer will follow to create the object layer by layer.
- **Step 3:** set up the SLA printer - prepare the SLA printer by ensuring it is properly calibrated and filled with the appropriate resin material. Make sure the build platform is clean and levelled.
- **Step 4:** Initiate the printing process - load the sliced file into the SLA printer's software interface. Set the printing parameters such as layer height, printing speed, and support structures if needed. Then, initiate the printing process.
- **Step 5:** Resin solidification - during printing, the SLA printer uses a UV laser to selectively solidify thin layers of liquid resin according to the sliced model. The laser beam traces the pattern of each layer onto the surface of a vat of liquid resin.

- **Step 6:** Build platform movement as each layer is solidified, the build platform gradually moves downward/upward, allowing the next layer of resin to be exposed to the laser. This process continues layer by layer until the entire object is printed.

- **Step 7:** After the 3D printing process is finished, there are additional steps necessary for the components. These include cleaning off any uncured resin using isopropyl alcohol (IPA), and for certain materials, a post-curing process are needed to enhance strength and stability. Following this, supports are removed from the parts and any remaining marks are sanded down for a smooth surface. SLA parts can then be easily machined, primed, painted, and assembled according to specific requirements or desired finishes.

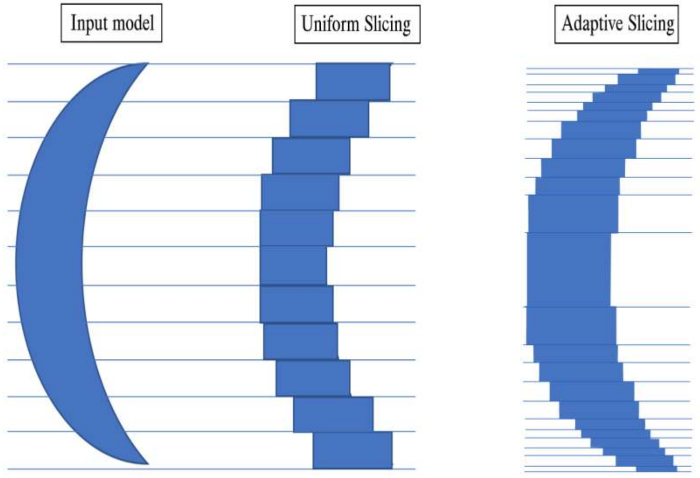
Software and slicing for SLA printing

- **Pre Form:** Developed by Form labs, Pre Form is widely used software specifically designed for Form labs SLA printers. It allows users to import, orient, and prepare models for printing. It also includes features for adding supports and optimizing print settings.
- **Blender:** While not exclusively designed for SLA printing, Blender is a powerful open-source 3D modeling software that can be used for creating models to be printed with SLA technology. It offers robust modeling and sculpting tools, along with support for various file formats.
- **Mesh mixer:** Autodesk's Mesh mixer is another popular choice for preparing models for SLA printing. It includes tools for mesh editing, analysis, and optimization. Users can also generate custom supports and hollow out models to save resin material.
- **Simplify 3D:** Although primarily known for FDM (Fused Deposition Modeling) printing, Simplify3D also supports SLA printers. It offers advanced slicing capabilities, allowing users to fine-tune print settings and optimize supports for SLA prints.

Parameters for slicing in 3D printer Software:

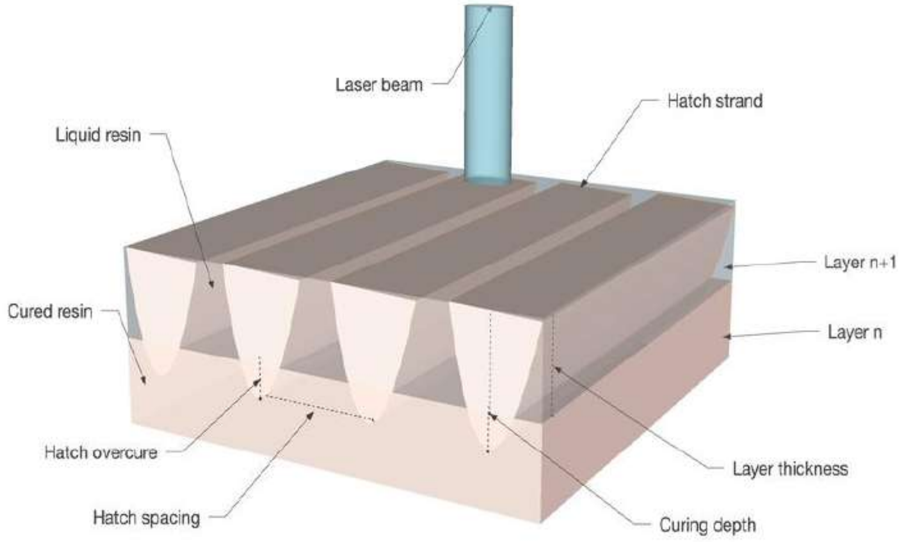
- **Layer Thickness:** Users can specify the desired layer thickness for the print job. This determines the height of each individual slice in the final printed object. Common layer thickness options range from a few microns to several millimeters, depending on the printer's capabilities and the desired level of detail.
- **Slicing Algorithms:** 3D Sprint Software utilizes advanced slicing algorithms to generate optimized tool paths for each layer of the 3D model. These algorithms take into account factors such as **print speed, layer adhesion, support structure placement, and surface quality** to produce high-quality prints with minimal defects.
- **Support Structures**: In addition to slicing the main body of the model, 3D Sprint Software also generates support structures as needed to prevent overhangs and ensure successful printing of complex geometries. Users can customize parameters such as support density, angle, and interface layers to achieve the desired balance between print quality and material usage.

- **Adaptive Slicing:** Some versions of 3D Sprint Software may feature adaptive slicing capabilities, where the software automatically adjusts the layer thickness and other slicing parameters based on the geometry of the model. This helps to optimize print times and material usage while maintaining print quality throughout the entire object.



- **Preview and Simulation:** Before sending the sliced file to the printer, users can preview each layer and simulate the printing process within 3D Sprint Software. This allows them to identify potential issues such as collisions, overheating, or warping and make adjustments as needed to ensure a successful print.

- **Hatching pattern:** It governs the internal filling of a solid and has a significant impact on the dimensional accuracy of the part.

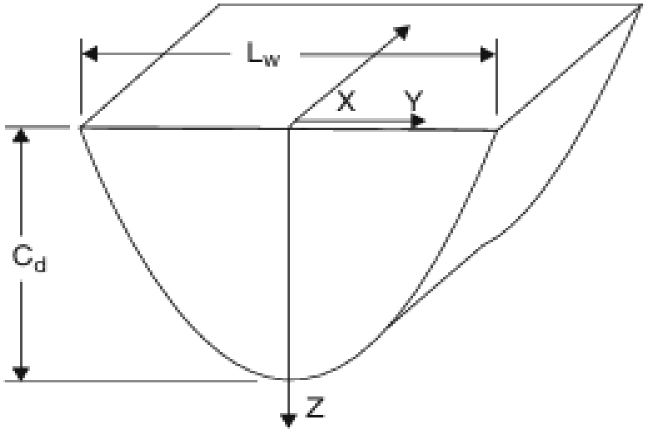


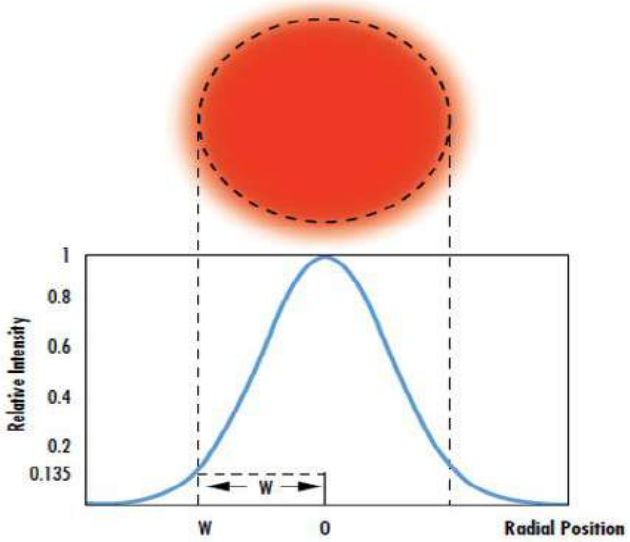
LASER Power Calculation

1. The Working Curve Equation

The most fundamental calculation for SLA is the semi-empirical model that relates the thickness of the cured layer to the laser energy:

$$C_d = D_p . \ln\left(\frac{E}{E_c}\right)$$





C_d **=(Cure Depth):** The thickness of the solidified resin layer.
D_p **=(Penetration Depth):** A resin-specific constant representing the depth at which the laser's irradiance is reduced to 1/e
E**=(Exposure Energy)** The energy per unit area (mJ/cm^2) delivered by the laser to the resin surface.
E_c**=(Critical Exposure)** The minimum energy dose required to reach the resin's gel point (the start of solidification)

Total Laser Power and Irradiance

$$P = \frac{1}{2}\pi.W_0^{\,2}.H_0$$

P **(Total Laser Power):** The measured power of the laser beam, typically between 300–500 mW at the diode.
W_0**(Beam Radius):** The radius of the laser spot at the resin surface.
H_0**(Peak Irradiance):** The maximum intensity at the center of the laser beam

$$E \approx \sqrt{\frac{2}{\pi}}\cdot\frac{P}{W_0.v_s}$$

v_s**= (Scanning Speed):** The velocity at which the galvanometers move the laser spot across the resin

$$LW = D\times\sqrt{\frac{C_d}{D_p}}$$

LW = Line width, D = Laser Spot Size,

MATERIAL SELECTION FOR SLA PRINTING

- **Photo polymerization Compatibility**: Ensure that the material is compatible with photo polymerization and verify that the material undergoes rapid and reliable curing when exposed to the specific wavelengths of light emitted by the printer's laser or UV light source.
- **Viscosity and flow Characteristics**: Select a resin with an appropriate viscosity to enable smooth printing without issues such as dripping or running, while still allowing for good surface finish.
- **Mechanical properties:** Consider the mechanical properties of the printed parts, including strength, stiffness, toughness, and elongation at break.
- **Thermal properties**: Assess the material's thermal stability and resistance to heat deformation during printing and post-processing.
- **Chemical resistance**: Select a resin with appropriate chemical resistance to ensure the durability and longevity of the printed parts in their intended environment.
- **Surface finish and detail resolution**: Choose a resin that offers good resolution and surface quality, especially for applications requiring high precision and intricate details.
- **Biocompatibility and safety:** For applications in healthcare, medical devices, or consumer products, prioritize the biocompatibility and safety of the resin. Ensure that the selected material complies with relevant regulatory standards and does not pose any health risks to end-users.
- **Availability and Cost:** Assess the availability and cost of the resin, including factors such as material availability, lead times, and pricing.

PREPARING THE SLA/DLP PRINTER FOR PRINTING

- Carefully select the appropriate resin material for your specific application, taking into account factors such as strength, toughness, and temperature resistance. Before you begin, make sure to shake the resin bottle thoroughly for 15 minutes.
- **Inspect Resin Quality:** Check the quality of the resin for any signs of contamination or degradation. If the resin appears compromised, replace it with fresh resin from a sealed container.
- **Clean the Build Platform**: Inspect the build platform for any debris or leftover resin from previous prints. Use a clean, lint-free cloth and isopropyl alcohol to wipe down the build platform thoroughly; ensuring it's free from any residues that could affect print quality.
- **Calibrate Build Platform**: Follow the printer's calibration procedure to ensure the build platform is properly aligned and leveled.
- **Prepare Print Files**: Load the digital files (typically in .STL format) for the objects you intend to print onto the printer's software or interface. Arrange and orient the models as desired, considering factors such as support structures and print orientation for optimal results.
- **Generate Supports**: If your print requires support structures to prevent warping or collapsing during printing, use the printer's software to generate these supports automatically or manually as needed.

PREPARING THE SLA/DLP PRINTER FOR PRINTING

- **Initiate Printing**: Once all preparations are complete, close the printer's cover or door and power on the machine.
- Navigate the printer's interface to select the desired print file and start the printing process. Monitor the print job periodically to ensure it progresses smoothly and address any issues that may arise, such as resin spills or failed prints.
- **Post-Printing Cleanup:** After the print job is complete, carefully remove the printed components from the build platform using appropriate tools, such as a scraper. Rinse the printed object in a container of isopropyl alcohol to remove any excess resin. Dispose of any used resin and clean the printer's components, such as the resin tank and build platform, according to the manufacturer's instructions.
- **Shutdown and Maintenance:** Once printing is finished and cleanup is complete, power off the printer and unplugs it from the power source. Perform any recommended maintenance tasks, such as cleaning filters or lubricating moving parts, to keep the printer in optimal condition for future use.

POST-PROCESSING TECHNIQUES

- **Support Removal:** SLA parts typically require support structures during the printing process to prevent sagging or warping. After printing, these supports need to be removed carefully to avoid damaging the part. Techniques such as manual removal, mechanical cutting, or dissolution in solvents (where applicable) are commonly used.
- **Washing/Cleaning:** SLA-printed parts often have uncured resin residue on their surfaces. Washing the parts in a solvent bath or using ultrasonic cleaning can help remove this residue and improve surface cleanliness.
- **Curing:** SLA-printed parts undergo a partial curing process during printing, but additional curing may be required to fully strengthen the parts. UV curing chambers or post-curing ovens are used to expose the parts to UV light or heat, promoting further polymerization and enhancing their mechanical properties.
- **Sanding and Polishing:** To achieve smoother surface finishes and remove layer lines, sanding and polishing techniques can be employed. This may involve manual sanding with progressively finer grits of sandpaper or automated processes such as tumbling or abrasive blasting.
- **Surface Coating:** Applying coatings such as paints, varnishes, or clear coats can further enhance the appearance and functionality of SLA-printed parts. These coatings can provide additional protection, improve surface smoothness, or add decorative finishes.
- **Surface Treatment:** Chemical or mechanical treatments can be used to modify the surface properties of SLA-printed parts. For example, chemical etching or plasma treatment can alter surface roughness or wettability, improving adhesion for subsequent processes like painting or bonding.
- **Assembly and Finishing:** Assembled parts may require additional post-processing steps such as machining, tapping, threading, or bonding to achieve the desired final product. These processes may be performed manually or using specialized equipment depending on the complexity of the assembly.

INSPECTING AND TESTING THE PRINTED OBJECT

- **Visual Inspection:** Examine the printed components for any visible defects such as warping, layer misalignment, or surface irregularities. Check for any uncured resin residue on the surface, which may indicate incomplete curing.
- **Dimensional accuracy:** Use accurate measurement instruments like calipers or coordinate measuring machines (CMM) to confirm the precision of dimensions. Compare the dimensions of the printed object to the intended CAD model to identify any discrepancies.
- **Surface quality analysis**: Perform surface roughness measurements using profile meters.
- **Material properties testing:** Conduct material property tests to evaluate mechanical characteristics such as tensile strength, flexural strength, and impact resistance.
- **Functional testing**: Subject the printed object to functional tests relevant to its intended use, such as load-bearing tests, fitment checks, or fluid flow analysis for fluidic components. Evaluate the performance of the printed object under simulated real-world conditions to ensure it meets functional requirements.
- **Environmental testing:** Expose the printed object to environmental factors such as temperature extremes, humidity, UV radiation, or moisture to evaluate its durability and stability over time.
- **Documentation and Reporting**: Record detailed inspection and test results, including any deviations from specifications or quality standards.

Advantages of Vat Photo-polymerisation

- Simple and Compact
- Good quality and accuracy : Surface finish and resolution is 0.38-0.61 μm and 10-150 μm.
- Multi-material Compatibility
- Prototyping
- Micro-manufacturing

Limitation of Vat Photo-polymerisation

- Costly
- Requires post-curing
- Support structures
- Material limitations

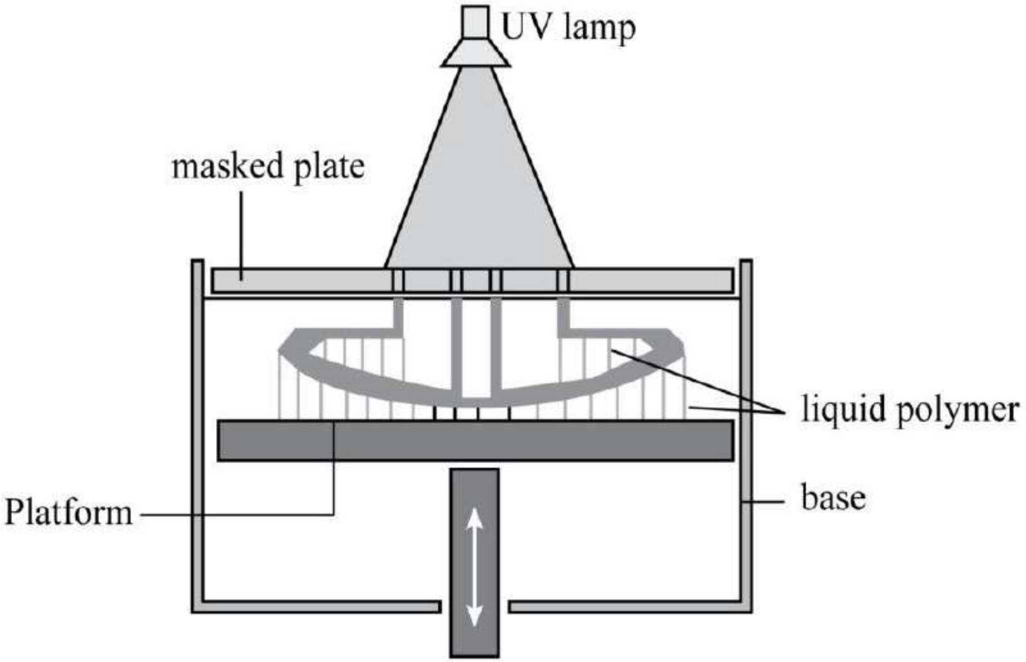
CUBITAL'S SOLID GROUND CURING (SGC)

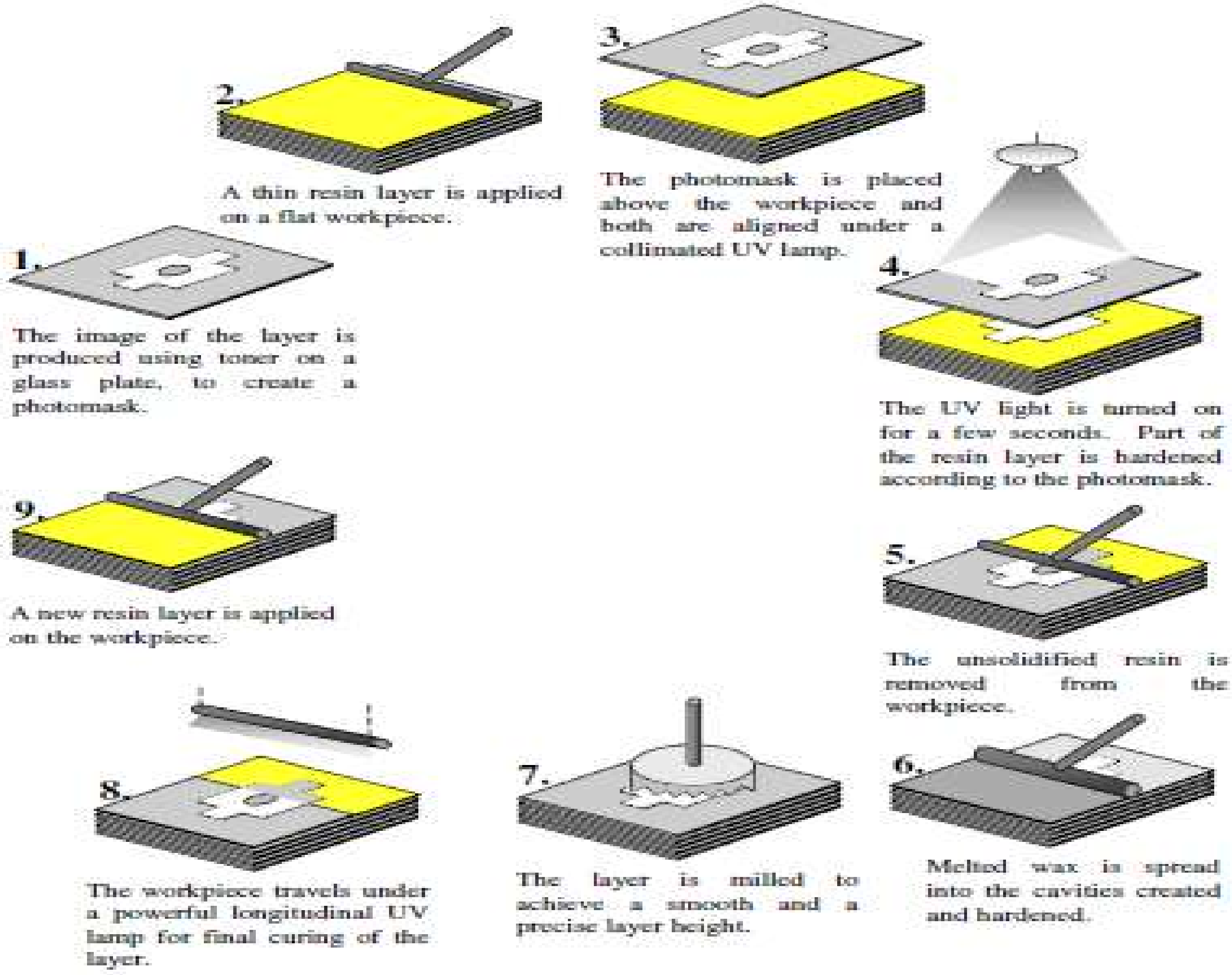
- The Solid Ground Curing (SGC) System is produced by Cubital Ltd.

Model	Solider 4600	Solider 5600
Irradiation medium	High power UV lamp	
XY resolution (mm)	Better than 0.1	
Surface definition (mm)	0.15	0.15
Elevator vertical resolution (mm)	0.15	0.1–0.2
Minimum feature size (mm)	0.4 (horizontal, *X–Y*) 0.15 (vertical, *Z*)	0.4 (horizontal, *X–Y*) 0.15 (vertical, *Z*)
Work volume, *XYZ* (mm × mm × mm)	350 × 350 × 350	500 × 350 × 500
Production rate (cm^3/hr)	550	1311
Minimum layer thickness (mm)	0.06	0.06
Dimensional accuracy	0.1%	0.1%
Size of unit, *XYZ* (m × m × m)	1.8 × 4.2 × 2.9	1.8 × 4.2 × 2.9
Data control unit	Data Front End (DFE) workstation	
Power supply	380–415 V_{AC}, 3 phase, 50 kW	380–415 V_{AC}, 3 phase, 50 kW

Process

- The Cubital's Solid Ground Curing process includes three main steps:
  1. data preparation,
  2. mask generation
  3. model making





Advantages

- **Parallel processing.** The process is based on instant, simultaneous curing of a whole cross-sectional layer area (rather than point-by point curing). It has a high speed throughput that is about eight times faster than its competitors. Its production costs can be 25% to 50% lower. It is a time and cost saving process.
- **Self-supporting.** It is user-friendly, fast, and simple to use. It has a solid modeling environment with unlimited geometry. The solid wax supports the part in all dimensions and therefore a support structure is not required.
- **Fault tolerance.** It has good fault tolerances. Removable trays allow job changing during a run and layers are erasable.
- **Unique part properties**. The part that the Solider system produces is reliable, accurate, sturdy, machinable, and can be mechanically finished.
- **CAD to RP software**. Cubital's RP software, Data Front End (DFE), processes solid model CAD files before they are transferred to the Cubital's machines. The DFE is an interactive and user friendly software.
- **Minimum shrinkage effect**. This is due to the full curing of every layer.
- **High structural strength and stability**. This is due to the curing process that minimizes the development of internal stresses in the structure. As a result, they are much less brittle.
- **No hazardous odors are generated.** The resin stays in a liquid state for a very short time, and the uncured liquid is wiped off immediately. Thus safety is considerably higher.

Disadvantages

- **Requires large physical space.** The size of the system is much larger than other systems with a similar build volume size.
- **Wax gets stuck in corners and crevices.** It is difficult to remove wax from parts with intricate geometry. Thus, some wax may be left behind.
- **Waste material produced.** The milling process creates shavings, which have to be cleaned from the machine.
- **Noisy.** The Solider system generates a high level of noise as compared to other systems.

Applications

- **General applications**. Conceptual design presentation, design proofing, engineering testing, integration and fitting, functional analysis, exhibitions and pre-production sales, market research, and inter-professional communication.
- **Tooling and casting applications**. Investment casting, sand casting, and rapid, tool-free manufacturing of plastic parts.
- **Mold and tooling**. Silicon rubber tooling, epoxy tooling, spray metal tooling, acrylic tooling, and plaster mold casting.
- **Medical imaging**. Diagnostic, surgical, operation and reconstruction planning and custom prosthesis design.

Probable Questions (To be submitted as Assignment-II):

- Explain Photo-polymerisation phenomenon. What are the differences between acrylics and epoxies?
- How laser power , scan speed and beam diameter affect the quality of build in vat photo-polymerisation?
- Explain the different Advantages and dis advantages of SLA.
- Explain the detail mechanism and process of SLA with its applications.
- Explain the details of process chain and working principle of SGC.
- What are the applications of SGC?
- What are the advantages and disadvantages of using SGC?
- What are the different parameters for Slicing in 3D Printer Software?
- What are the different criteria for the material selection for the SLA 3D printers?
- What are the different post processing techniques used in SLA 3D printing?

Activity Assignment-II

- Download one open source additive manufacturing software (Cura,Slice3r etc.). Import the STL file of a solid cylinder of diameter 60 mm and height 120 mm. Find the effect of layer thickness , print speed and orientation on the build time. Make a complete video recording of the screen while performing the above assignment and submit in any of the storage device.

End of the Module-II

Additive Manufacturing
Module-3

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Subject Code: MFPE3011
Semester: 6th
University: BPUT, Odisha

Declaration

This is Prepared for the Education Purpose only

Source: https://www.theguardian.com/education/2014/oct/31/education-traditional-teaching-versus-progressive

Module-III: (10 Hours)

- Solid based systems: Laminated object manufacturing (LOM): Models and specifications, Process, Working principle, Applications, Advantages and disadvantages, Case studies. Fused Deposition Modeling (FDM): Models and specifications, Process, Working principle, Applications, Advantages and disadvantages, Case studies, practical demonstration

Sheet Lamination

- According to ASTM/ISO, Sheet lamination is defined as an additive manufacturing process in which sheets of material are bonded to form a part.
- The mandatory conditions for any process to qualify as sheet lamination are as follows:

  1. The input material is in sheet form.
  2. Bonding of sheets is the primary mechanism for forming the part.
  3. No melting and solidification of build material.

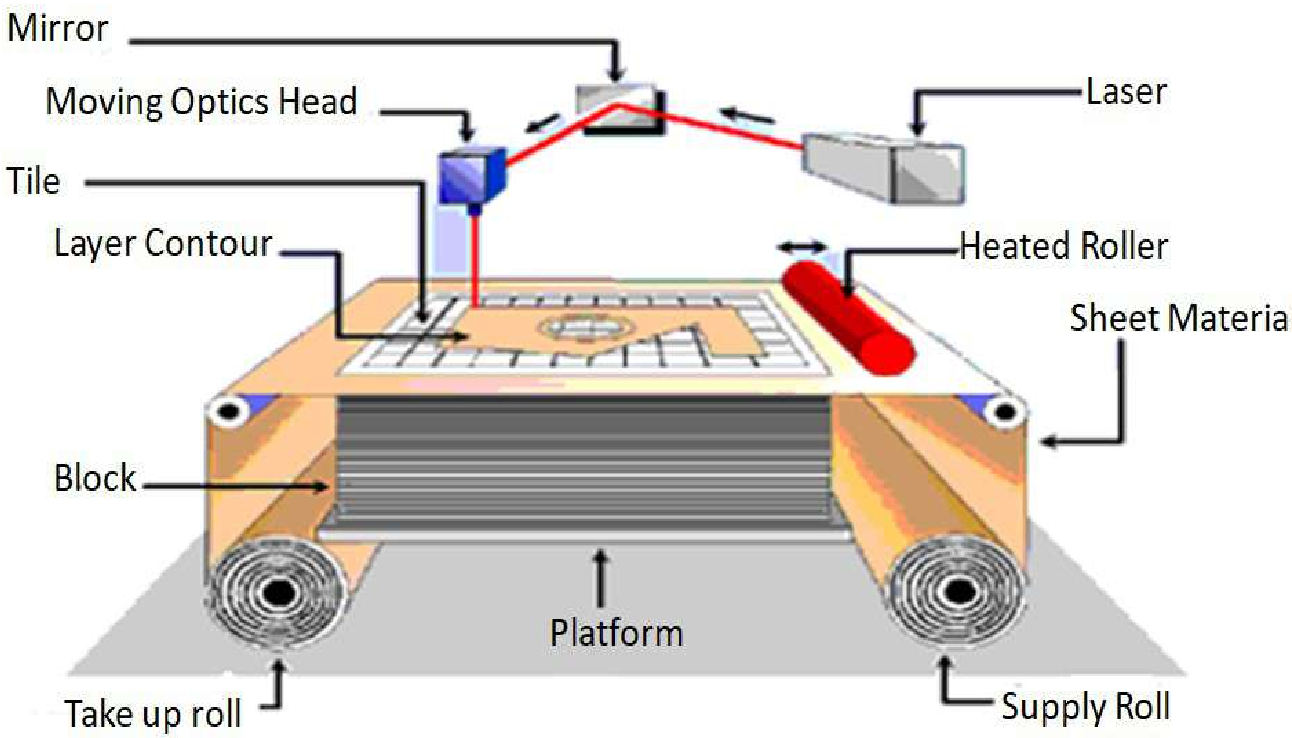
Sheet Lamination

- **Bond-then-form**
  - Laminated Object Manufacturing
  - Selective deposition lamination
  - Plastic sheet Lamination
  - Ultrasonic consolidation
- **Form-then-bond**
  - Computer-aided manufacturing of laminated engineering materials(CAM-LEM)
  - Offset fabbing

Laminated object manufacturing (LOM):

- Solid-based rapid prototyping systems are very different from the liquid-based photo-curing systems.
- They are also different from one another, though some of them do use the laser in the prototyping process.
- The basic common feature among these systems is that they all utilize solids (in one form or another) as the primary medium to create the prototype.
- The Laminated Object Manufacturing® (LOM™) process is an automated fabrication method in which a 3D object is constructed from a solid CAD representation by sequentially laminating the part cross-sections.
- The process consists of three phases: pre-processing; building; post-processing.

Laminated object manufacturing (LOM):

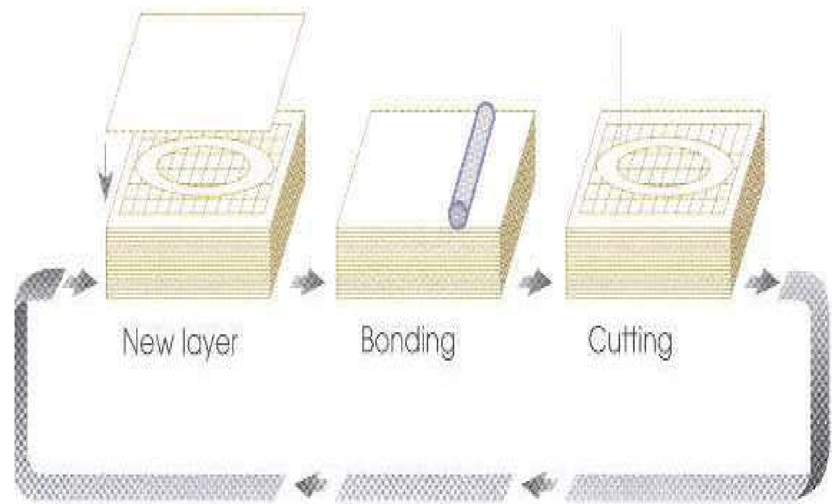


Pre-processing

- The pre-processing phase comprises several operations.
- The initial steps include generating an image from a CAD-derived STL file of the part to be manufactured, sorting input data, and creating secondary data structures.
- These are fully automated by LOMSlice^{TM}, the LOM^{TM} system software, which calculates and controls the slicing functions.
- Orienting and merging the part on the LOM^{TM} system are done manually.
- These tasks are aided by LOMSlice^{TM}, which provides a menu-driven interface to perform transformations (e.g., translation, scaling, and mirroring) as well as merges.

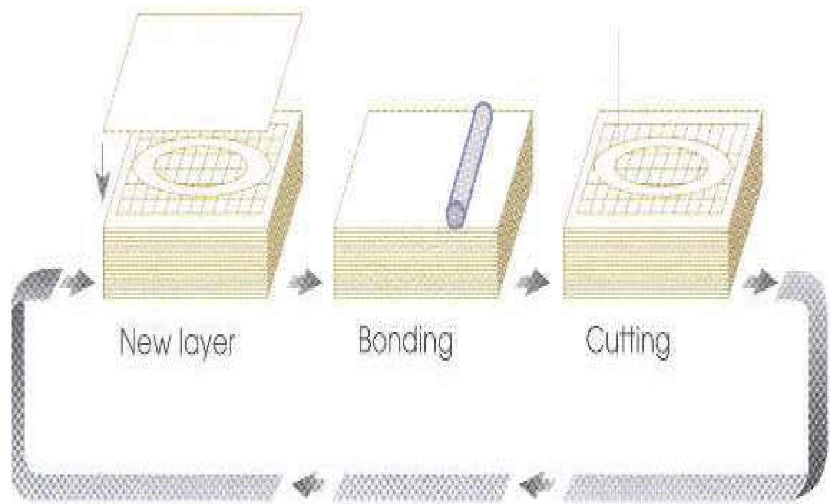
Building

- In the building phase, thin layers of adhesive-coated material are sequentially bonded to each other and individually cut by a CO_2 laser beam.
- LOMSlice™ creates a cross-section of the 3D model measuring the exact height of the model and slices the horizontal plane accordingly. The software then images crosshatches which define the outer perimeter and convert these excess materials into a support structure.
- The computer generates precise calculations, which guide the focused laser beam to cut the cross-sectional outline, the crosshatches, and the model's perimeter. The laser beam power is designed to cut exactly the thickness of one layer of material at a time. After the perimeter is burned, everything within the model's boundary is "freed" from the remaining sheet.



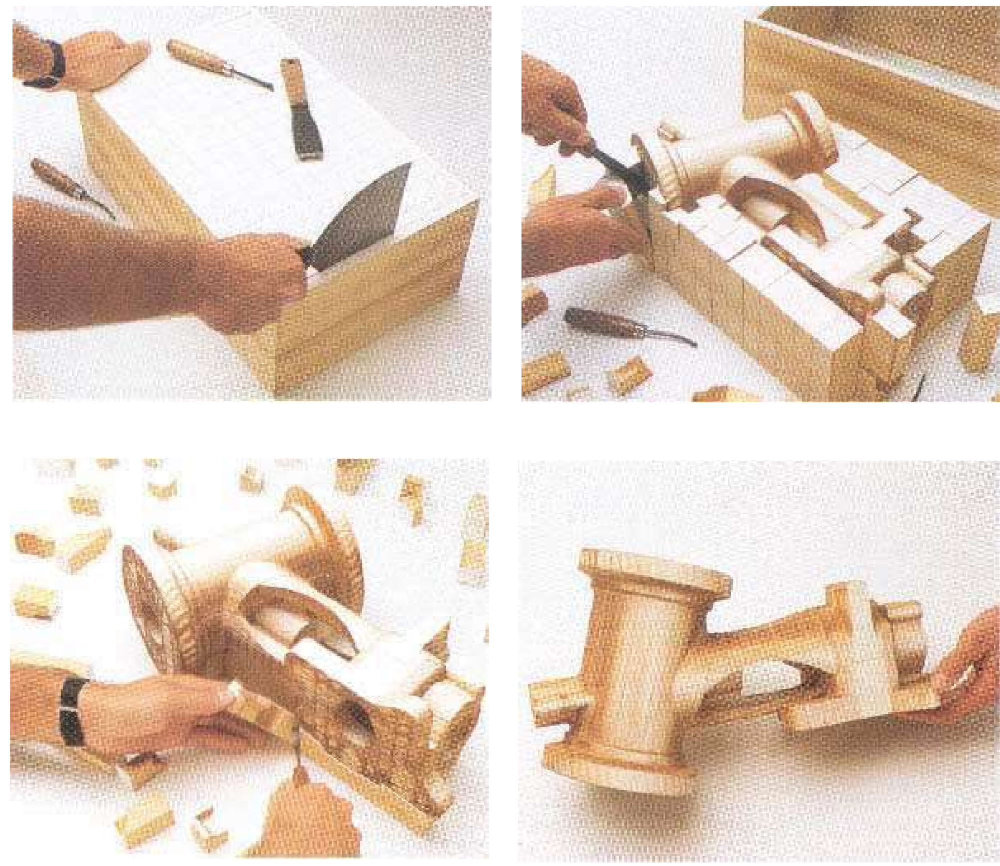
Building

- The platform with the stack of previously formed layers descends and a new section of material advances. The platform ascends and the heated roller laminates the material to the stack with a single reciprocal motion, thereby bonding it to the previous layer.
- The vertical encoder measures the height of the stack and relays the new height to LOMSlice^{TM}, which calculates the cross section for the next layer as the laser cuts the model's current layer.



Post-processing

- The last phase, post-processing, includes separating the part from its support material and finishing it.
- The metal platform, home to the newly created part, is removed from the LOM™ machine. A forklift may be needed to remove the larger and heavier parts from the LOM-2030H™.
- Normally a hammer and a putty knife are all that is required to separate the LOM™ block from the platform. However, a live thin wire may also be used to slice through the double-sided foam tape, which serves as the connecting point between the LOM™ stack and the platform.
- The surrounding wall frame is lifted off the block to expose the crosshatched pieces of the excess material. Crosshatched pieces may then be separated from the part using wood carving tools.



Materials

- Potentially, any sheet material with adhesive backing can be utilized in Laminated Object Manufacturing.
- It has been demonstrated that plastics, metals, and even ceramic tapes can be used.
- However, the most popular material has been Kraft paper with a polyethylene-based heat seal adhesive system because it is widely available, cost-effective, and environmentally benign .
- In order to maintain uniform lamination across the entire working envelope it is critical that the temperature remain constant.
- A temperature control system, with closed-loop feedback, ensures the system’s temperature remains constant, regardless of its surrounding environment.

Principle

- Parts are built, layer-by-layer, by laminating each layer of paper or other sheet-form materials and the contour of the part on that layer is cut by a CO_2 laser.
- Each layer of the building process contains the cross-sections of one or many parts. The next layer is then laminated and built directly on top of the laser-cut layer.
- The *Z-control is activated by an elevation platform, which lowers* when each layer is completed, and the next layer is then laminated and ready for cutting. The *Z-height is then measured for the exact* height so that the corresponding cross sectional data can be calculated for that layer.
- No additional support structures are necessary as the "excess" material, which are cross-hatched for later removal, act as the support.

Advantages

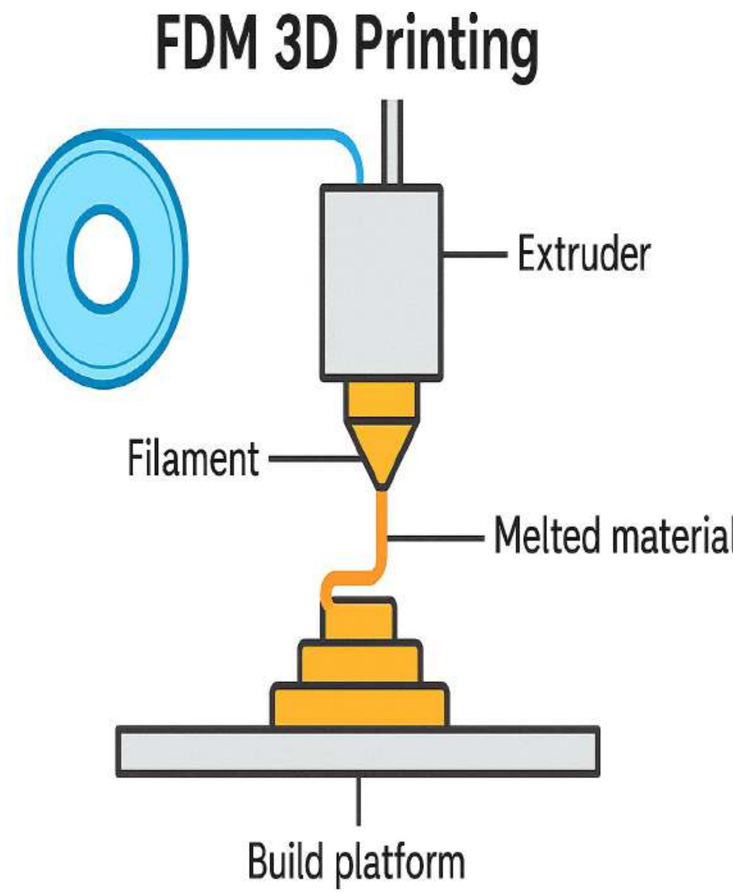
- ***Wide variety of materials****. In principle, any material in sheet form* can be used in the LOMTM systems. These include a wide variety of organic and inorganic materials such as paper, plastics, metals, composites and ceramics.
- ***Fast build time****. The laser in the LOM^{TM} process does not scan the* entire surface area of each cross-section, rather it only outlines its periphery.
- ***High precision****. The feature to feature accuracy that can be* achieved with LOMTM machines is usually better than 0.127 mm (0.005").
- ***Support structure****. There is no need for additional support structure* as the part is supported by its own material that is outside the periphery of the part built.
- ***Post-curing****. The LOM^{TM} process does not need to convert* expensive, and in some cases toxic, liquid polymers to solid plastics or plastic powders into sintered objects.

Disadvantages

- ***Precise power adjustment***. *The power of the laser used for cutting* the perimeter (and the crosshatches) of the prototype needs to be precisely controlled so that the laser cuts only the current layer of lamination and not penetrate into the previously cut layers. Poor control of the cutting laser beam may cause distortion to the entire prototype.
- ***Fabrication of thin walls***. *The LOM™ process is not well suited for* building parts with delicate thin walls, especially in the *Z-direction.*
- ***Integrity of prototypes***. *The part built by the LOM™ process is* essentially held together by the heat sealed adhesives. The integrity of the part is therefore entirely dependent on the adhesive strength of the glue used, and as such is limited to this strength.
- ***Removal of supports***. *The most labor-intensive part of the LOM™* process is its last phase of post-processing when the part has to be separated from its support material within the rectangular block of laminated material.

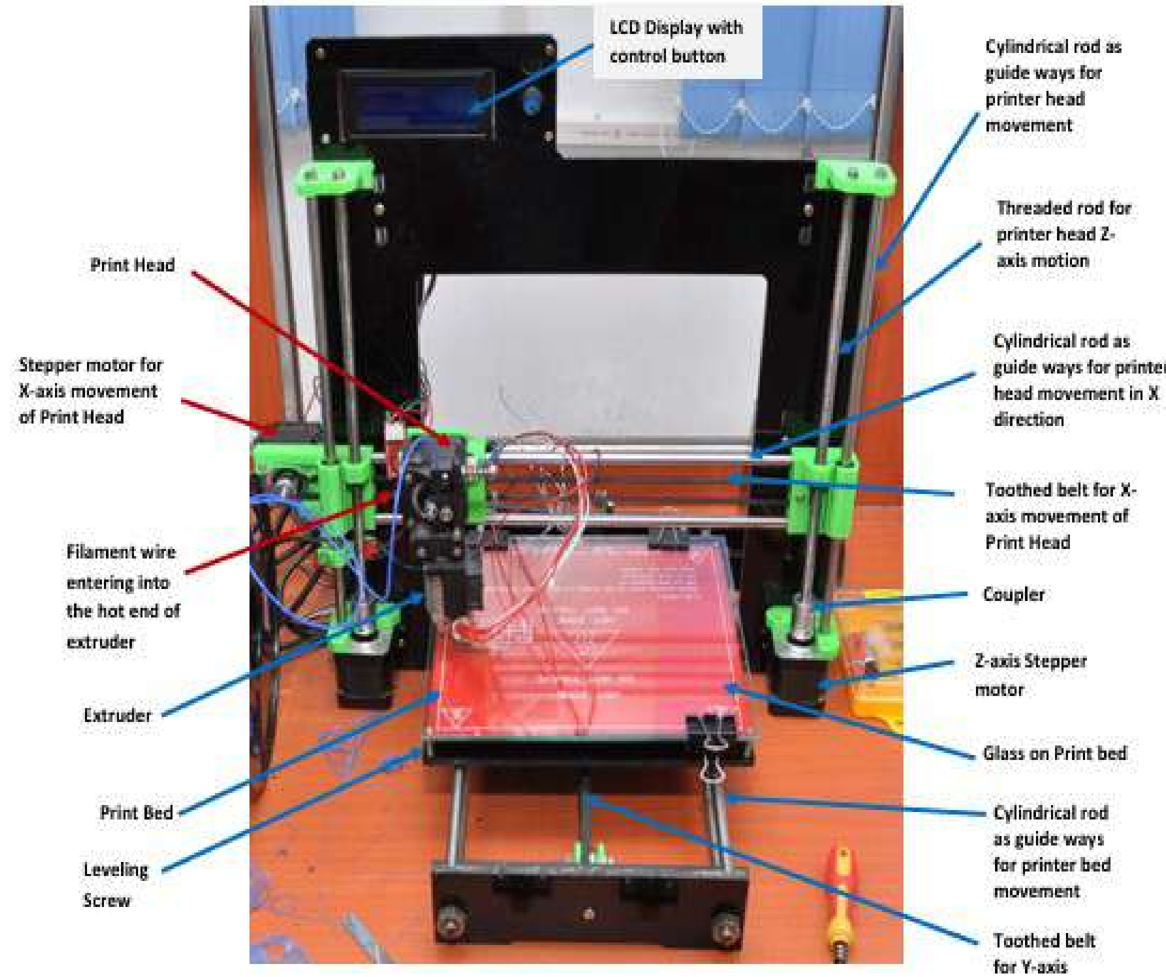
Material Extrusion

- In 1988, Scott Crump invented the material extrusion process and the patent was granted on 9th June 1992.
- The process is most commonly known by the names *Fused Deposition Modelling (FDM) and Fused Filament Fabrication(FFF).*
- *FDM* is primarily deployed for building polymer components.
- *Material Extrusion* system have the largest installed base of AM machines in the world.
- The first material extrusion based FDM was introduced to the market in 1991 by Stratasys Inc.
- Material extrusion is defined as an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.



FUSED DEPOSITION MODELING (FDM)

- Fused Deposition Modelling (FDM), also known as the material extrusion additive manufacturing technique or Fused Filament Fabrication, utilizes polymers as the raw material (filament in the form of wire) for creating 3D objects.
- The filament is usually heated to a molten state and then extruded through the nozzle of the machine (3D printer).
- The nozzle head can move in three Cartesian (Translatory) degrees of freedom (DoF) to deposit the extruded polymer on the build plate layer by layer as per the G-Code of digital model.



COMPONENTS OF FDM PRINTER

- ***Frame and Structure*** - The frame provides the structural support for the entire printer. It's usually made of metal or plastic to ensure stability during the printing process.
- ***Print Bed*** - The print bed is the surface where the object is built layer by layer. It can be heated or unheated depending on the printer model and the type of filament being used. Heated beds help in preventing warping and improve adhesion of the first layer.
- ***Extruder Assembly*** - The extruder assembly consists of a motor-driven gear system and a heated nozzle. It feeds the filament into the hot end where it's melted and extruded onto the print bed. Some printers have a single extruder, while others may have dual or more, allowing for multi-material or multi-color printing.
- ***Hot End*** - The hot end is where the filament is melted and deposited onto the print bed. It typically consists of a heating element (like a resistor or a cartridge heater) and a temperature sensor (usually a thermistor or thermocouple).The nozzle size can vary depending on the desired print quality and speed.
- ***Filament*** - FDM printers use thermoplastic filament as the raw material for printing. Common types of filament include PLA (Polylactic Acid), ABS (Acrylonitrile Butadiene Styrene), PETG (Polyethylene Terephthalate Glycol), and more. Filament comes in spools and is available in various colors and diameters.

COMPONENTS OF FDM PRINTER

- ***Control Board and Electronics*** - The control board is the brain of the 3D printer, responsible for interpreting the G-code instructions and controlling the movement of the printer components. It typically includes a micro controller, stepper motor drivers, and other necessary electronics.
- ***Stepper Motors*** - Stepper motors are used to precisely control the movement of the printer's components, including the extruder, print bed, and possibly other axes if it's a multi-axis printer. They provide accurate positioning and are capable of both linear and rotational motion.
- ***Cooling Fans*** - Cooling fans are used to cool down the printed layers quickly to prevent warping and improve print quality. They are often positioned near the hot end and the printed object.
- ***End stops and Sensors*** – End stops are sensors that detect the physical limits of the printer's axes. They are used to home the printer (establish a reference point) and prevent the motors from moving beyond their mechanical limits, which could damage the printer.
- ***Display and User Interface*** - Many FDM printers come with a display screen and user interface for controlling the printer settings, initiating prints, and monitoring the printing progress. These components work together to enable the FDM printer to create three dimensional objects layer by layer from digital designs.

SELECTION CRITERIA FOR FDM MATERIALS

- ***Melting point-*** Since FDM involves heating the filament to melt it, the material must have a melting point within a suitable range. If the melting point is too low, the object may deform during printing, while if it's too high, the filament may degrade or not extrude properly.
- ***Material's strength and durability*** - The chosen material should be able to withstand the stresses and environmental conditions. For example, if you're making a prototype for a mechanical part, so we need material with high tensile strength and resistance to impact.
- ***Material's flexibility or stiffness -*** Some applications may require a flexible material that can bend without breaking, while others may need a rigid material for structural integrity.
- ***Compatibility -*** Compatibility with post-processing techniques is also essential. Certain materials may be easier to sand, paint, or glue than others
- ***Cost and availability -*** Some materials may be more affordable or easier to source than others, which can significantly impact your project's budget and timeline.

Material Name	Properties	Industrial application
ABS (Acrylonitrile Butadiene Styrene)	+Good strength +Good temperature resistance - More susceptible to warping	Automotive, aerospace, medical-device
PLA (Polylactic acid)	+ Excellent visual quality + Easy to print with - Low impact strength	Ideal for model and prototypes that require aesthetic detail and environmentally-friendly for both home and office
NYLON	+ High strength + Excellent wear and chemical resistance - Low humidity resistance	Ideal material for applications that demand impact-protective components and high fatigue endurance, including antenna covers, custom production tooling, friction-fit inserts and snap fits in automotive and aerospace industries
PETG (Polyethylene terephthalate glycol)	Food Safe* + Good strength + Easy to print	ideal for functional prototypes, durable end-use parts, and, medical components
TPU (Thermoplastic Polyurethane)	+ Very flexible - Difficult to print accurately	Exceptional flexibility (i.e .elongation at break) and corrosion resistance to many common industrial chemicals and oils. Highly versatile material with the both rubber and plastics properties for variety of industrial application
PEI (Polyethyleneimine)	+ Excellent strength to weight + Excellent fire and chemical resistance - High cost	Due to its high strength-to-weight ratio and existing certification, it is ideal for rapid prototyping and advanced tooling applications in aerospace ,automotive ,medical and food-production industries


PLA
TOUGH
NYLON
METAL
N Carbon Fiber
[NEW]
N12 Carbon Fiber
PETG
ABS
ASA
LABS
SEBS
LABS
PETG ESD
LABS
PETG CF
LABS
DURABIO
PC - ABS
PC ABS FR

Process Parameters

1. Nozzle Temperature

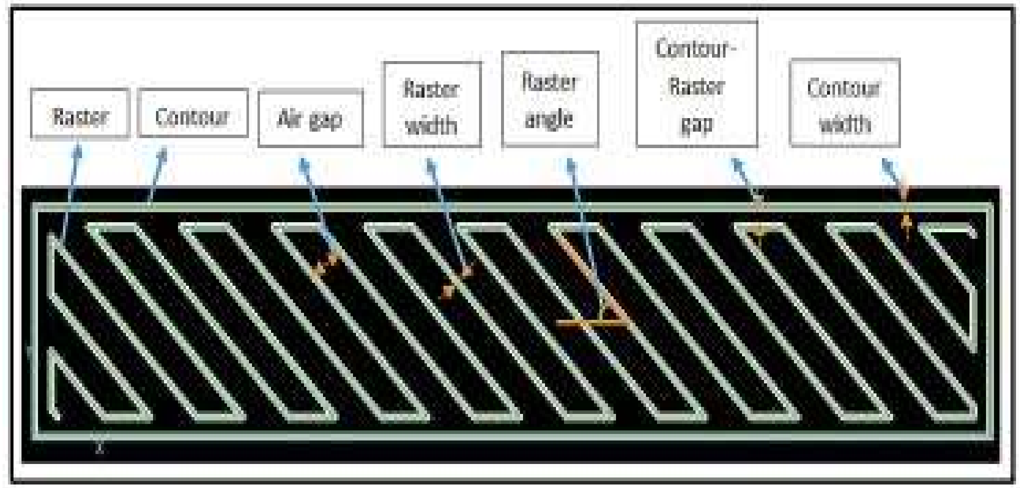
- Controls how well the filament melts and flows.
- Too low → poor layer bonding, under-extrusion
- Too high → stringing, blobs
- Depends on material (e.g., PLA ~180–220°C, ABS ~220–260°C)

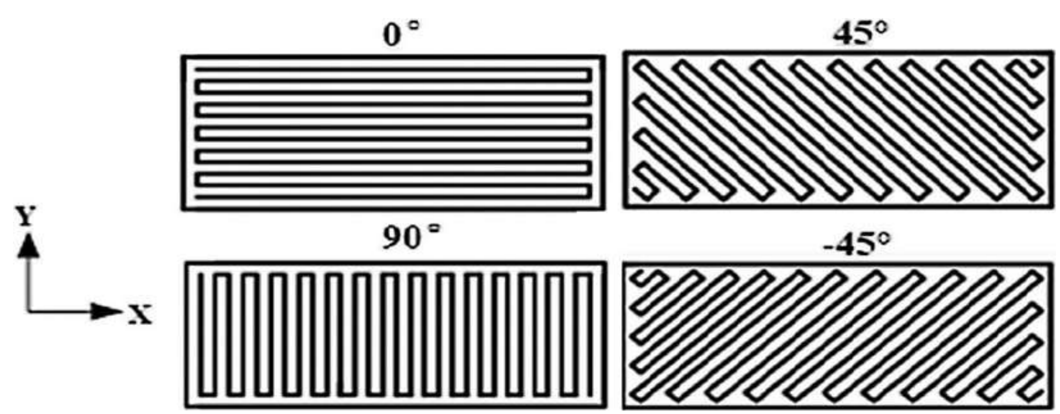
2. Bed Temperature

- Helps first layer adhesion and reduces warping.
- PLA: ~50–70°C
- ABS: ~90–110°C
- Too low → prints detach
- Too high → bottom layer deformation

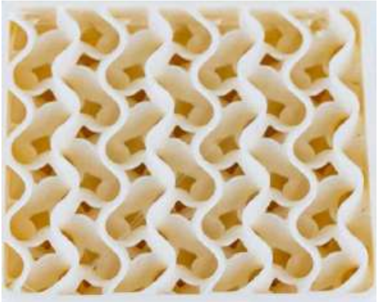
3. Print Speed

- Measured in mm/s.
- Faster = shorter print time but lower quality.
- Typical range: 30–80 mm/s
- High speed → ringing, poor accuracy





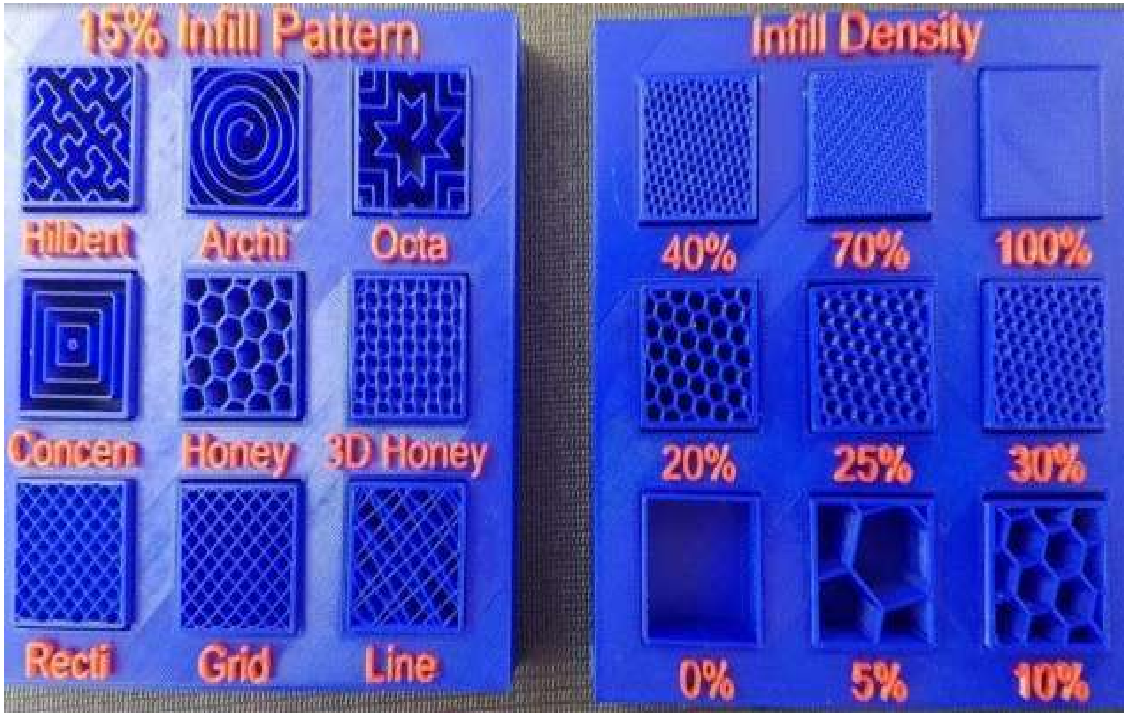
Process Parameters



4. Layer Height

- Thickness of each printed layer.
- Smaller height → better detail but longer print time
- Larger height → faster but rough surface
- Typical: 0.1–0.3 mm

5. Infill Density & Pattern



- Determines internal structure.
- Density: 0–100%
- Common patterns: grid, honeycomb, gyroid
- Higher infill → stronger but heavier & slower

6. Print Cooling (Fan Speed)

- Controls how fast layers solidify.
- PLA → high cooling (better detail)
- ABS → low cooling (prevents cracking)

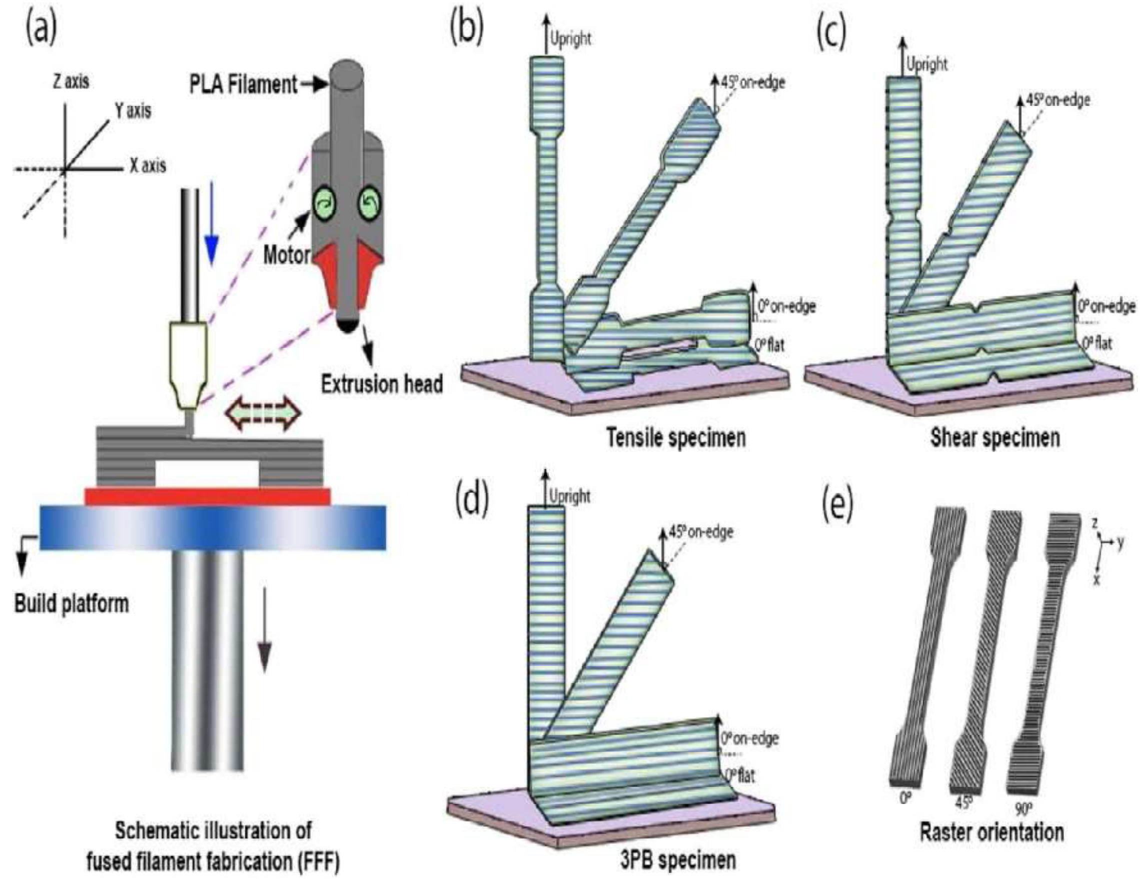
Process Parameters

7. Retraction Settings

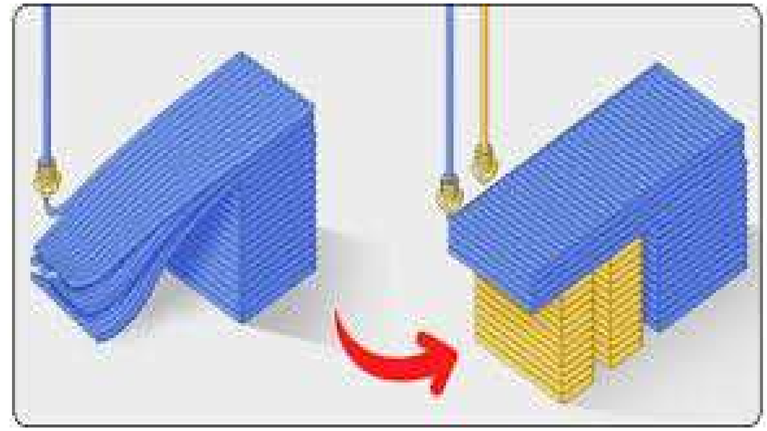
- Pulls filament back to reduce stringing.
- Key parameters:
  - Retraction distance (mm)
  - Retraction speed (mm/s)
- Improper settings → stringing or clogs

8. Build Orientation

- Direction in which the object is printed.
- Affects:
  - Strength (anisotropic behavior)
  - Surface finish
  - Support requirement

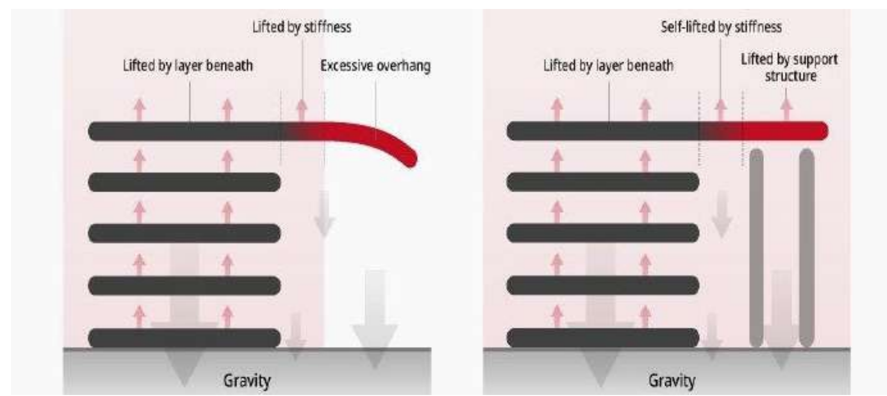


Process Parameters



9. Support Structures

- Used for overhangs (>45° typically).
- Parameters:
  - Support density
  - Placement (touching build plate / everywhere)
- Too dense → hard to remove
- Too sparse → poor support



10. Flow Rate (Extrusion Multiplier)

- Controls how much material is extruded.
- Too high → blobs, over-extrusion
- Too low → gaps, weak layers

11. First Layer Settings

- Critical for adhesion.

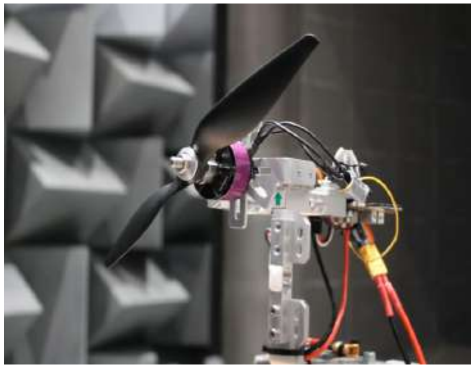
Includes:

- First layer speed (slow)
- First layer height
- First layer extrusion width

Advantages of FDM 3D Printers

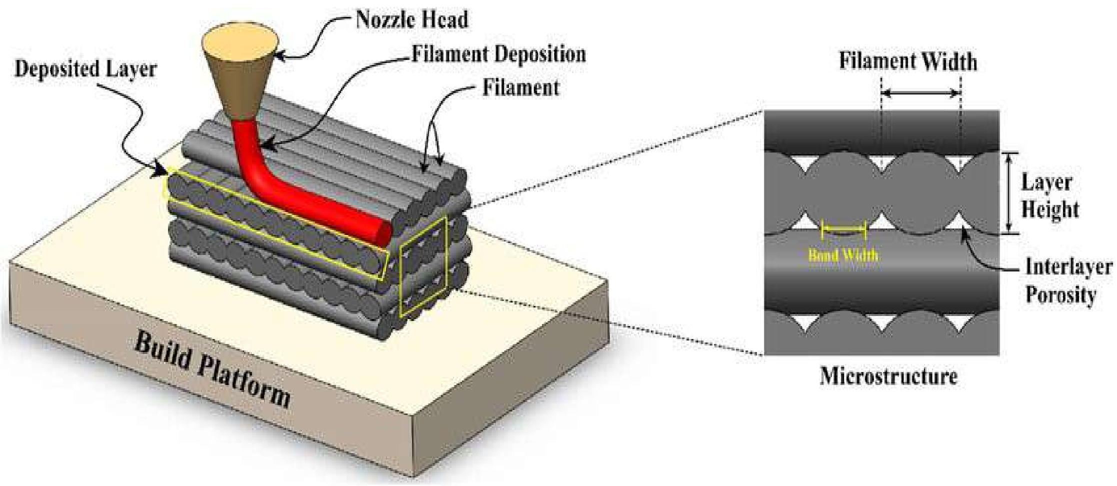
- Low cost
- Simplicity and Safety
- No Material wastage
- Diverse Engineering Materials
- Potential for new material properties
- Easy material change
- Easy Support removal
- Accessibility

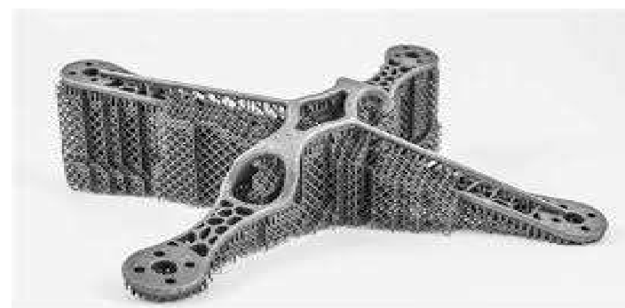





Disadvantages of FDM 3D Printers

- Surface finish and accuracy
- Build Speed
- Anisotropy
- Supports





Probable Questions (To be submitted as Assignment-III):

1. Define Laminated Object Manufacturing (LOM).
2. What is Fused Deposition Modeling (FDM)?
3. List any two materials used in FDM.
4. What is the role of adhesive in LOM?
5. State two advantages of FDM.
6. Explain the working principle of LOM with neat sketch.
7. Describe the process steps involved in FDM.
8. Compare LOM and FDM based on material, accuracy, and applications.
9. Discuss the advantages and limitations of LOM.
10. Explain different types of materials used in FDM and their properties.
11. Explain in detail the working principle, process, advantages, and disadvantages of FDM with diagram.
12. Describe the LOM process in detail, including models, specifications, and applications.
13. Compare solid-based AM systems (LOM & FDM) with liquid-based systems (SLA).
14. Discuss industrial applications and case studies of FDM technology.
15. Explain practical demonstration/setup of FDM machine, including components and working.

End of the Module-III