Centro E. Piaggio
bioengineering and robotics research center

IN SUPREMÆ DIGNITATIS • 1343 •

Additive manufacturing

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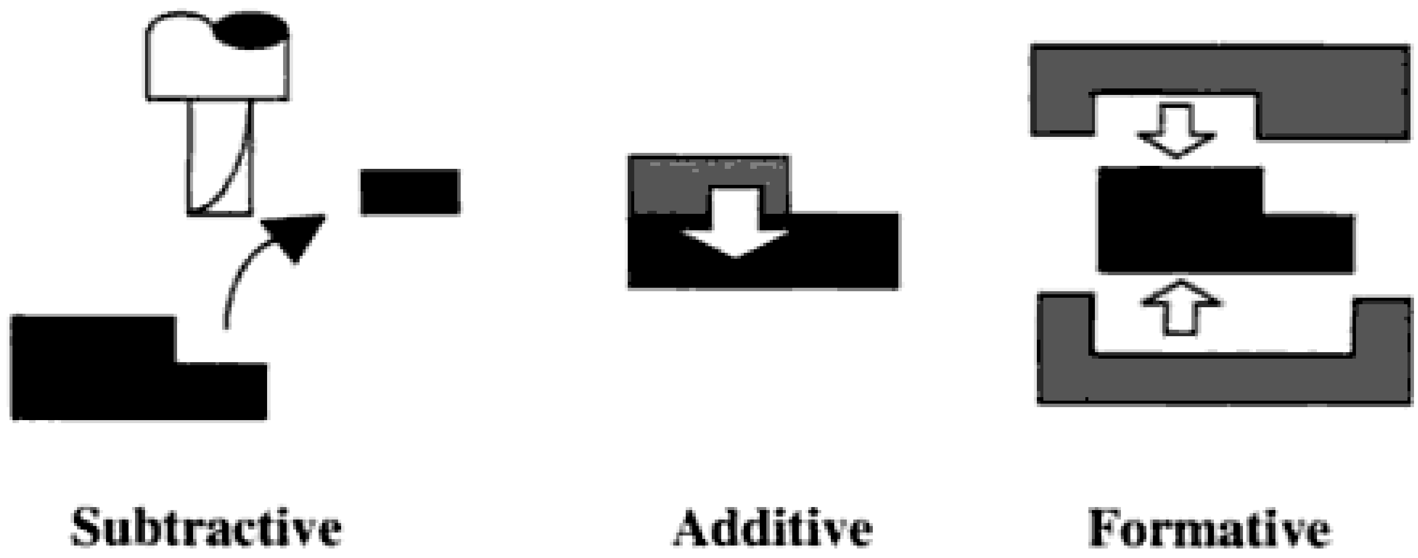
Building 3D object



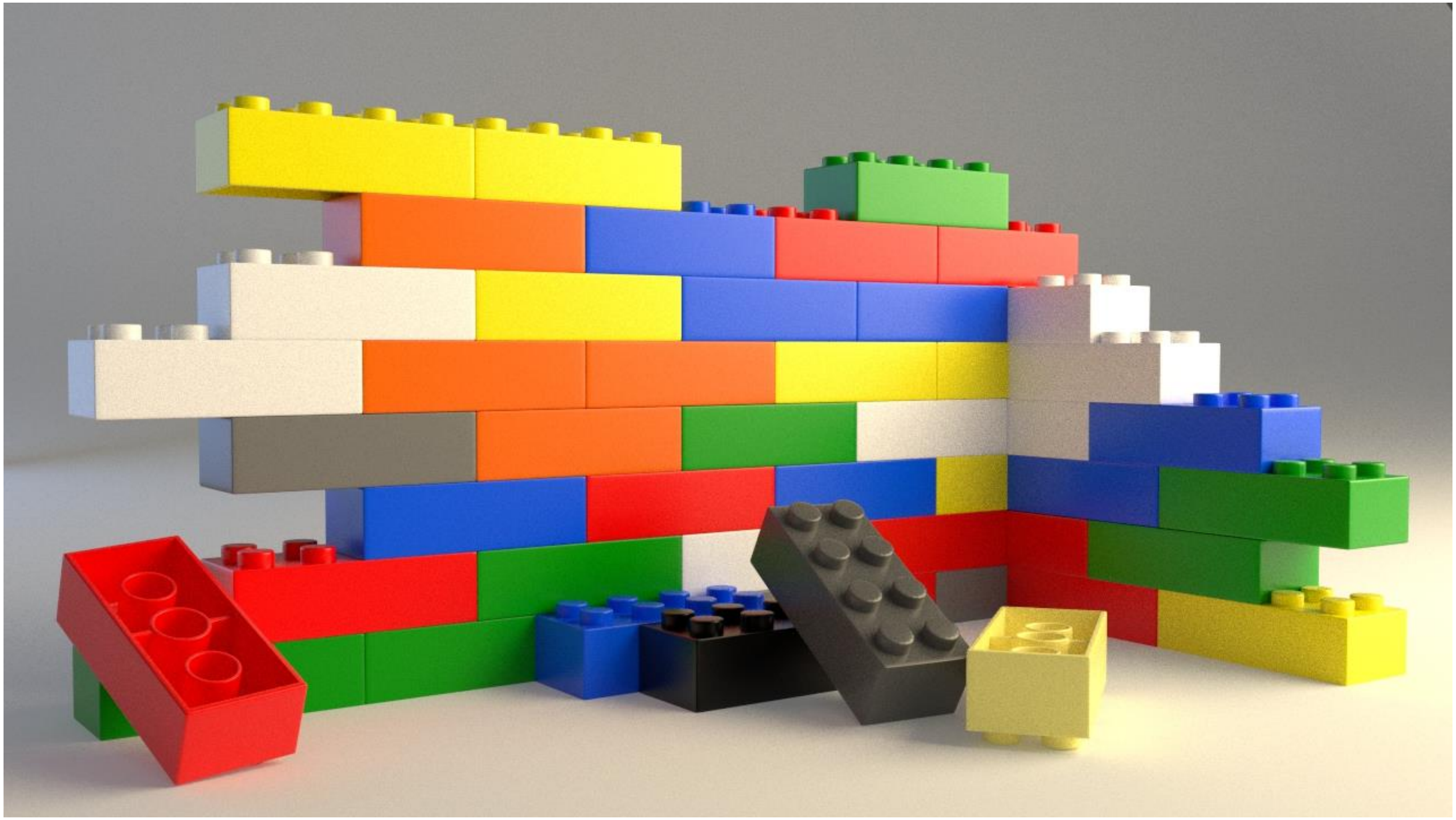
Building 3D object: subtractive

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

Building 3D object: formative

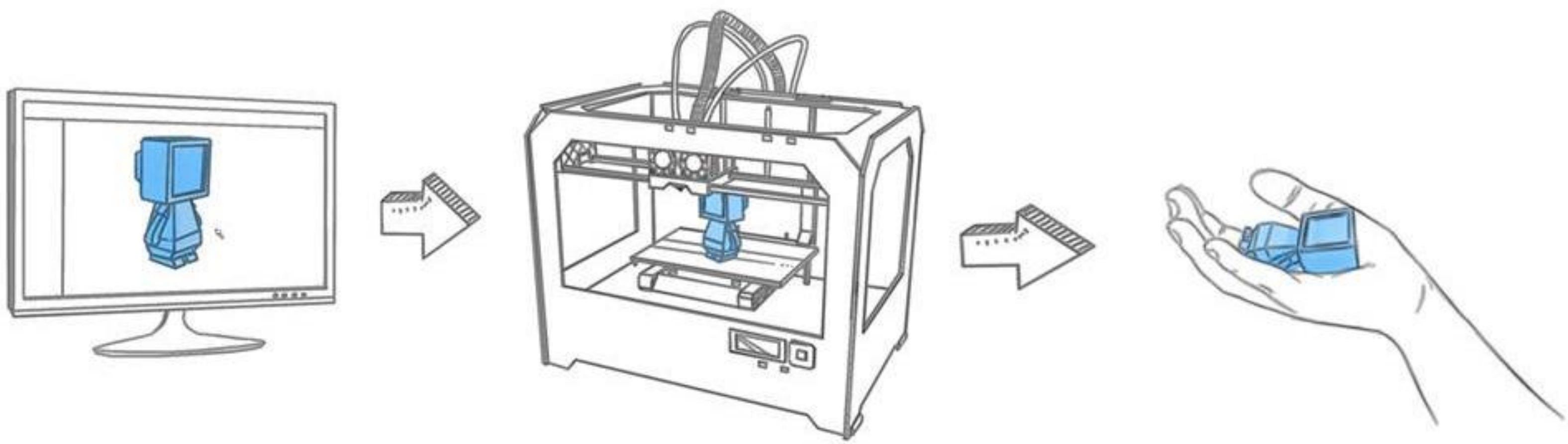
- Bending
- Forging
- Electromagnetic forming
- Plastic injection molding
- …

Building 3D object: additive



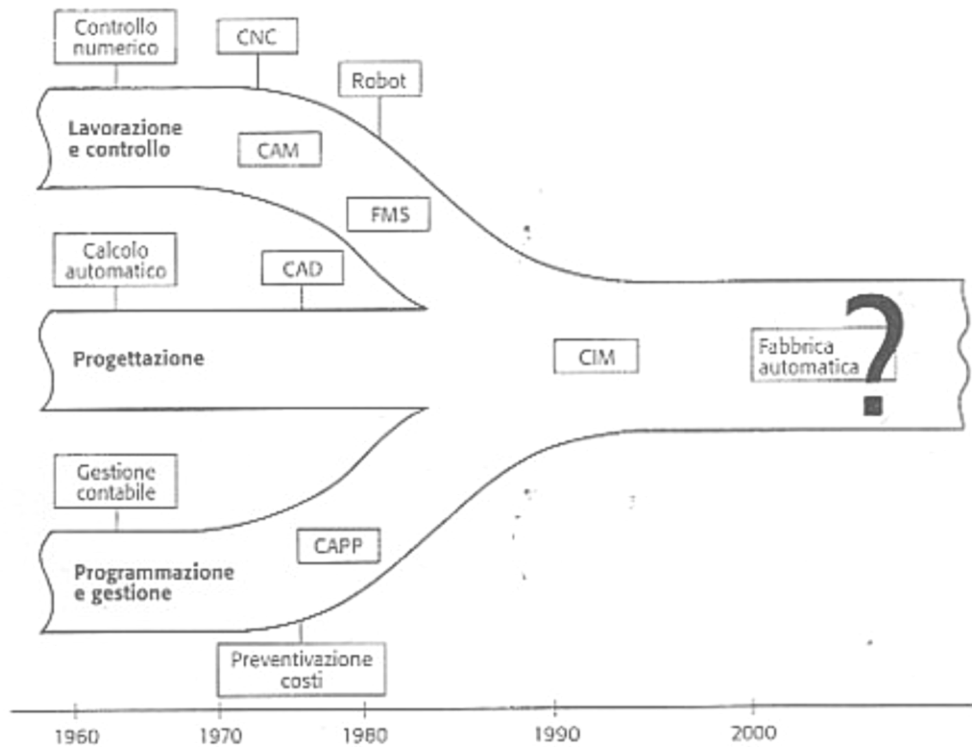
Additive manufacturing

- 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)

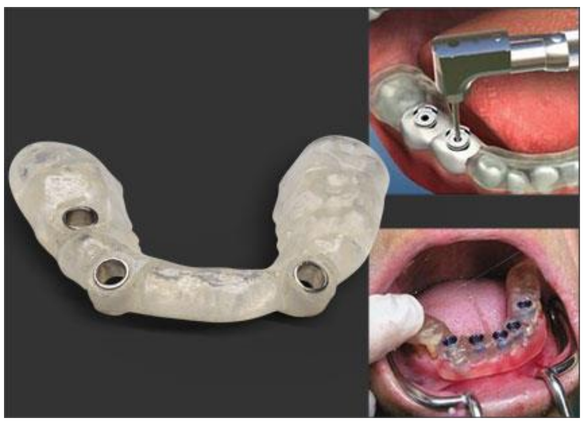
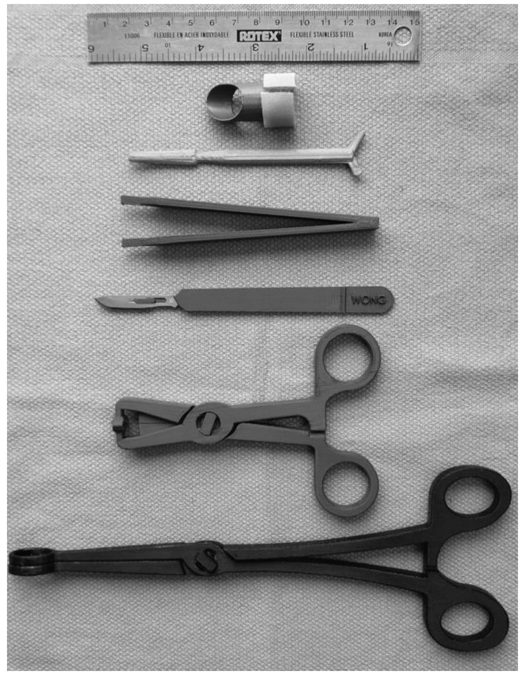
- CAD – Design
- CAE – Engineering
- CAM – Manufacturing
- CAPP – Process Planning
- CIM – Computer Integrated Manufacturing

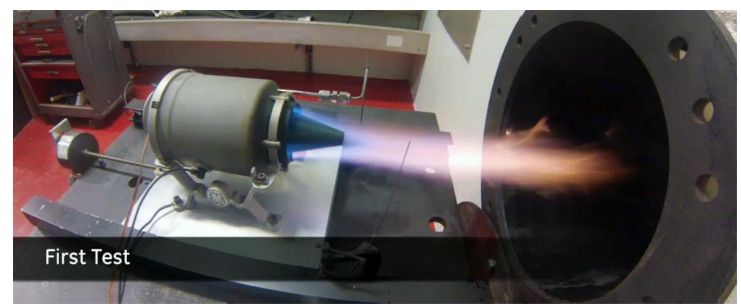


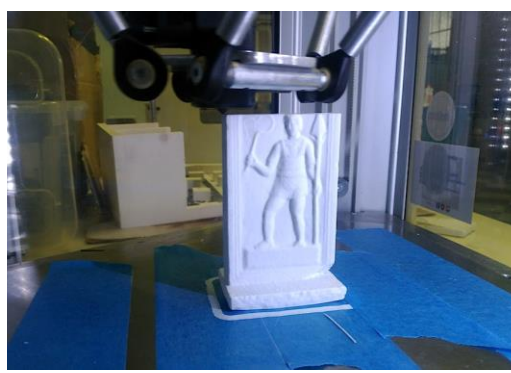
Additive manufacturing using…

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

Additive manufacturing what?

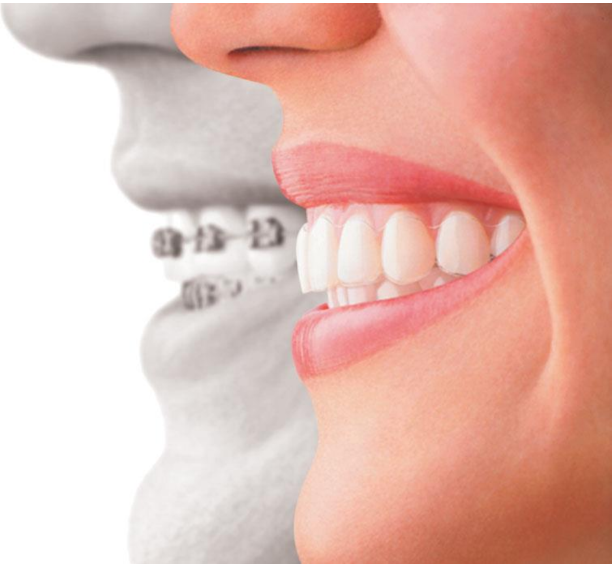







Invisalign Orthodontic Aligners

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



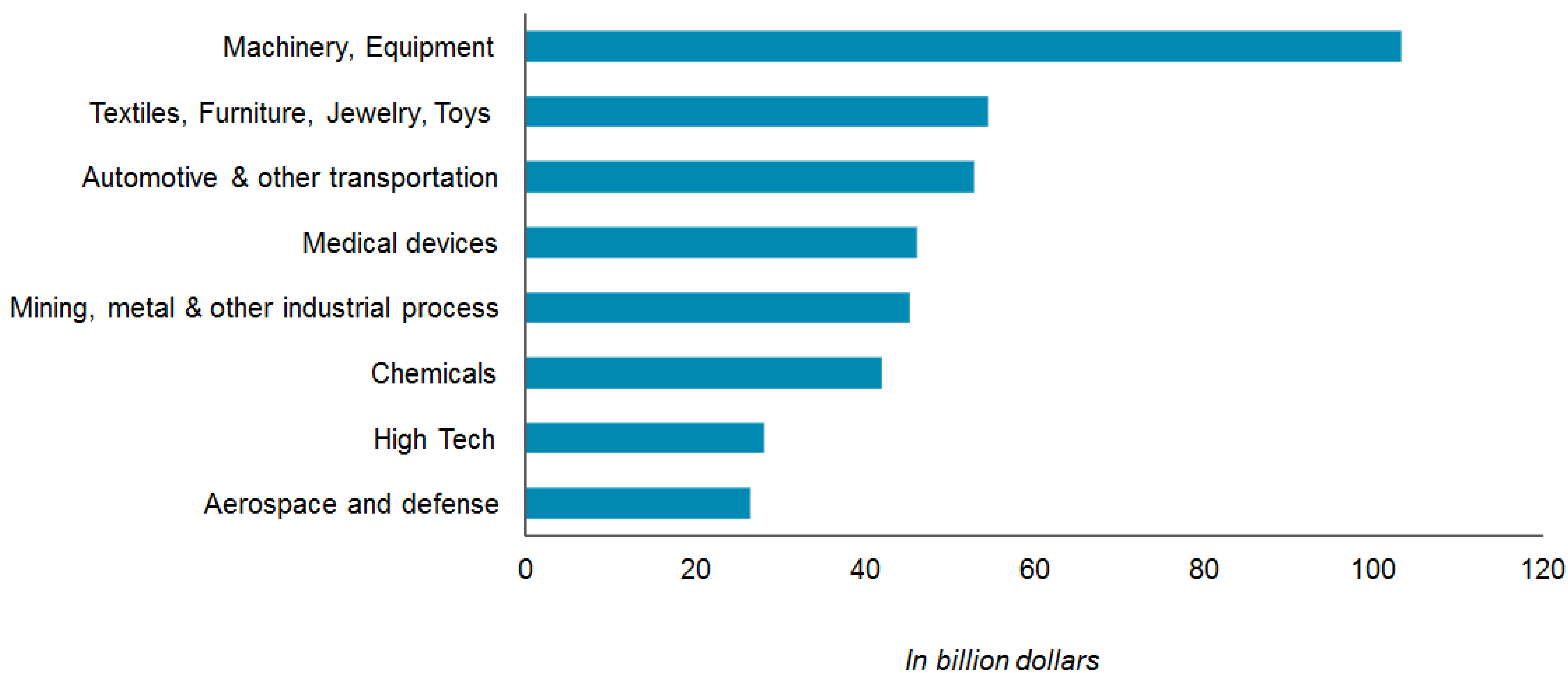
4D printing

- https://vimeo.com/58840897

Additive manufacturing by Industry Sectors

Manufacturing sub-sectors impacted by 3D printing - 2030
Global – forecast 2030

Total: $400 billion

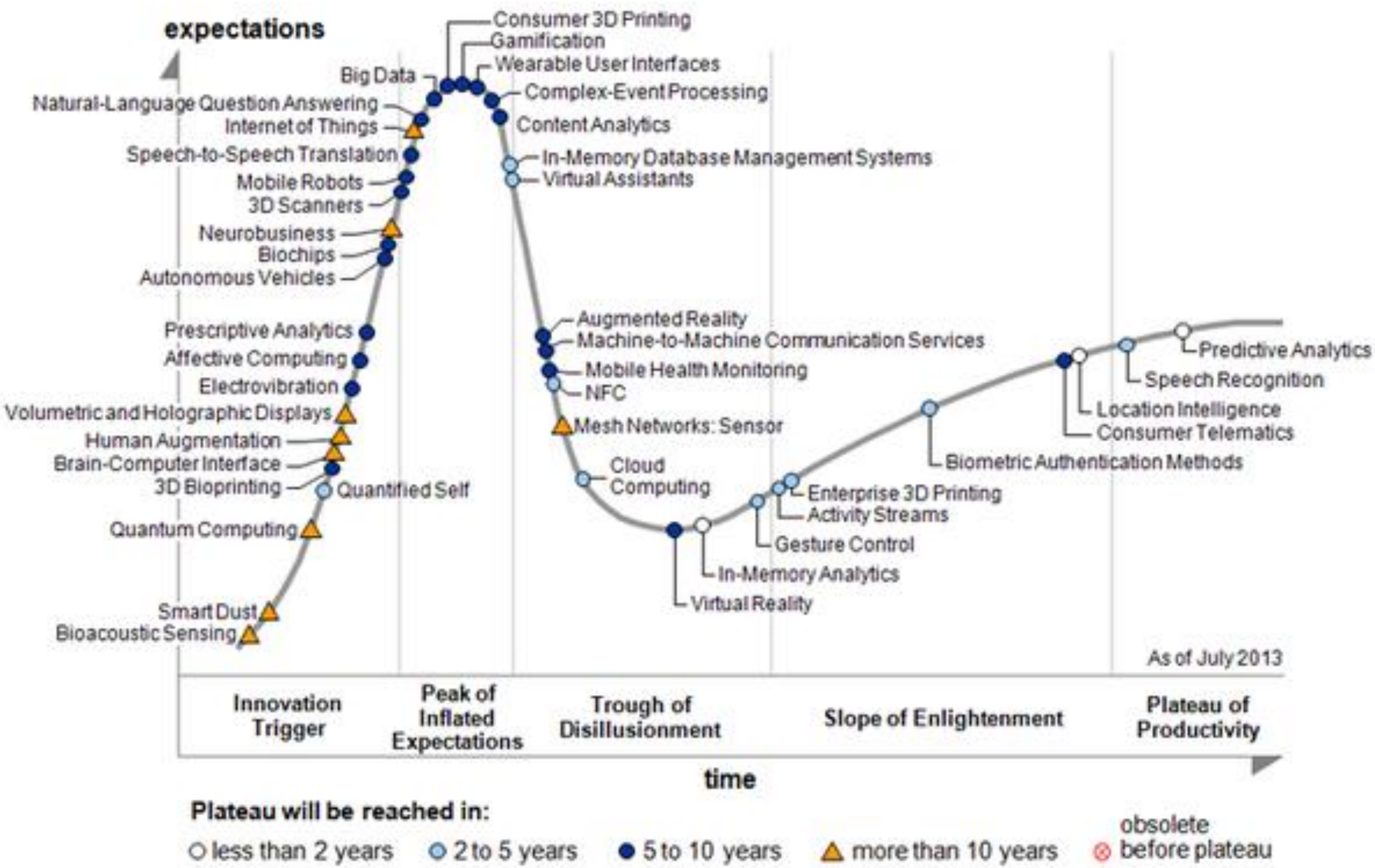


Source: Oliver Wyman modelization & analysis

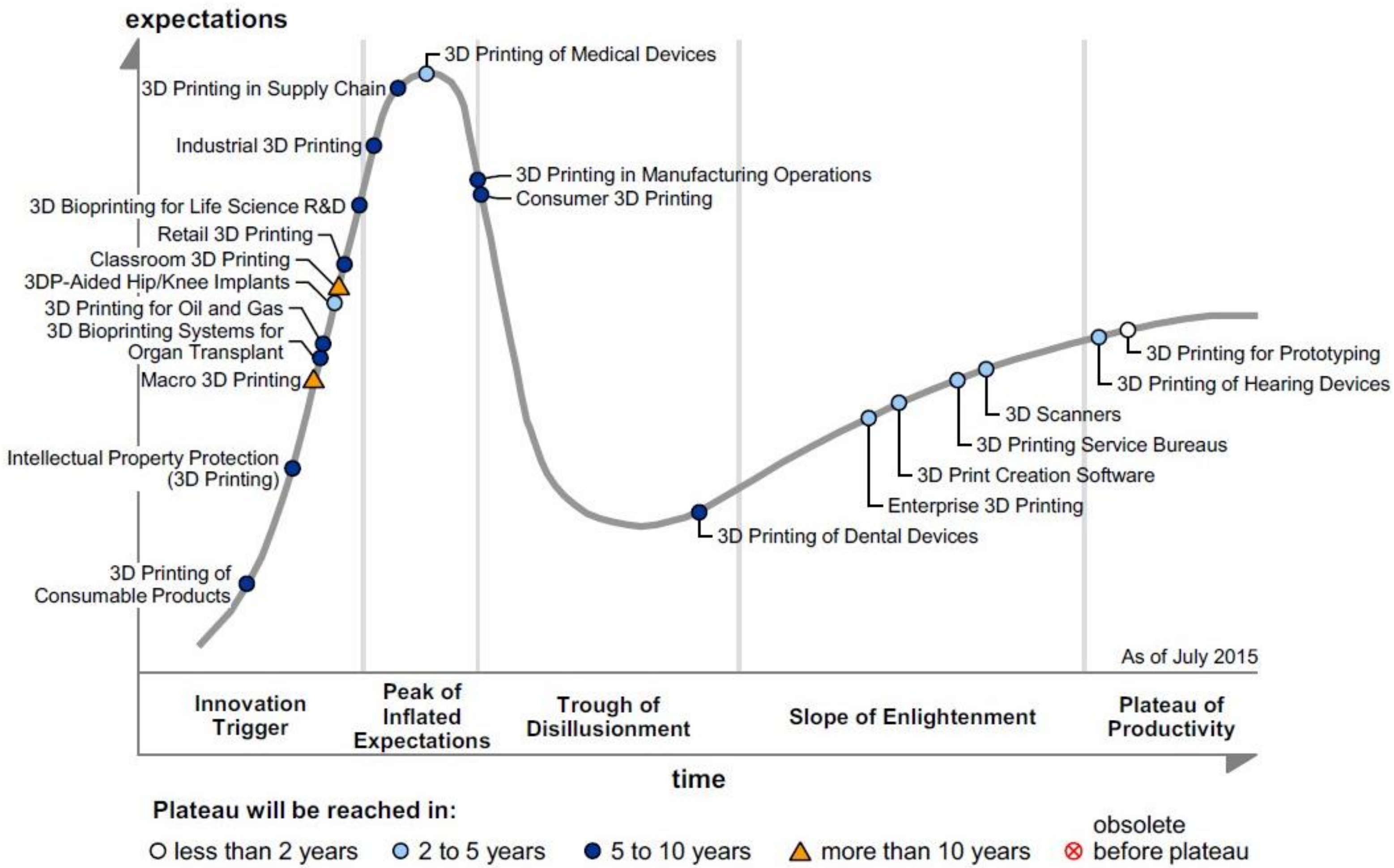
So, why additive manufacturing?

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

Hype cycle 2013

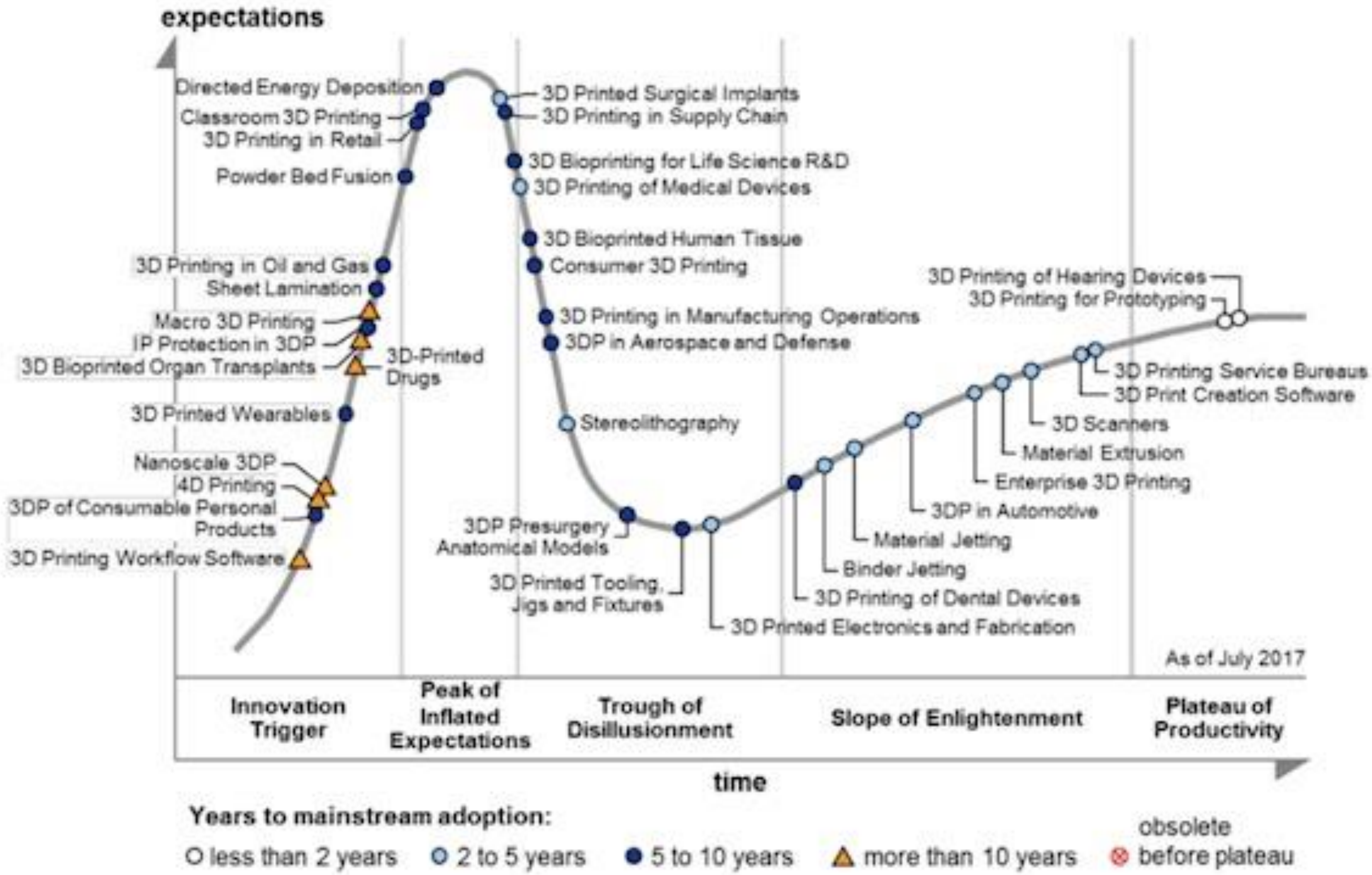


Hype cycle 2015

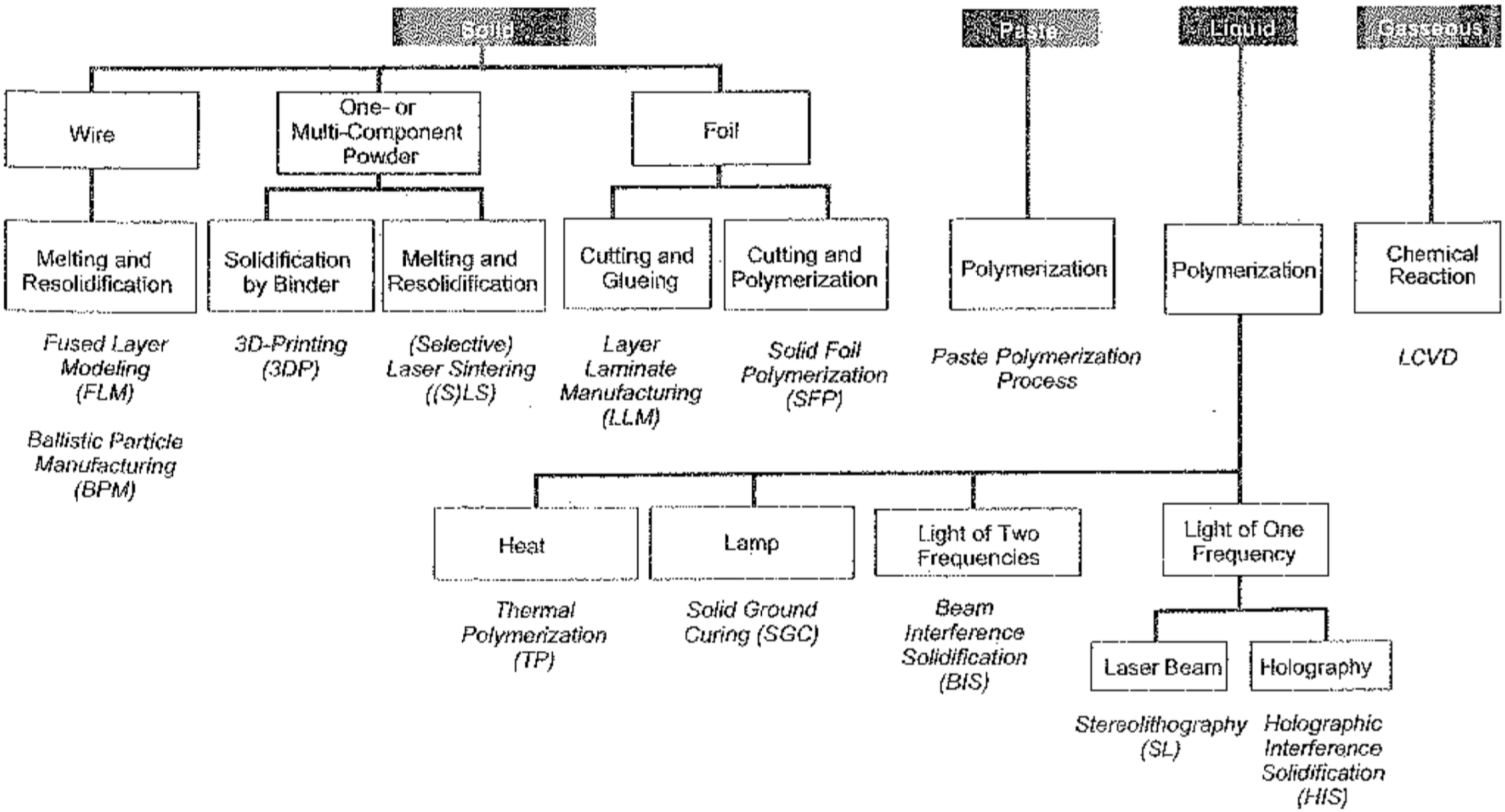


Source: Gartner (July 2015)

Hype cycle 2017



A possible classification



ASTM/ISO 52900 classification

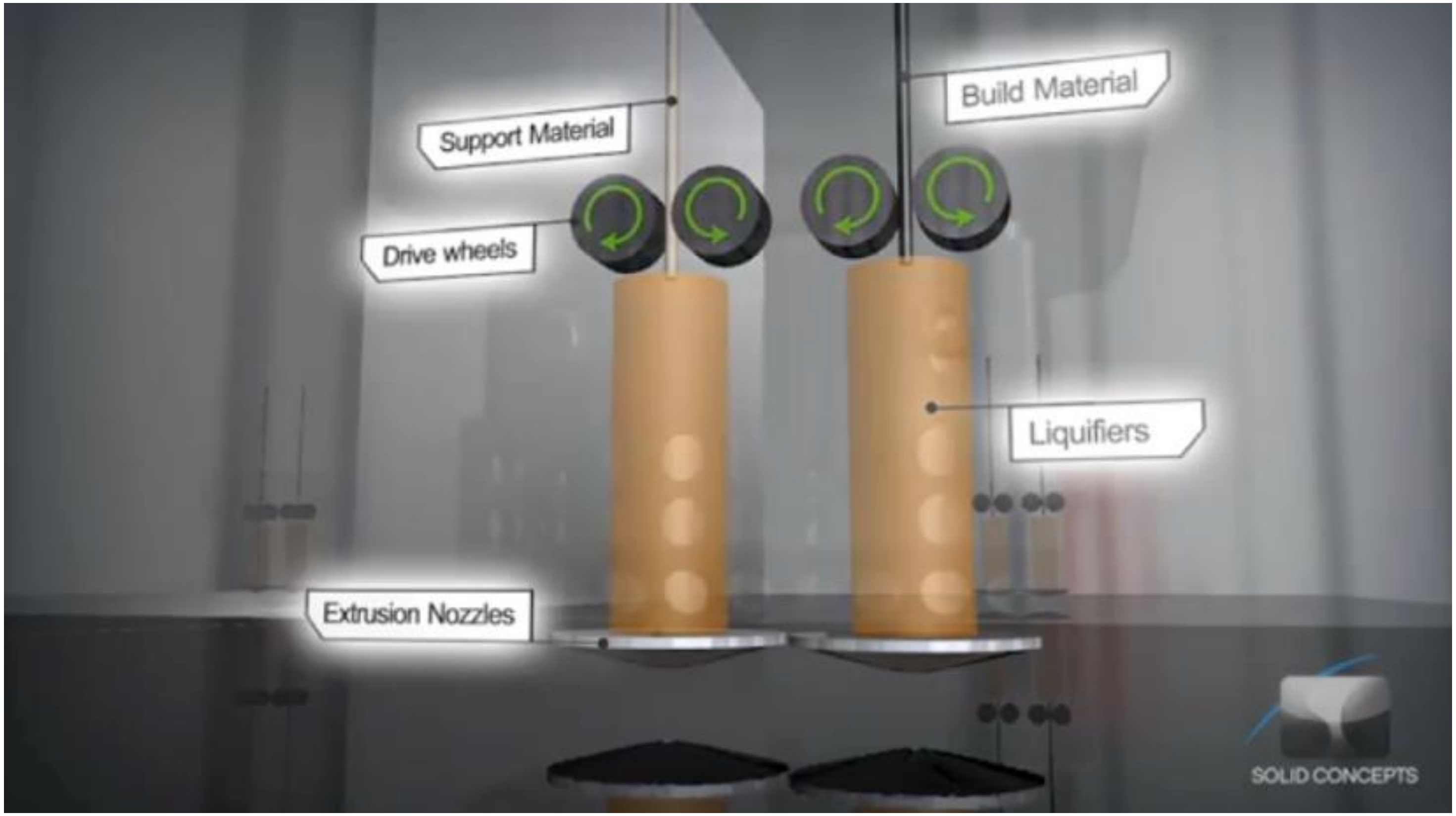
- **Binder jetting**: AM process in which a liquid bonding agent is selectively deposited to join powder materials;
- **Directed energy deposition:** AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited;
  - Note: “Focused thermal energy” means that 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://ubora-kahawa.azurewebsites.net/resources/49a844d5-ed82-4820-8d10-5d921d6926b1

Material extrusion

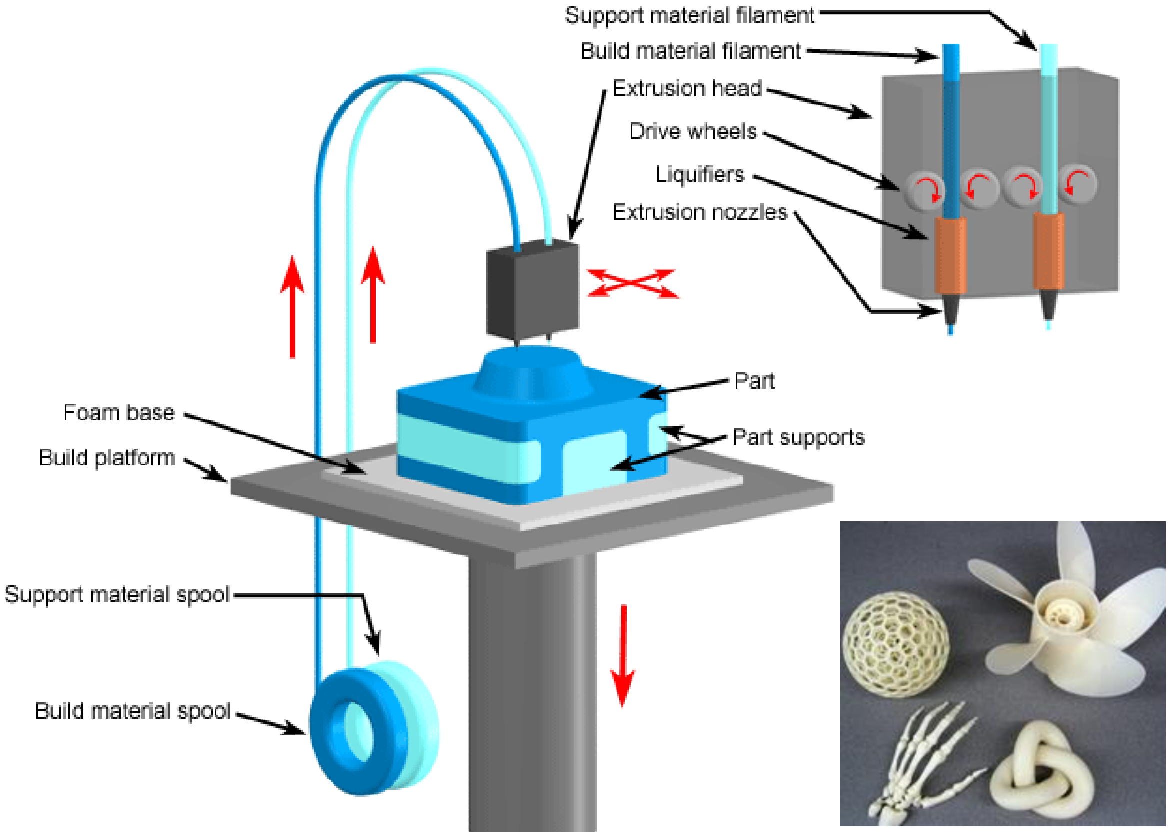
Fused deposition modelling

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



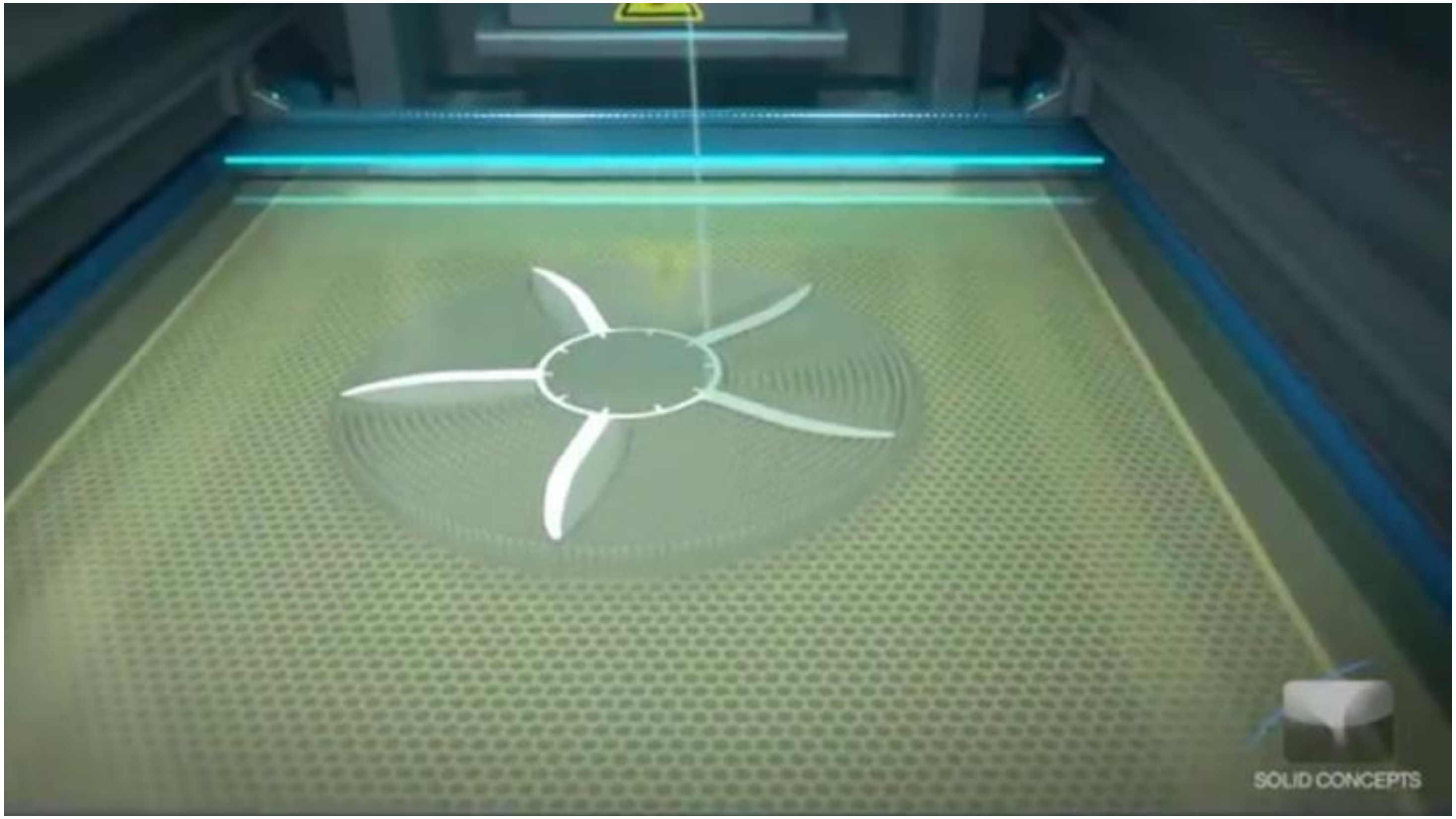
Fused deposition modelling

- “Standard” materials:
  - Poly-Lactic-Acid (PLA) (soft and hard)
  - Acrylonitril-Butadiene-Stiren (ABS)
  - Polycarbonate (PC)
- “Experimental” materials:
  - Nylon
  - Poly vinyl alcohol (PVA)
  - Conductive (carbon and graphen loaded materials)
  - Metallic loaded plastic



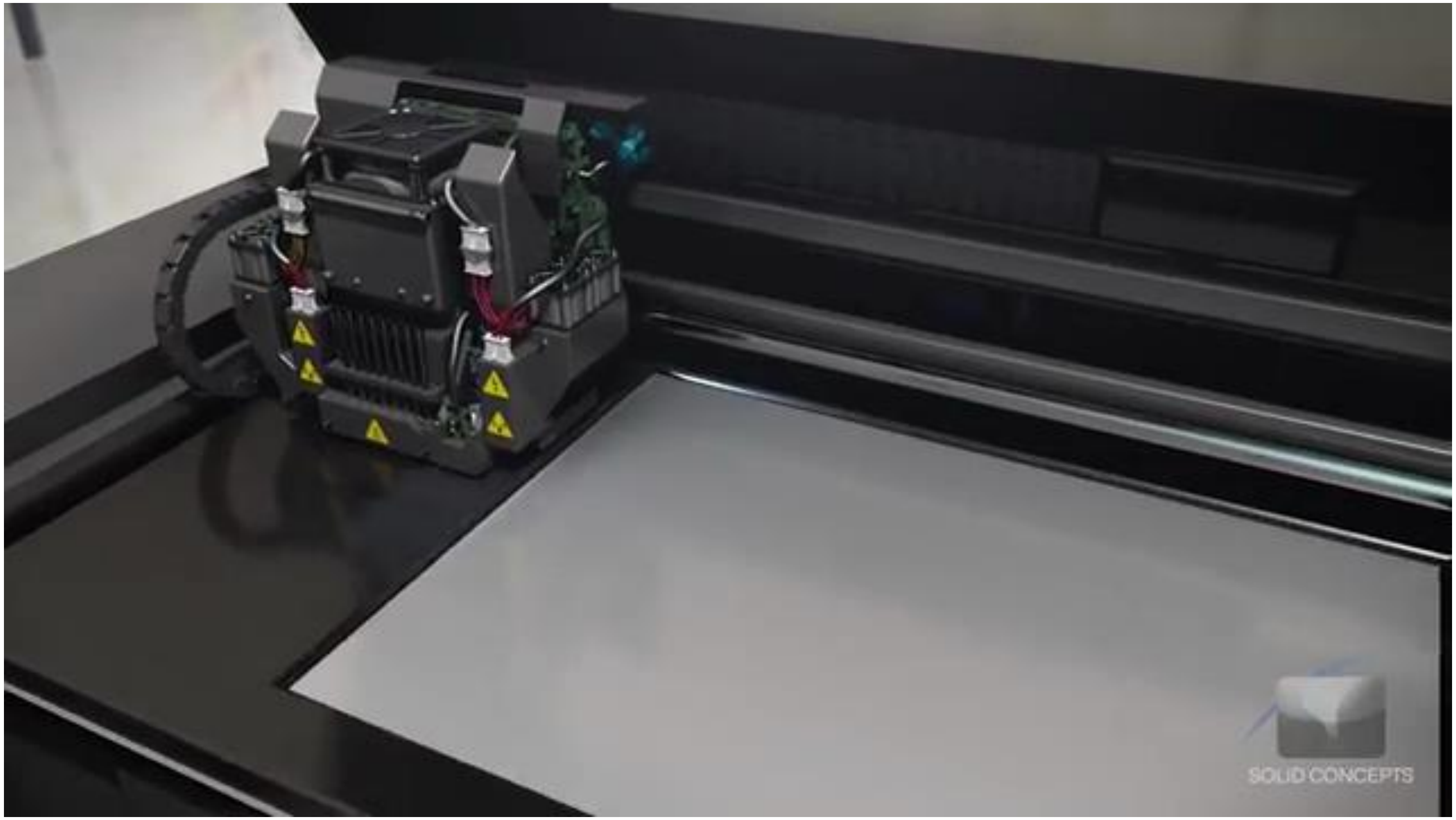
Vat Photopolimerization

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



Material Jetting

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



Powder bed fusion

Laser Sintering

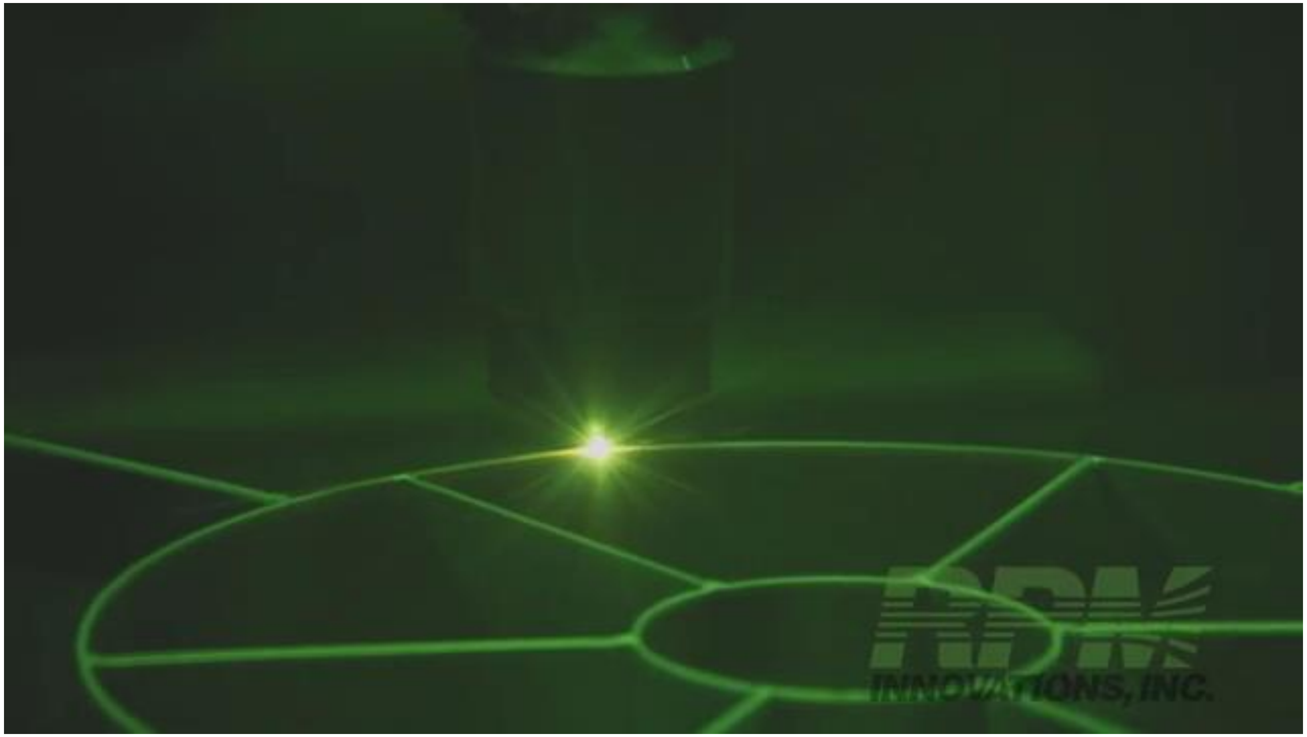
https://www.youtube.com/watch?v=bgQvqVq-SQU

Laser sintering

- Polymers
  - nylon, ABS, PVC,
    and polystyrene,
  - 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
- Green sand (for sand casting).

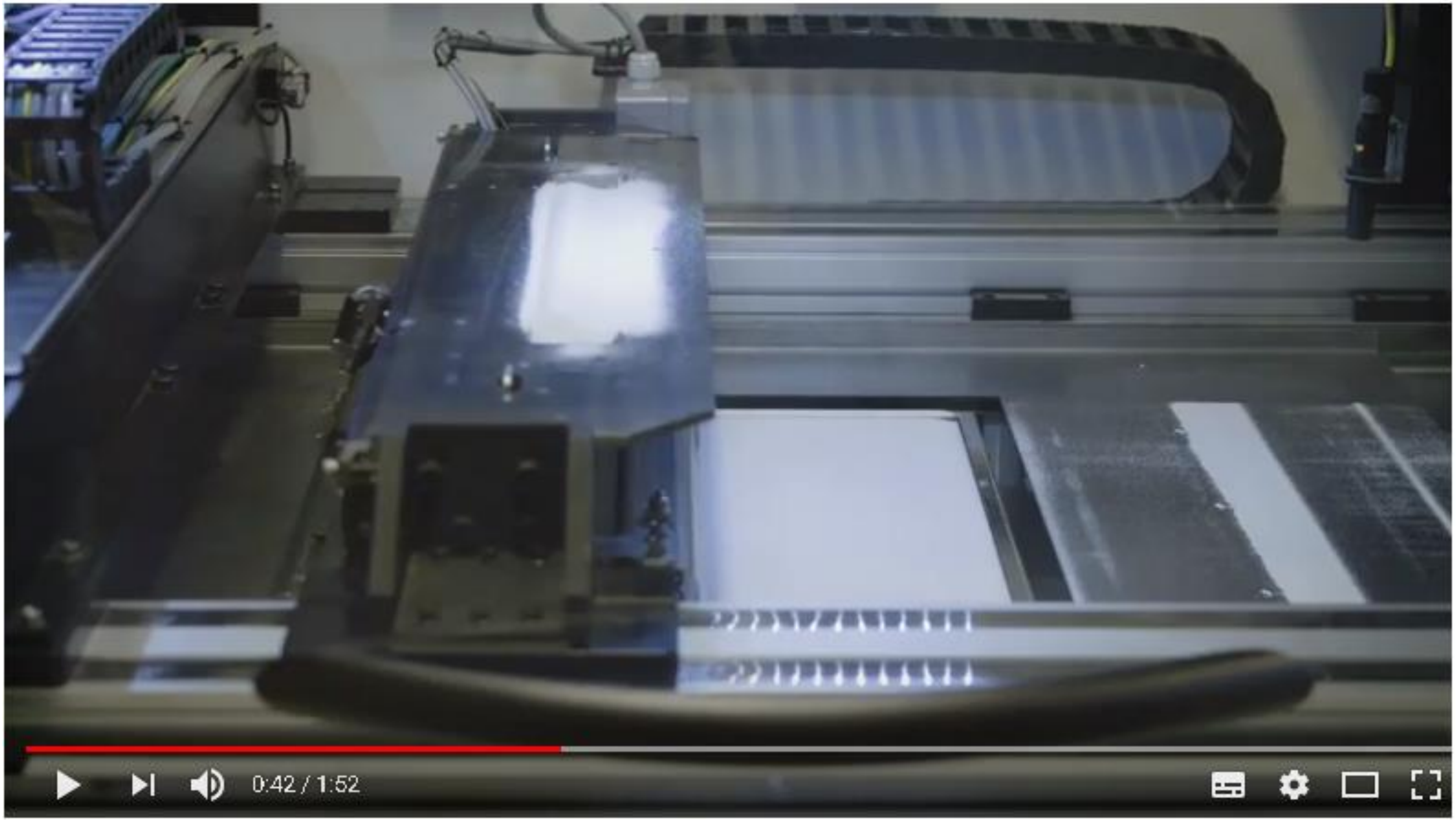
Directed energy deposition

- 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								

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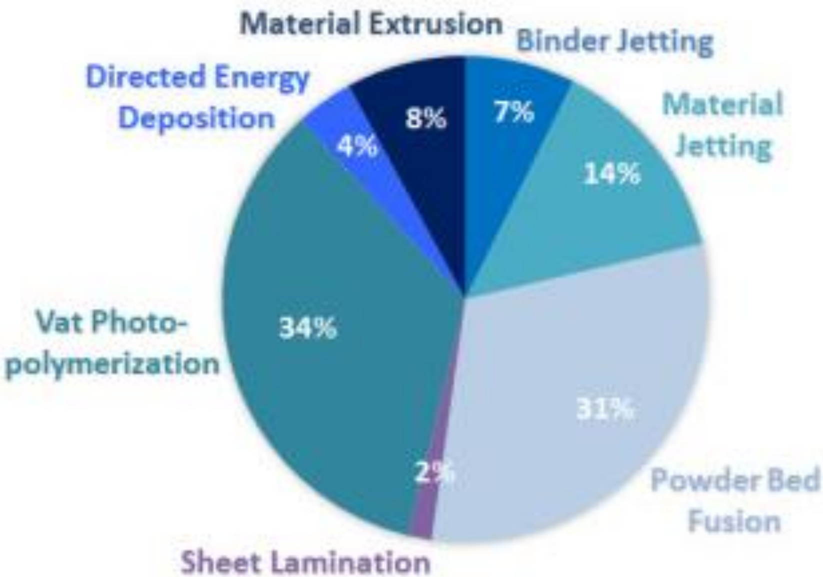
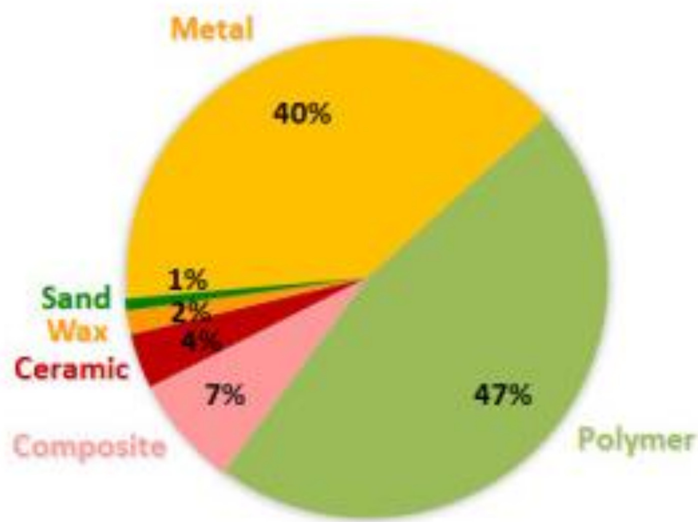
Additive Manufacturing Machines by Process

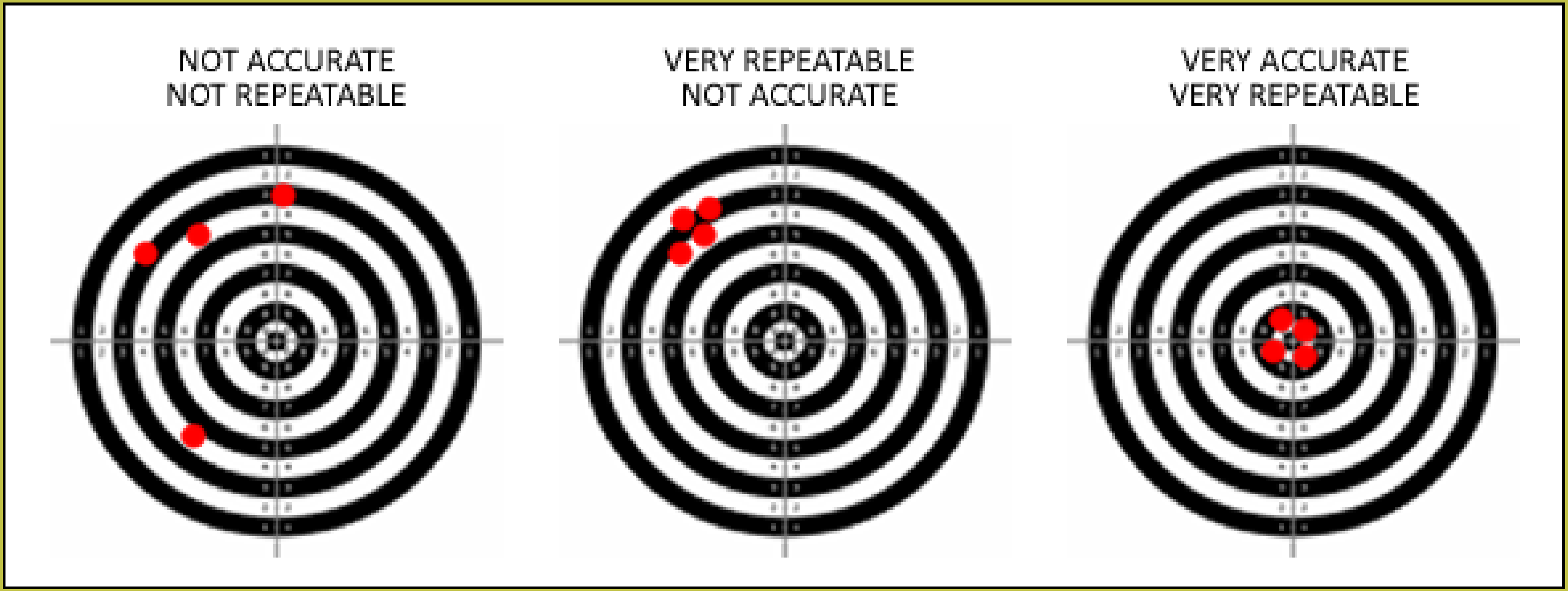


Additive Manufacturing Materials by Material Type



GENERAL CONSIDERATION ON ADDITIVE MANUFACTURING TECHNOLOGIES

Accuracy-repeatability-resolution



ACCURACY
Degree of comformity of a measurement to a standard or known value

REPEATABILITY
The closeness of aggreement amoung a number of consecutive measurements

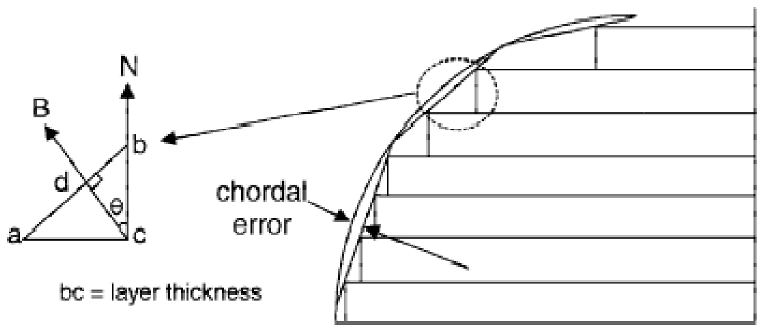
RESOLUTION
The smallest degree of movement that a scale can detect

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

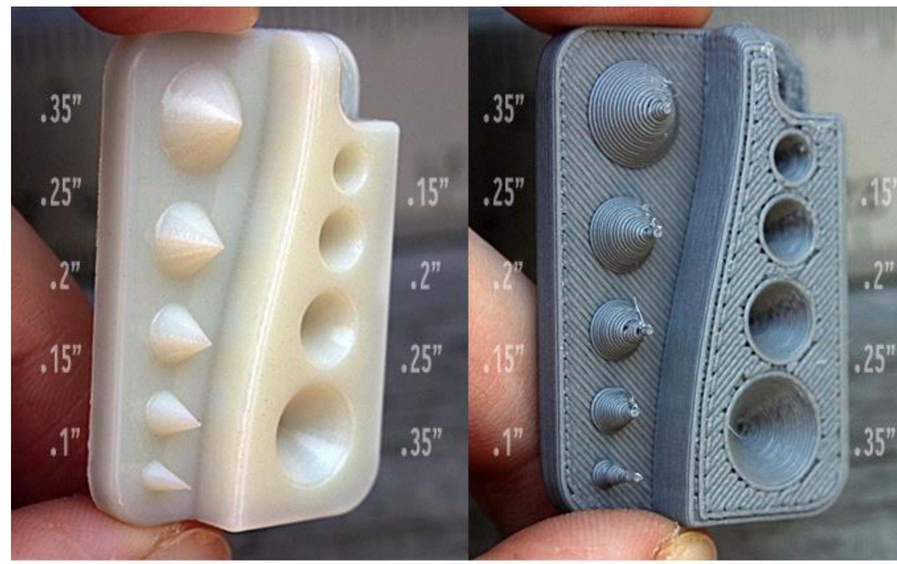
Accuracy

- 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

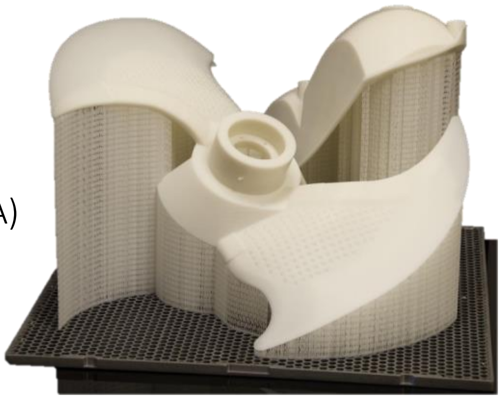
Surface finish

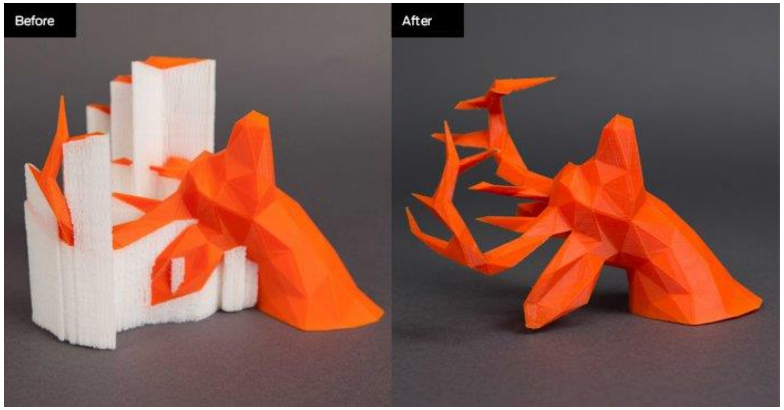
- The finish and appearance of a part are related to accuracy, but also depend on the method of RP employed.
- Technologies based on powders have a sandy or diffuse appearance, sheet-based methods might be considered poorer in finish because the stairstepping is more pronounced.

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.

Other general information

Technology	SLA	SLS	FDM	Wax Inkjet	3D printer	LOM
Max Part Size (cm)	30x30x50	34x34x60	30x30x50	30x15x21	30x30x40	65x55x40
Speed	Average	Average to fair	Poor	Poor	Excellent	Good
Accuracy	Very good	Good	Fair	Excellent	Fair	Fair
Surface finish	Very good	Fair	Fair	Excellent	Fair	Fair to poor
Strenghts	Market leader, large part size, accuragy, wide product	Market leader, accuracy, materials, large part size	Lab on desktop, price, materials	Accuracy, finish, lab on desktop	Speed, lab on desktop, price, color	Large part size, good for large castings, material cost
Weaknesses	Post processing, messy liquids	Size and weight, system price, surface finish	Speed	Speed limited, materials, part size	Limited materials, fragile parts, finsh	Part stability, smoke, finish and accuracy

+ Other general information

Machine	Cost	Material	Application
Fused Deposition Modeler 1600 (FDM)	$10/hr	ABS or Casting Wax	Strong Parts Casting Patterns
Laminated Object Manufacturing (LOM)	$18/hr	Paper (wood-like)	Larger Parts Concept Models
Sanders Model Maker 2 (Jet)	$3.30/hr	Wax	Casting Pattern
Selective Laser Sintering 2000 (SLS)	$44/hr	Polycarbonate TrueForm SandForm	light: 100%; margin: 0">Casting Patterns Concept Models
Stereolithography 250 (SLA)	$33/hr	Epoxy Resin (Translucent)	Thin walls Durable Models
Z402 3-D Modeller (Jet)	$27.50/hr	Starch/Wax	Concept Models

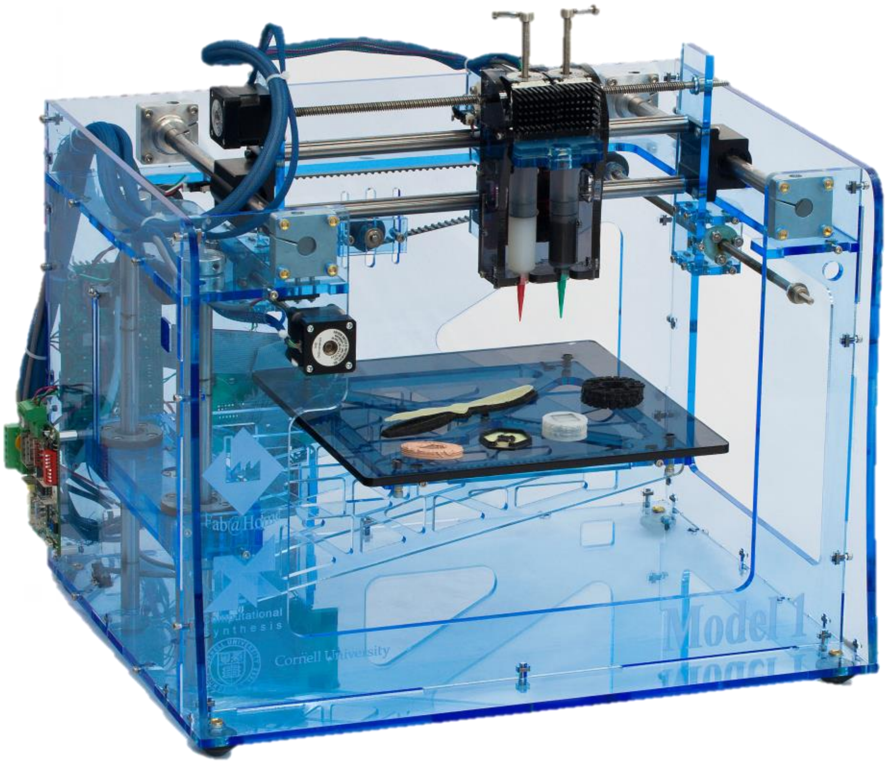
Cost - Vendors

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/

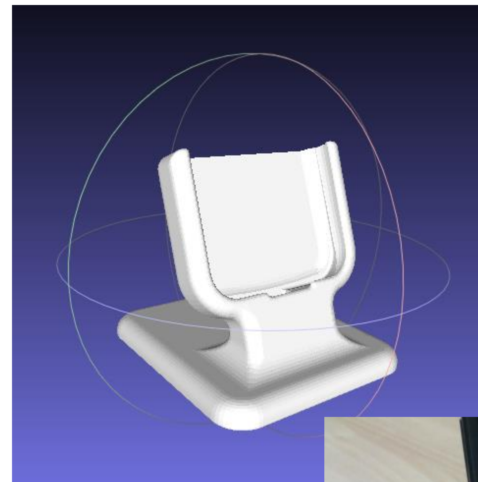
- https://www.3dhubs.com/

Environmental and health issues

ADDITIVE MANUFACTURING PROCESS FLOW

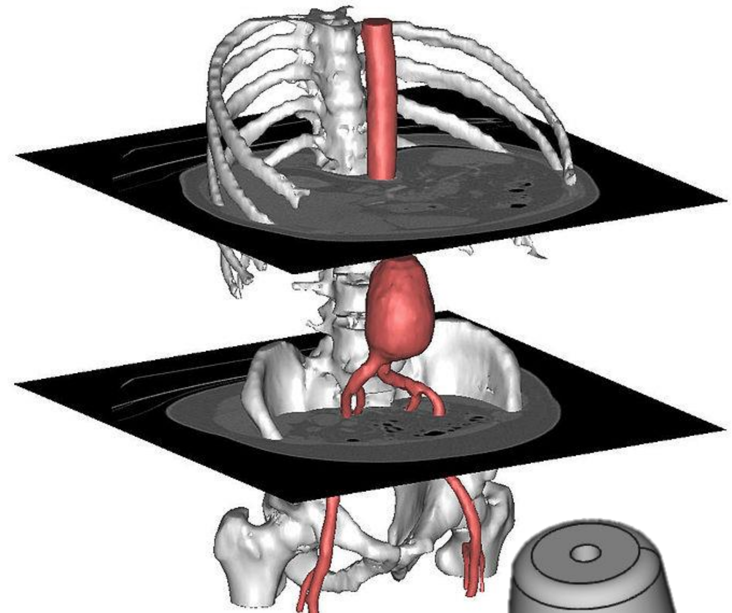
Additive manufacturing process flow

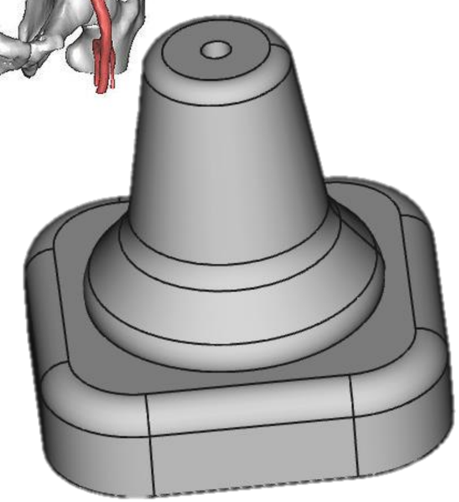
- Solid 3D modeling
- Export (Tessellation/Voxelization)
- Support Generation
- “Slicing” of the Model
- Model Physical Buildup
- Cleanup and Post Curing
- Surface Finishing



Solid 3D modeling

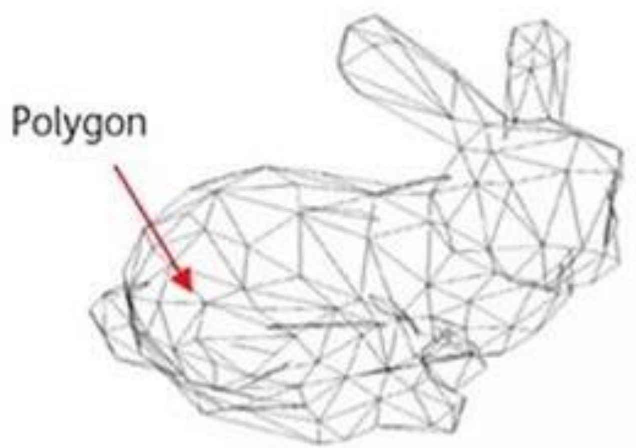
- Representation of a volume
  - CAD model
    - Your specific design
    - Web repository (http://www.thingiverse.com, https://www.youmagine.com, https//3dprint.nih.gov, http://www.appropedia.org, http://opensourceecology.org, http://reprap.org)
  - Instruments output
    - Segmentation of medical Images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

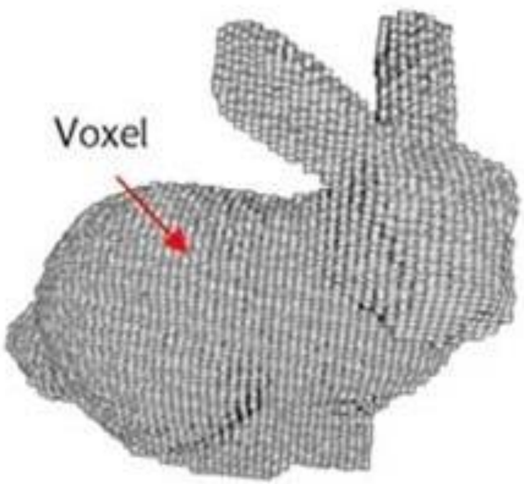




Tessellation / voxelization

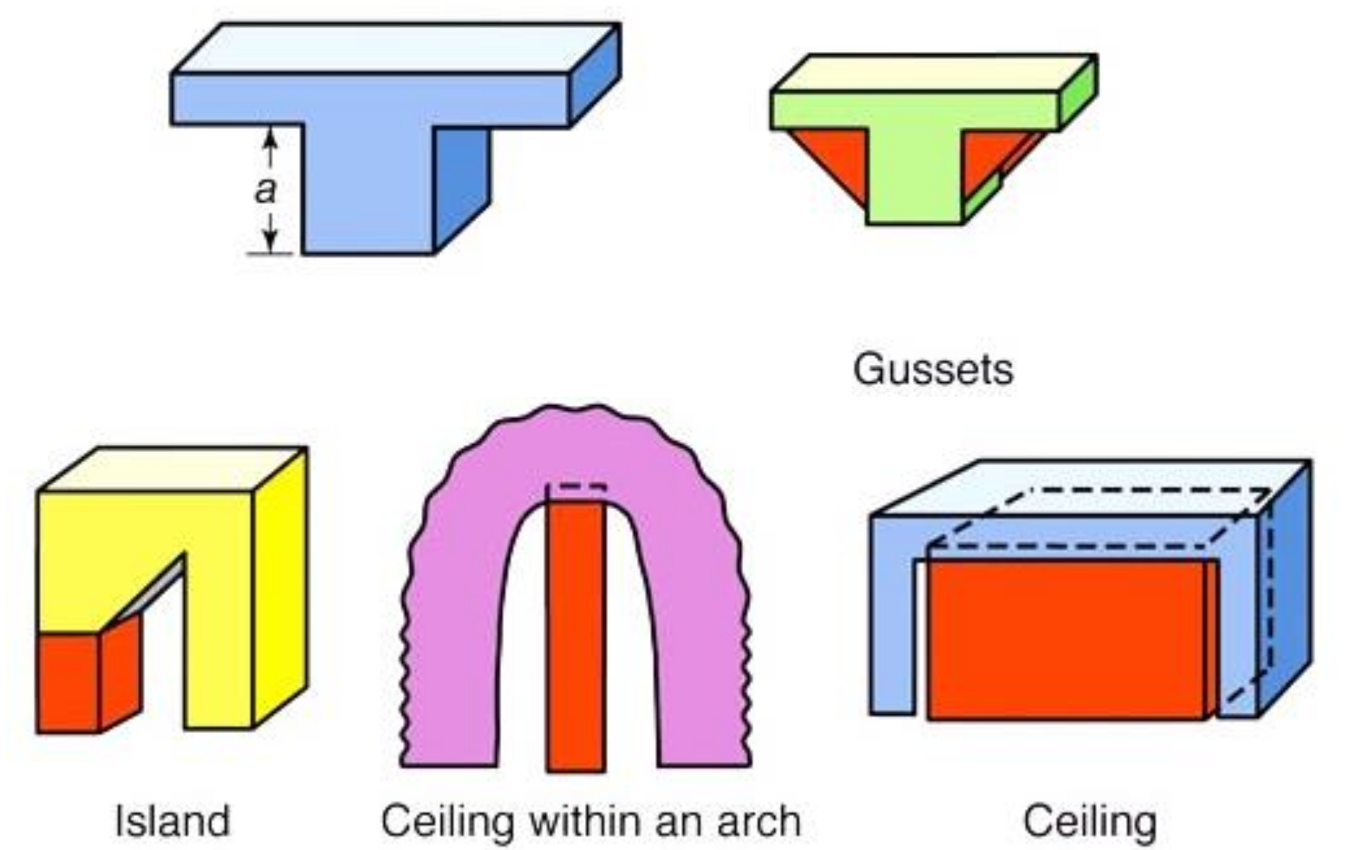
- Exchange formats for exporting 3D model
  - Polygon-based representation (STL, AMF, 3MF, OBJ, PLY)
  - Voxel based models





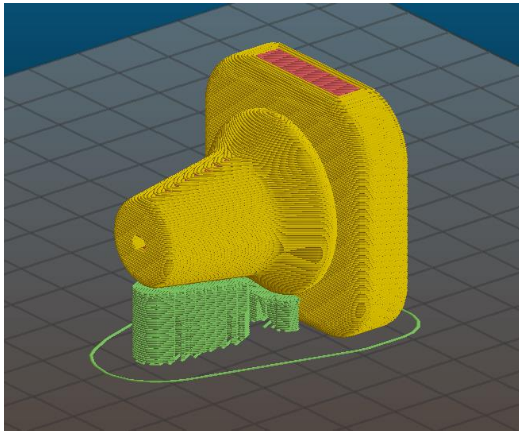
(a) Polygon-based representation (b) Voxel-based representation

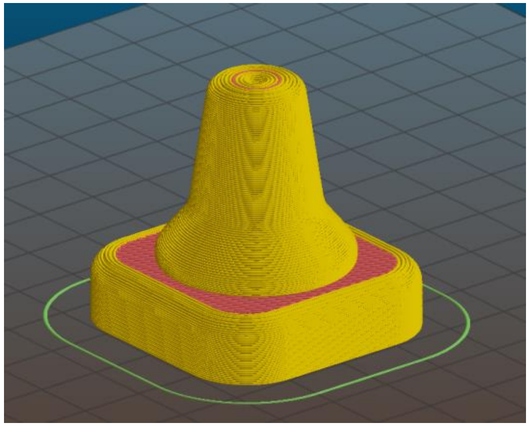
Support generation



Support generation

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

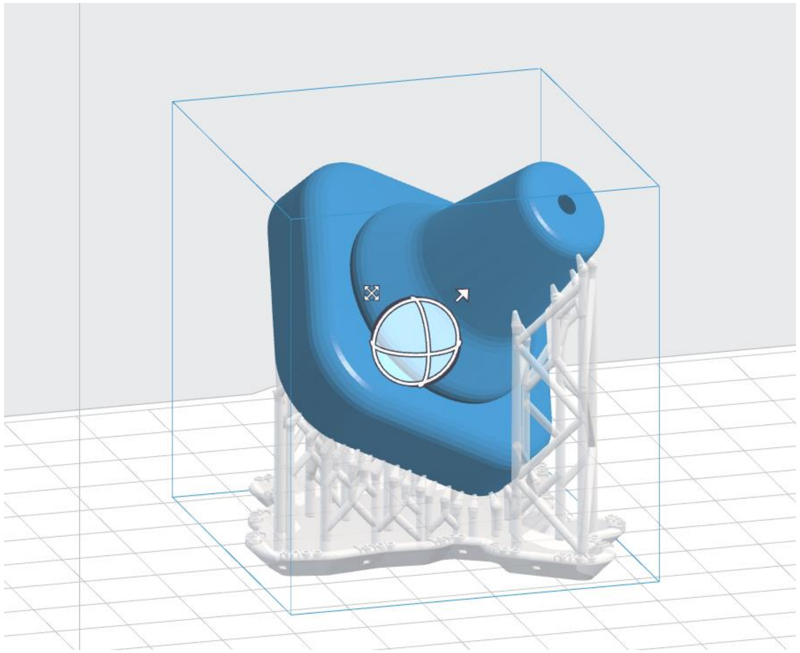




Fused deposition modelling

Support generation

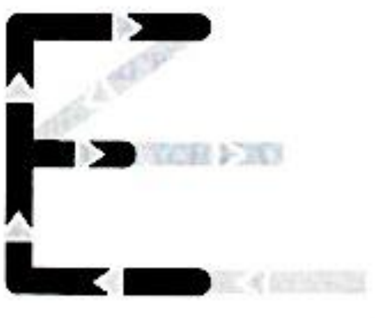
- Support generation may depend on
  - objects orientation,
  - on the specific additive manufacturing technology



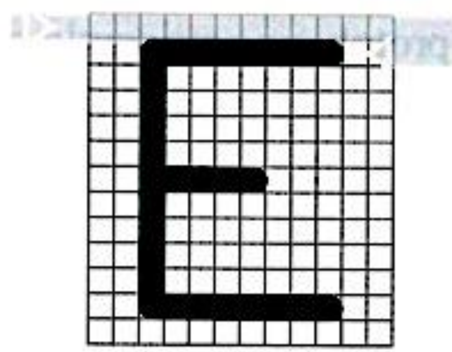
Stereolithography

Slicing the model

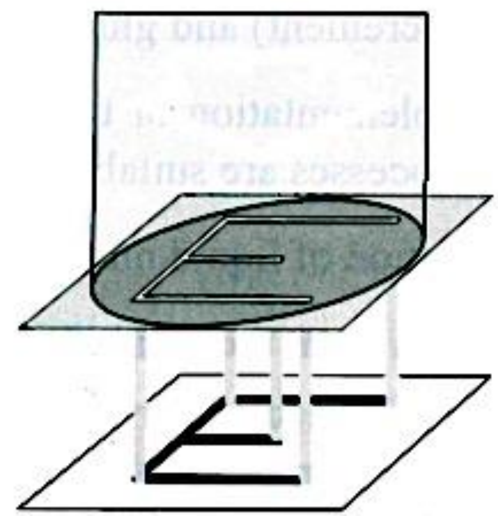
- Patterning



Vector



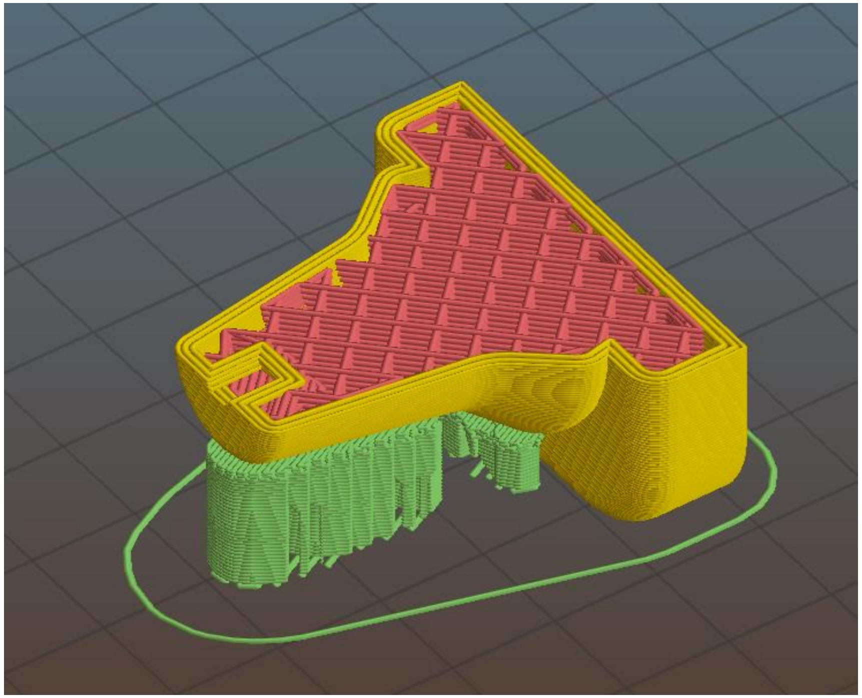
Raster

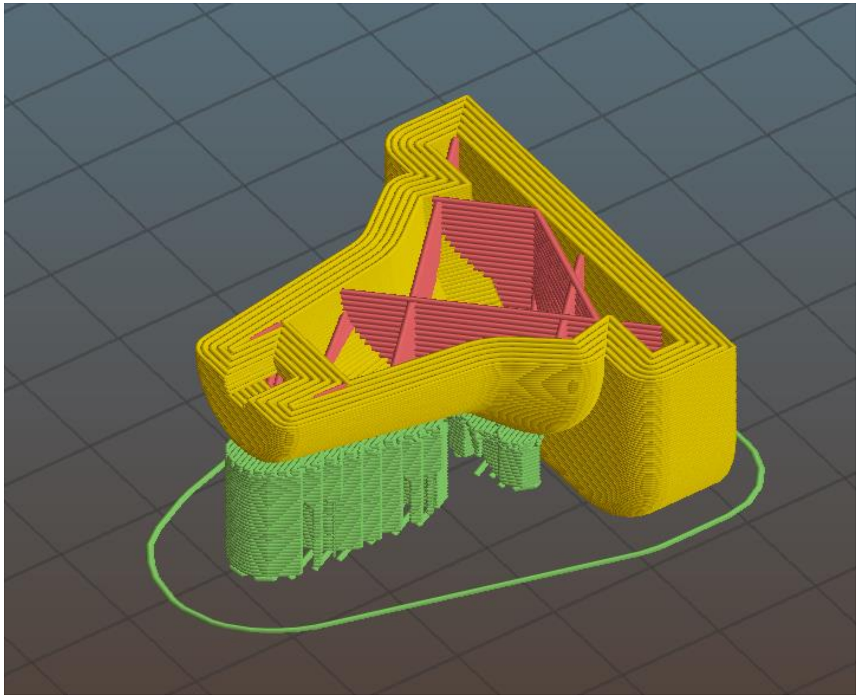


Projection

Slicing the model

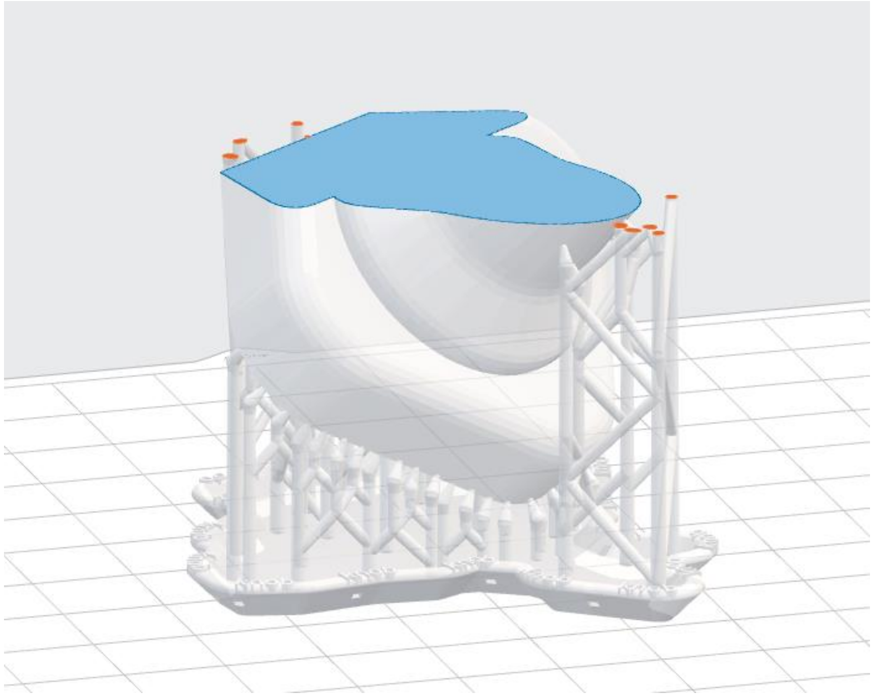
- Patterning and printing parameters

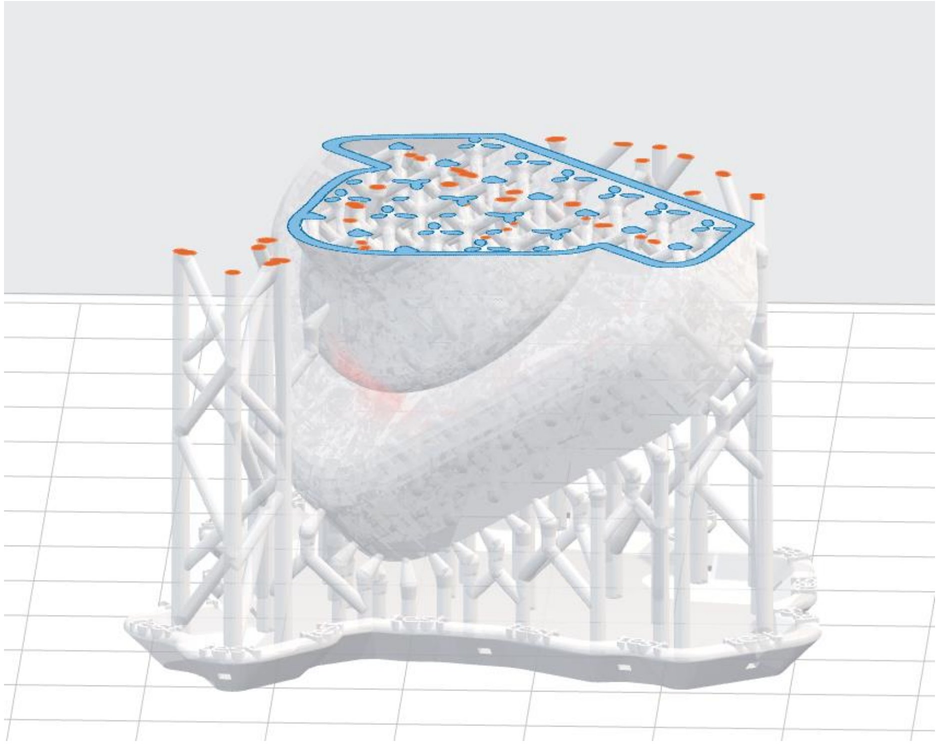




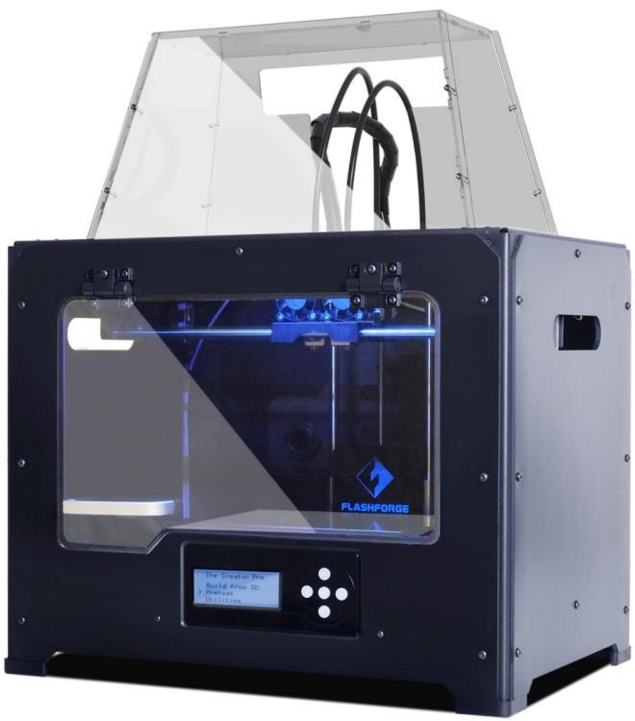
Slicing the model

- Patterning and printing parameters

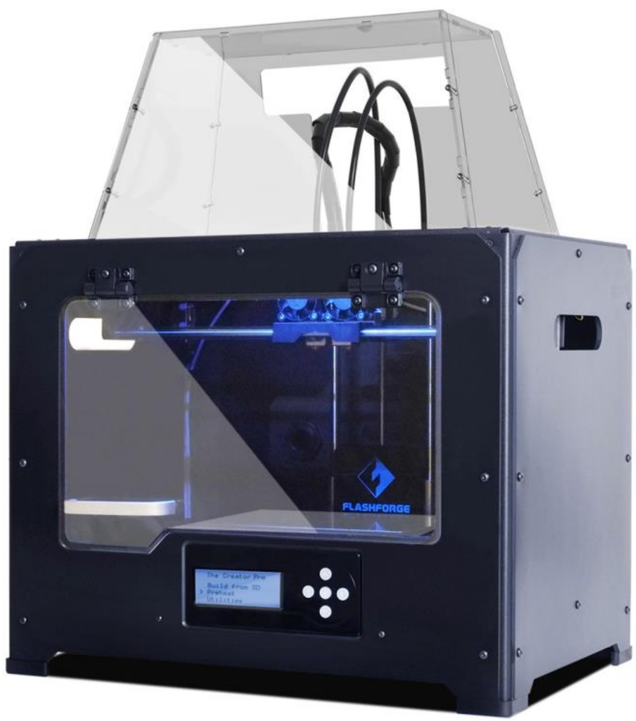


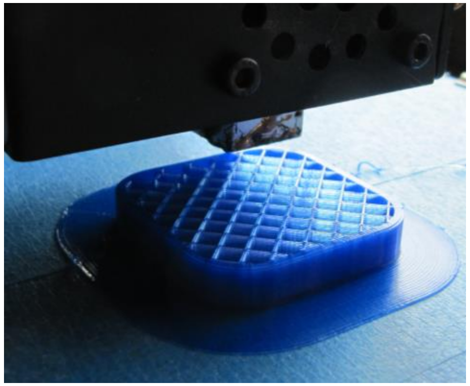


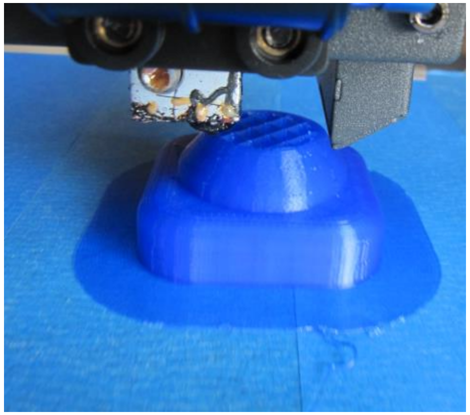
Model physical buildup



Model physical buildup

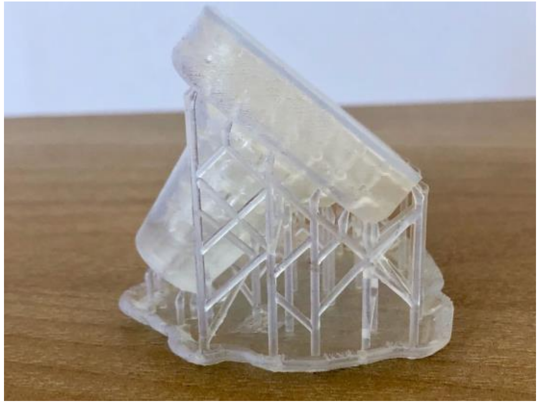




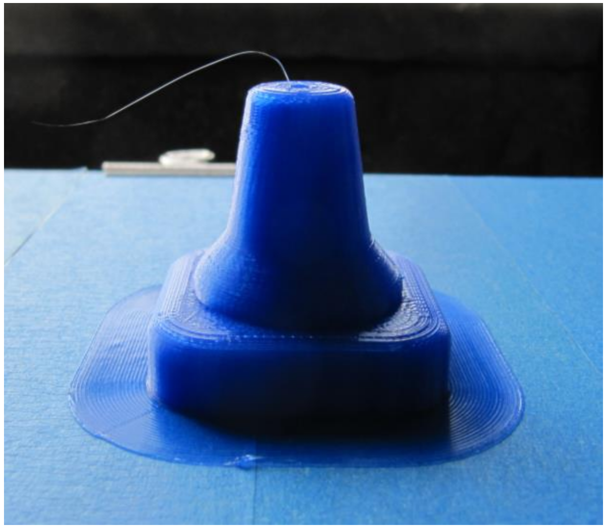


Cleanup and post curing
Surface finishing

- Stereolithography



- Fused Deposition modelling



Teaching material

- https://drive.google.com/drive/folders/1Sq0h1mXle2g29bFELLOQ_0v5UybmJOrT?usp=sharing
  - Subscribe the mailing list
  - Dispense.gdoc (continuous update, contribute to the teaching material by editing with the “suggested mode”