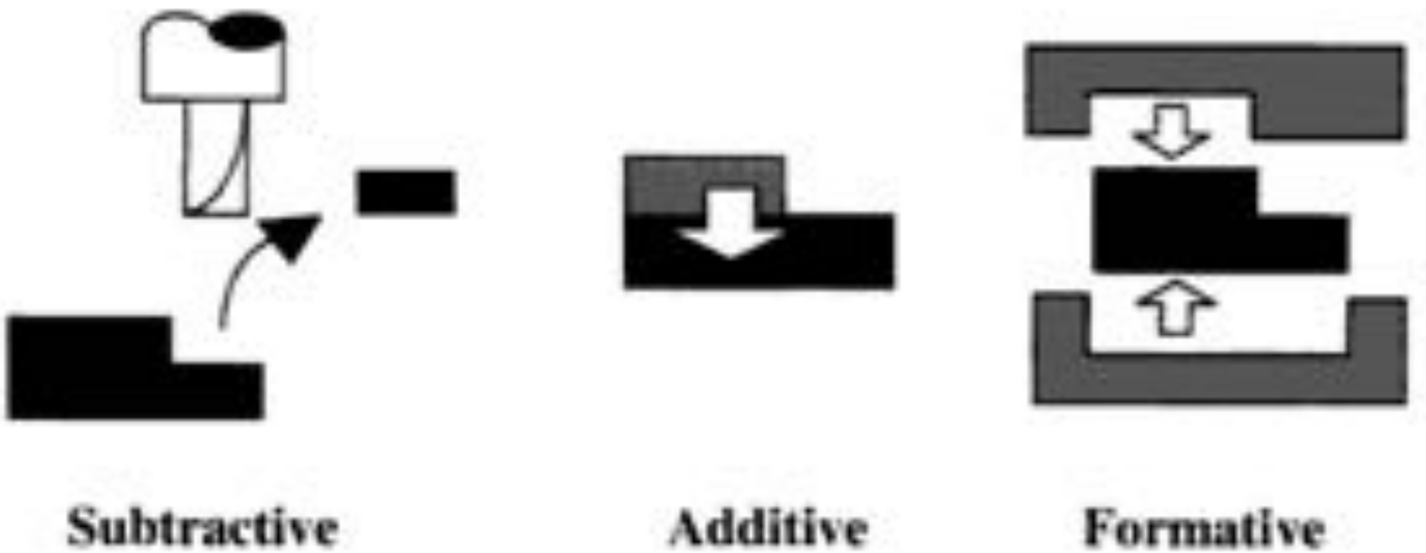
Additive manufacturing

carmelo.demaria@centropiaggio.unipi.it

Building 3D object



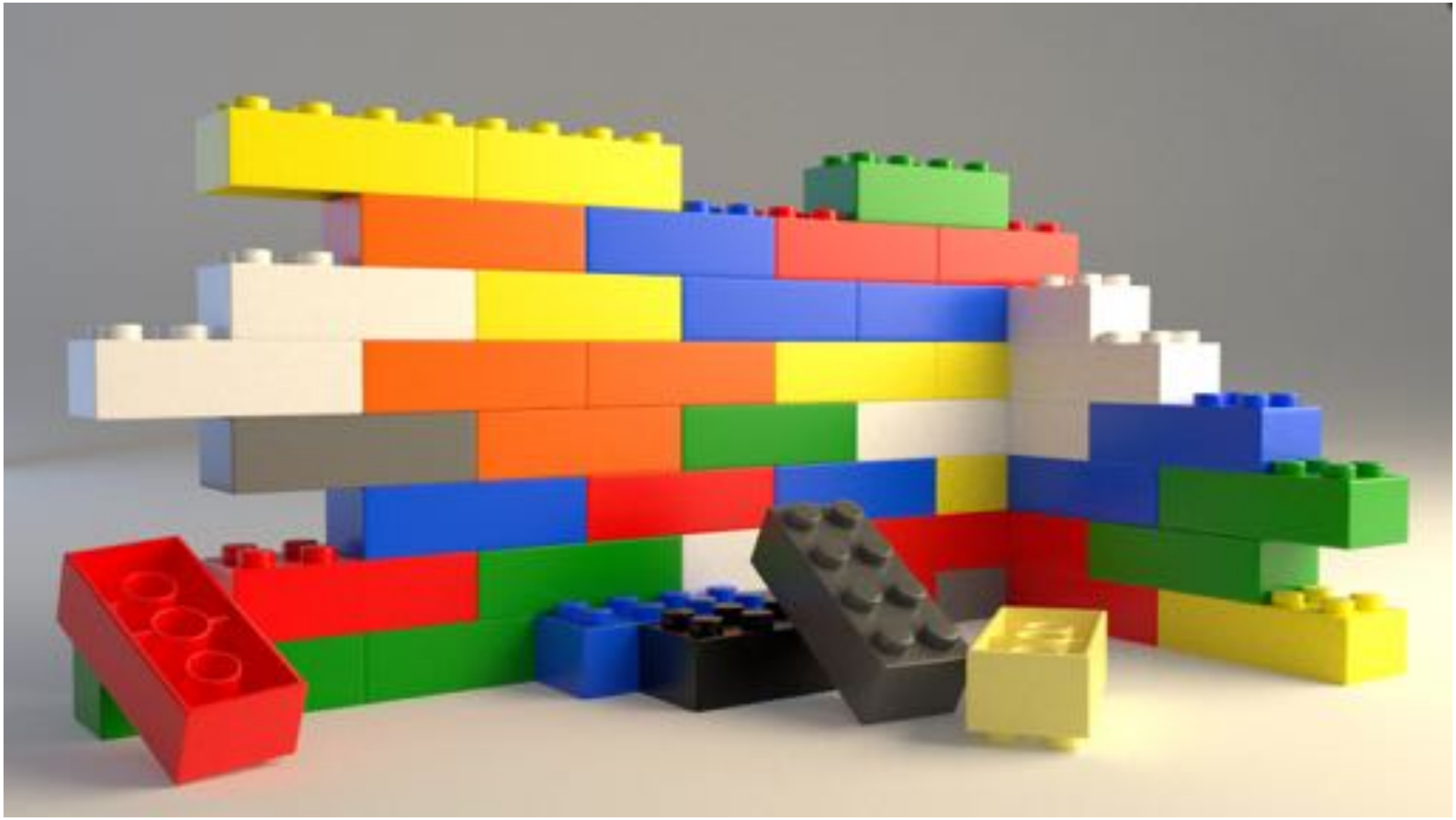
Building 3D object: subtractive

- Milling
- Turning
- Drilling
- Planning
- Sawing
- Grinding
- EDM
- Laser cutting
- Water jet cutting
- …

Building 3D object: formative

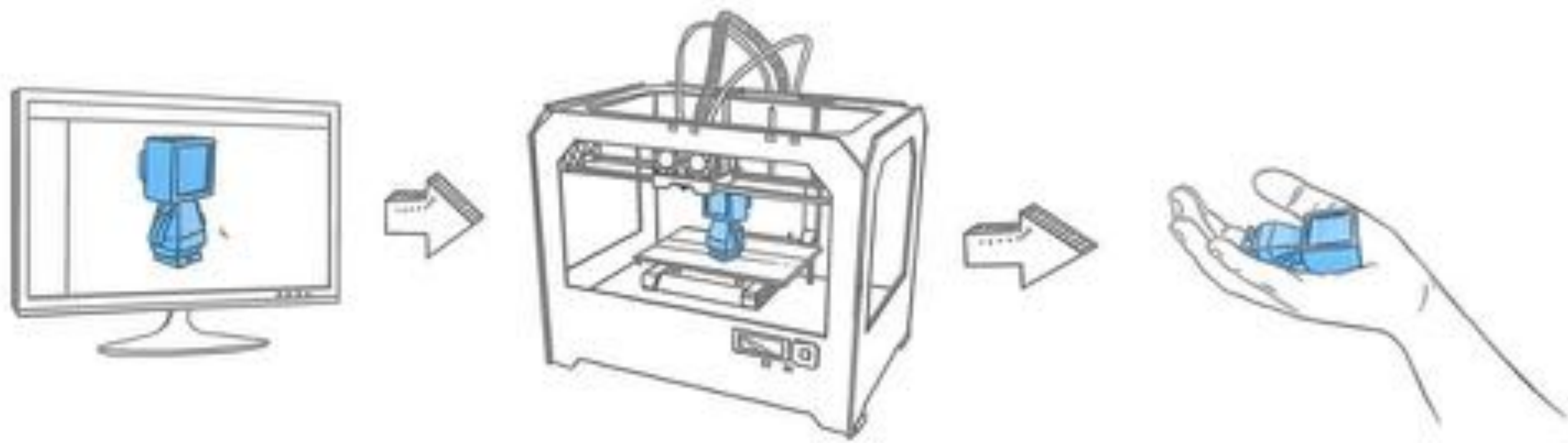
- Bending
- Forging
- Electromagnetic forming
- Plastic injection molding
- …

Building 3D object: additive



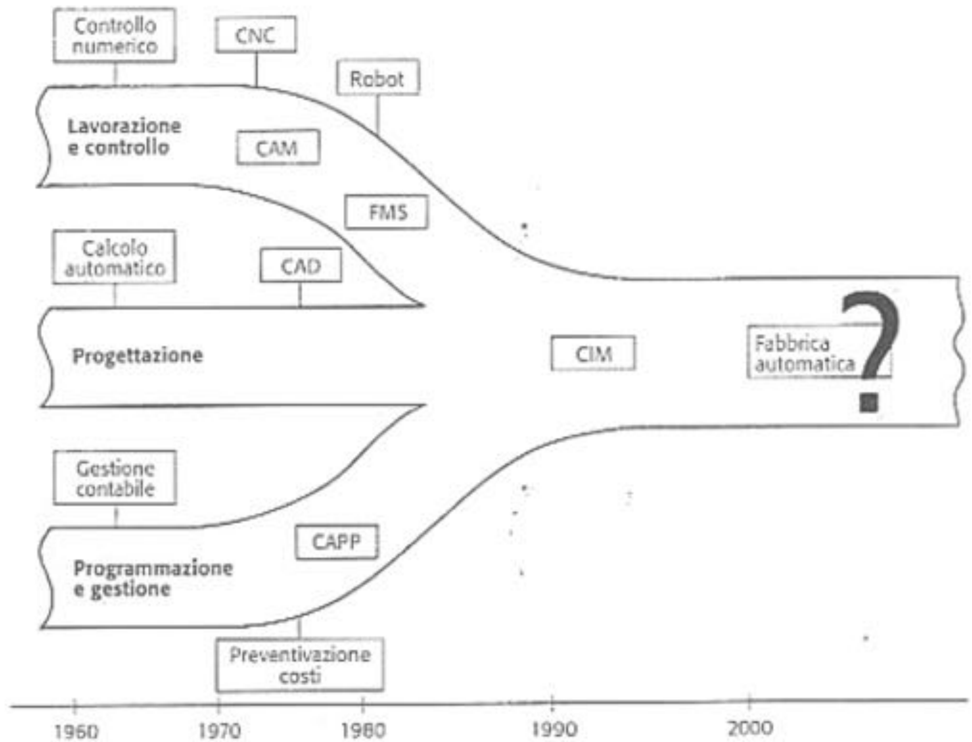
Additive manufacturing

- Additive manufacturing is a process of making a 3D solid object of virtually any shape **from a digital model**.
- It is achieved using an additive process, where successive layers of material are laid down in different shapes.



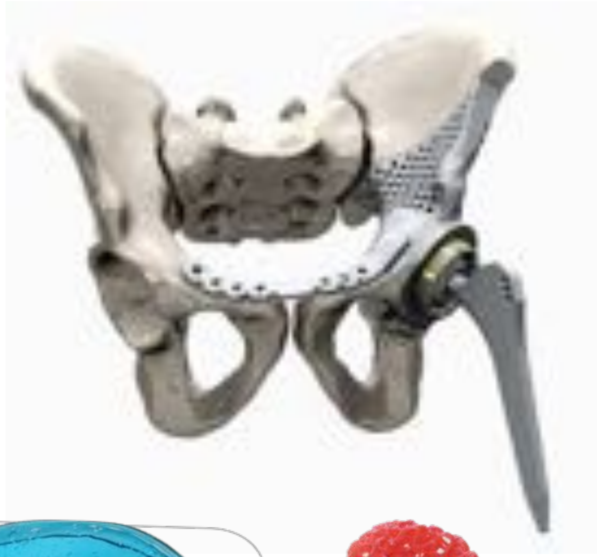
Computer Aided technologies (Cax)

- CAD – Design
- CAE – Engineering
- CAM – Manufacturing
- CAPP – Process Planning
- CIM – Computer Integrated Manufacturing

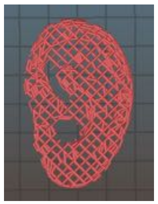


Additive manufacturing using…

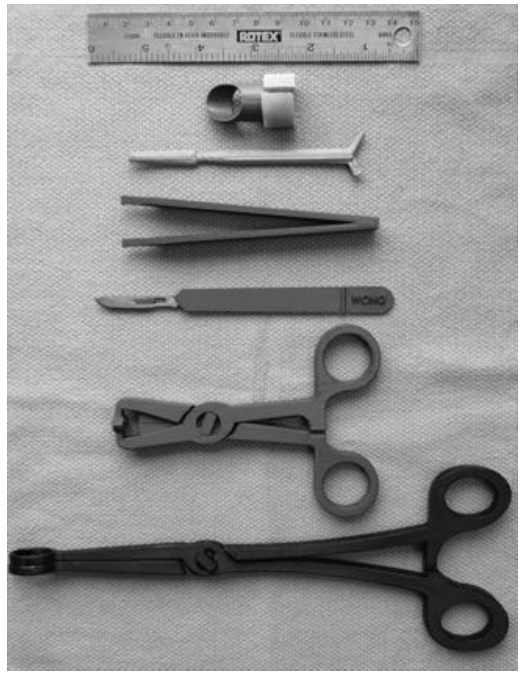
- Polymers
  - Thermoplastics
  - Resins
  - Wax
- Slurries and gels
- Metals
- Ceramics
- Biological materials

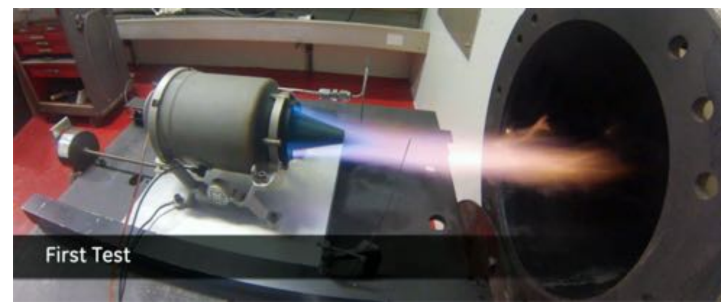


+ Additive manufacturing what?











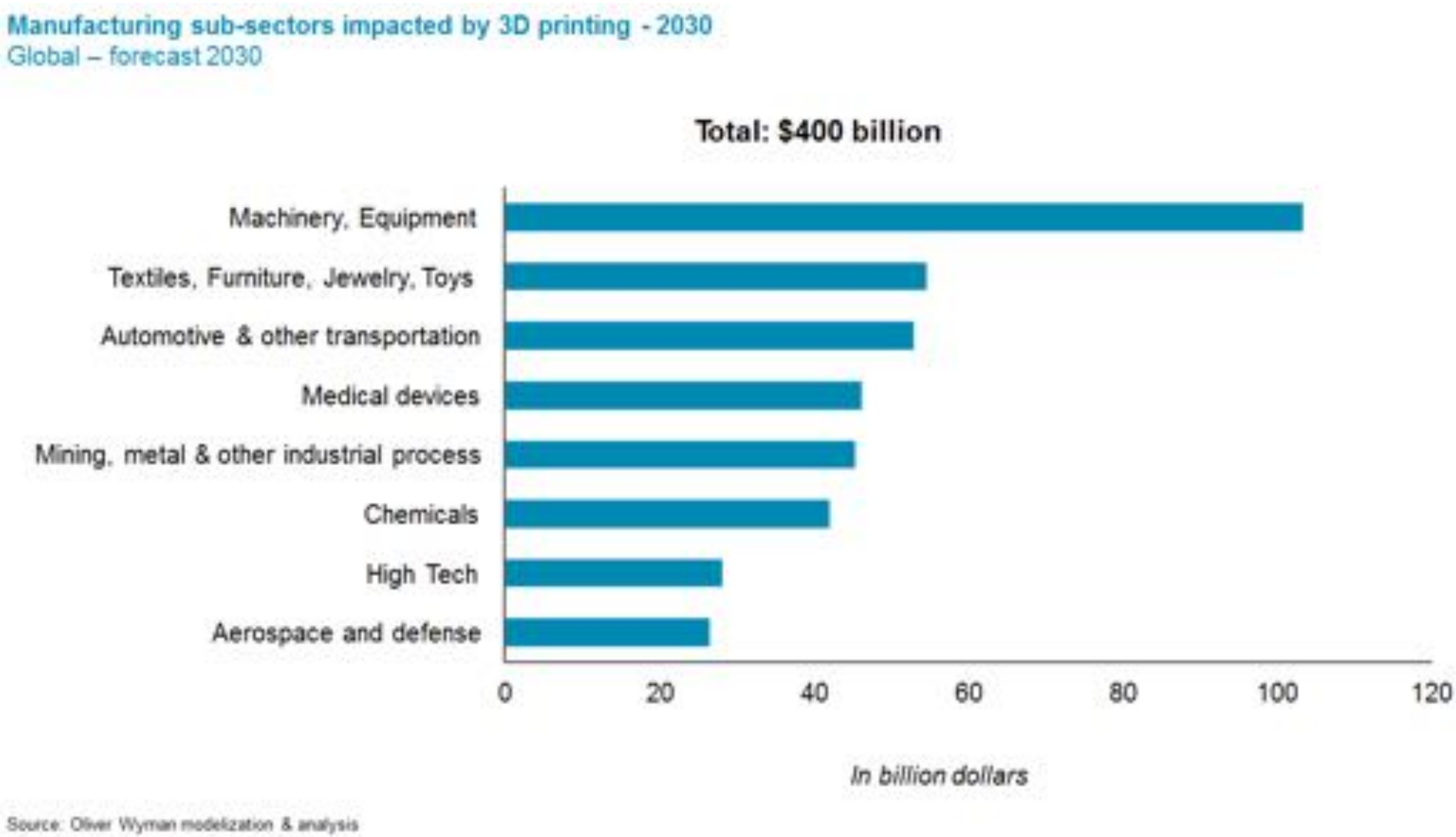
Invisalign Orthodontic Aligners

- An aligner for orthodontic use manufactured using a combination of <u>rapid tooling</u> and thermoforming.

4D printing

- https://vimeo.com/58840897

Additive manufacturing by Industry Sectors

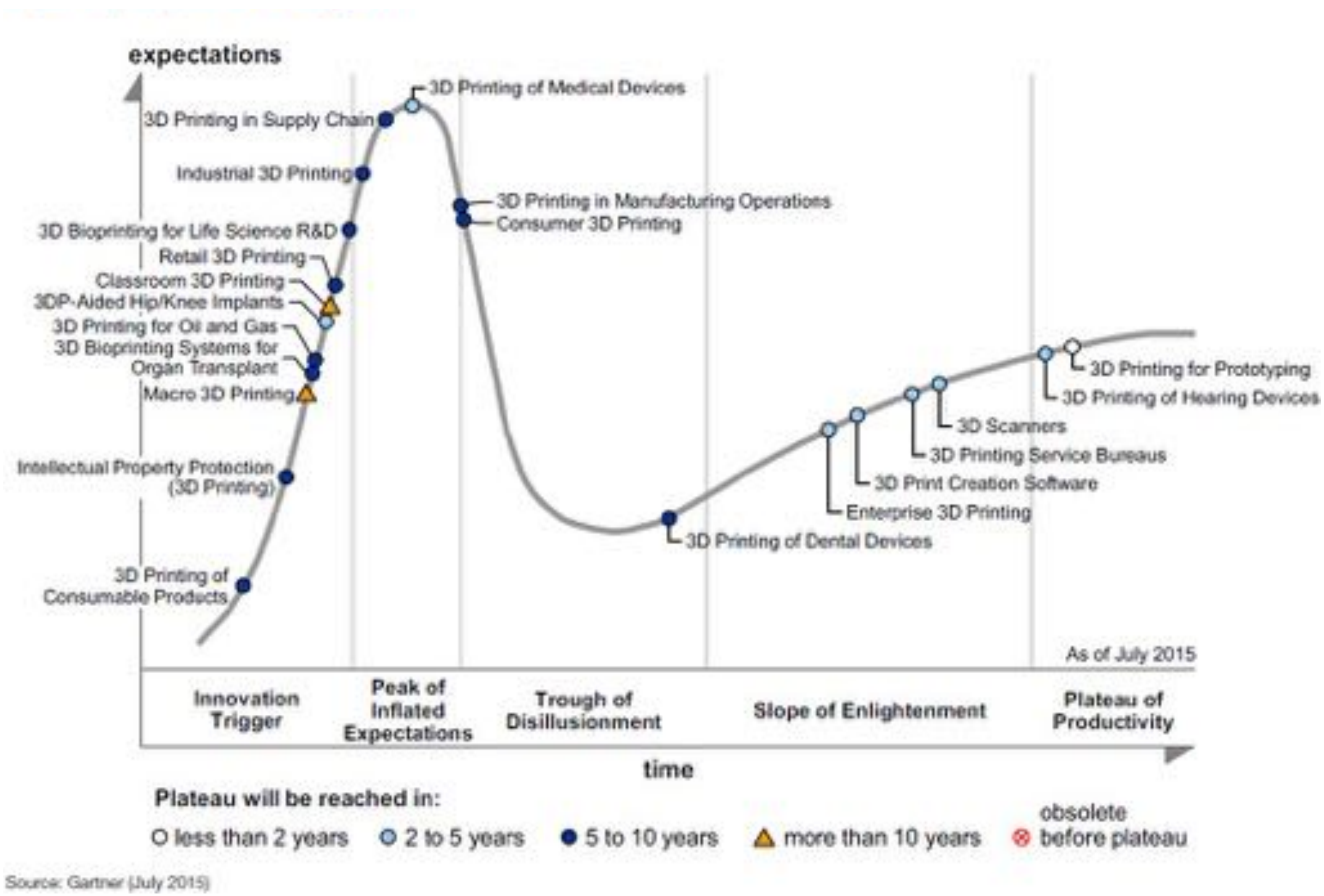


So, why additive manufacturing?

- Functional complexity
- Geometric complexity
- Multi-material parts
- Cost-sensitive storage
- Time-to-market
- Frequency of design changes
- Customization
- …

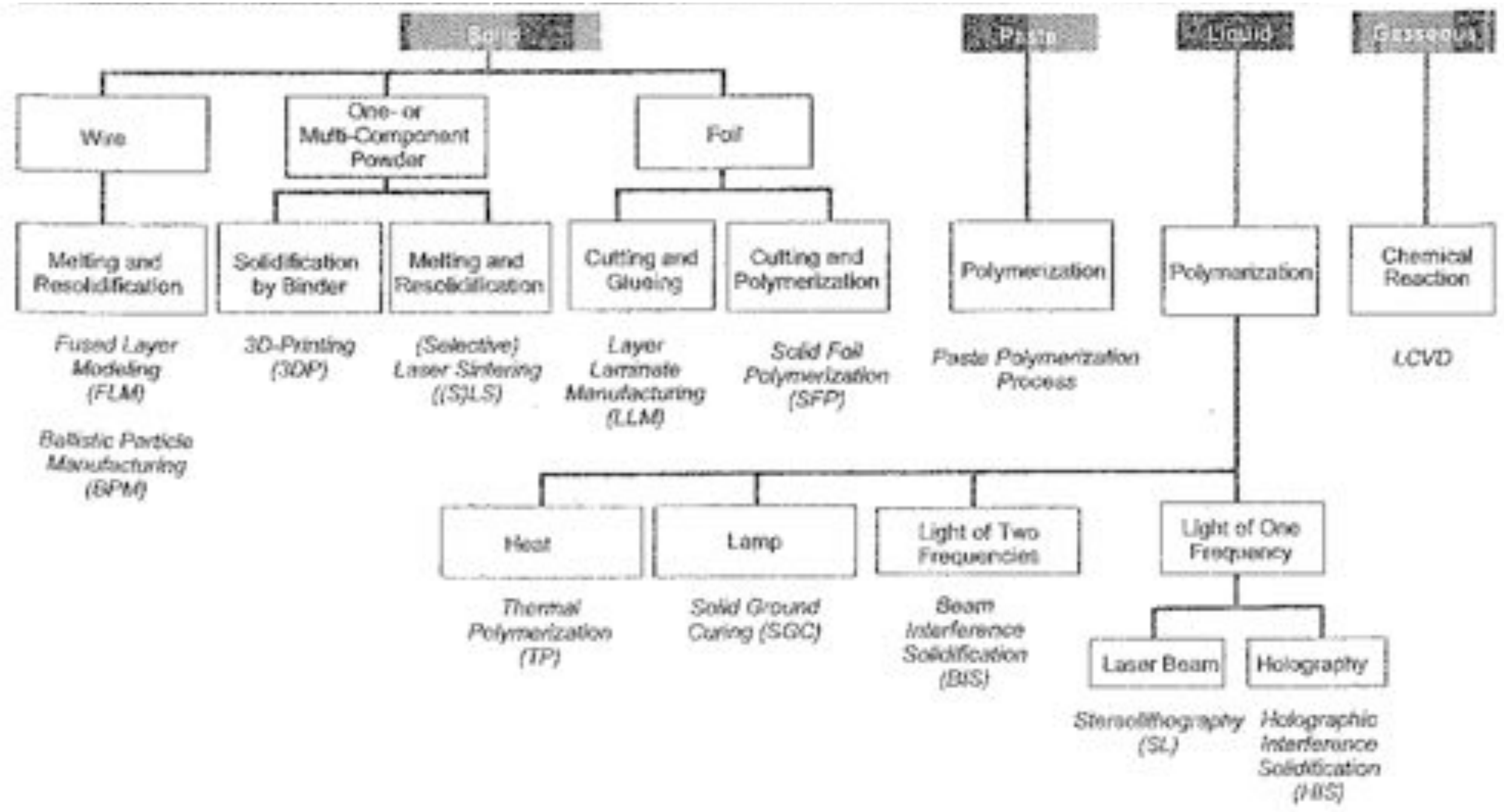
+ Hype cycle 2013

Hype cycle 2015



Hype cycle 2017

A possible classification



ASTM/ISO 52900 classification

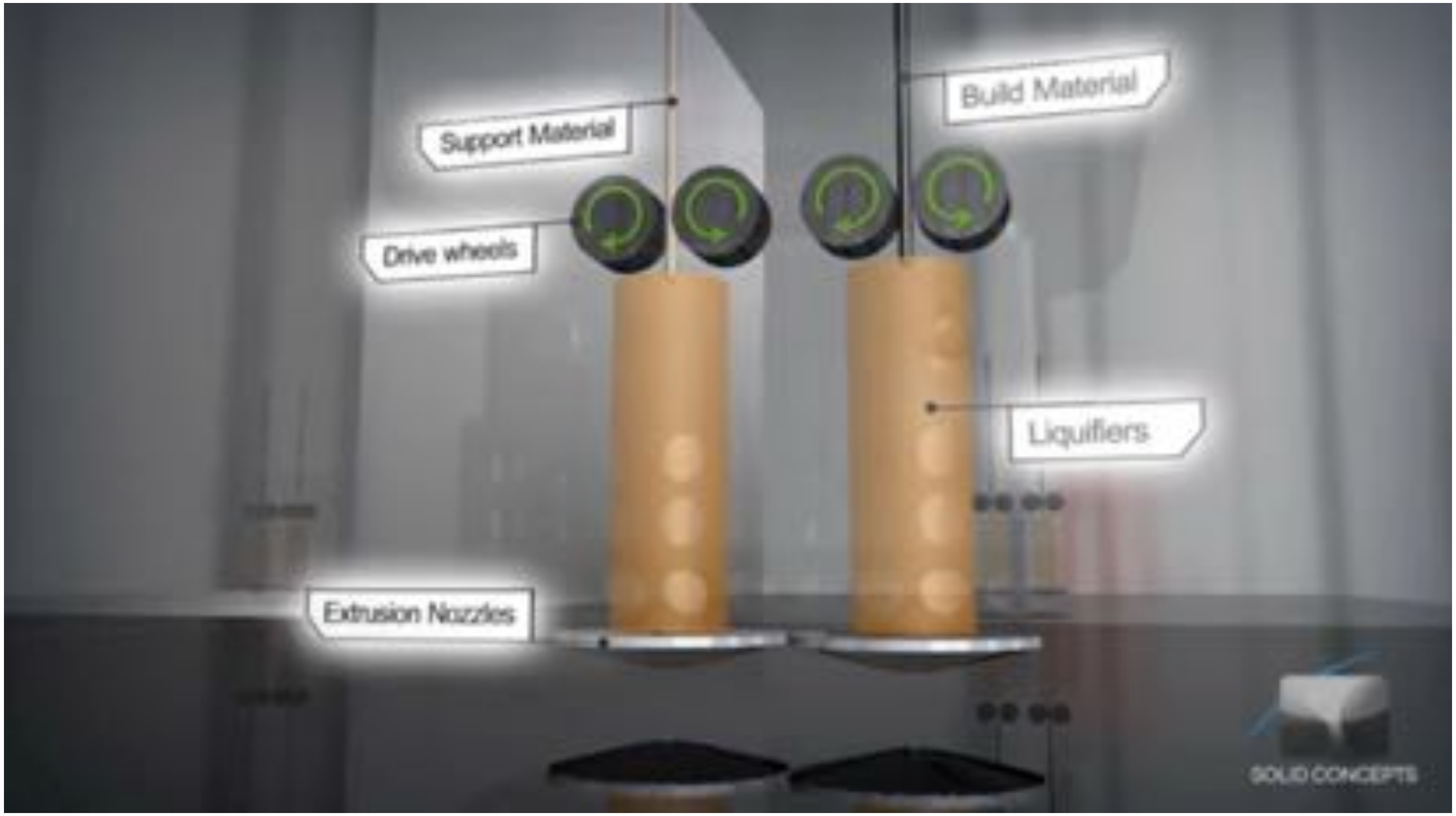
- **Binder jetting**: AM process in which a liquid bonding agent is selectively deposited to join powder materials;
- **Directed energy deposition:** AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited;
  - Note: “Focused thermal energy” means that an energy source (e.g. laser, electron beam, or plasma arc) is focused to melt the materials being deposited.
- **Material extrusion:** AM process in which material is selectively dispensed through a nozzle or orifice;
- **Material jetting:** AM process in which droplets of build material are selectively deposited
  - Note: Example materials include photopolymer and wax.
- **Powder bed fusion:** AM process in which thermal energy selectively fuses regions of a powder bed;
- **Sheet lamination:** AM process in which sheets of material are bonded to form a part;
- **Vat photopolymerisation:** AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

https://platform.ubora-biomedical.org/resources/49a844d5-ed82-4820-8d10-5d921d6926b1

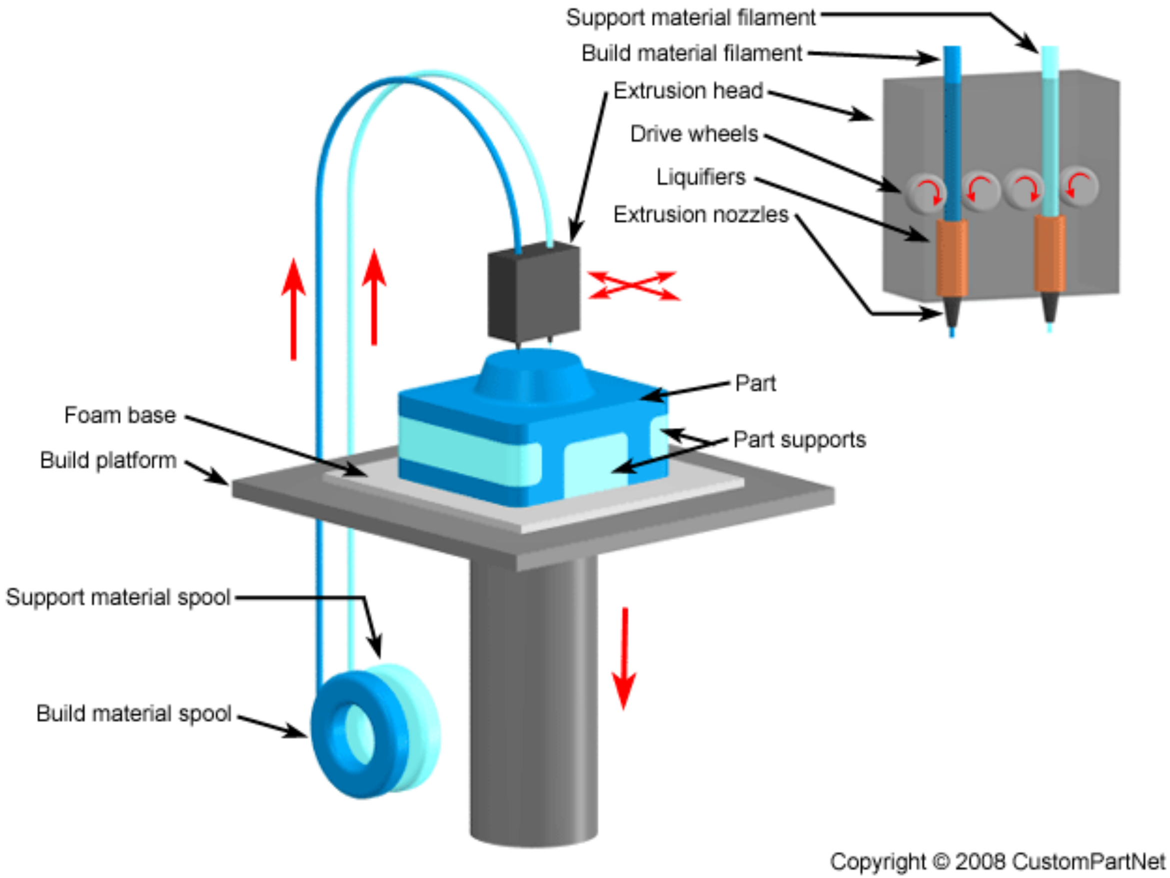
Material extrusion

Fused deposition modelling

https://www.youtube.com/watch?v=WHO6G67GJbM



Fused deposition modelling



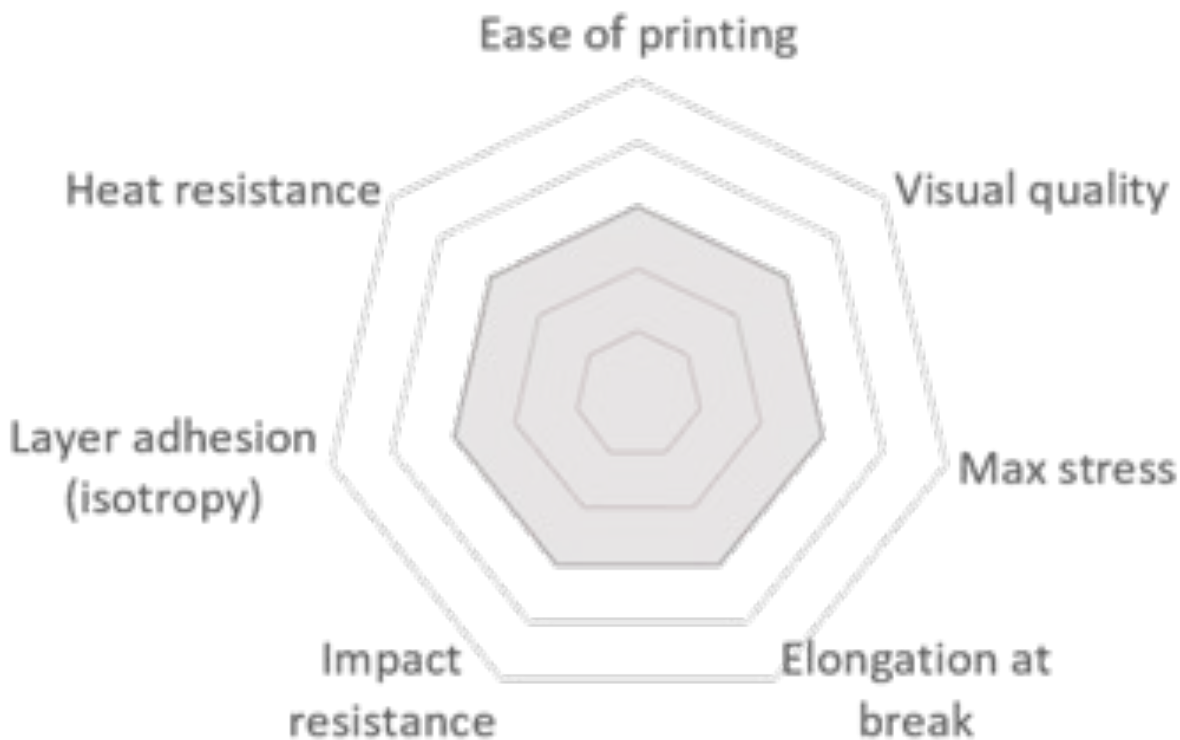
Materials

- “Standard” materials:
  - Poly-Lactic-Acid (PLA) (soft and hard)
  - Acrylonitril-Butadiene-Stiren (ABS)
  - Nylon
  - Polycarbonate (PC)
  - Poly vinyl alcohol (PVA)
  - Thermoplastic polyurethane (TPU)
  - Polyethylene Terephthalate Glycol (PETG)
  - Conductive (carbon and graphen loaded materials)
  - Metallic loaded plastics

https://www.3dhubs.com/knowledge-base/fdm-3d-printing-materials-compared

Choosing the right FDM material

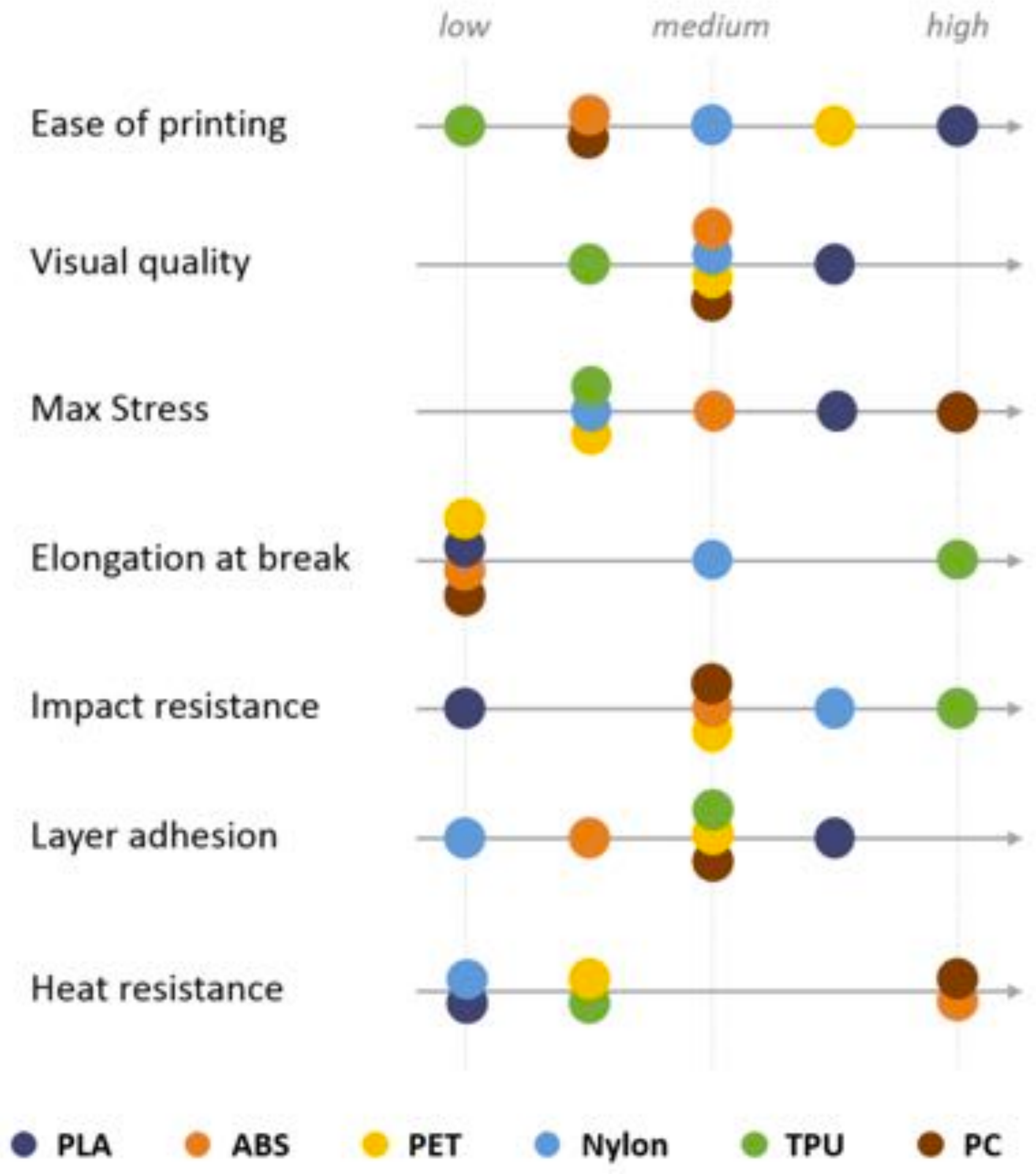
For a given application



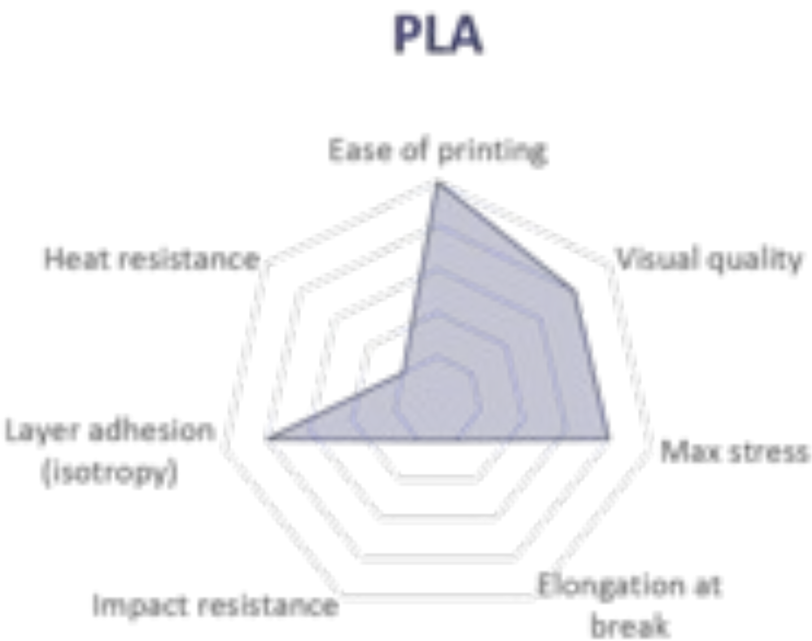
Other side properties: humidity resistance, toxicity [1]

[1]: Azimi et al, Emissions of Ultrafine Particles and Volatile Organic Compounds from Commercially Available Desktop Three-Dimensional Printers with Multiple Filaments, Environmental Science & Technology, 2016

Choosing the right FDM material



Polylactic acid

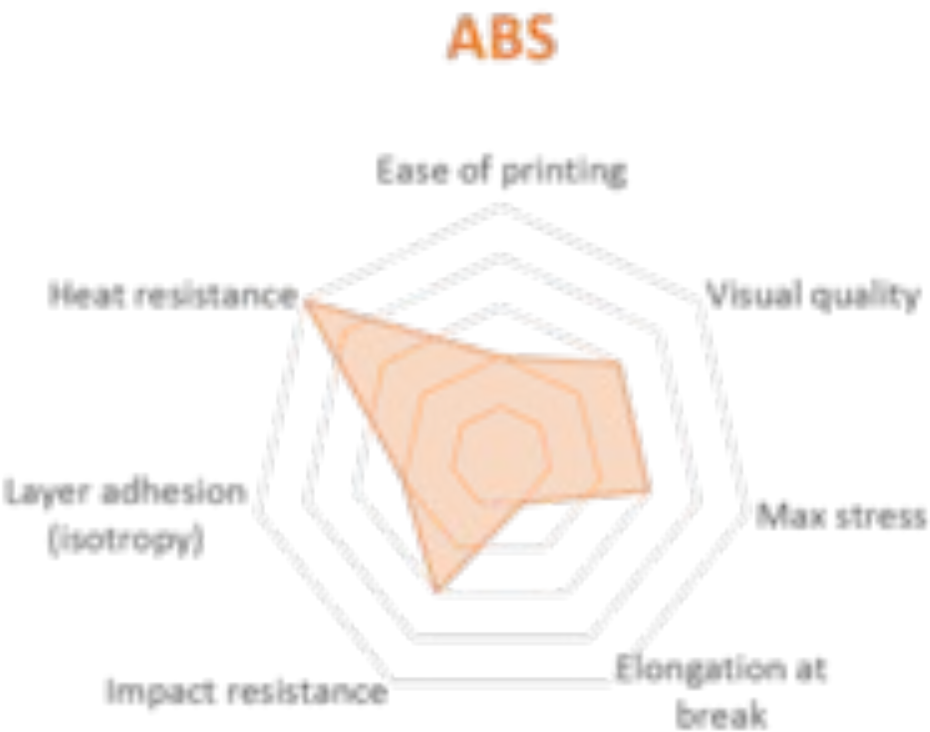


Nozzle Temp (°C)	**200-220**
Bed Temp (°C)	**60**

Pros	**Cons**
Biosourced, biodegradable	Low humidity resistance
Odorless	Can't be glued easily
Can be post-processed with sanding paper and painted with acrylics	
Good UV resistance	

PLA is the easiest polymer to print and provides good visual quality.
It is very rigid and actually quite strong, but is very brittle.

Acrylonitril-Butadiene-Stiren

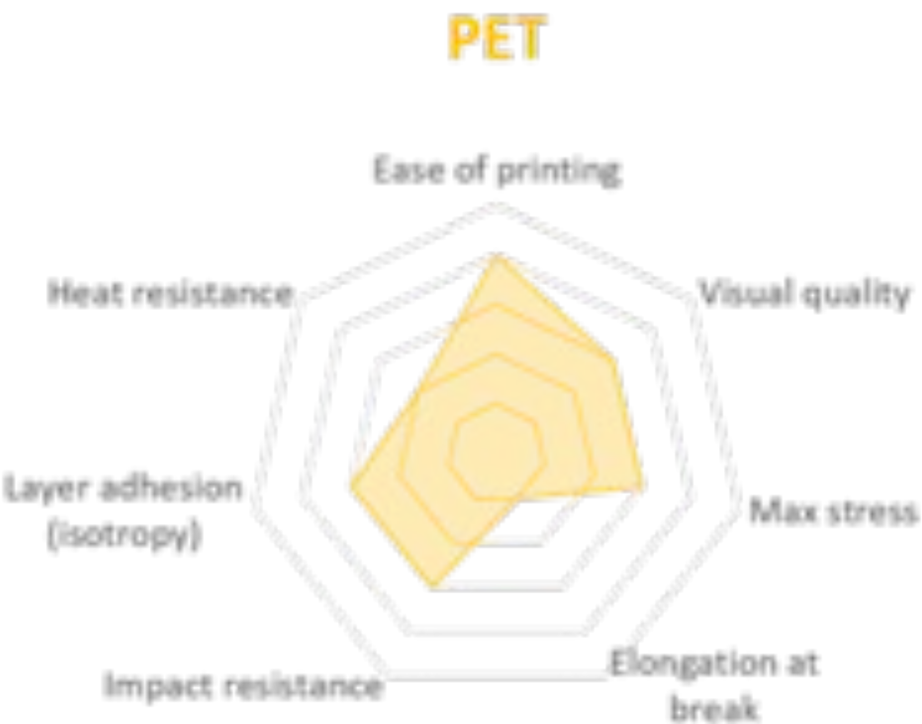


Nozzle Temp (°C)	**230-250**
Bed Temp (°C)	**80**

Pros	**Cons**
Can be post-processed with acetone vapors for a glossy finish	UV sensitive
Can be post-processed with sanding paper and painted with acrylics	Odor when printing
Acetone can also be used as strong glue	Potentially high fume emissions
Good abrasion resistance	

ABS is usually picked over PLA when higher temperature resistance and higher toughness is required.

Polyethylene Terephthalate Glycol

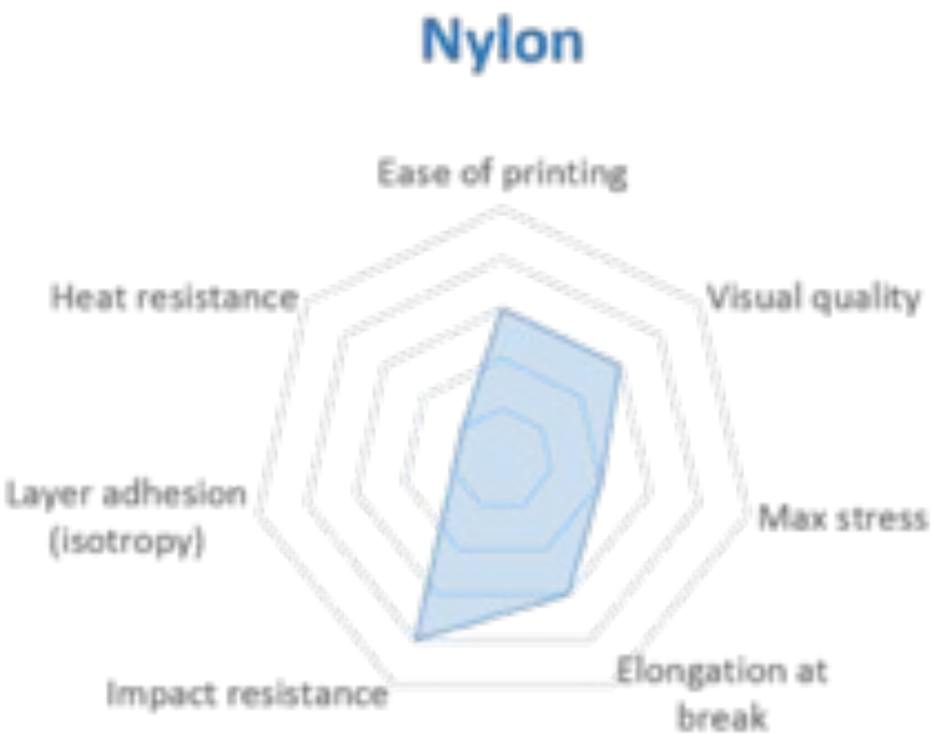


Nozzle Temp (°C)	**230-250**
Bed Temp (°C)	**80**

Pros	**Cons**
Can come in contact with foods	Heavier than PLA and ABS
High humidity resistance	
High chemical resistance	
Recyclable	
Good abrasion resitance	
Can be post-processes with sanding paper and painted with acrylics	

PET is a slightly softer polymer that is well rounded and possesses interesting additional properties with few major drawbacks.

Nylon 6

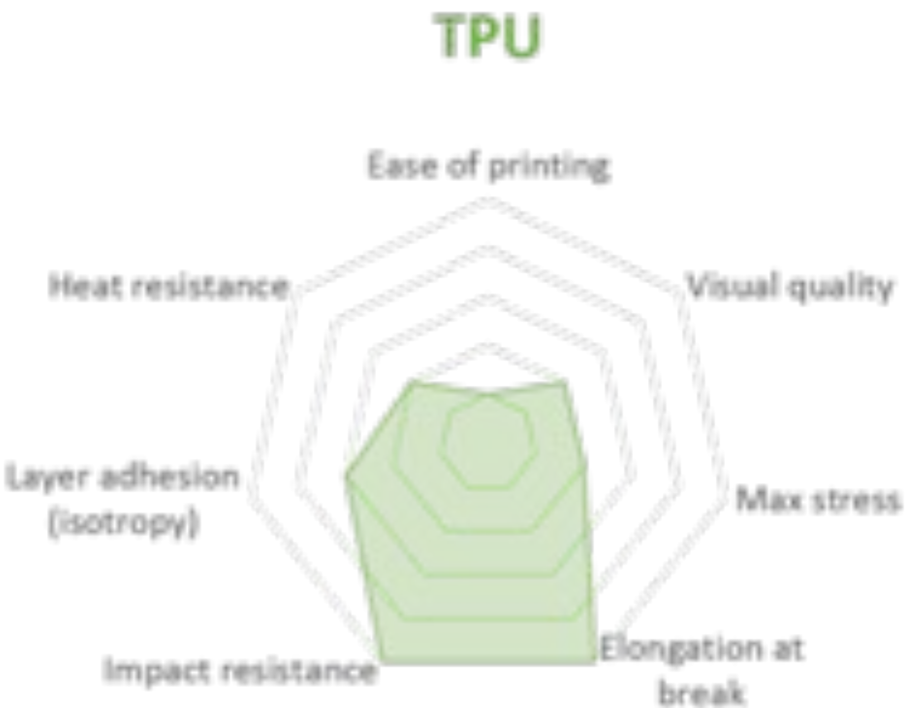


Nozzle Temp (°C)	**235 - 245**
Bed Temp (°C)	**60**

Pros	**Cons**
Good chemical resistance	Absorbs moisture
High strength	Potentially high fume emissions

Nylon possesses great mechanical properties, and in particular, the best impact resistance for a non-flexible filament. Layer adhesion can be an issue, however.

Thermoplastic polyurethane 95A

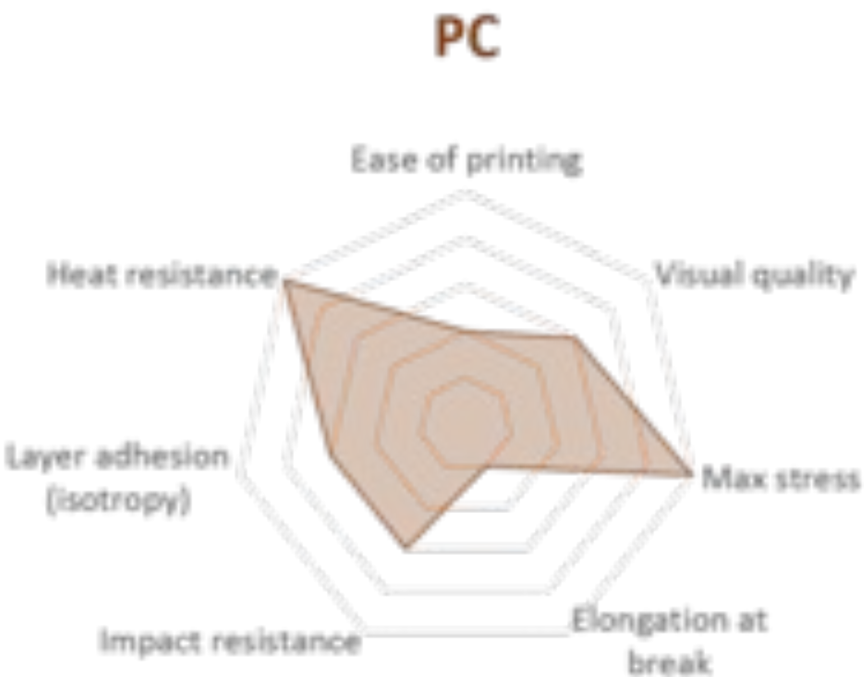


Nozzle Temp (°C)	**225 - 235**
Bed Temp (°C)	**0**

Pros	**Cons**
Good abrasion resistance	Difficult to post process
Good resistance to oil and grease	Can't be glued easily

TPU is mostly used for flexible applications, but its very high impact resistance can open for other applications.

Polycarbonate (PC)



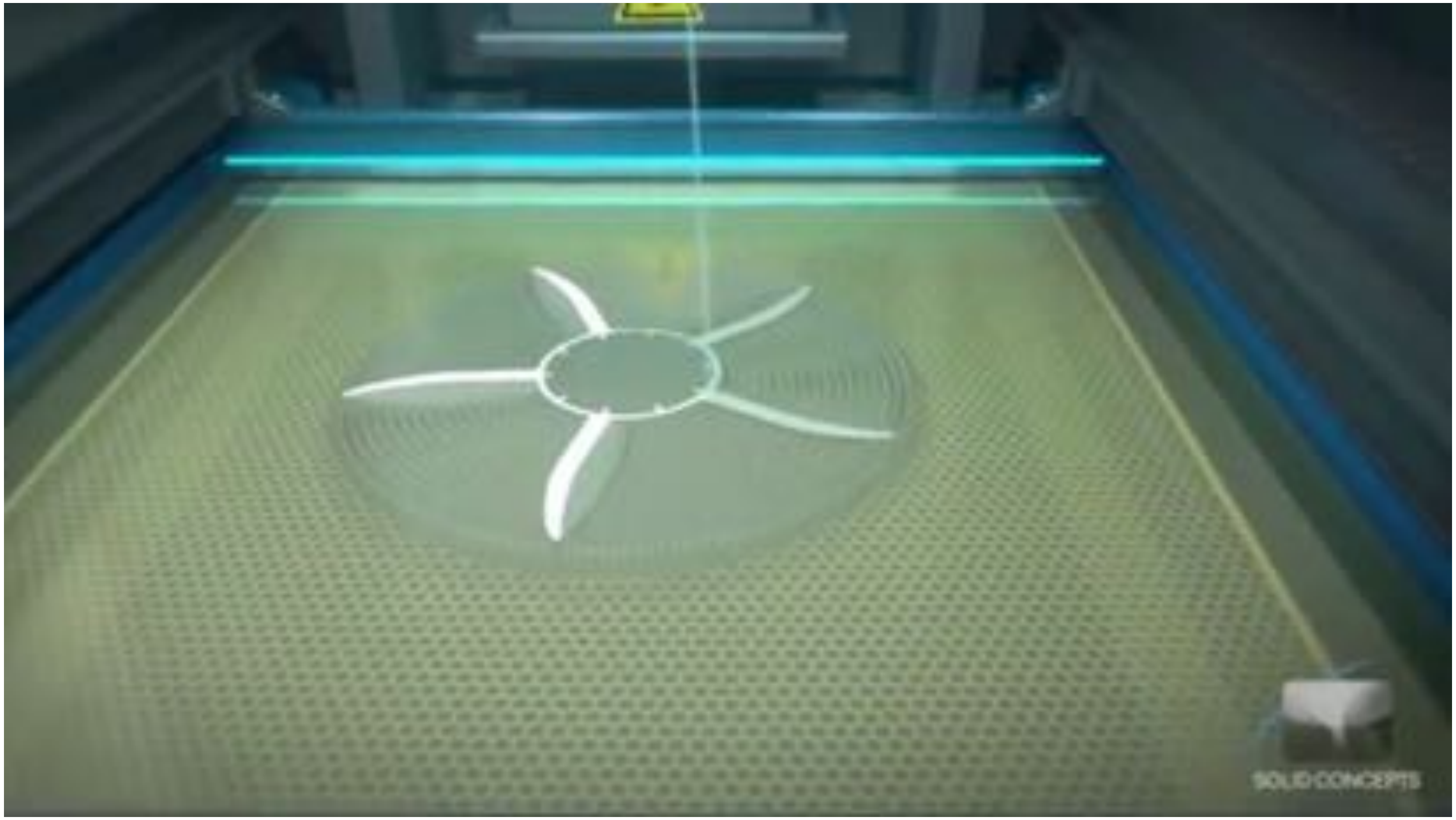
Nozzle Temp (°C)	**250 - 270**
Bed Temp (°C)	**80**

Pros	**Cons**
Can be sterilized	UV sensitive
Easy to post-process (sanding)	

PC is the strongest material of all, and can be an interesting alternative to ABS as the properties are quite similar.

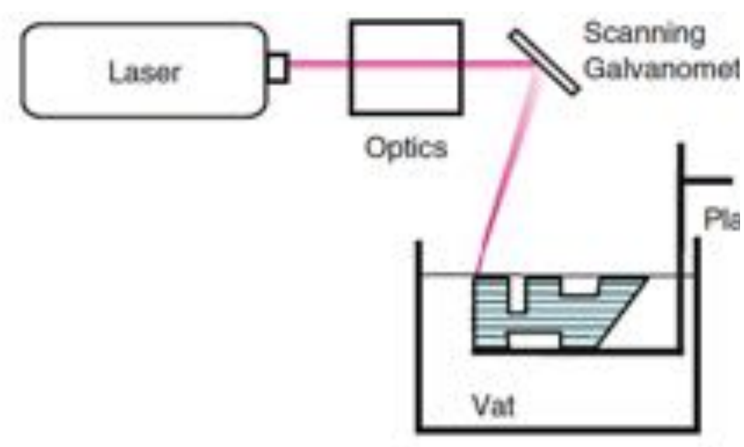
Vat Photopolimerization

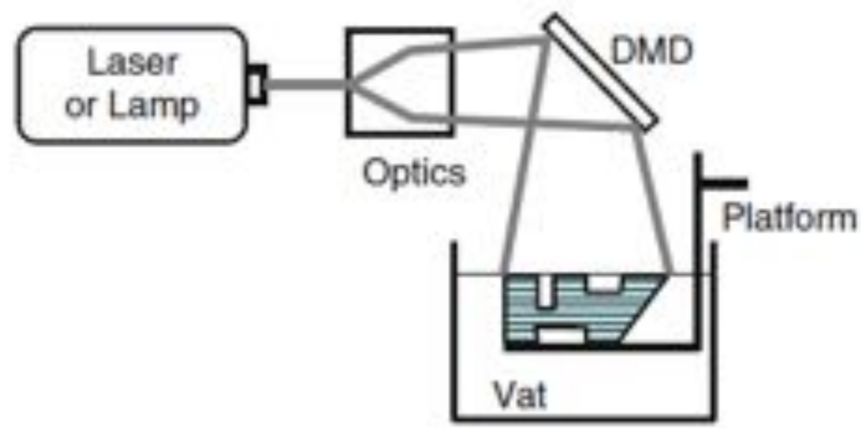
- https://www.youtube.com/watch?v=NM55ct5KwiI



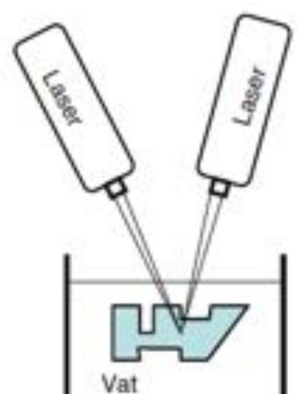
Stereolithography configurations

- Vector scan
- Mask projection





- Two photon approach



3D System SLA 7000

Laser	He-Cd
Lunghezza d’onda	0.325 um
Potenza	800 mW
Spessore minimo	0.025 mm
Volume vasca	253
Volume di lavoro	500 x 500 x 600 mm3
Velocità di scansione	Max 9.52 m/s
Diametro Spot	Da 0.23 a 0.84 mm

Nomenclature

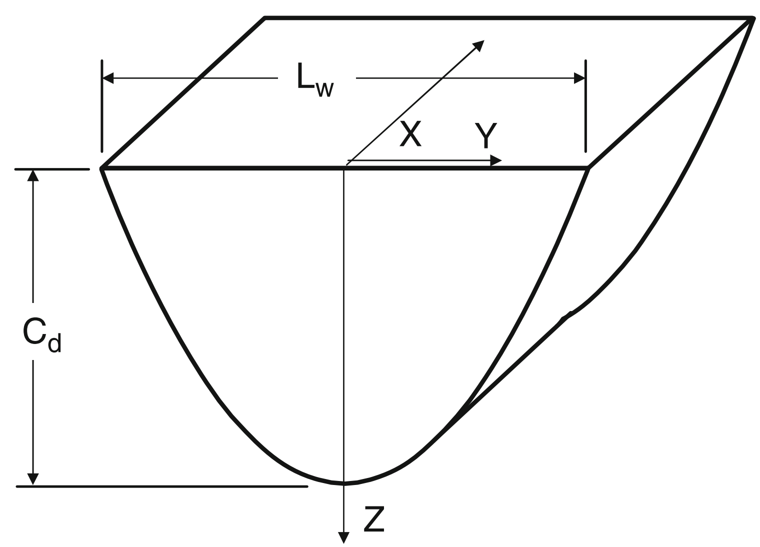
- C_d = cure depth = depth of resin cure as a result of laser irradiation [mm]
- D_p = depth of penetration of laser into a resin until a reduction in irradiance of 1/e is reached = key resin characteristic [mm]
- E = exposure, possibly as a function of spatial coordinates [energy/unit area][mJ/mm^2]
- E_c = critical exposure = exposure at which resin solidification starts to occur [mJ/mm_2]
- E_{max} = peak exposure of laser shining on the resin surface (center of laser spot) [mJ/mm2]
- H(x,y,z) = irradiance (radiant power per unit area) at an arbitrary point in the resin = time derivative of E(x,y,z) [W/mm2]
- P_L = output power of laser [W]
- V_s = scan speed of laser [mm/s]
- W_0 = radius of laser beam focused on the resin surface [mm]

Scan line of a Gaussian Laser

- The line width is proportional to the beam spot size.
- If a greater cure depth is desired, line width must increase, all else remaining the same.

$$C_\mathrm{d} = D_\mathrm{p} \ln\left[\sqrt{\frac{2}{\pi}} \frac{P_\mathrm{L}}{W_0 V_\mathrm{s} E_\mathrm{c}}\right]$$

$$L_\mathrm{w} = W_0 \sqrt{2C_\mathrm{d}/D_\mathrm{p}}$$



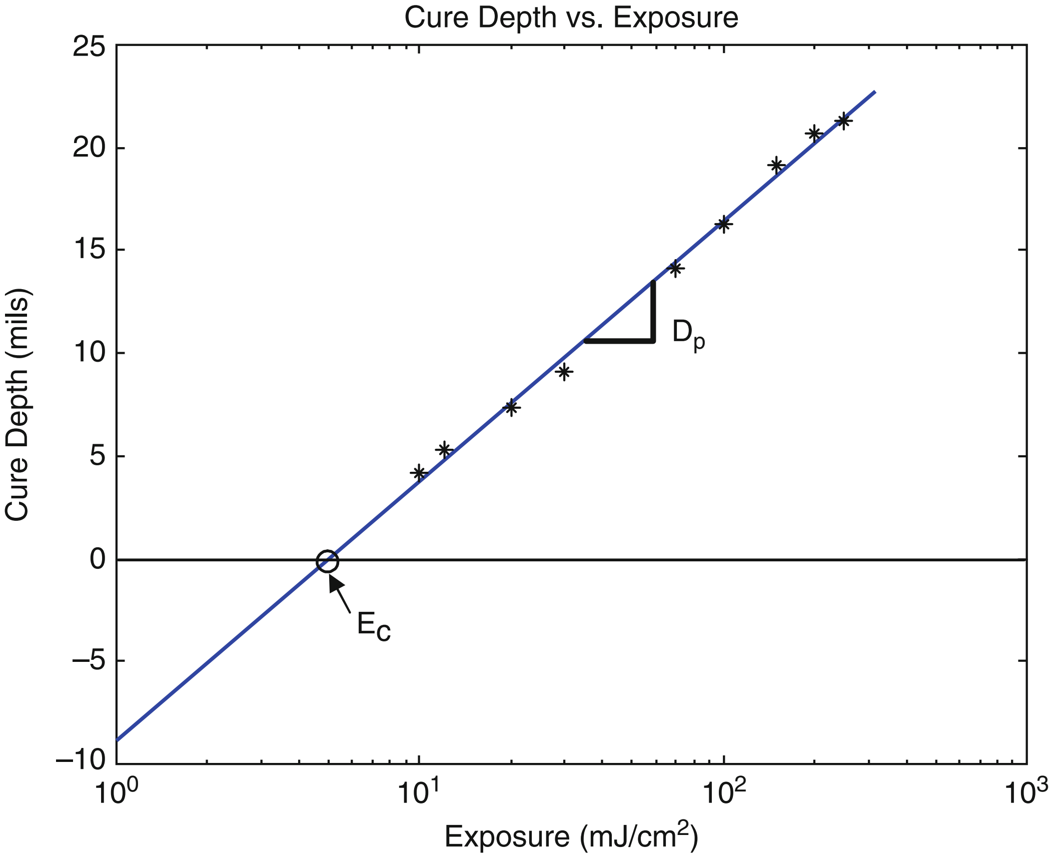
Working curve

- The cure depth is proportional to the natural logarithm of the maximum exposure on the centerline of a scanned laser beam.
- A semilog plot of Cd vs. Emax should be a straight line. This plot is known as the working curve for a given resin.
- The slope of the working curve is precisely Dp at the laser wavelength being used to generate the working curve.
- The x-axis intercept of the working curve is Ec, the critical exposure of the resin at that wavelength. Theoretically, the cure depth is 0 at Ec, but this does indicate the gel point of the resin.
- Since Dp and Ec are purely resin parameters, the slope and intercept of the working curve are independent of laser power.
- In practice, various Emax values can be generated easily by varying the laser scan speed

Working curve

$$\boxed{C_\mathrm{d} = D_\mathrm{p} \ln\left(\frac{E_\mathrm{max}}{E_\mathrm{c}}\right)}$$

$$C_\mathrm{d} = D_\mathrm{p} \ln\left[\sqrt{\frac{2}{\pi}} \frac{P_\mathrm{L}}{W_0 V_\mathrm{s} E_\mathrm{c}}\right]$$

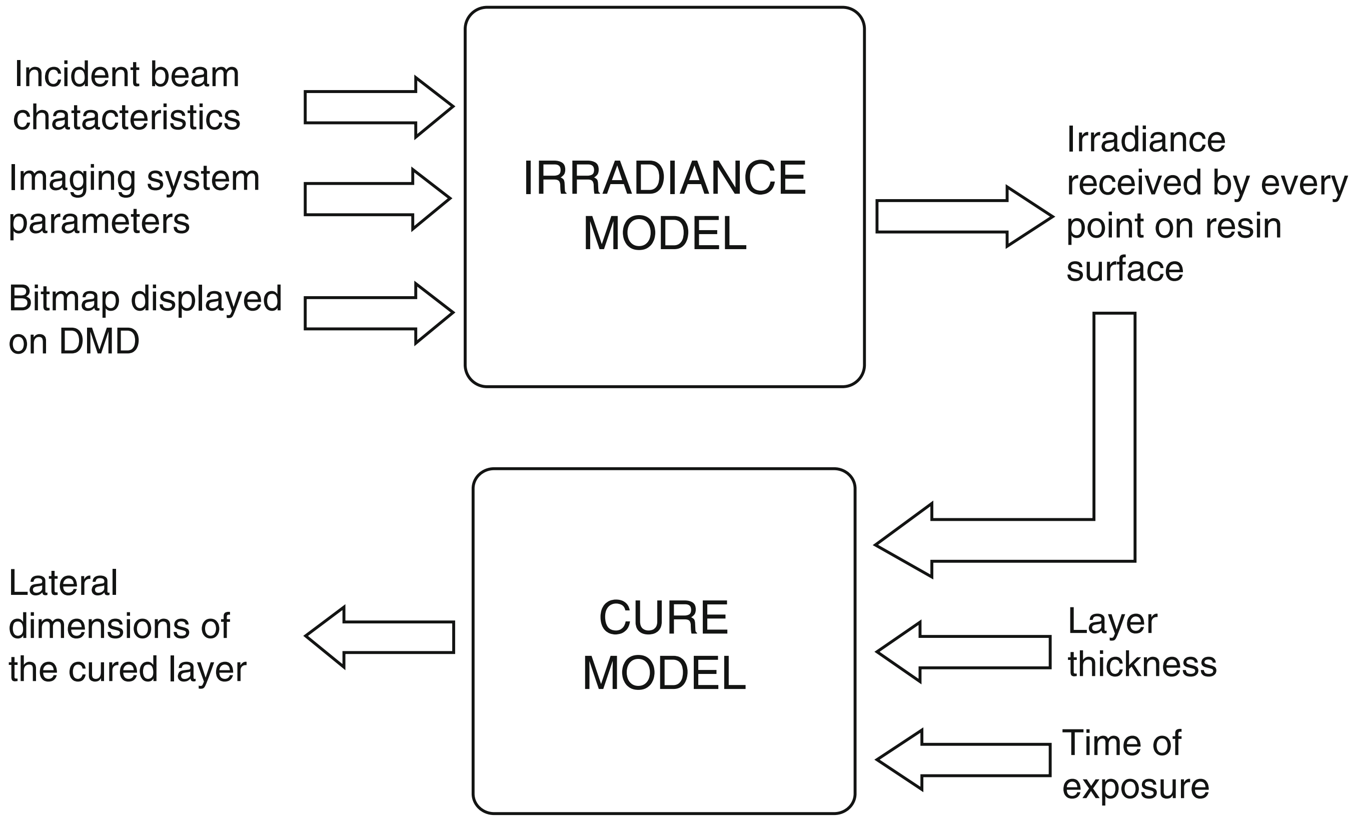


Example material: Somos 18120

TECHNICAL DATA - LIQUID PROPERTIES	
Appearance	Translucent
Viscosity	~300 cps @ 30°C
Density	~1.16 g/cm^3 @ 25°C

TECHNICAL DATA - OPTICAL PROPERTIES		
E_C	6.73 mJ/cm^2	[critical exposure]
D_P	4.57 mils	[slope of cure-depth vs. In (E) curve]
E_{10}	57.0 mJ/cm^2	[exposure that gives 0.254 mm (.010 inch) thickness]

Exposure consideration



$$C_d = D_p \ln \frac{E}{E_c} = D_p \ln \frac{H \cdot T}{E_c}$$

Commercial system

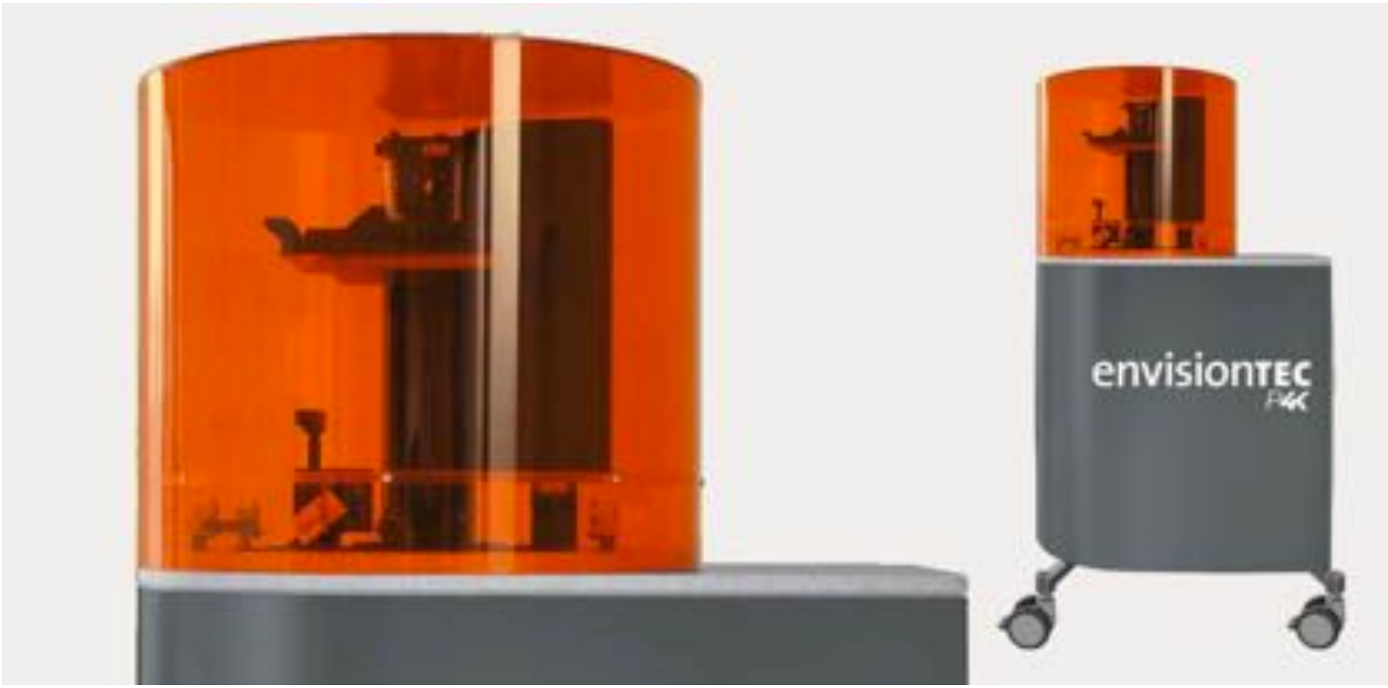
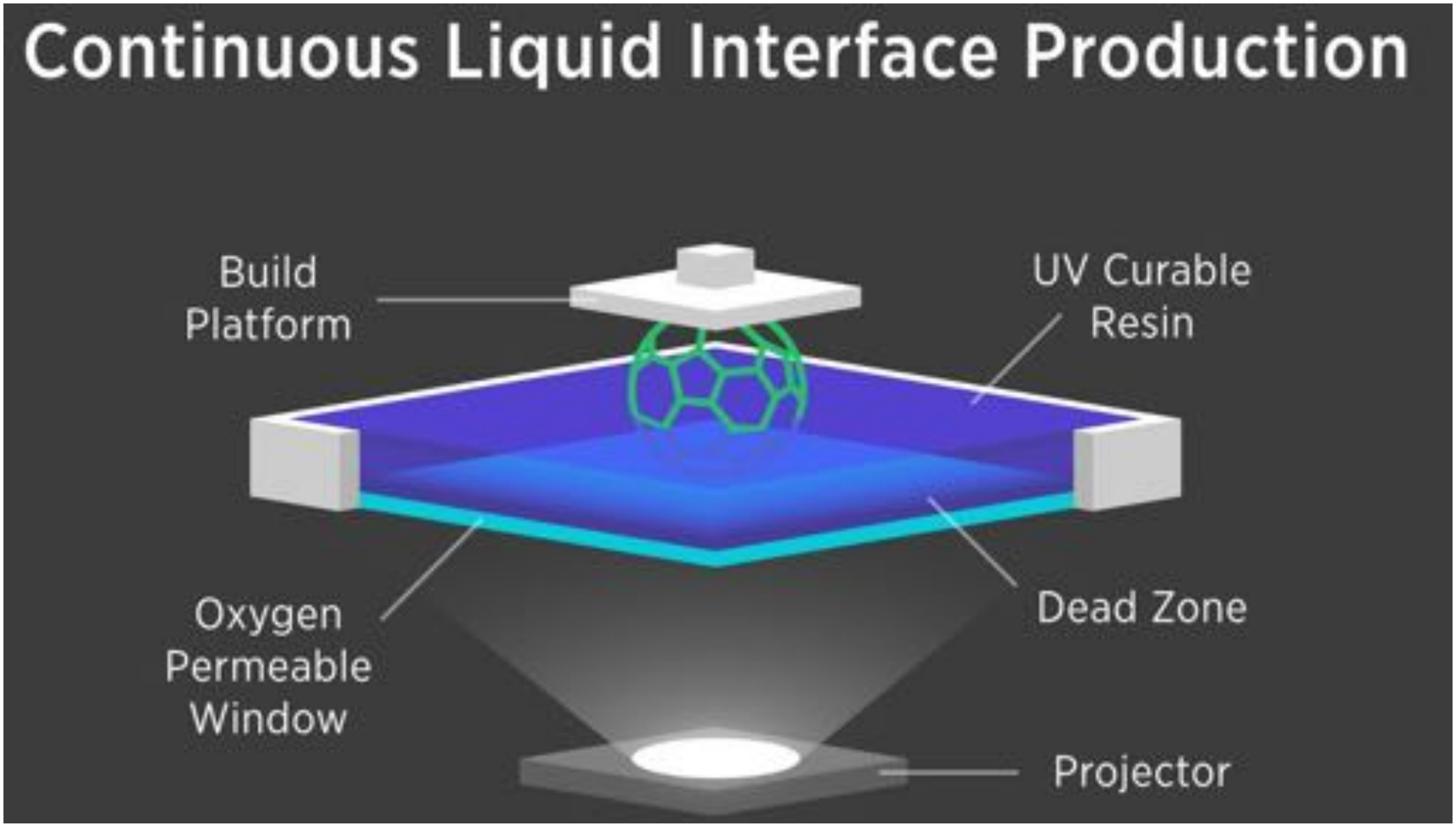


Table 4.3 Specifications on EnvisionTEC Perfactory Standard Zoom machine

Lens system		$f = 25$–45 mm
Build envelope	Standard	$190 \times 142 \times 230$ mm
	High resolution	$120 \times 90 \times 230$ mm
Pixel size	Standard	86–136 µm
	High resolution	43–68 µm
Layer thickness	25–150 mm	

Carbon 3D

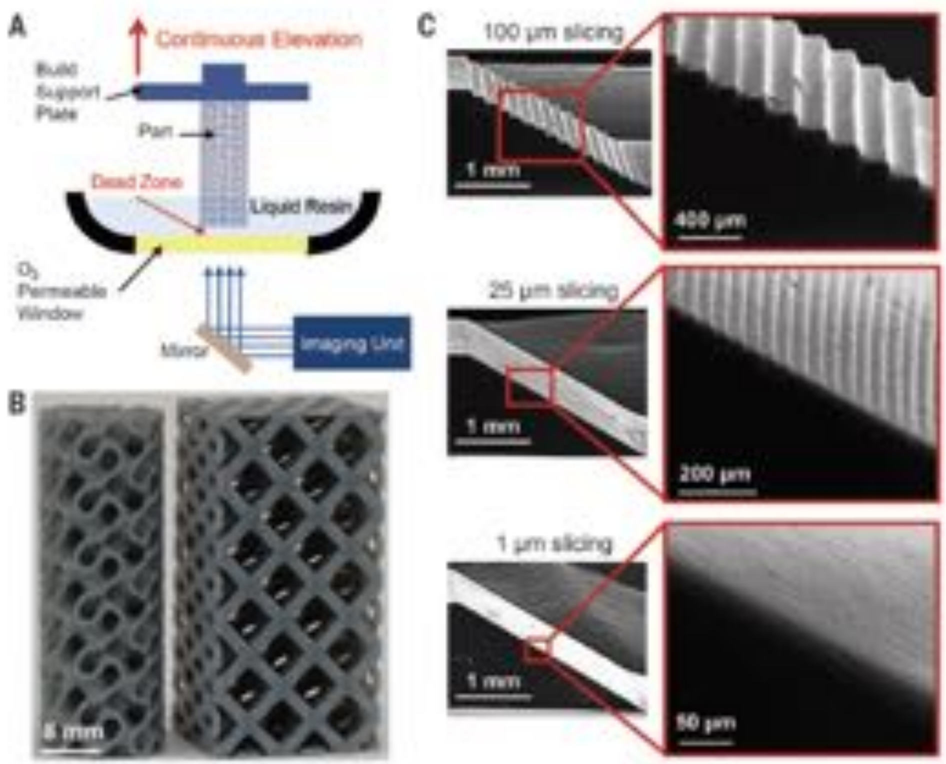


Continuous Liquid Interface Production
Build Platform
UV Curable Resin
Oxygen Permeable Window
Dead Zone
Projector

+ Carbon 3D

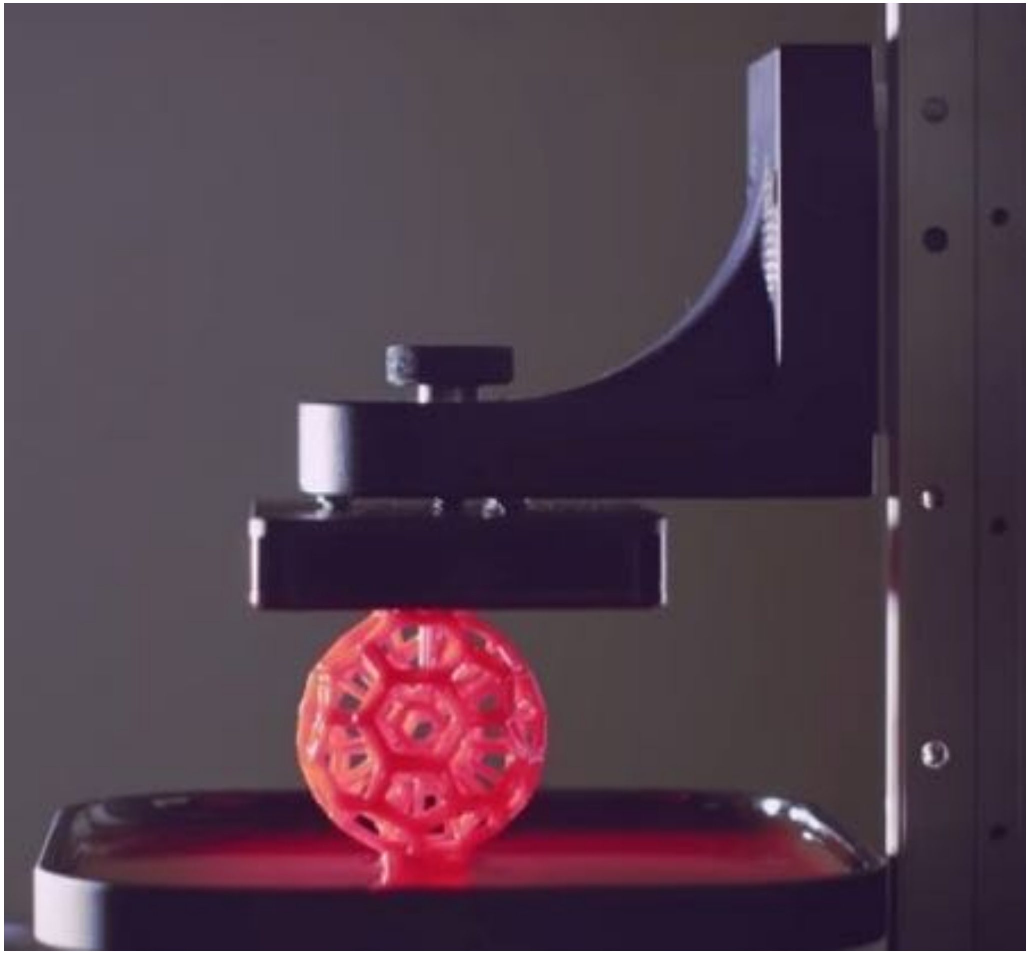
Continuous liquid interface production of 3D objects

John R. Tumbleston,[1] David Shirvanyants,[1] Nikita Ermoshkin,[1] Rima Janusziewicz,[2]
Ashley R. Johnson,[3] David Kelly,[1] Kai Chen,[1] Robert Pinschmidt,[1] Jason P. Rolland,[1]
Alexander Ermoshkin,[1*] Edward T. Samulski,[1,2*] Joseph M. DeSimone[1,2,4*]

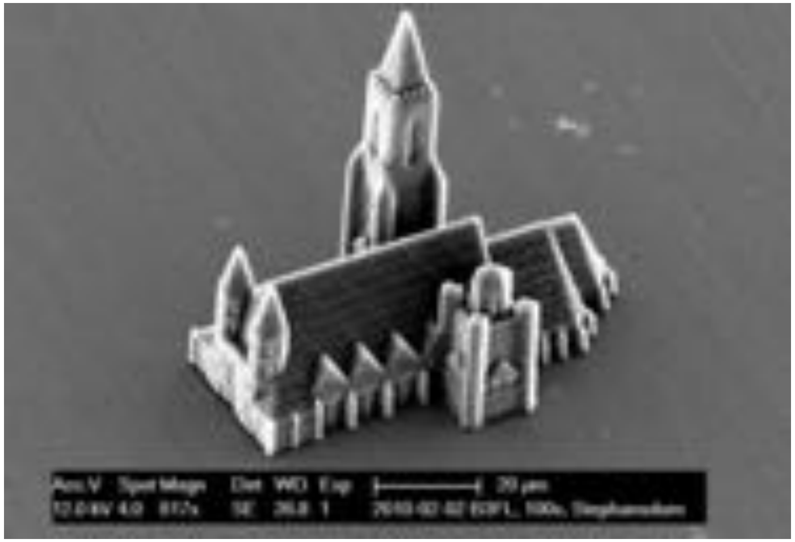


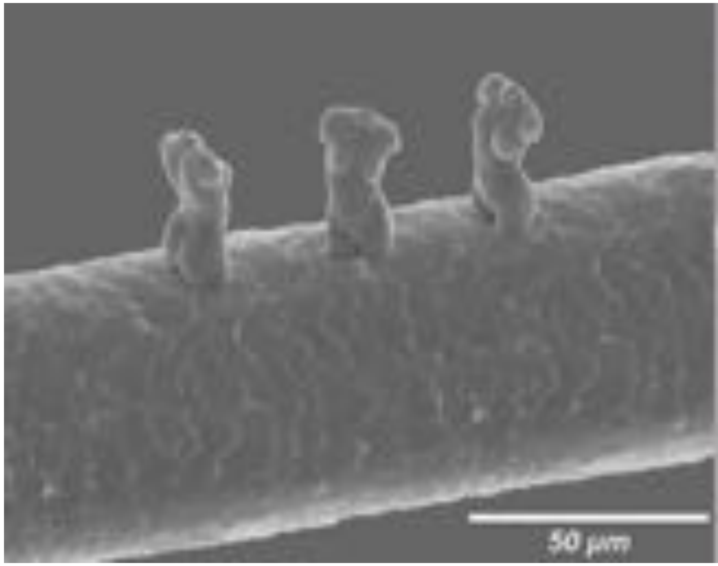
Corrected 23 March 2015; see full text.

Carbon 3D



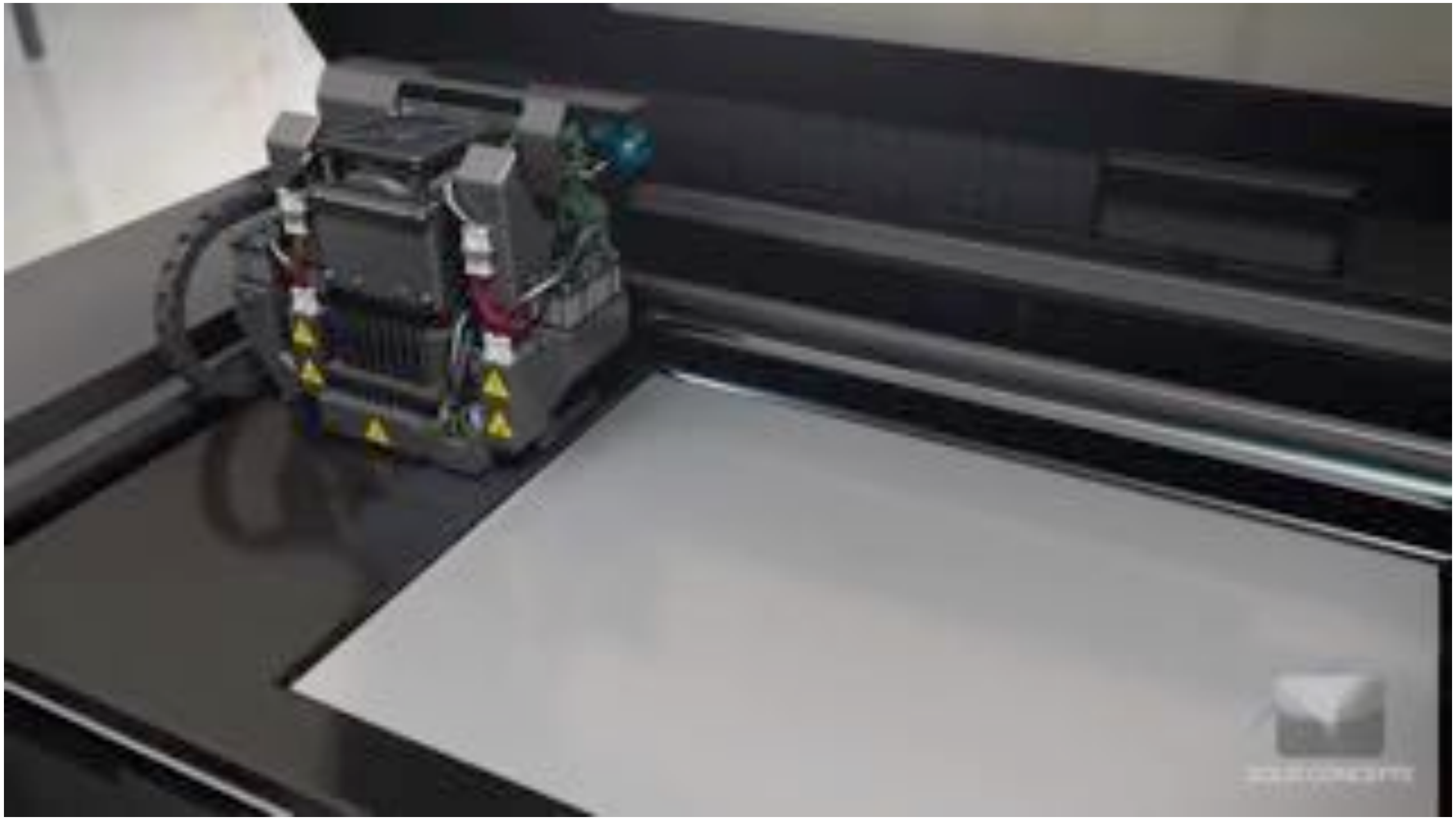
Two photon stereolithography





Material Jetting

Polyjet: https://www.youtube.com/watch?v=Som3CddHfZE



Powder bed fusion

Laser Sintering

https://www.youtube.com/watch?v=bgQvqVq-SQU

Powder bed fusion processes

- AM process in which thermal energy selectively fuses regions of a powder bed
- First commercial example: Selective laser sintering (SLS), invented by Carl Deckard during his PhD in Texas University in 1987
- Basic set of characteristics:
  - one or more thermal sources
  - methods for controlling powder fusion
  - mechanism for adding and smoothing powder layers
- Laser is the most common thermal source (laser sintering)
  - polymer laser sintering (pLS)
  - metal laser sintering (mLS)

Laser Sintering

Baseline description

https://www.youtube.com/watch?v=bgQvqVq-SQU

Laser Sintering

Baseline description

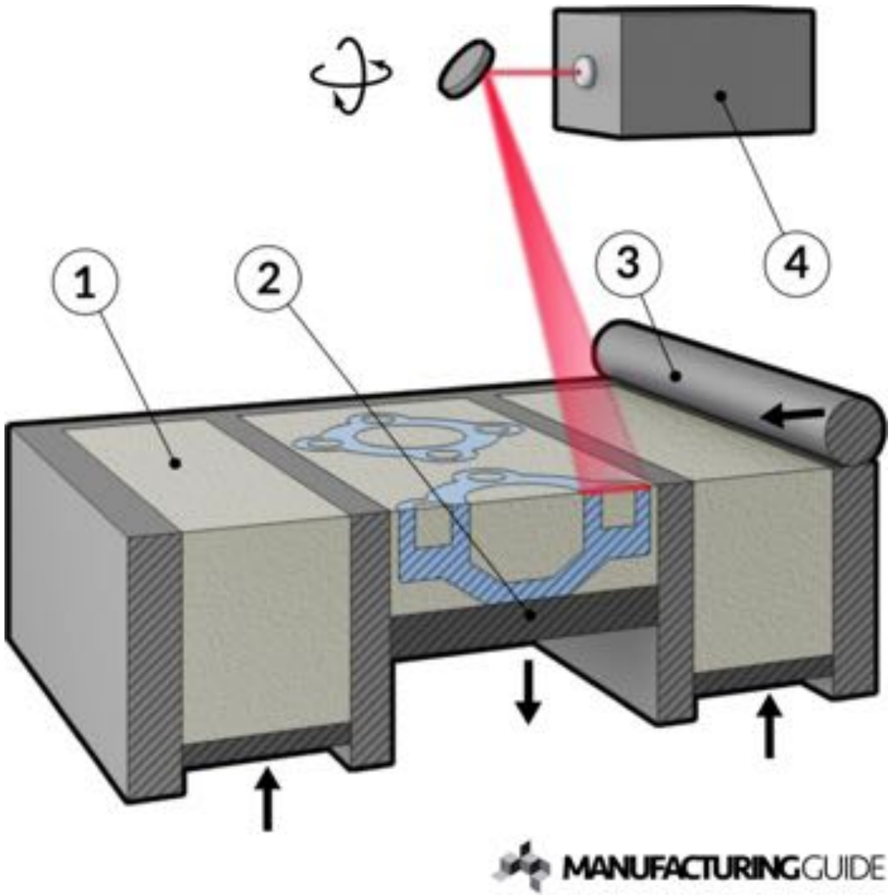


Figure 20.7 Schematic illustration of the selective-laser-sintering process. *Source*: After C. Deckard and P. F. McClure.
Manufacturing, Engineering & Technology, Fifth Edition, by Serope Kalpakjian and Steven R. Schmid.
ISBN 0-13-148965-8. © 2006 Pearson Education, Inc., Upper Saddle River, NJ. All rights reserved.

SLS samples

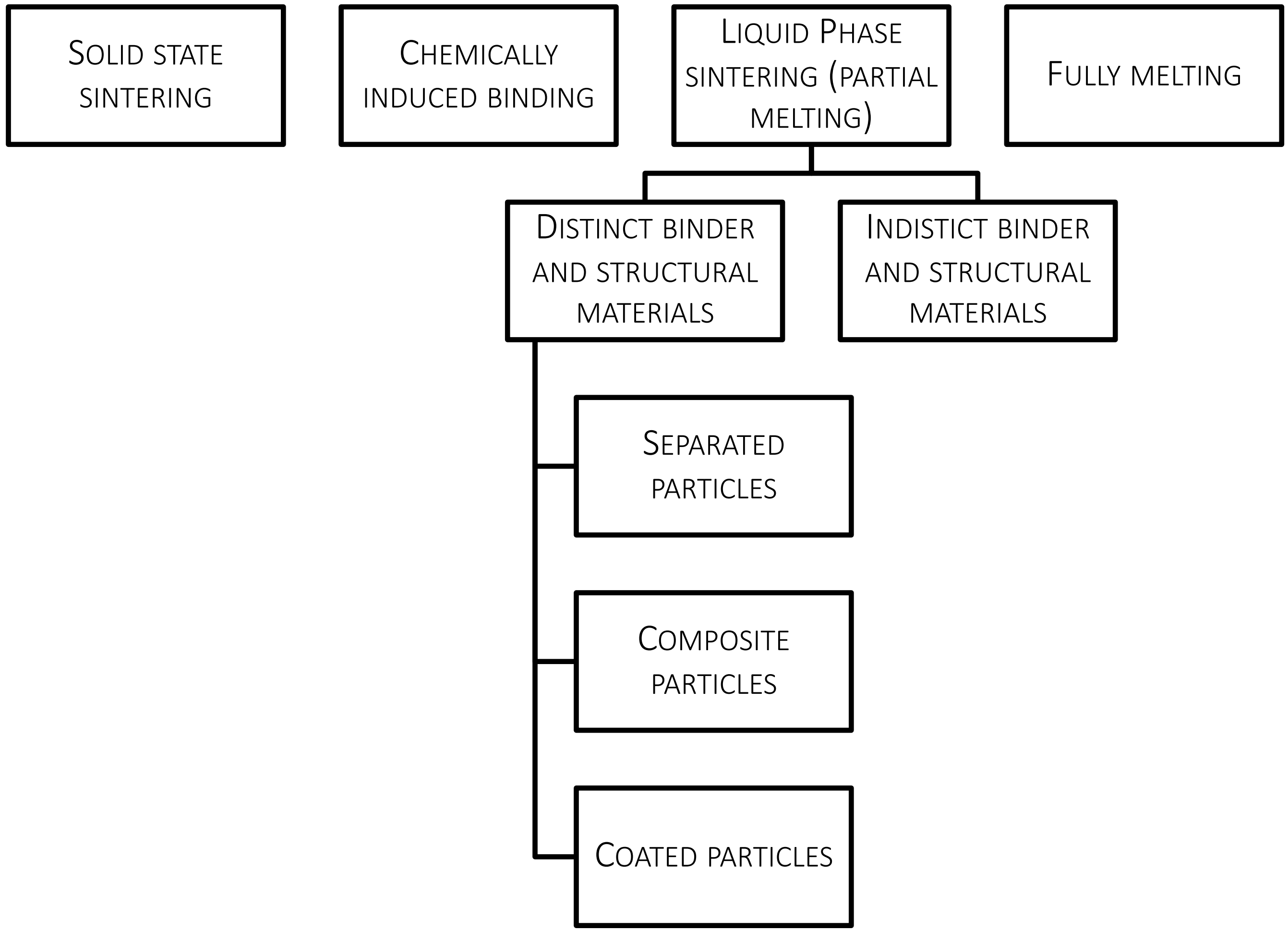
Laser Sintering

- The fabrication chamber is maintained at a temperature just below the melting point of the powder
- Heat from the laser need only elevate the temperature slightly to cause sintering. This greatly speeds up the process;
- No supports are required with this method since overhangs and undercuts are supported by the solid powder bed;
- Surface finishes and accuracy are not quite as good as with stereolithography, but material properties can be quite close to those of the intrinsic materials

Materials

- Polymers and composites
  - amorphous vs (semi-)crystalline polymers
  - nylon (polyamide), ABS, PVC, and polystyrene, PCL, PLA
  - nylon/polycarbonate powders are health hazards (dangerous to breathe).
  - glass-filled or with other fillers
  - metals encapsulated in plastic.
- Metals
  - low melting metal alloys of nickel bronze, steel, titanium, alloy mixtures, and composites
- Ceramics and ceramic composites
  - Green sand (for sand casting), hydroxyapatite
  - Metal ceramic composites (chemically induced sintering processes)

Powder fusion mechanism

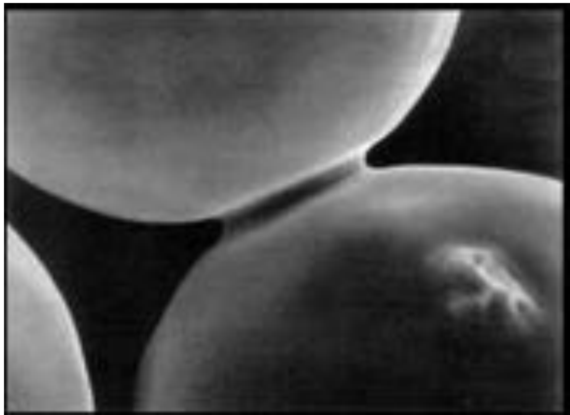


Solid state sintering process

- Mechanism: diffusion between powder particles (intrinsically slow)
- Driving force: minimization of the total free energy $E_s = \gamma \times S$ (S=surface)
- Larger the surface to volume ratio, greater is the driving force (smaller particles sinter more rapidly)
- Diffusion rates depends on temperature with an Arrhenius law.

+ Solid state sintering process in AM

- Side effects:
  - increase of average particle size of recycled powder
  - "part growth": the final model results bigger due to solid state sintering of new powder at the shell of the model
    - compensation at building scanning strategy
    - removal during post processing
  - decrease of porosity



Liquid phase sintering and partial melting

- Fusion of powder particles when a portion of constituentes within a collection of powder particles become molten, while other portions remain solid
- Molten constituentes act as “glue”
- Distinction between binder and structural materials
  - separate particles
  - composite particles
  - coated particles
  - no distiction (partial melting)

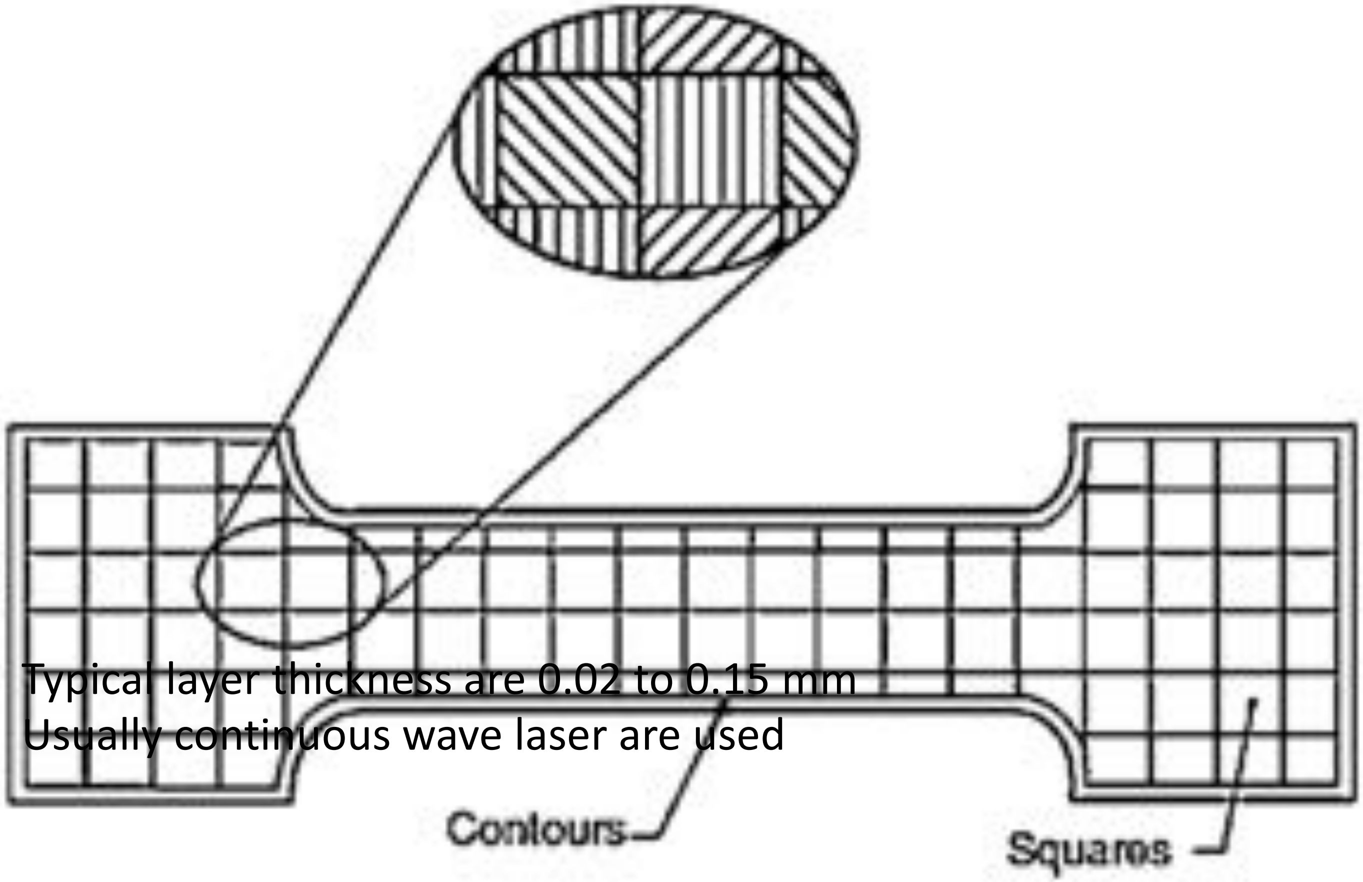
Relevant physical properties

- Melting temperature
- Fluid Dynamic properties
  - Viscosity
  - Surface tension
- Heat conduction properties
  - Thermal conductivity
  - Specific heat
- Thermal expansion

Process parameters

- Laser related parameters
  - laser power, spot size, pulse duration, pulse frequency, etc.
- Scanning relaterd paramters
  - scan speed, scan spacing, and scan pattern
- Powder related parameters
  - particle shape, size and distribution, powder bed density, layer thickness, material properties, etc ...
- Temperature related parameters
  - powder bed temperature, powder feeder temperature, temperature uniformity, etc ...

Scanning strategies

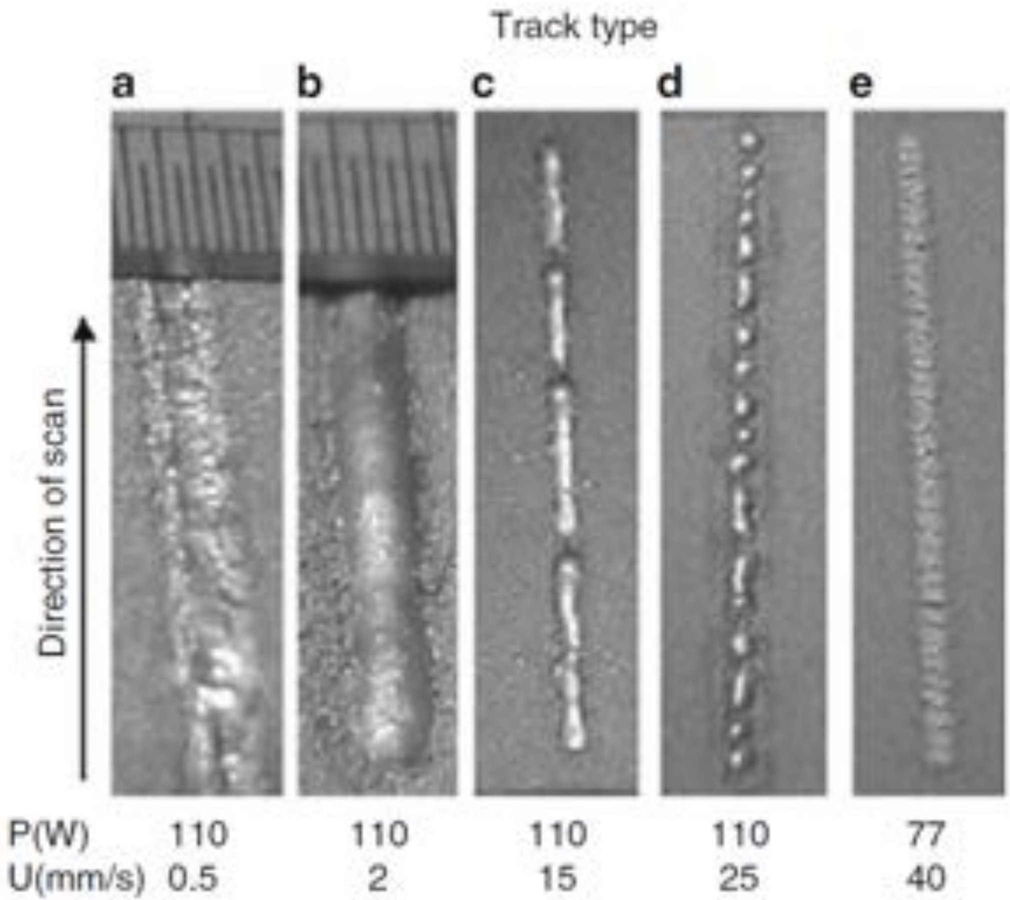


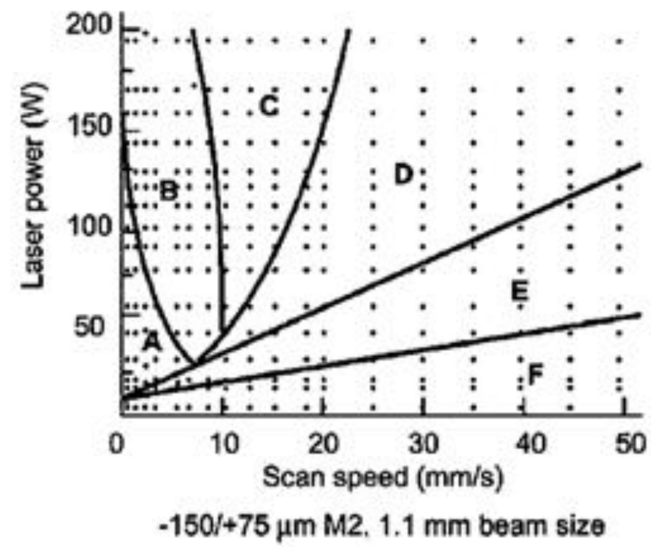
- Typical layer thickness are 0.02 to 0.15 mm
- Usually continuous wave laser are used

Applied energy density

- $E_A = P/(U \times SP)$
  - E_A = applied energy density (Andrews number) [J/m^2]
  - P = laser power [W]
  - U = scan velocity [m/s]
  - SP = scan spacing between parallel scan lines [m]

Applied energy density

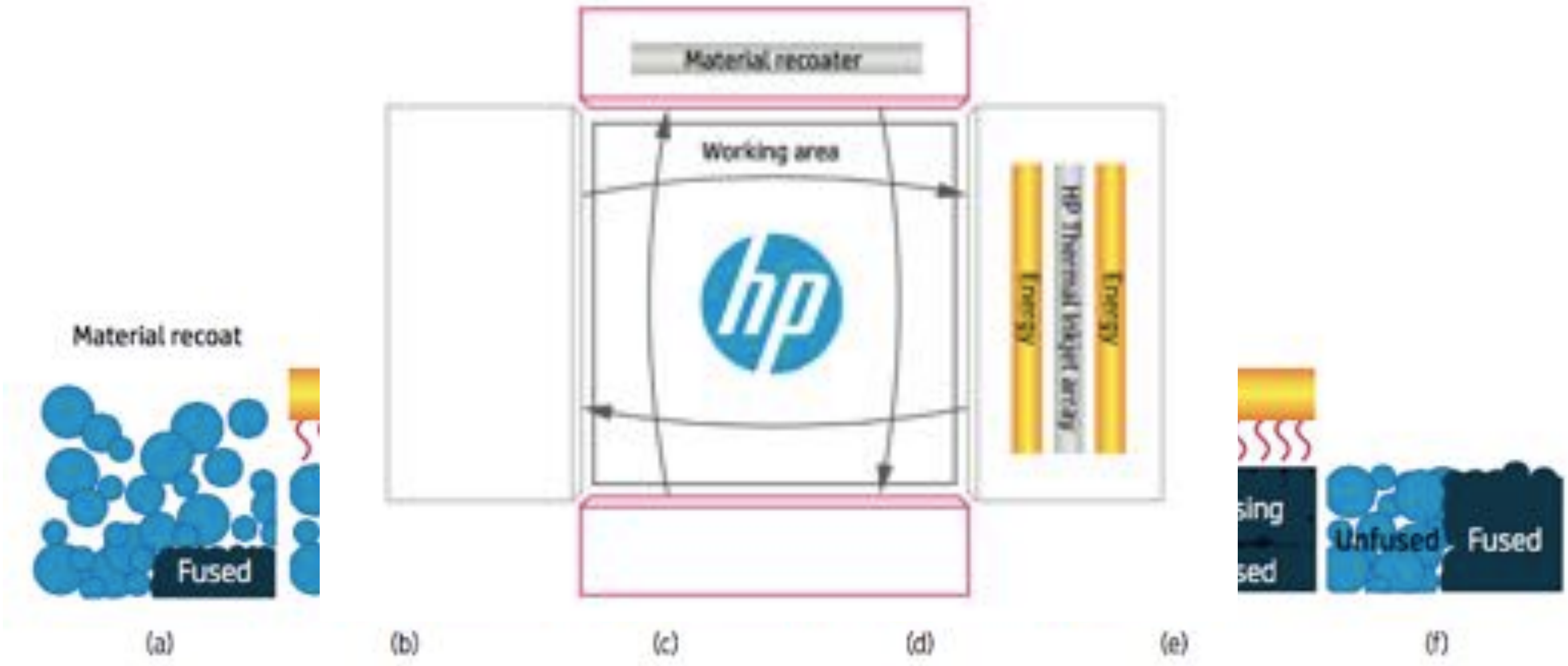




Multijet Fusion

- https://www.youtube.com/watch?time_continue=1&v=VXntl3ff5tc
- https://www.youtube.com/watch?v=qEPqlVs11KM

Multijet Fusion

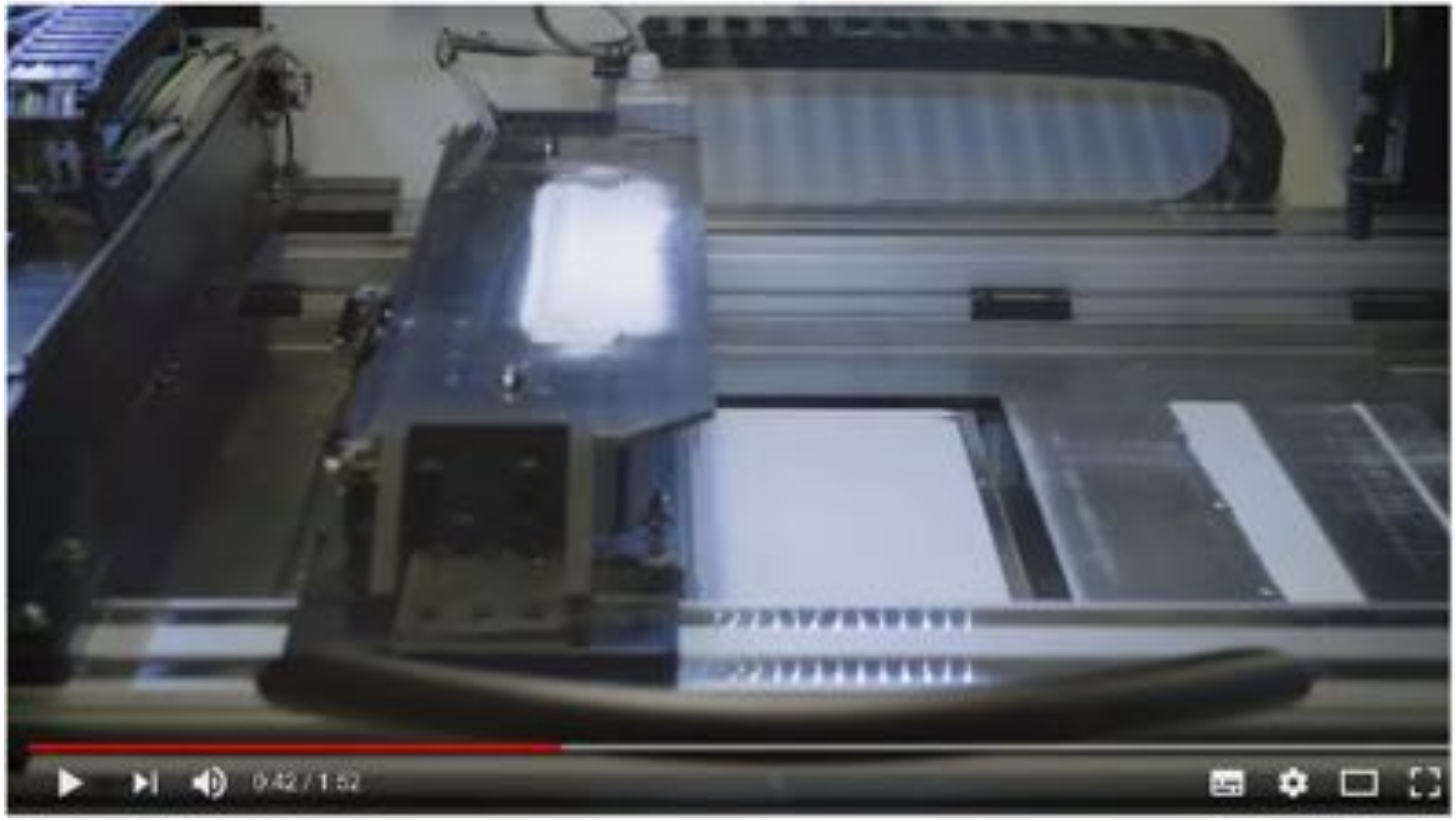


Directed energy deposition

- Laser engineering net shaping (LENS)
- https://www.youtube.com/watch?v=d2foaRi4nxM

Binder Jetting

https://www.youtube.com/watch?v=RNNxEoXuvuw

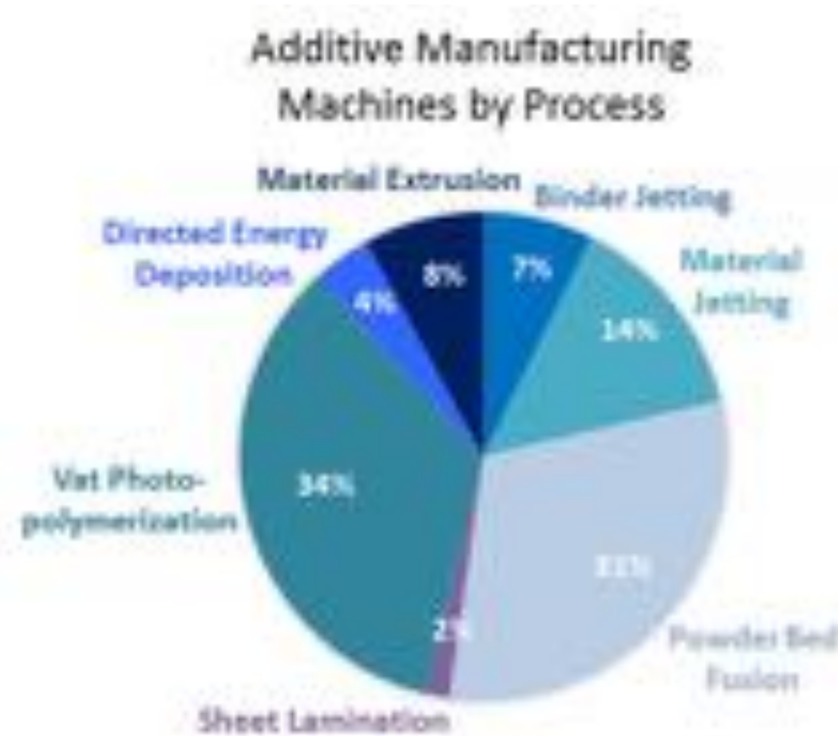


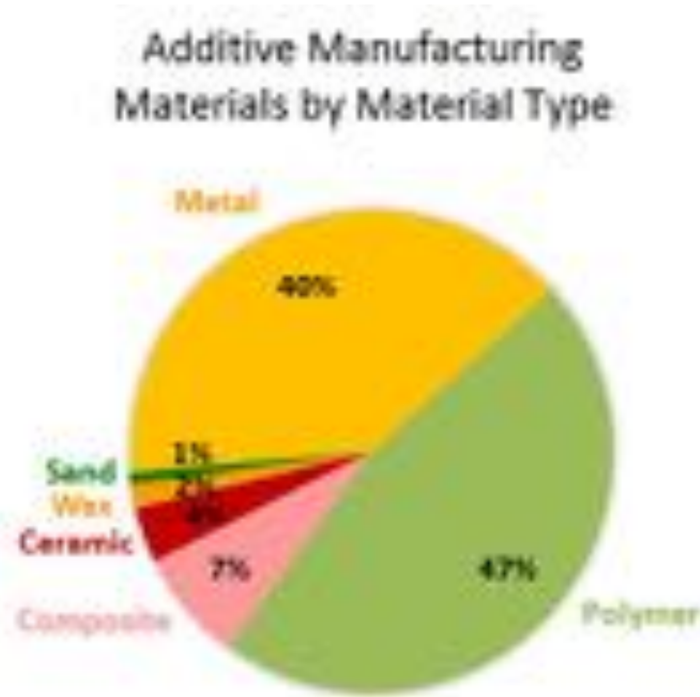
Sheet lamination

- https://www.youtube.com/watch?v=GjJKuteh4xM

Materials

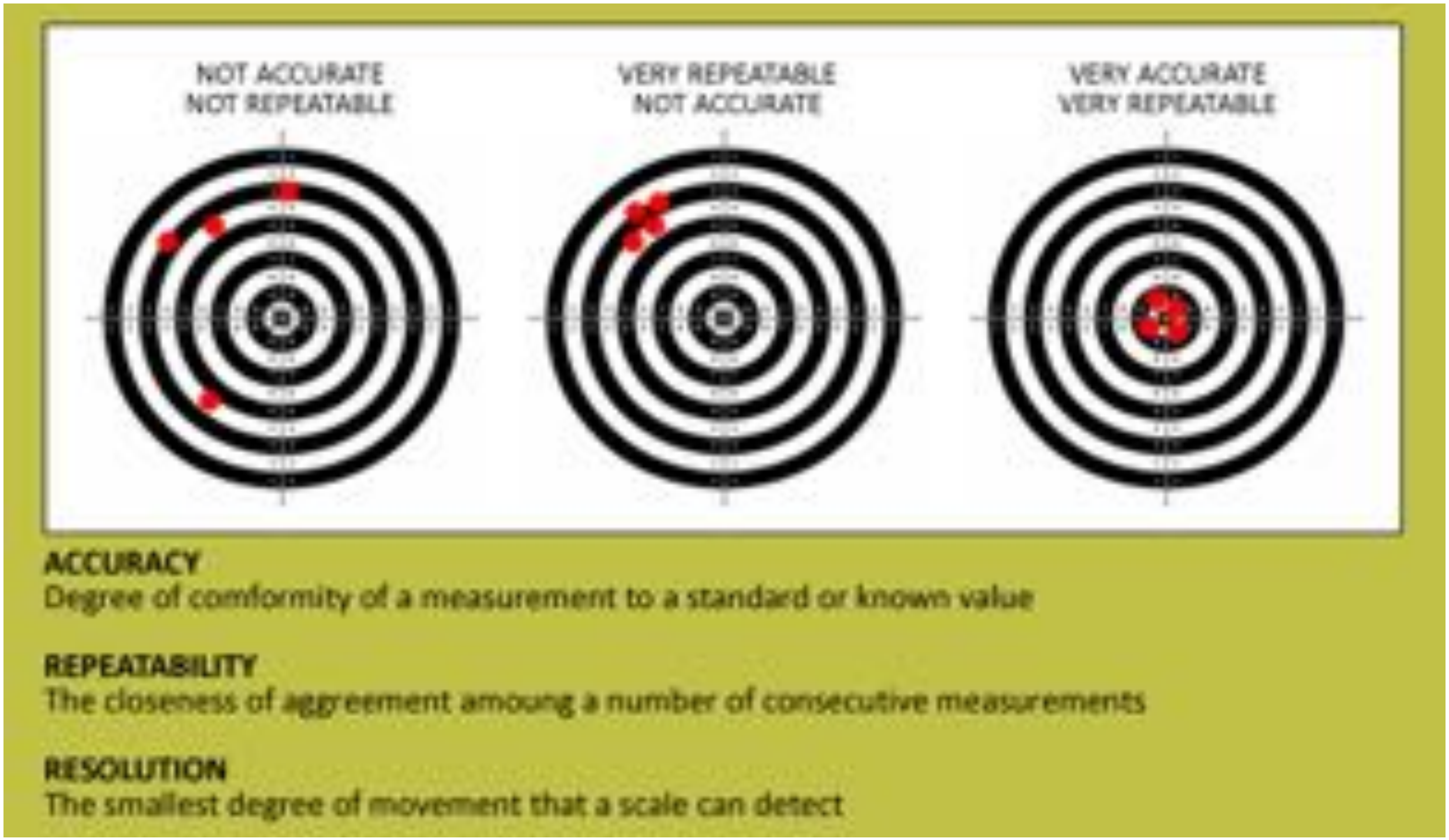
Materials	Example materials	Process categories						
		Vat photo-polymer-ization	Material jetting	Binder jetting	Powder bed fusion	Material extrusion	Directed energy deposition	Sheet lamination
Thermoset Polymers	Epoxies and acrylates	X	X					
Thermo-plastic polymers	Polyamide, ABS, PPSF		X	X	X	X		X
Wood	paper							X
Metals	Steel, Titanium alloys, Cobalt chromium			X	X		X	X
Industrial ceramic materials	Alumina, Zirconia, Silicone nitride	X		X	X			X
Structural ceramic materials	Cement, Foundry sand			X	X	X		
Note: Combinations of the above material classes, e.g. a composite, are possible								


Additive Manufacturing
Machines by Process
Material Extrusion
Binder Jetting
Directed Energy
Deposition
Material
Jetting
8%
7%
4%
14%
Vat Photo-
polymerization
34%
2%
Powder Bed
Fusion
Sheet Lamination


Additive Manufacturing
Materials by Material Type
Metal
40%
Sand
1%
Wax
Ceramic
7%
47%
Composite
Polymer

GENERAL CONSIDERATION ON ADDITIVE MANUFACTURING TECHNOLOGIES

Accuracy-repeatability-resolution

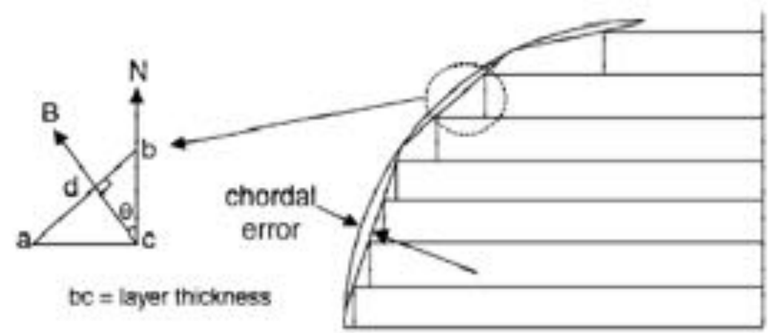


Accuracy

	Layer thickness(mm)	Accuracy (mm)
Stereolithography	0.05 - 0.3	0.01 - 0.2
Layered Object Manufacturing	0.1 - 1	0.1 - 0.2
Fused Deposition Modelling	≈0.05	0.130 - 0.260
Selective laser sintering	≈0.08	0.03 - 0.4

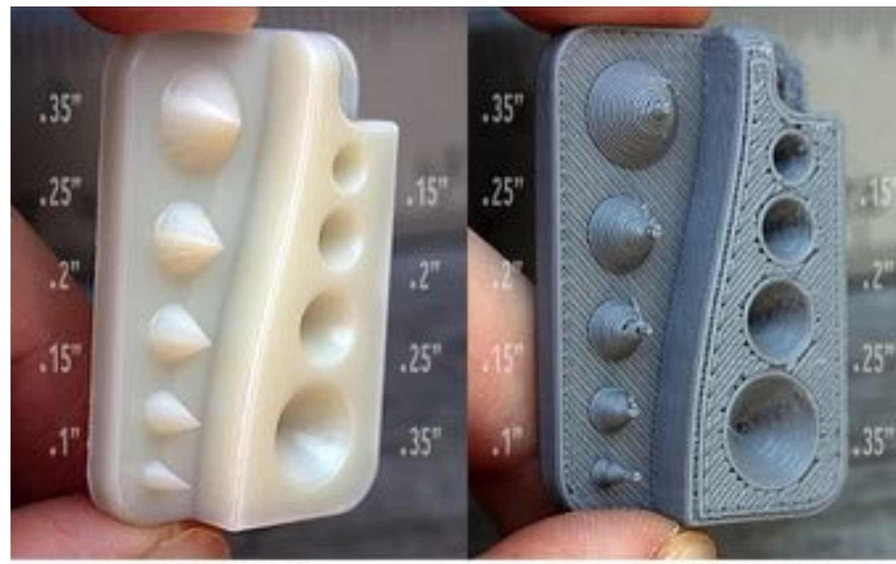
Accuracy

- Stair stepping



Accuracy and resolution

- Tolerances are still not quite at the level of CNC,
- Because of intervening energy exchanges and/or complex chemistry one cannot say with any certainty that one method of RP is always more accurate than another, or that a particular method always produces a certain tolerance.



Objet30 Pro Dimension SST 1200

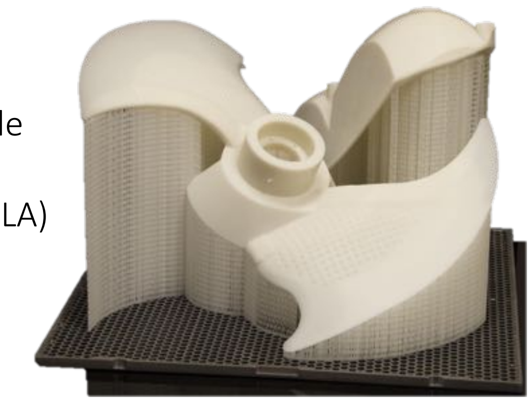
Surface finish

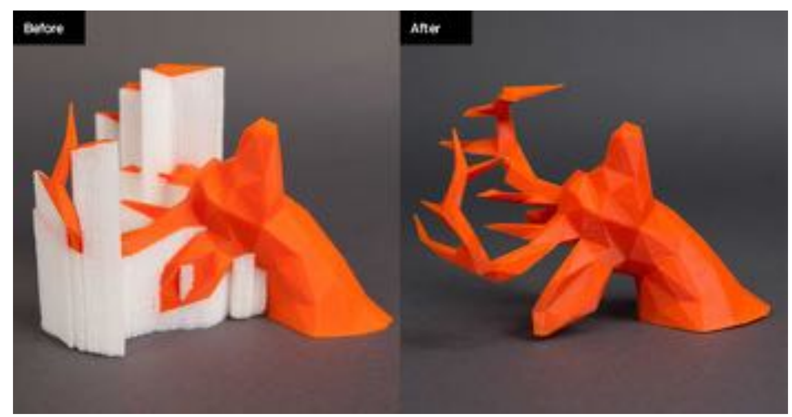
- The finish and appearance of a part are related to accuracy, but also depend on the method of RP employed.
- Technologies based on powders have a sandy or diffuse appearance, sheet-based methods might be considered poorer in finish because the stairstepping is more pronounced.

Costs

- System costs
  - from $30,000 to $800,000
  - training, housing and maintenance (a laser for a stereolithography system costs more than $20,000)
- Material
  - High cost
  - Available choices are limited.
- Costs and time due to secondary operations
  - Post Curing (Stereolithography)
  - Infiltration, for fragile parts (3DP, SLS)
  - Final machining of metal parts
  - Removing of the support structures

Not soluble support structure (SLA)





Soluble support structure (white material, FDM)

Additive vs subtractive

- AM can not become complete replacement for the SM (Milling, Turning, EDM etc.)
- AM technologies are instead complementary for:
  - complex or intricate geometric forms,
  - simultaneous fabrication of multiple parts into a single assembly,
  - multiple materials or composite materials in the same part.
- Thus, AM is the enabling technology for controlled material composition as well as for geometric control.

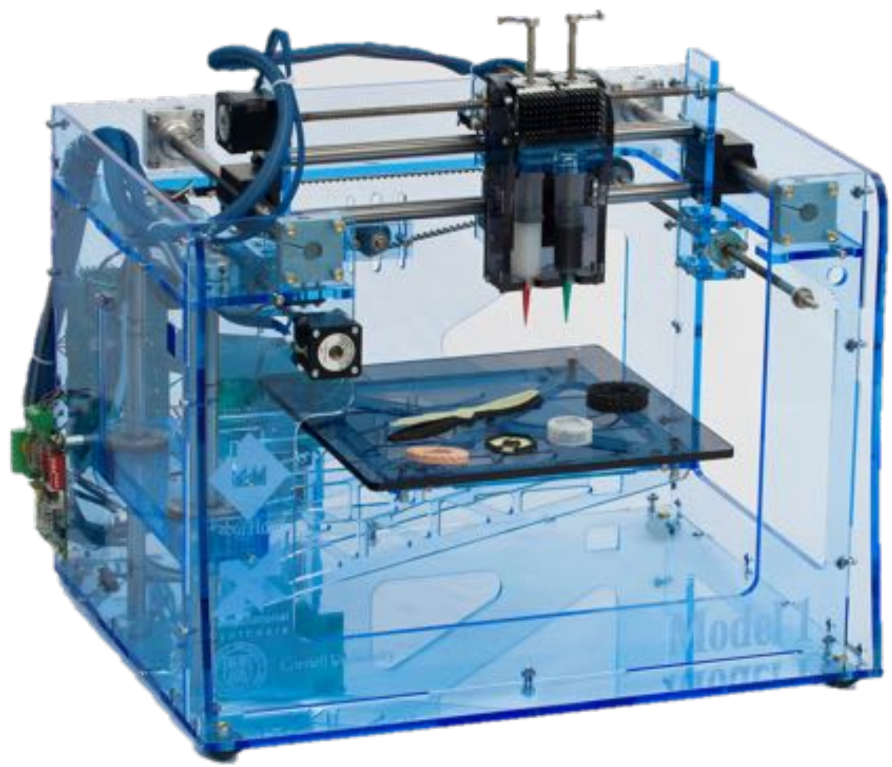
Cost - Vendors

Photopolymer		
3D System (formerly DTM)	US	http://www.3dsystems.com
EOS	Germany	http://www.eos.info/en
CMET	Japan	http://www.cmet.co.jp/eng/
Envisiontec Perfactory	Germany	http://www.envisiontec.de

Deposition			
Stratasys	FDM	US	http://www.stratasys.com
Solidscape (now it is a Stratasys company)	Inkjet	US and the Netherlands	http://www.solid-scape.com
3D Systems (formerly DTM)	Thermojet™	US	http://www.3dsystems.com
Soligen	casting cores/patterns	US	http://www.soligen.com

Selective laser sintering		
3D Systems	US	http://www.3dsystems.com
EOS	Germany	http://www.eos.info/en

Open source 3D printers



Asking for a quote

- https://www.stratasysdirect.com/

- https://www.3dhubs.com/

Environmental and health issues

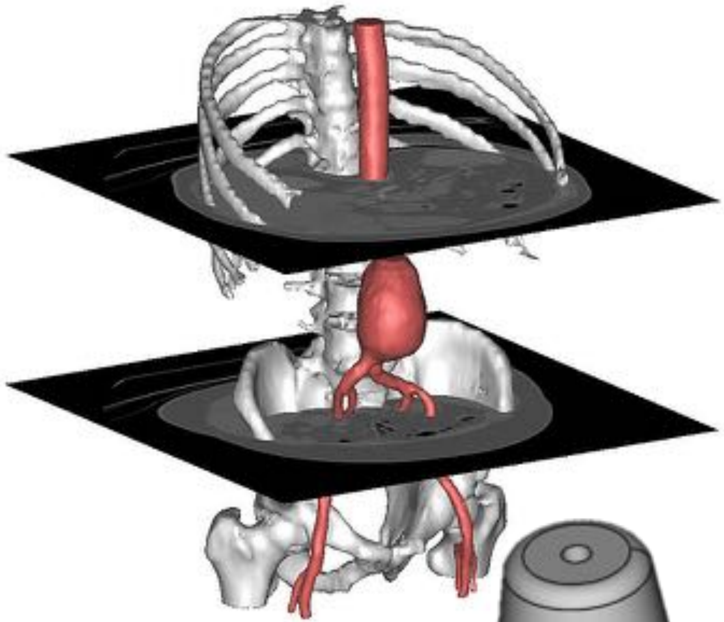
ADDITIVE MANUFACTURING PROCESS FLOW

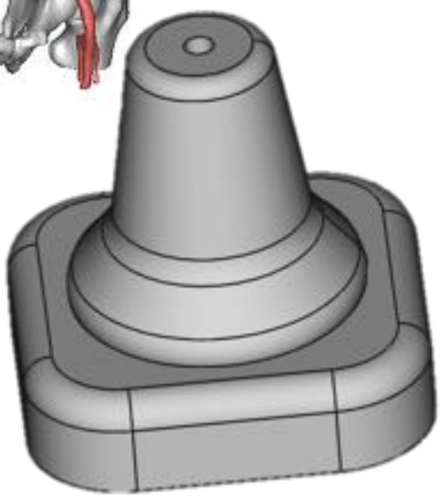
Additive manufacturing process flow

- Solid 3D modeling
- Export (Tessellation/Voxelization)
- Support Generation
- “Slicing” of the Model
- Model Physical Buildup
- Cleanup and Post Curing
- Surface Finishing

Solid 3D modeling

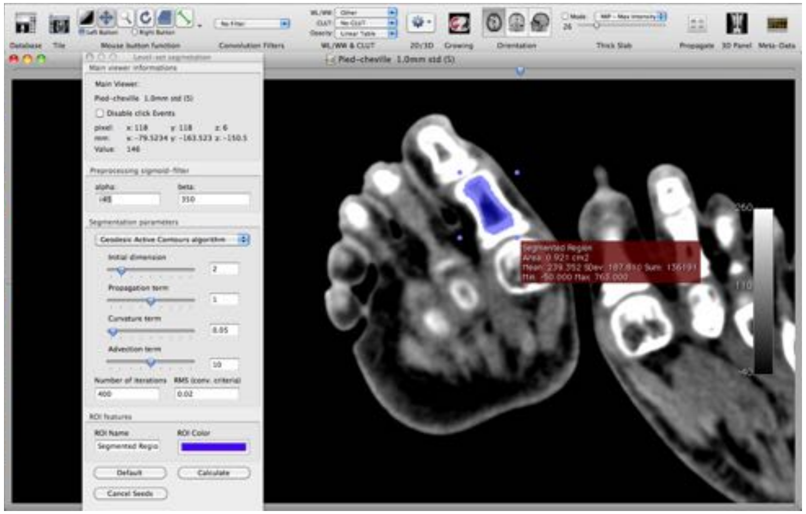
- Representation of a volume
  - CAD model
    - Your specific design
    - Web repository (http://www.thingiverse.com, https://www.youmagine.com, https//3dprint.nih.gov, http://www.appropedia.org, http://opensourceecology.org, http://reprap.org)
  - Instruments output
    - Segmentation of medical Images (Tomographic Data: CT scan, RM scan)
    - Surface scanning (Laser)



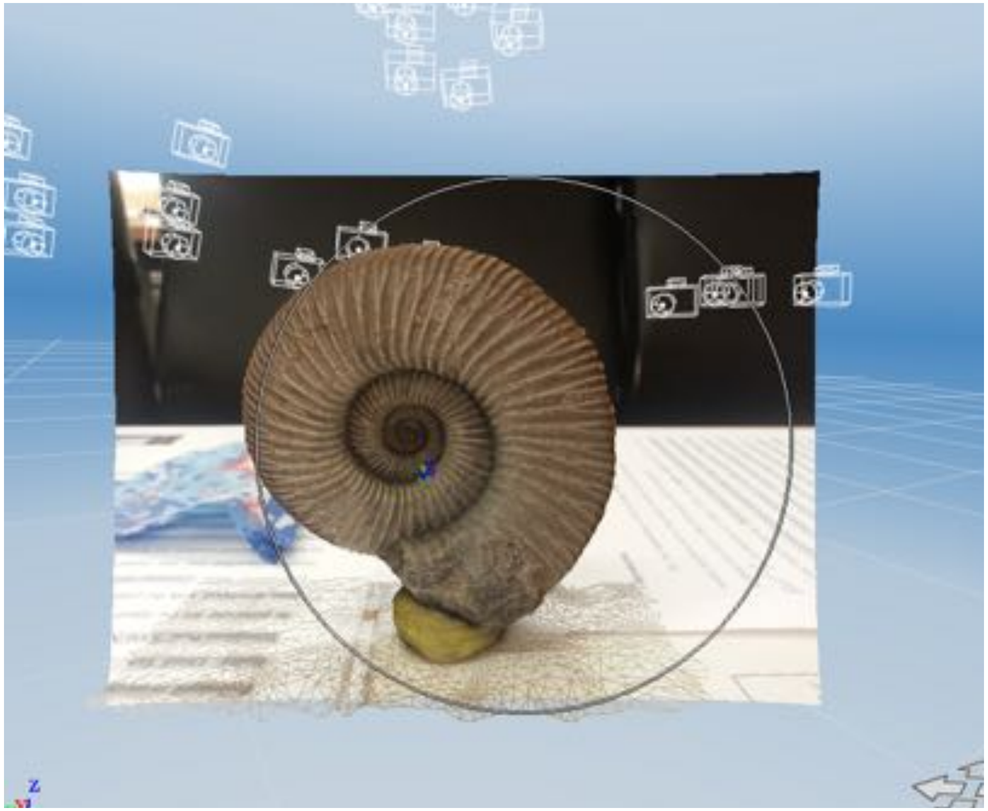


Segmentation

- Segmentation subdivides an image into its constituent regions or objects.
- The level of subdivision depends on the problem being solved
- If the starting point is a 3D volumetric set, the identified region can be a printable object
- Well developed in the medical field:
  - OsiriX (www.osirix-viewer.com)
  - 3DSlicer (www.slicer.org)
  - ImageJ (rsb.info.nih.gov/ij)
  - MIPAV (mipav.cit.nih.gov)
  - itk-SNAP (www.itksnap.org)



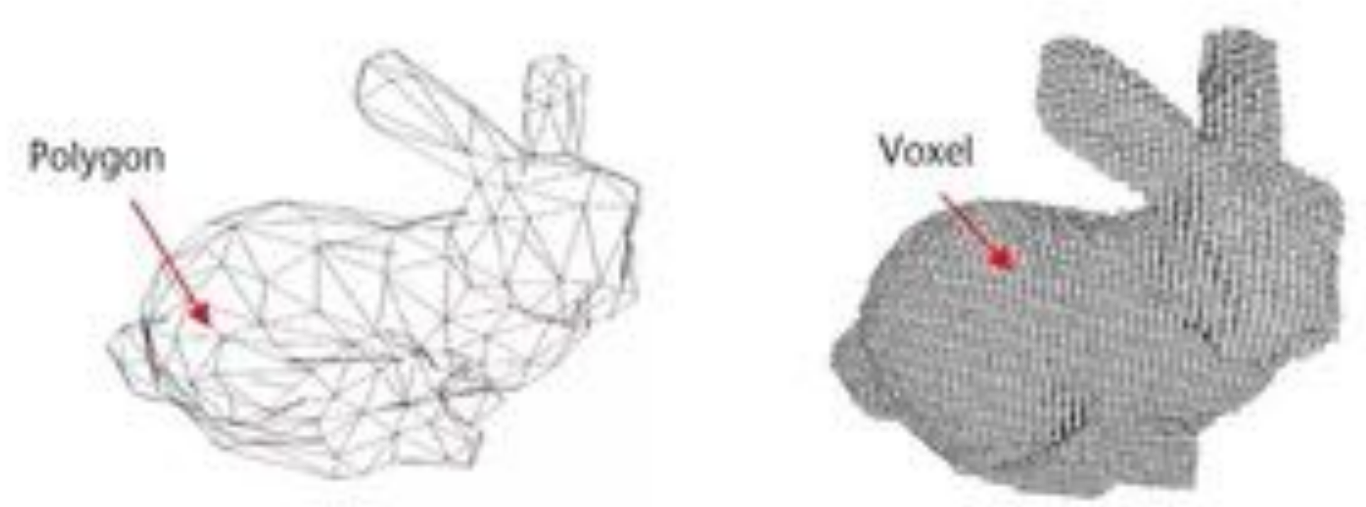
Optical scanner (photocamera)



Optical scanner (photocamera)

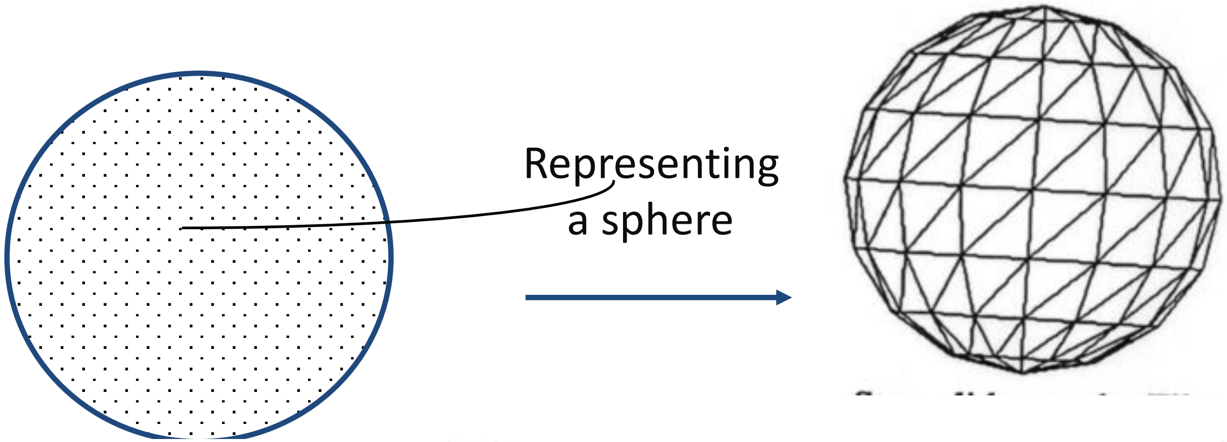
Tessellation / voxelization

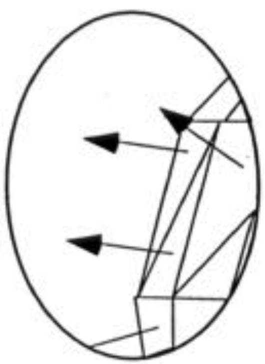
- Exchange formats for exporting 3D model
  - Polygon-based representation (STL, AMF, 3MF, OBJ, PLY)
  - Voxel based models



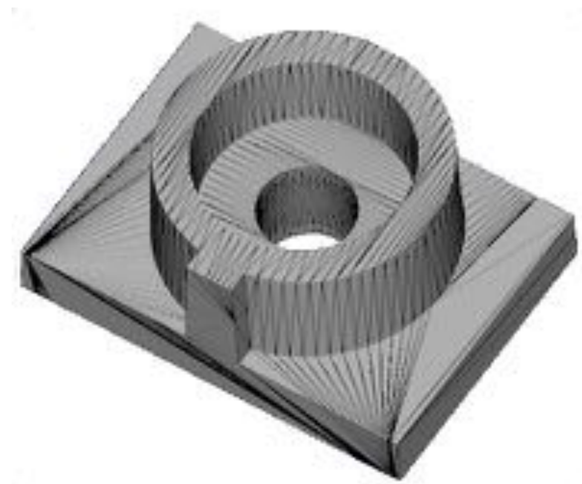
(a) Polygon-based representation (b) Voxel-based representation

Example of *.stl Representation





```
solid obj1
  facet normal 1.457591e-01 -9.885599e-01 -3.877669e-02
    outer loop
      vertex 9.614203e+00 4.757629e+00 0.000000e+00
      vertex 7.875000e+00 4.501190e+00 0.000000e+00
      vertex 9.483117e+00 4.764183e+00 -6.598330e-01
    endloop
  endfacet
  facet normal 1.161178e-01 -9.870778e-01 -1.104267e-01
    outer loop
      vertex 9.483117e+00 4.764183e+00 -6.598330e-01
      vertex 7.875000e+00 4.501190e+00 0.000000e+00
      vertex 9.109818e+00 4.782848e+00 -1.219212e+00
    endloop
  endfacet
  facet normal 6.134766e-02 -9.843393e-01 -1.652652e-01
```



AMF format

- Additive Manufacturing Format
- XML, meta-format: Format of formats
  - Text based
  - Easy to read/write/parse
  - Existing editing tools
  - Extensible
  - Highly compressible
- Part (objects) defined by regions and materials
  - Regions defined by triangular mesh
  - Materials defined by properties/names
- Mesh properties can be specified
  - Color, Tolerance, Texture
- Materials can be combined
  - Graded materials
  - Microstructure
- Tolerance, encryption and watermarking

AMF - Basic Structure

```xml
<?xml version="1.0"?>
<AMF>
  <Object PrintID = "0" units = "mm">
    <Mesh>
      <Vertices>
        <Vertex VertexID="0">
          <VertexLocation x="0" y="1.332" z="3.715"/>
        </Vertex>
        <Vertex VertexID="1">
          <VertexLocation x="0" y="1.269" z="3.715"/>
        </Vertex>
        ...
      </Vertices>

      <Region FillMaterialID = "0">
        <Triangle V1 = "0" V2 = "1" V3 = "3"/>
        <Triangle V1 = "0" V2 = "1" V3 = "4"/>
        ...
      </Region>
    </Mesh>
  </Object>
</AMF>
```

Addresses needs:
Simple / Watertight /
Backward Compatible
(STL)

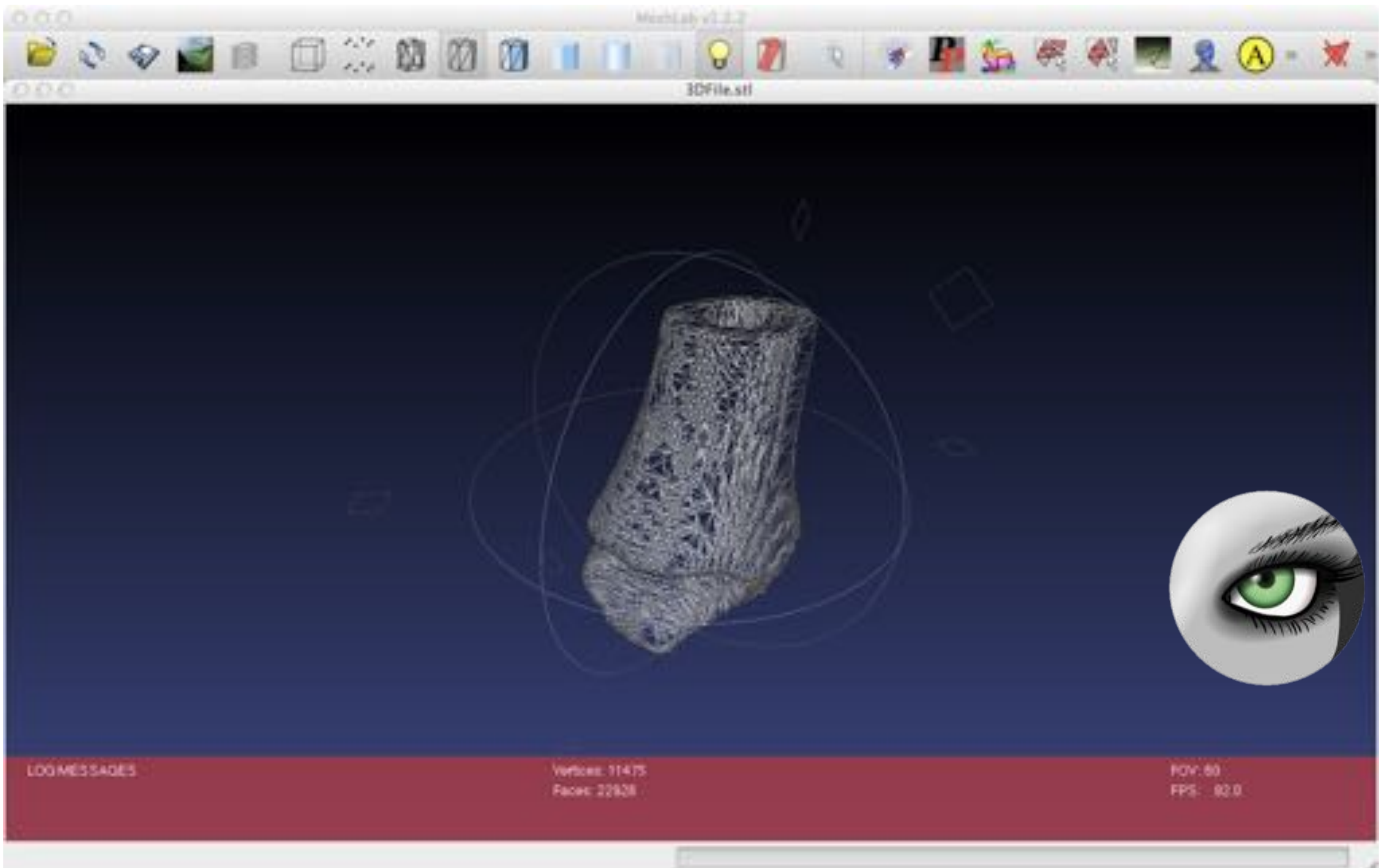
AMF - Multiple Materials

```
<?xml version="1.0"?>
<AMF>
  <Palette>
    <Material MaterialID = "0">
      <Name>StiffMaterial</Name>
    </Material>
    <Material MaterialID = "1">
      <Name>FlexibleMaterial</Name>
    </Material>
  </Palette>

  <Object PrintID = "0" units = "mm">
    <Mesh>
      <Vertices>
        ...
      </Vertices>
      <Region FillMaterialID = "0">
        ...
      </Region>
      <Region FillMaterialID = "1">
        <Triangle V1 = "5" V2 = "6" V3 = "7"/>
        <Triangle V1 = "5" V2 = "7" V3 = "9"/>
        ...
      </Region>
    </Mesh>
  </Object>
</AMF>
```

Addresses needs: Multiple Materials, No leaks between regions (shared vertices)

Mesh management

http://meshlab.sourceforge.net



Voxelization

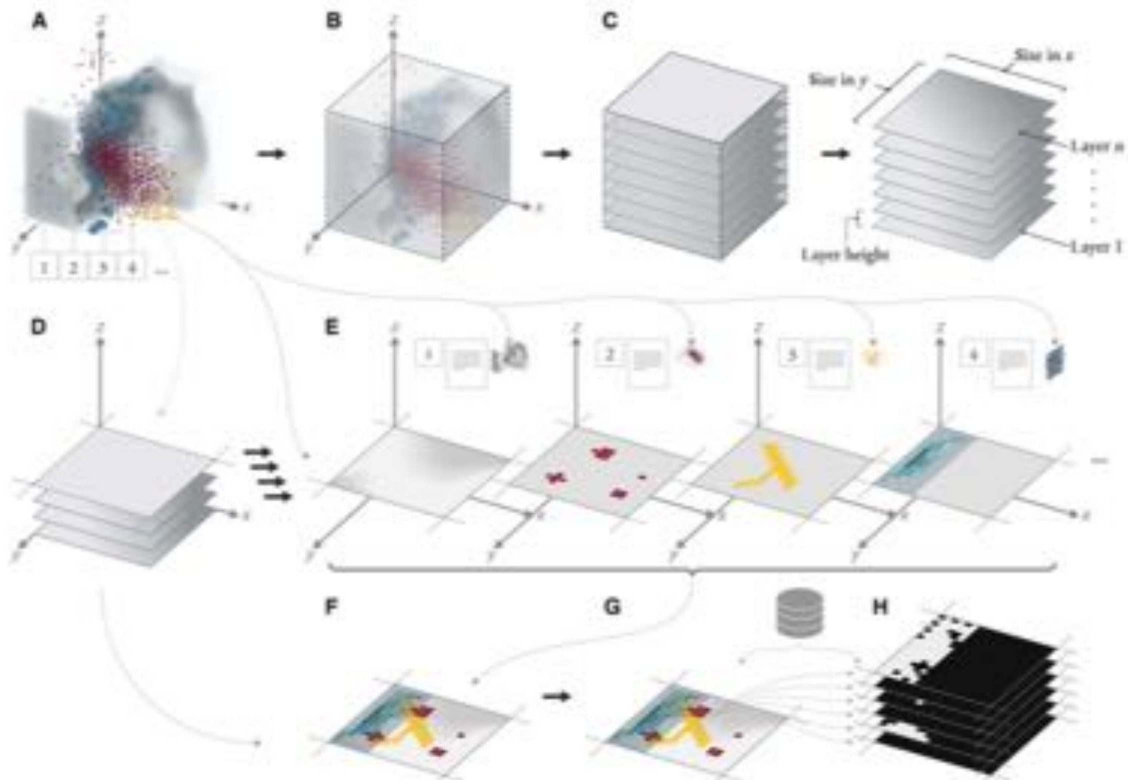
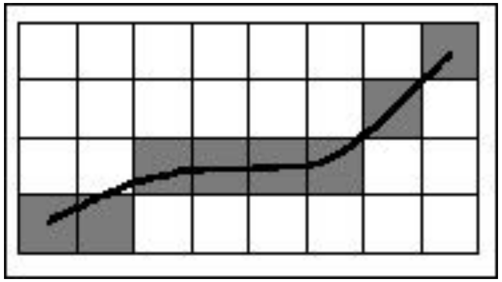


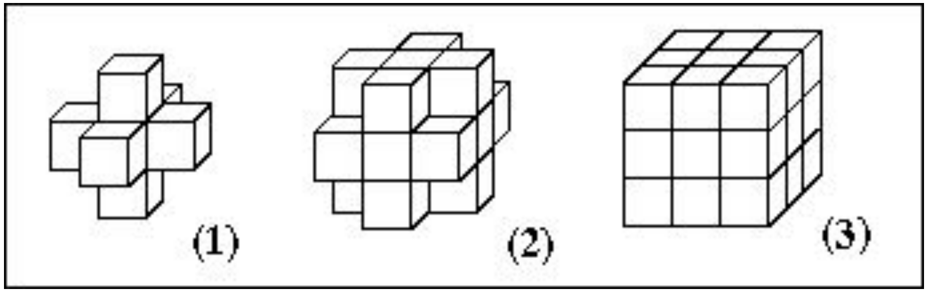
Fig. 1. General workflow for the conversion of data sets to 3D-printed data physicalizations. For a given composition of data sets (**A**), a hull is generated first (**B**). Here, the composition of data sets contains a volumetric (1), point cloud (2), graph (3), and image stack (4) data set. (**C**) The enclosure, together with the available printer resolution, thus determines the dimension and number of the generated layers. The data set is then processed for each layer (**D**), according to "Volumes," "Point clouds," "Curves and graphs," and "Image-based" sections, respectively (**E**), to generate, to generate per-pixel material information. Here, every layer's pixel contains an associated position and is given the actual data set and additional information governing the desired appearance of the final physical visualization. The material information of each data set is then composited (**F**) and converted to material-mixing ratios (**G**). Finally, the material-mixing ratios are dithered to binary bitmap layers (**H**), one for each material given in the printer.

Applicable to Volumes, Point cloud, scientific data (curve and graphs), images

Voxelization



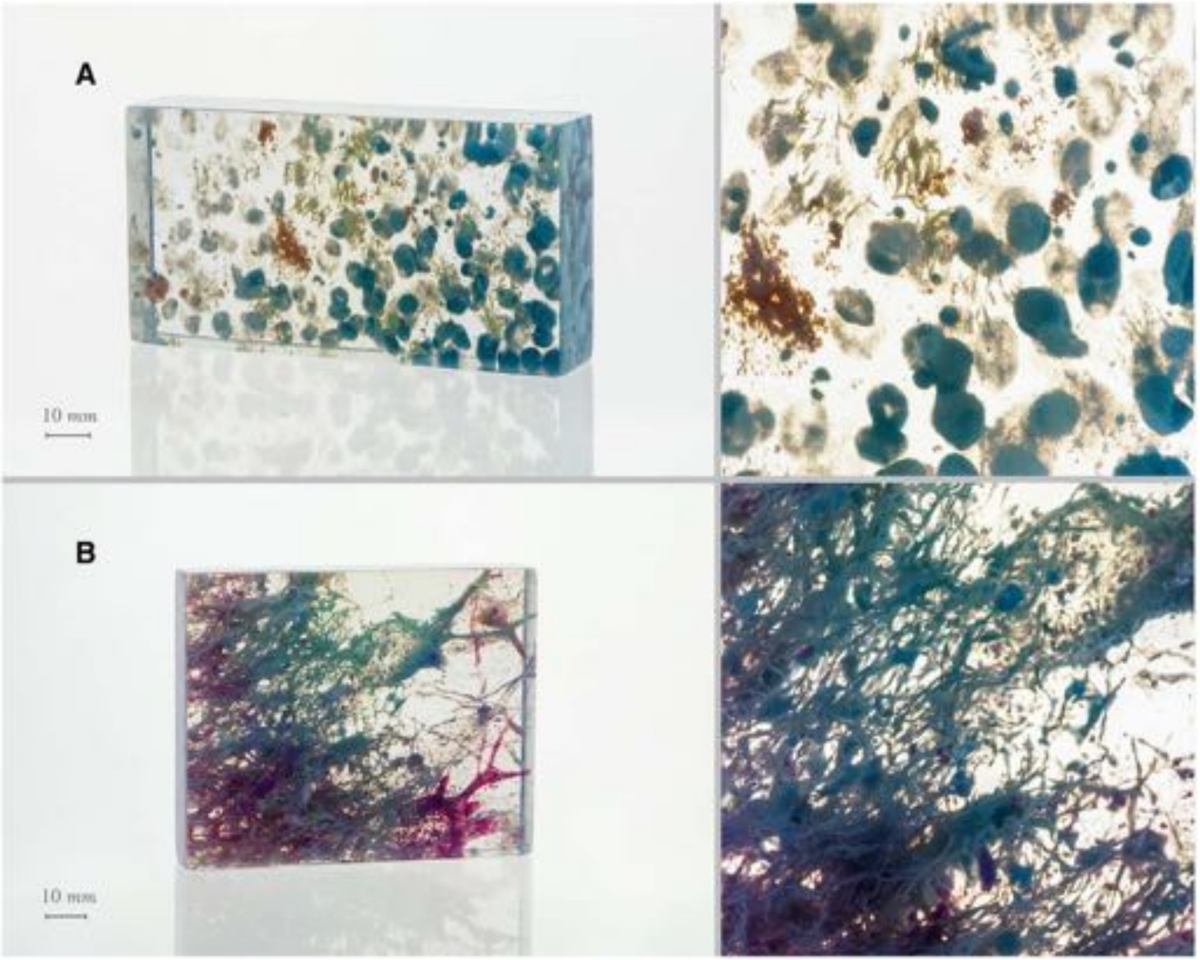
2D discrete curve (shaded pixels) that intuitively separates its two sides even without containing all those pixels pierced by the continuous line.



The three types of voxel adjacencies in 3D discrete space: (1) the six voxels that a are 6-adjacent to the voxel at the center (not seen), (2) the eighteen voxels that are 18- adjacent to the voxel at the center, (3) the twenty six voxels that are 26-adjacent to the voxel at the center

https://labs.cs.sunysb.edu/labs/projects/volume/Papers/Voxel/index.html

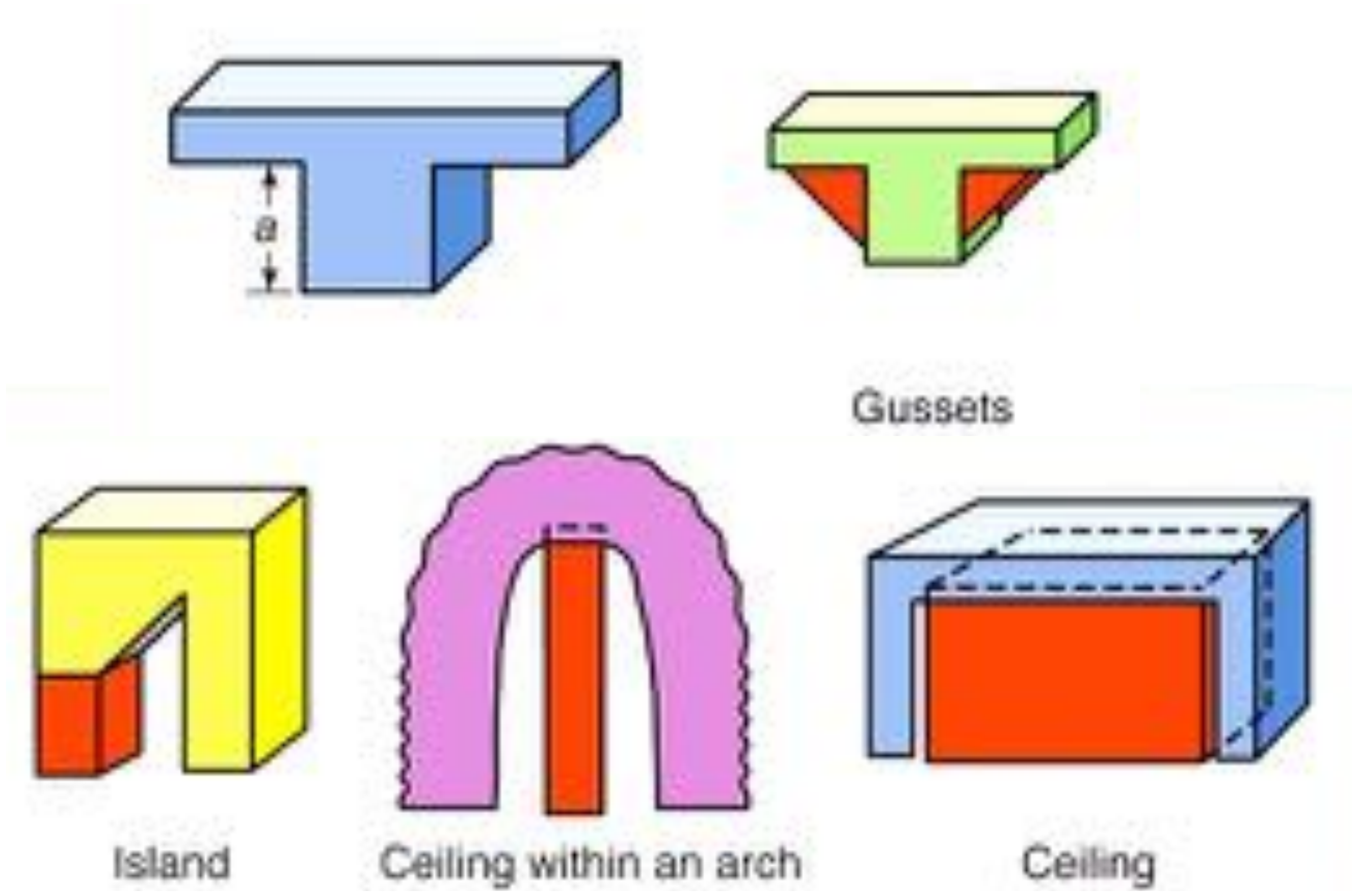
Data physicalization



Data physicalization
(Physical visualization)

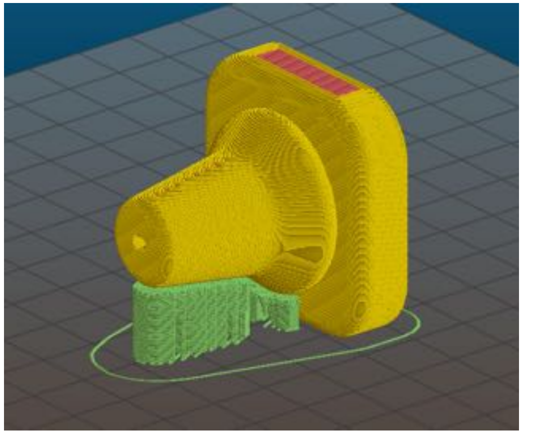
Bader, Christoph, et al. "Making data matter: Voxel printing for the digital fabrication of data across scales and domains." *Science advances* 4.5 (2018): eaas8652.

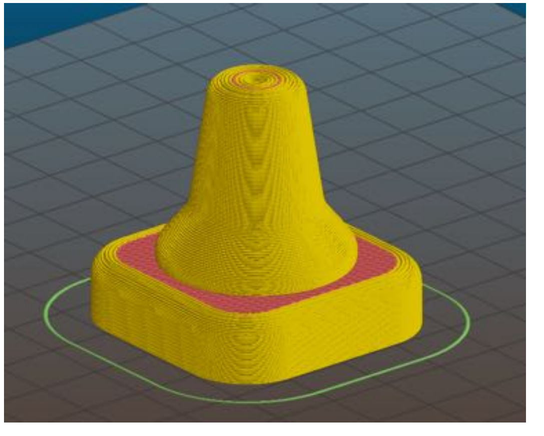
Support generation



Support generation

- Support generation may depend on
  - objects orientation,
  - on the specific additive manufacturing technology

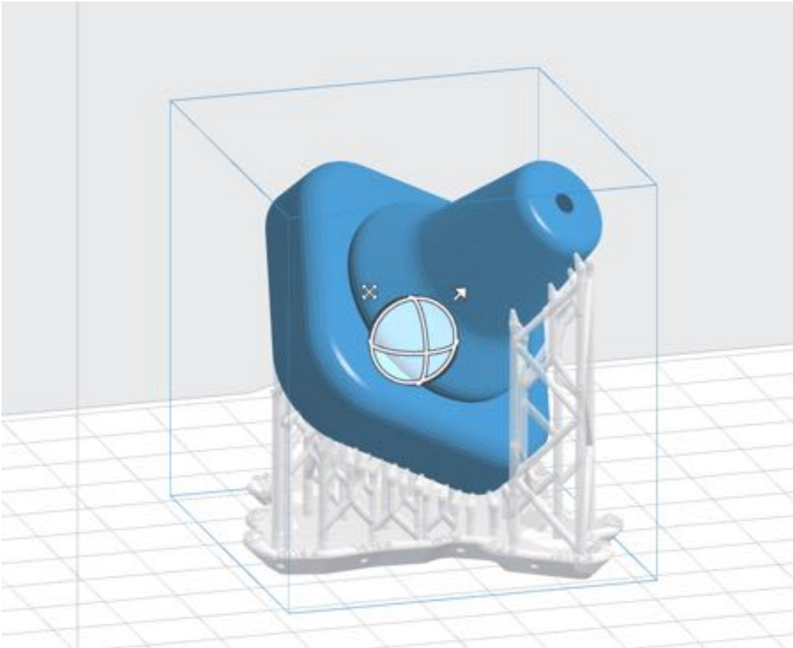




Fused deposition modelling

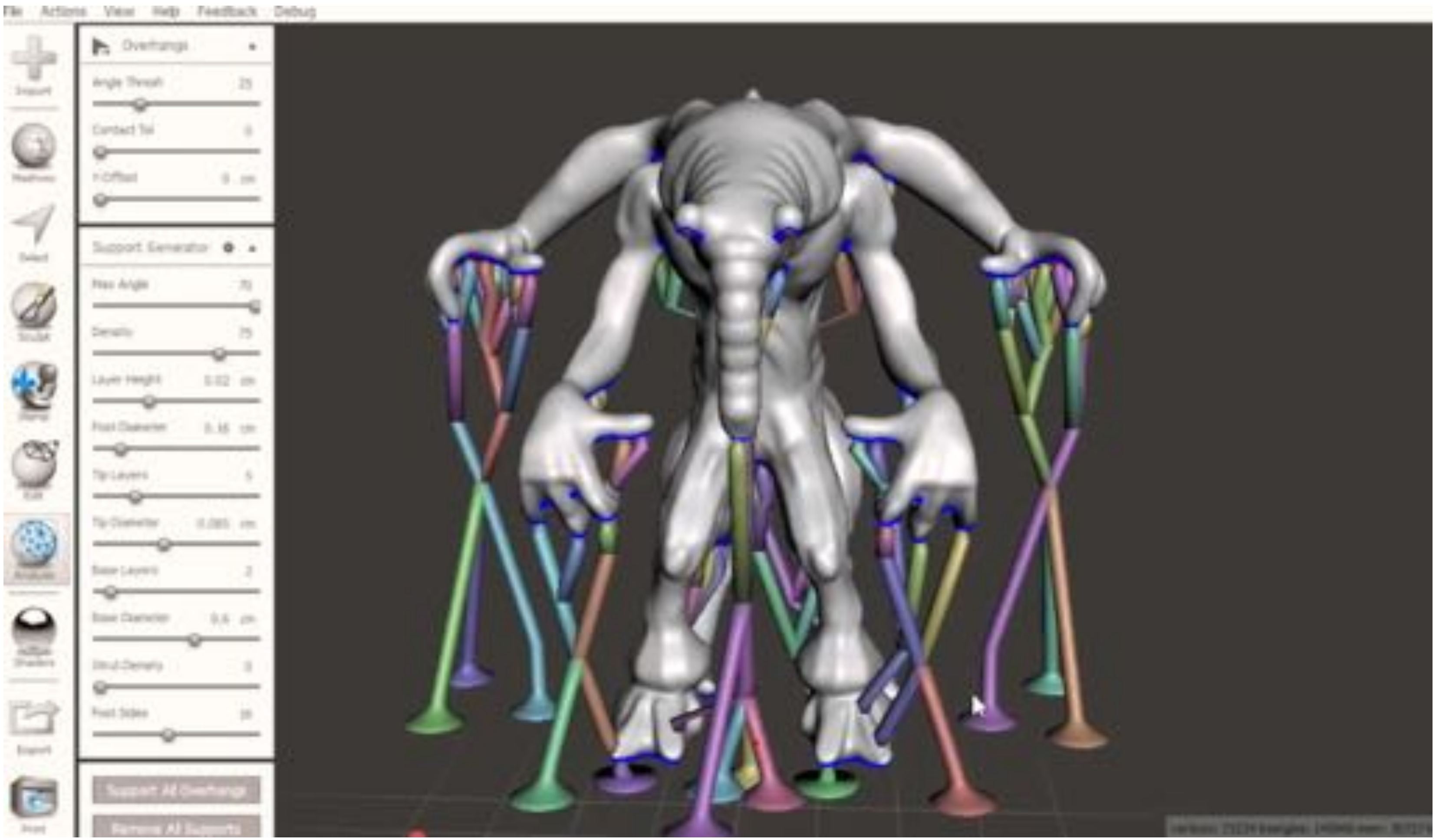
Support generation

- Support generation may depend on
  - objects orientation,
  - on the specific additive manufacturing technology



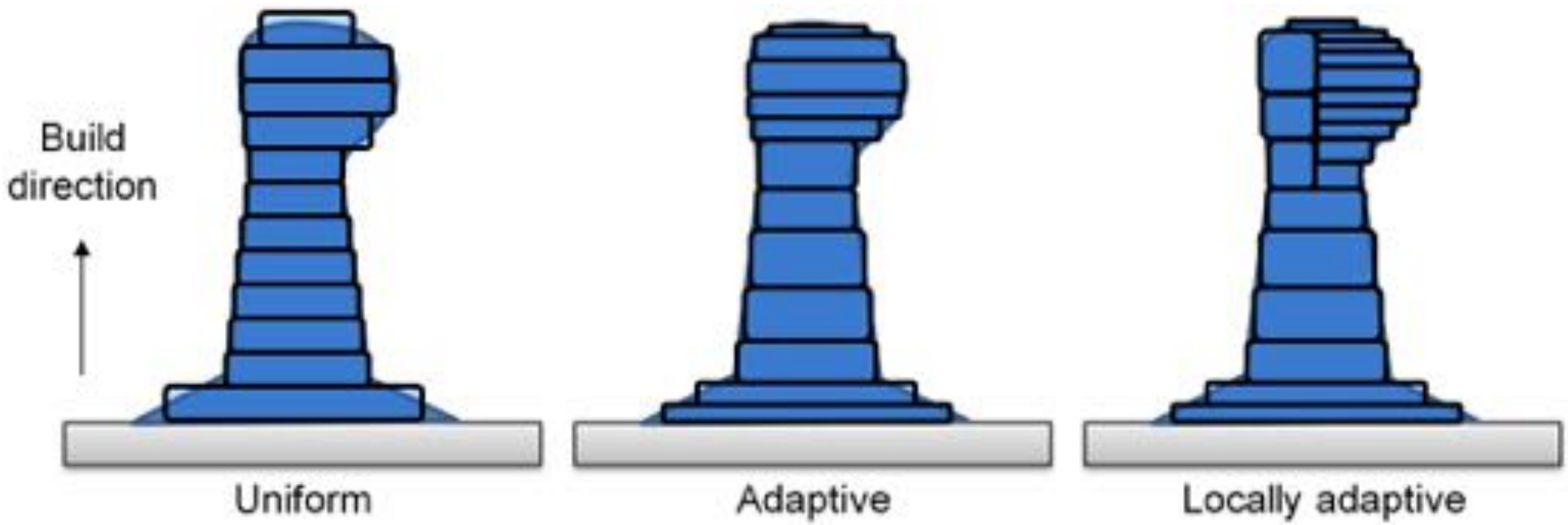
Stereolithography

Support design



www.meshmixer.com/

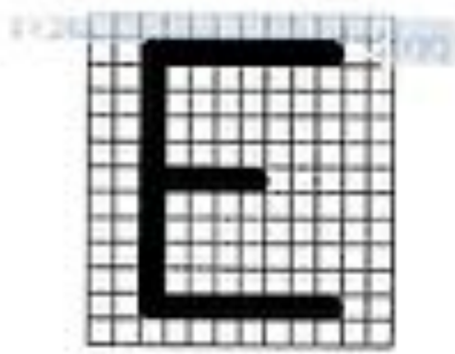
(non-)uniform slicing



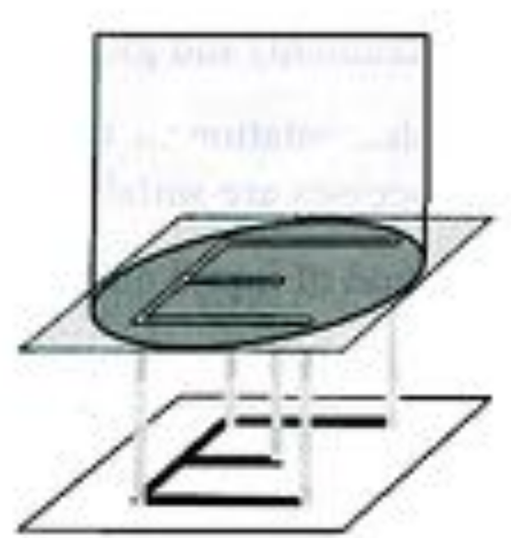
Slicing the model

- Patterning

Vector



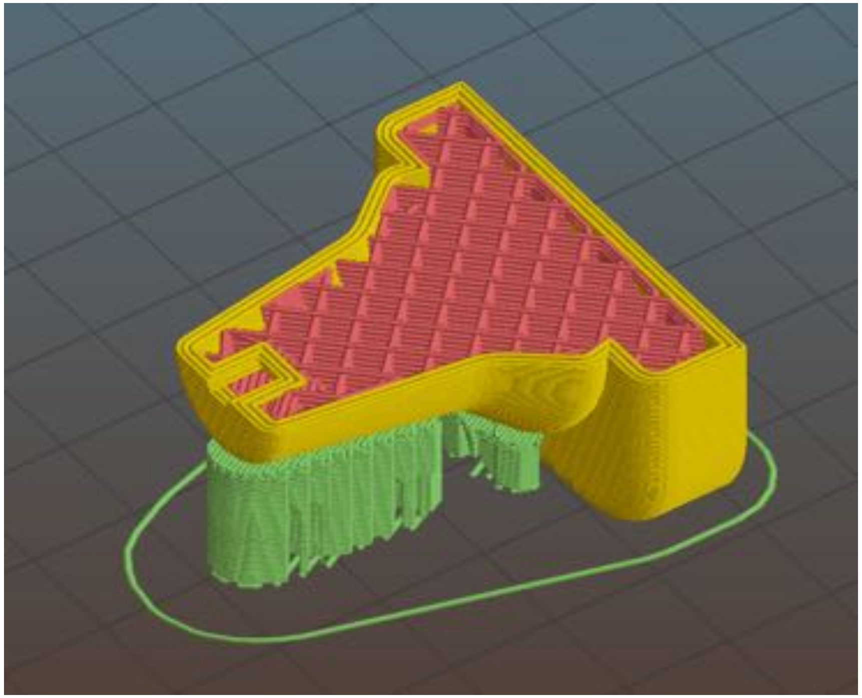
Raster

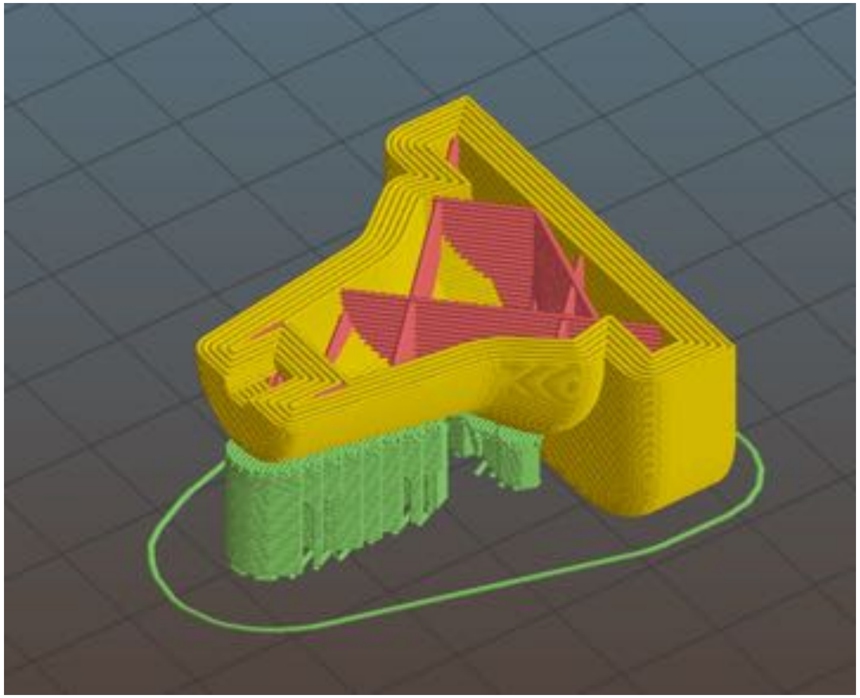


Projection

Slicing the model

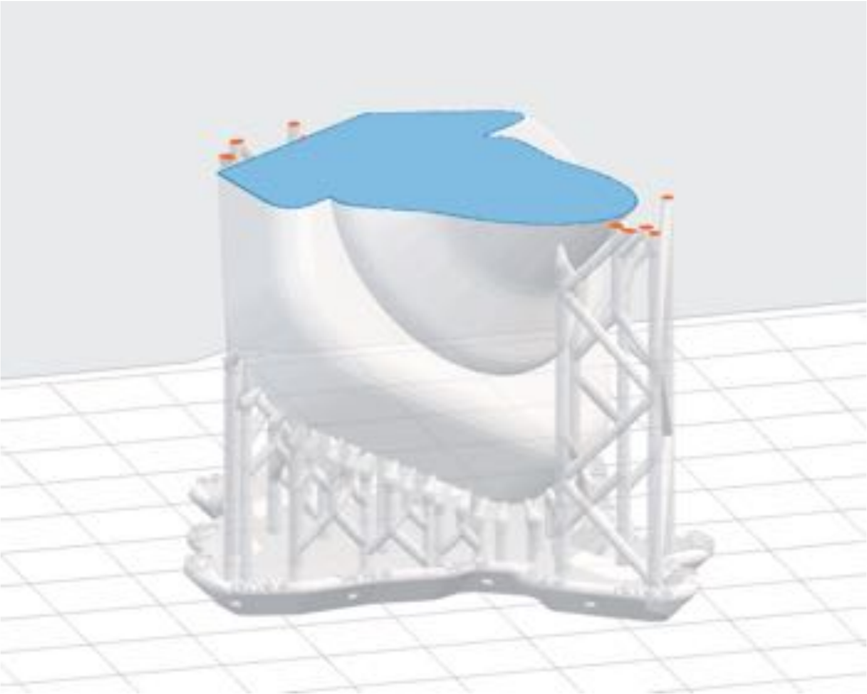
- Patterning and printing parameters

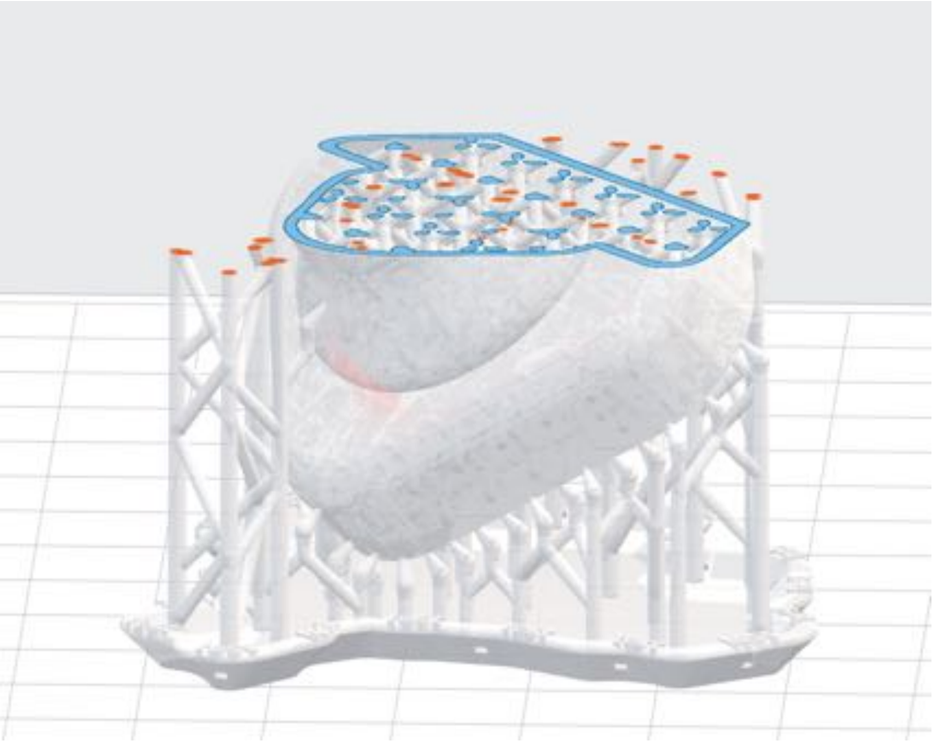




Slicing the model

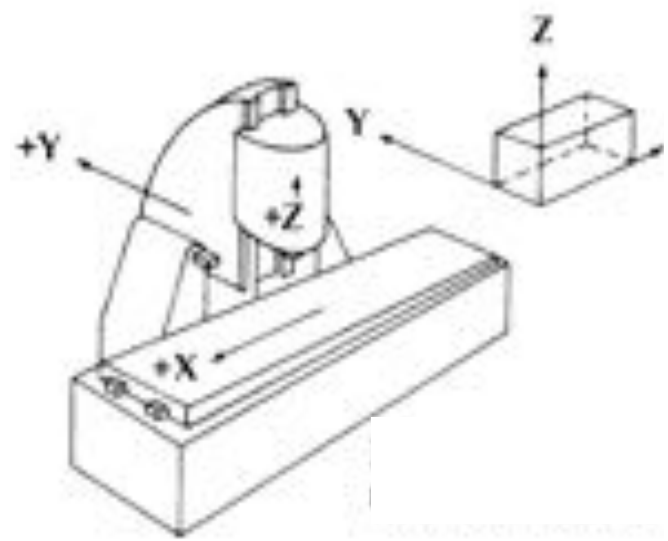
- Patterning and printing parameters



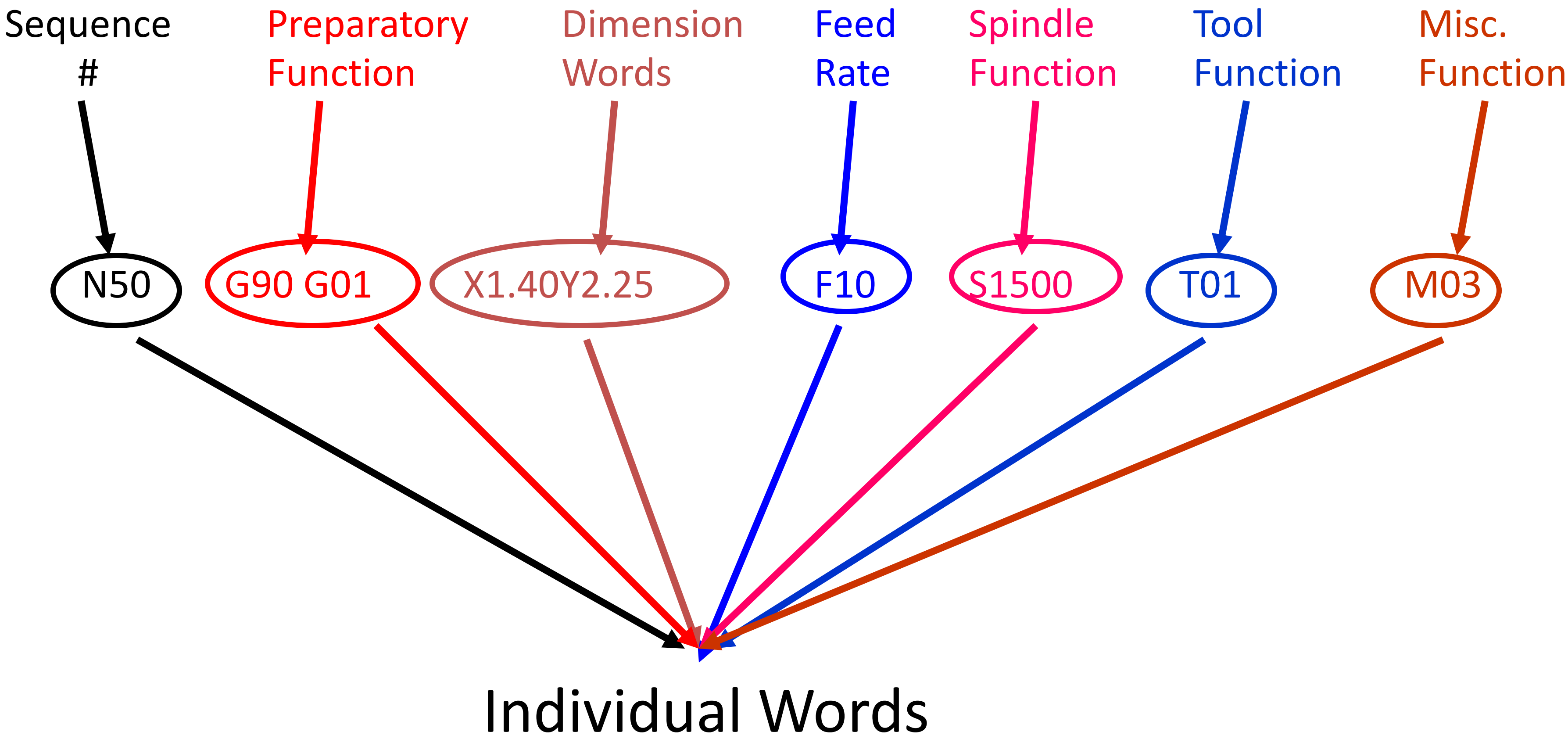


Vectorial pattern G-CODE generation

- G – Code Programming
- Originally called the "Word Address" programming format.
- Processed one line at a time sequentially.



Common Format of a Block



Word Address 1/3

- N – Sequence or line number
  - A tag that identifies the beginning of a block of code. N numbers are ignored by the controller during the program execution. It is used by operators to locate specific lines of a program when entering data or verifying the program operation.

- G – Preparatory function
  - G words specify the mode in which the milling machine is to move along its programmed axes. Preparatory functions are called prep functions or, more commonly **G codes**

Word Address 2/3

- Dimension Words
  - X – Distance or position in X direction
  - Y – Distance or position in Y direction
  - Z – Distance or position in Z direction

- M – Miscellaneous functions
  - M words specify CNC machine functions not related to dimensions or axial movements.

Word Address 3/3

- F – Feed rate (inches per minute or millimeters per minute)
  - Rate at which cutting tool moves along an axis.
- S – Spindle speed (rpm – revolutions per minute)
  - Controls spindle rotation speed.
- T – Tool number
  - Specifies tool to be selected.

G Word

- G words or codes tell the machine to perform certain functions. Most G words are modal which means they remain in effect until replaced by another modal G code.

Common G Codes

- G00 – Rapid positioning mode
  - Tool is moved along the shortest route to programmed X,Y,Z position. Usually NOT used for cutting.
- G01 – Linear Interpolation mode
  - Tool is moved along a straight-line path at programmed rate of speed.

- G02 – Circular motion clockwise (cw)
- G03 – Circular motion counter clockwise (ccw)

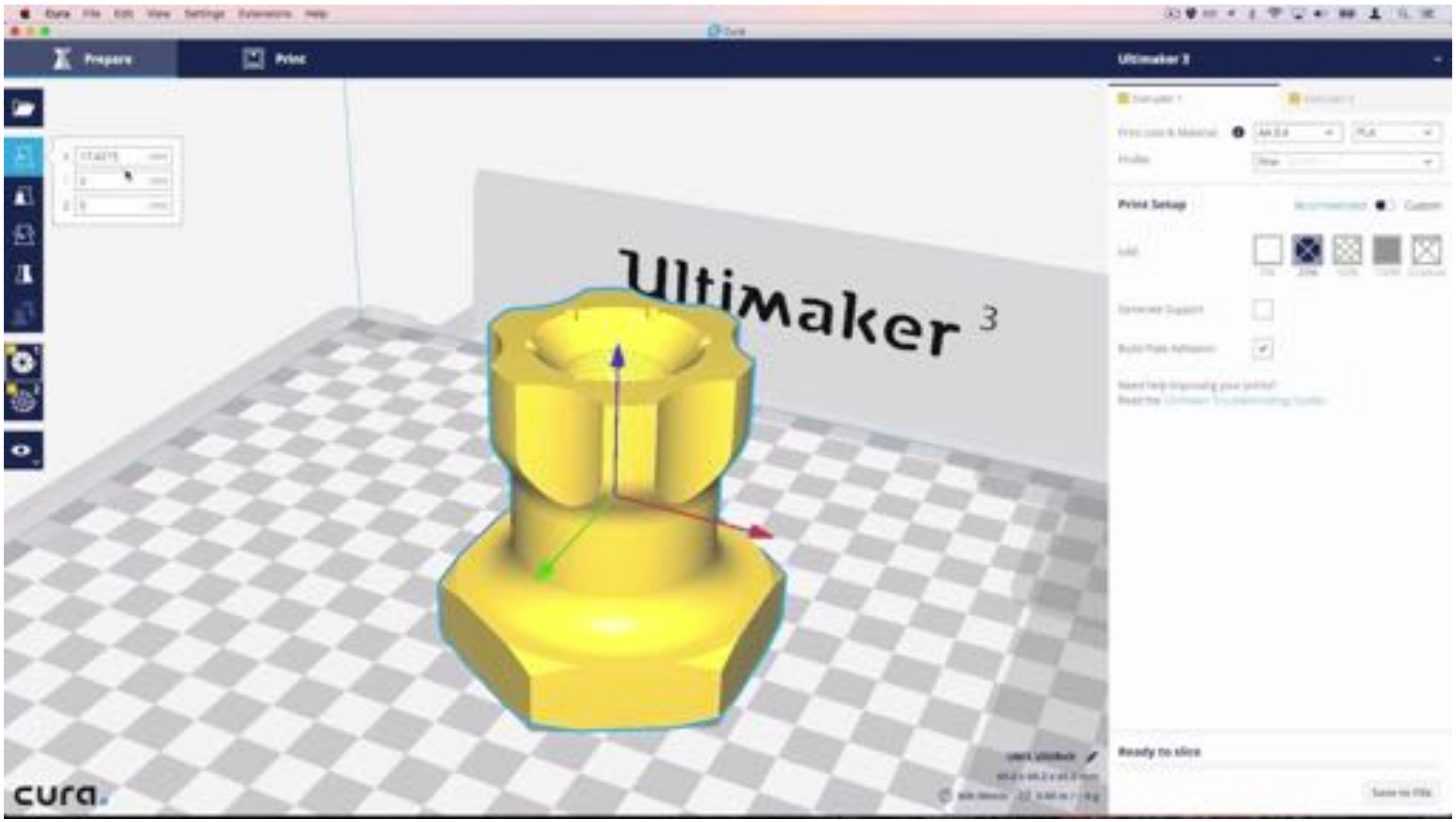
M Word

- M words tell the machine to perform certain machine related functions, such as: turn spindle on/off, coolant on/off, or stop/end program.

G-Code example

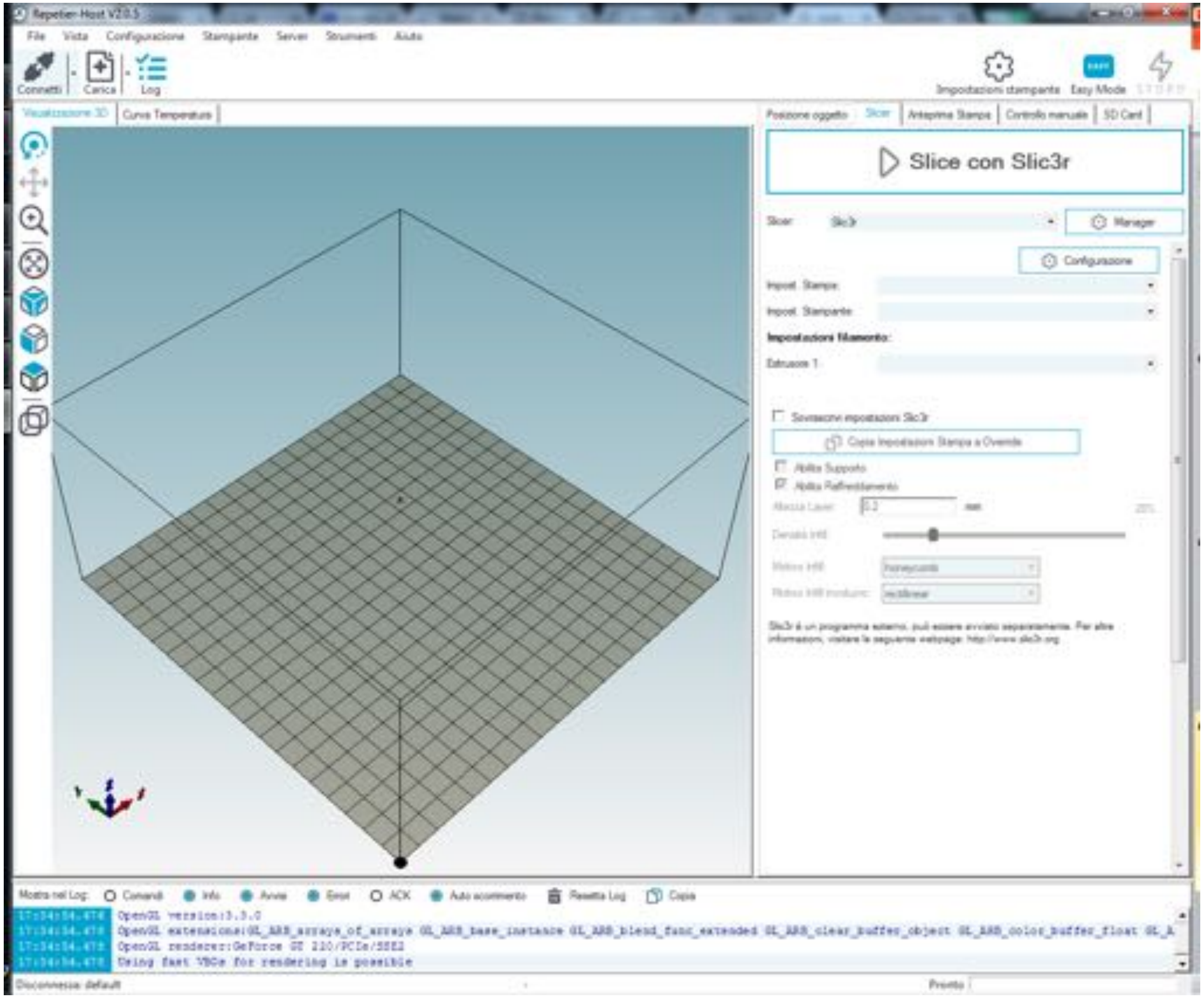
```
;Generated with Cura_SteamEngine 13.11.2
M109 T0 S227.000000
T0
;Sliced ?filename? at: Tue 26-11-2013 17:33:05
;Basic settings: Layer height: 0.2 Walls: 0.8 Fill: 20
;Print time: #P_TIME#
;Filament used: #F_AMNT#m #F_WGHT#g
;Filament cost: #F_COST#
G21        ;metric values
G90        ;absolute positioning
M107       ;start with the fan off
G28 X0 Y0  ;move X/Y to min endstops
G28 Z0     ;move Z to min endstops
G1 Z15.0 F?max_z_speed? ;move the platform down 15mm
G92 E0                  ;zero the extruded length
G1 F200 E3              ;extrude 3mm of feed stock
G92 E0                  ;zero the extruded length again
G1 F9000
M117 Printing...

;Layer count: 179
;LAYER:0
M107
G0 F3600 X87.90 Y78.23 Z0.30
;TYPE:SKIRT
G1 F2400 E0.00000
G1 F1200 X88.75 Y77.39 E0.02183
G1 X89.28 Y77.04 E0.03342
G1 X90.12 Y76.69 E0.05004
G1 X90.43 Y76.63 E0.05591
G1 X91.06 Y76.37 E0.06834
...
```

+ # Cura



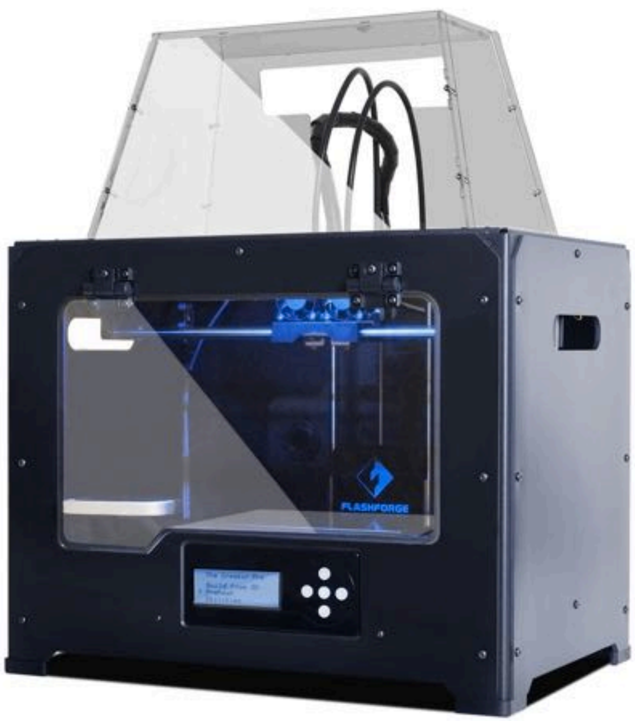
https://ultimaker.com/en/products/ultimaker-cura-software/list

Repetier Host



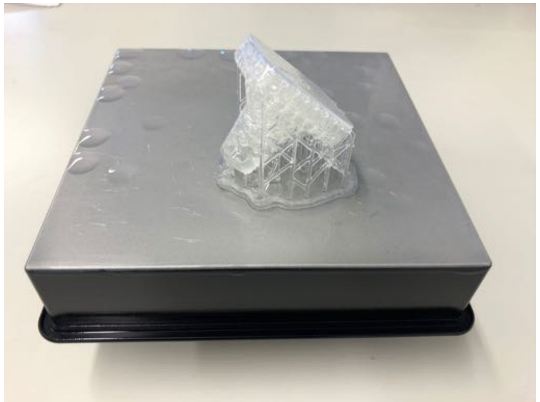
https://www.repetier.com/download-now/

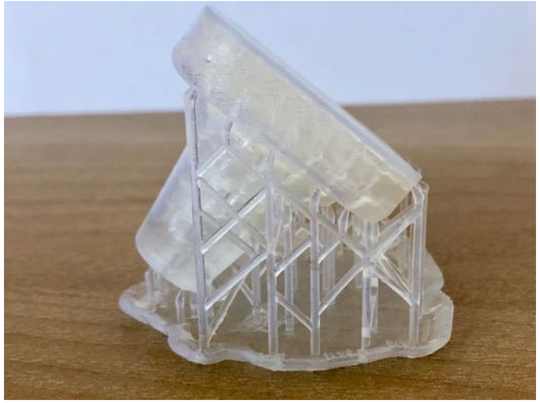
Model physical buildup



Cleanup and post curing Surface finishing

- Stereolithography





- Fused Deposition modelling