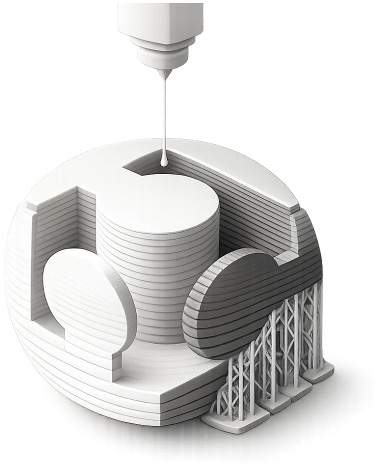
3D Scanning and Printing



Adrian Bowyer

Ohad Meyuhas

Jogin Francis

FABACADEMY

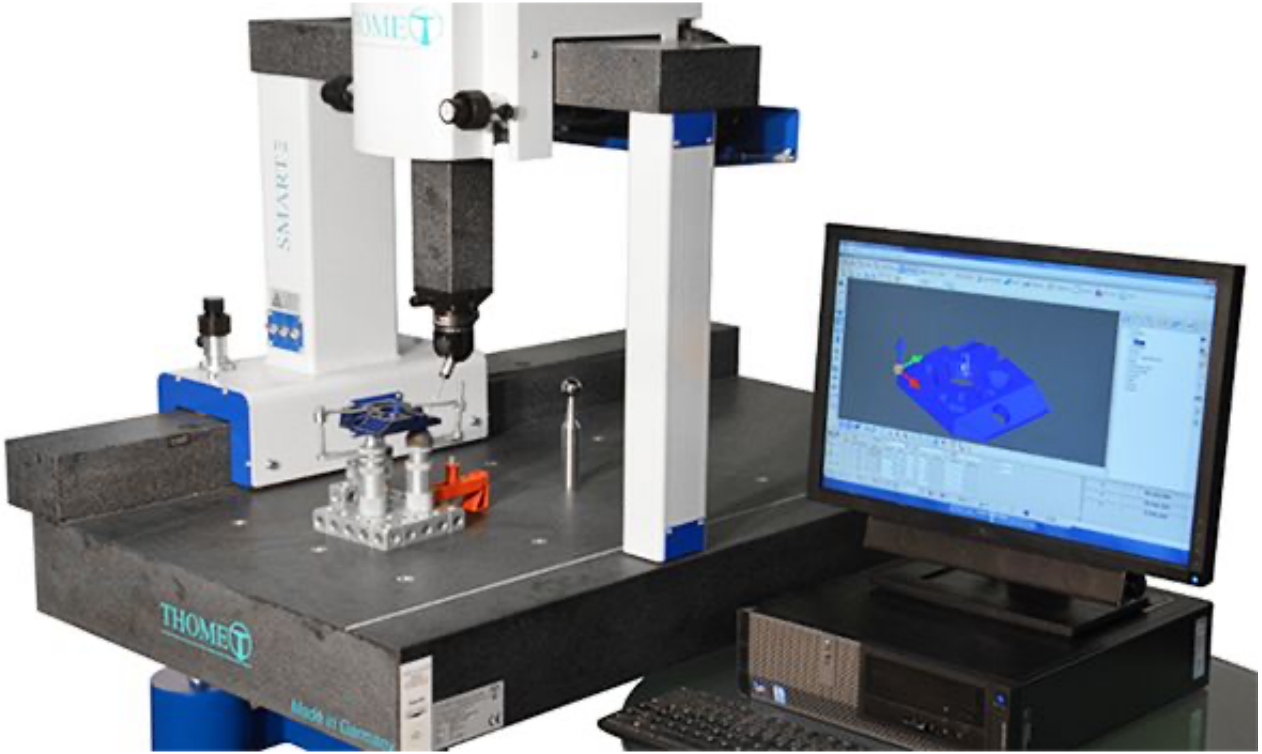
This Lecture

- Scanning existing objects
- Turning scans into useful files
- Scanning techniques and shortcomings

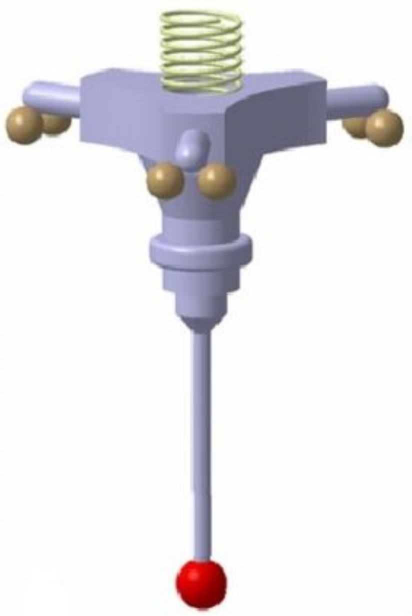
- 3D printing (Additive Manufacturing, AM)
- People making things
- Why 3D print to make things?
- 3D printers you can use – Fused filament fabrication and stereolithography
- 3D printing design rules – what they can and can't do
- 3D printing tricks and techniques

- Assignment: 3D print things, then scan another thing (and maybe print it)

Scanning

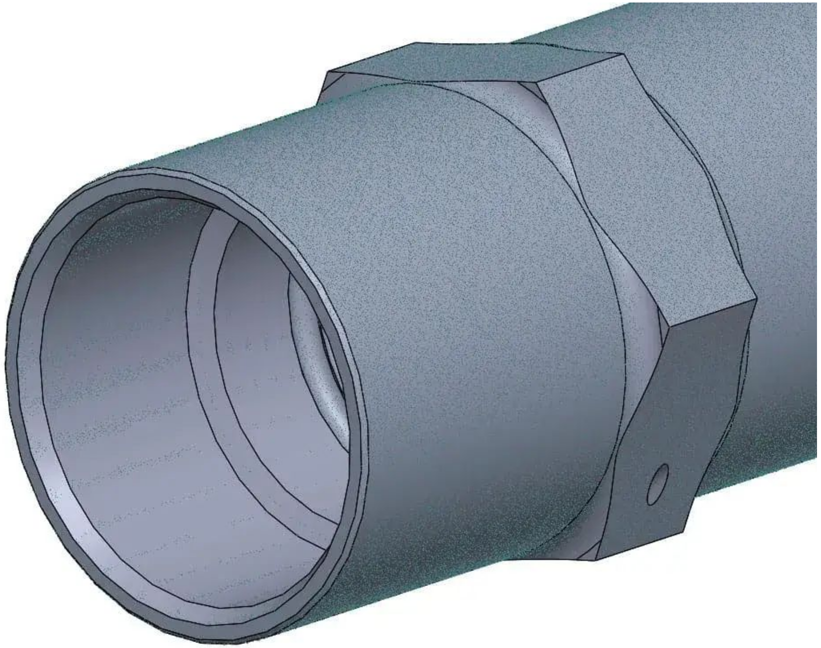


Coordinate measuring machine (CMM)



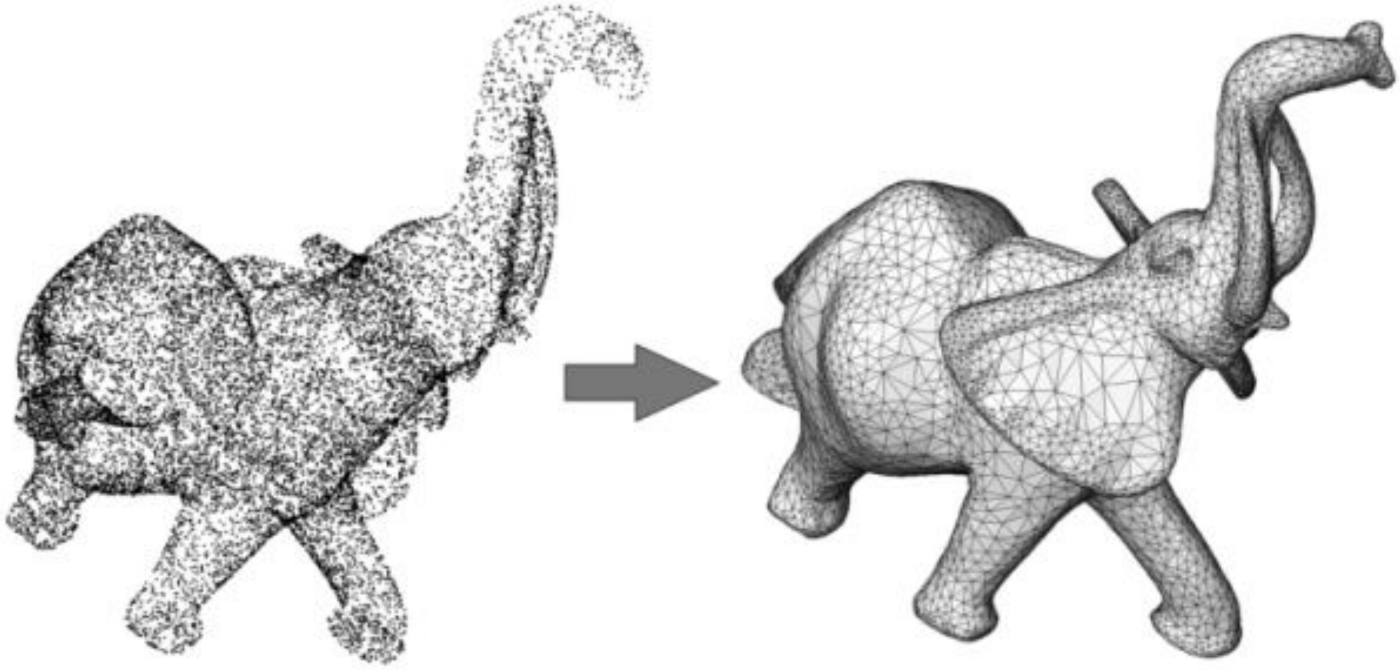
Touch probe

Scanning and probing



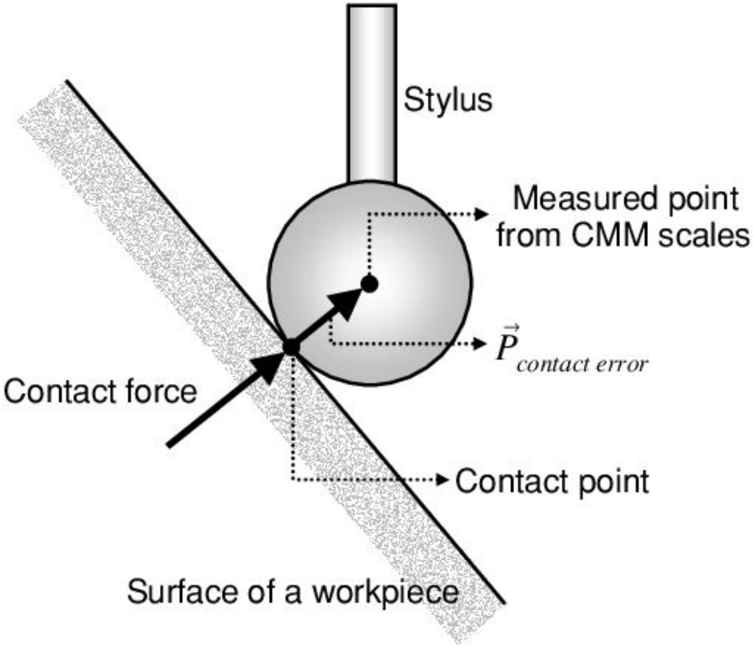
Point cloud

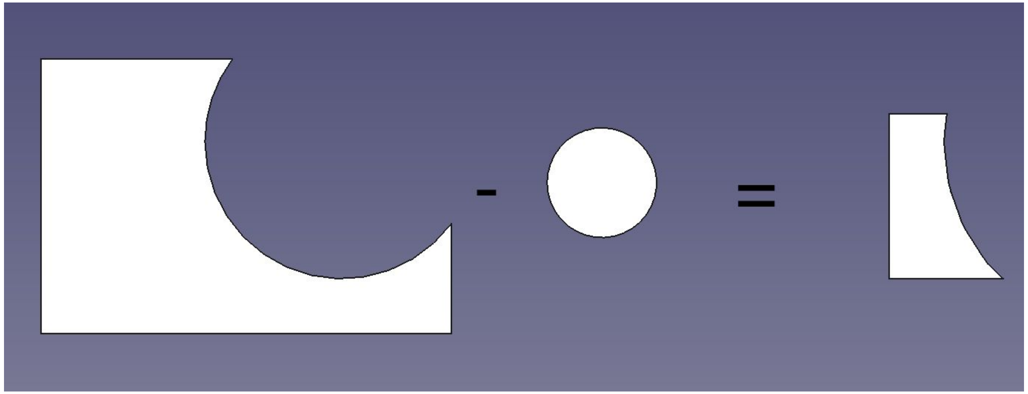
Scanning and probing



Point cloud to polygons (triangles)

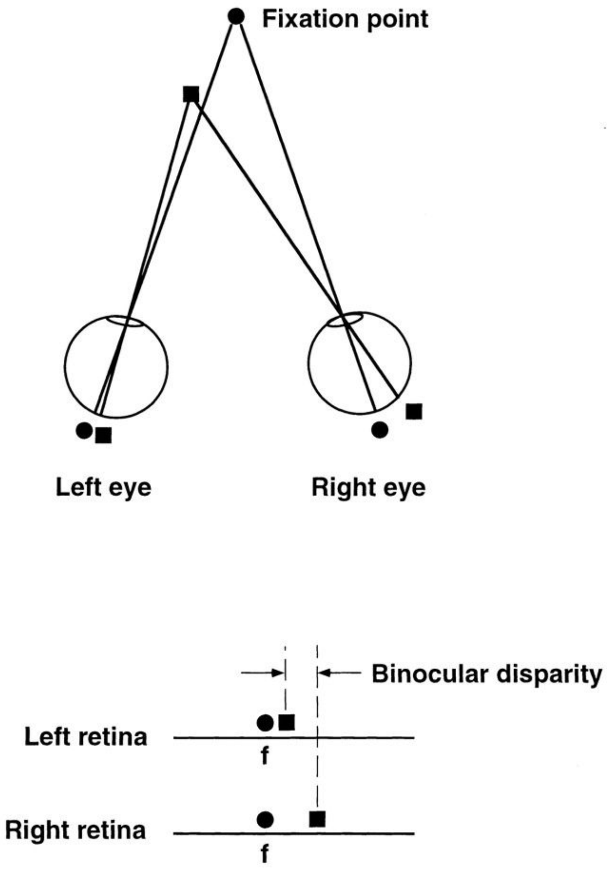
Scanning and probing





Maybe probe offsets, so use Minkowski sum (later)

Scanning – binocular vision



two eyes

one eye plus movement

Scanning toolchain

1. Gather images - easy

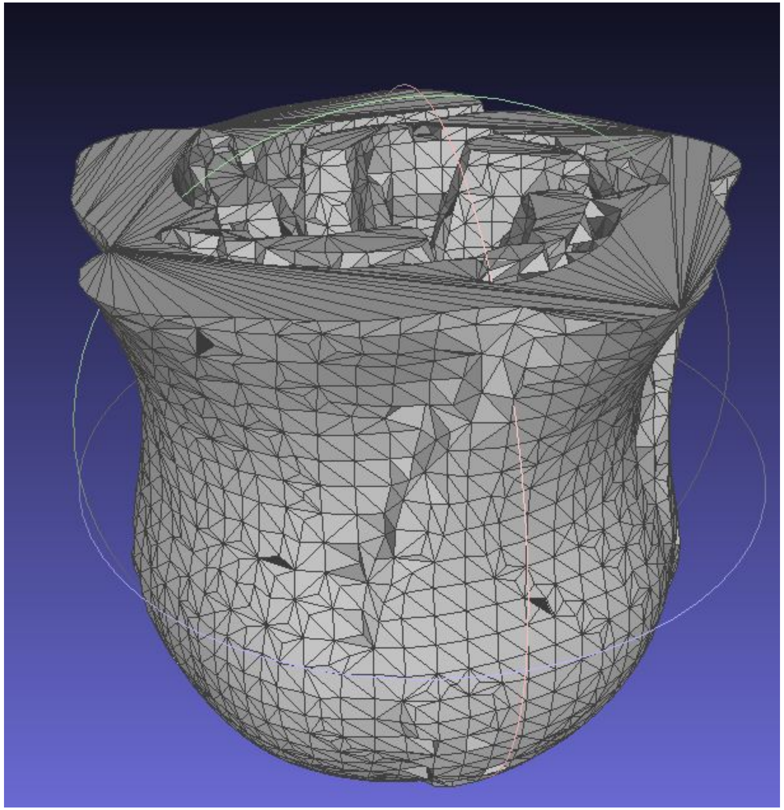
Scanning toolchain

2. Point correspondence - hard

Scanning toolchain

3. Three-dimensional point cloud - easy

Scanning toolchain

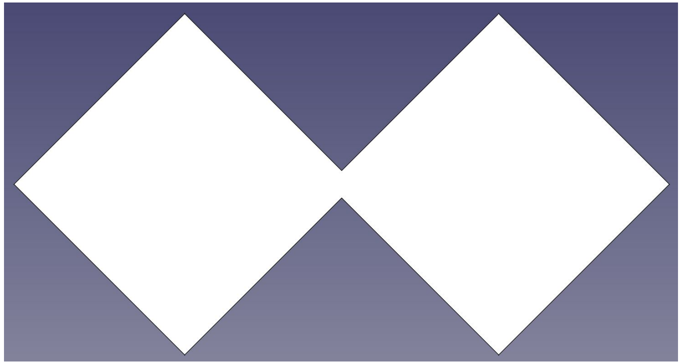


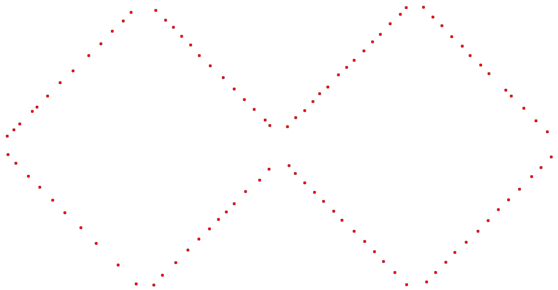
4. Meshed/triangulated solid - hard

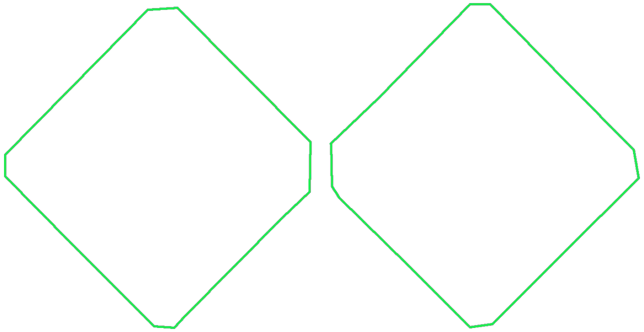
Scanning

Point correspondence – structured light, laser + camera

Scanning

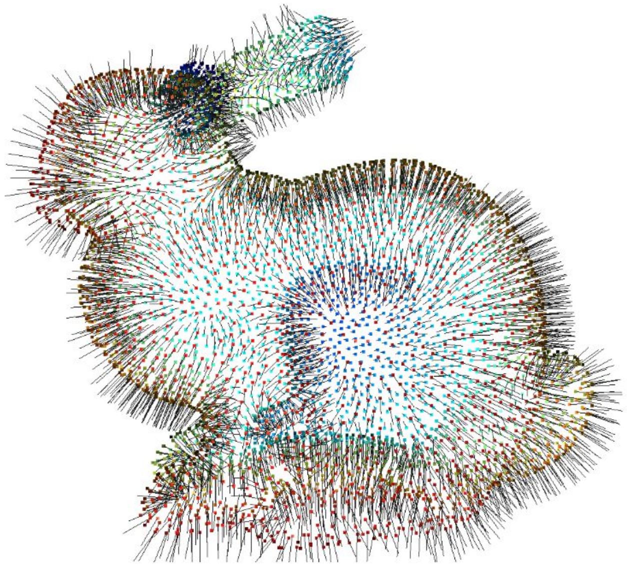






Why is meshing/triangulating a solid hard?

Scanning



Meshing/triangulating a solid - Poisson Surface Reconstruction

Scanning

FabScan**TT** – FabLab Aachen

Scanning

Creality CR-Scan Ferret Pro 3D Scanner

3D Printing

Four fundamental ways humans shape matter since pre-history

Cutting

Separation

Subtractive

Removal

Forming

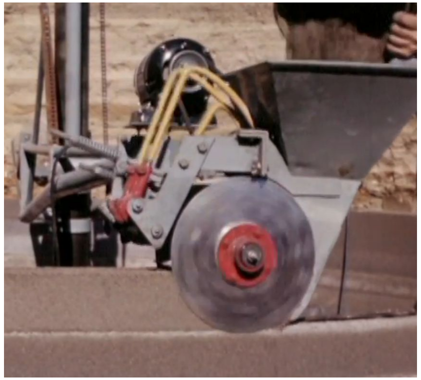
Deformation

Additive

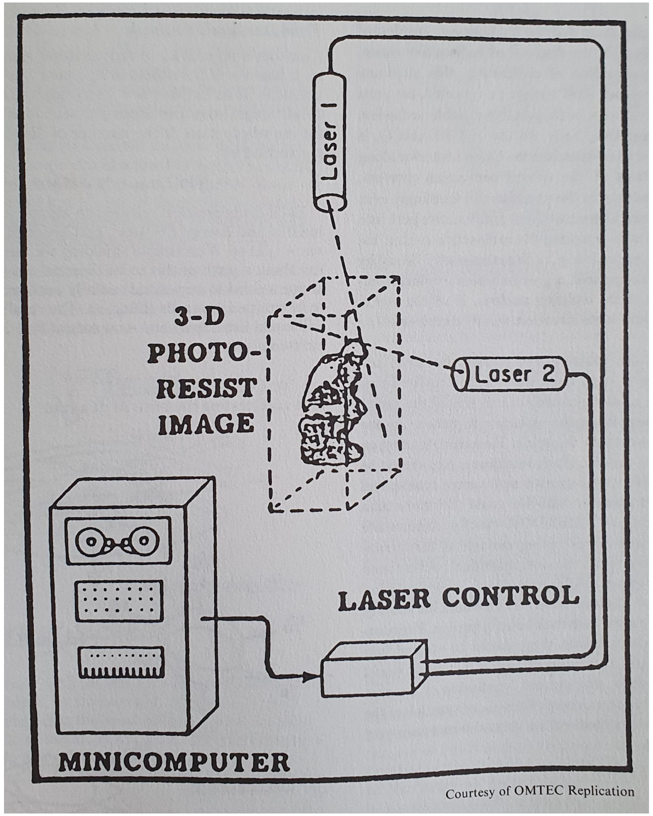
Accumulation

History

Very old 3D printing - William Urschel's wall building machine (1930s)



Old 3D printing

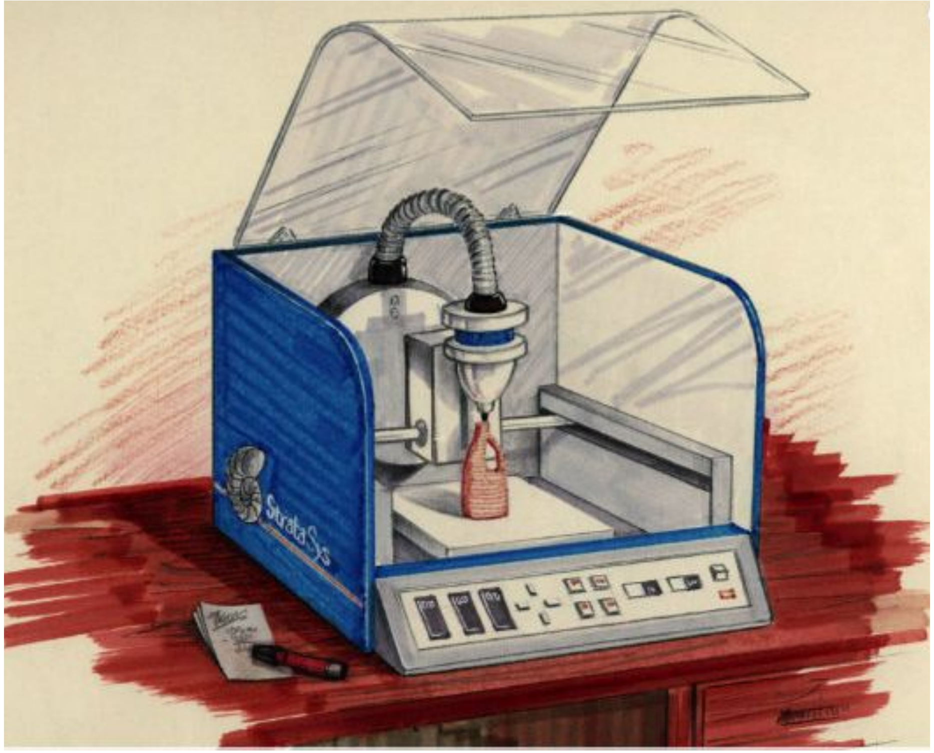


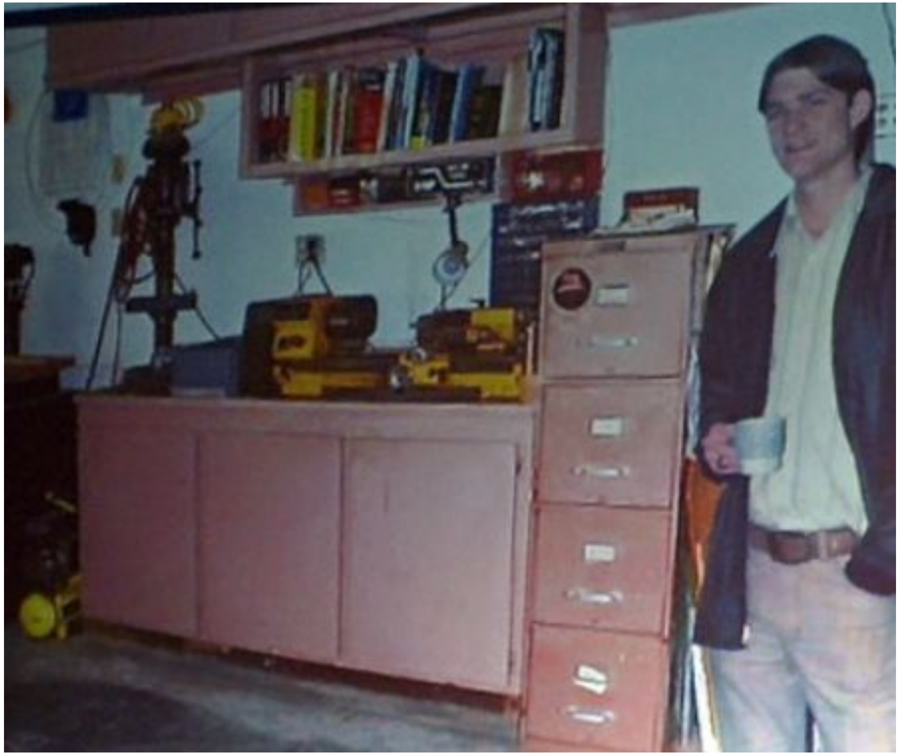
David Jones ("Daedalus", 1974), OMTEC (1978)

First commercial 3D printing

Charles Hull (1984)

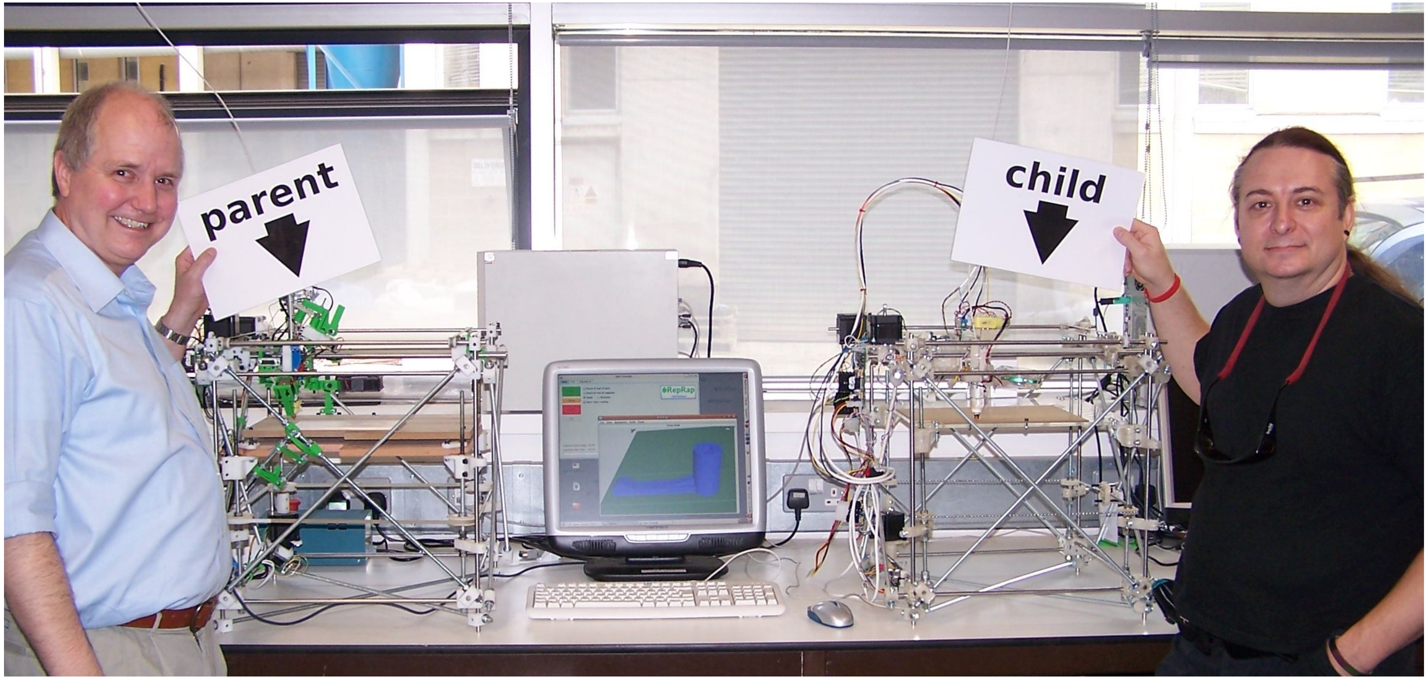
The Rise of FDM Printing (1988)

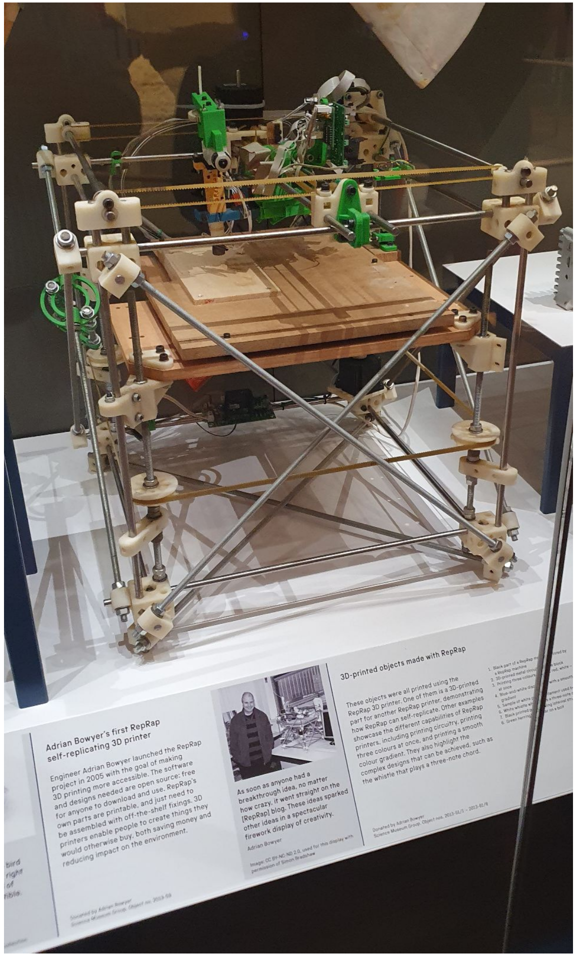




Scott Crump, FDM (1988), Stratasys

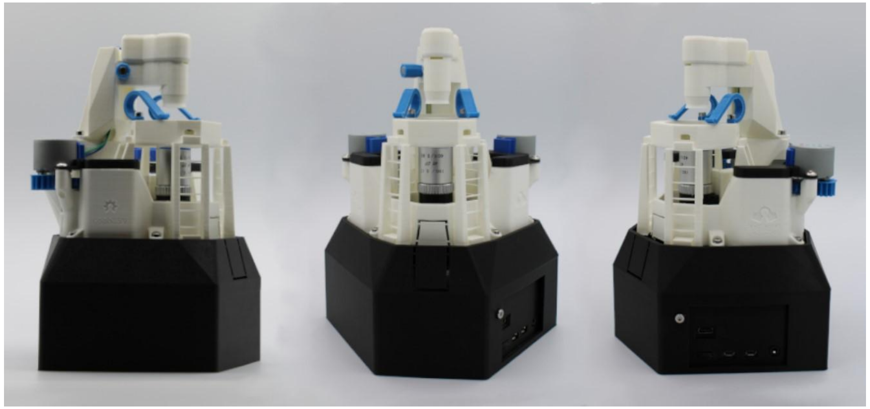
Self replicating 3D printing



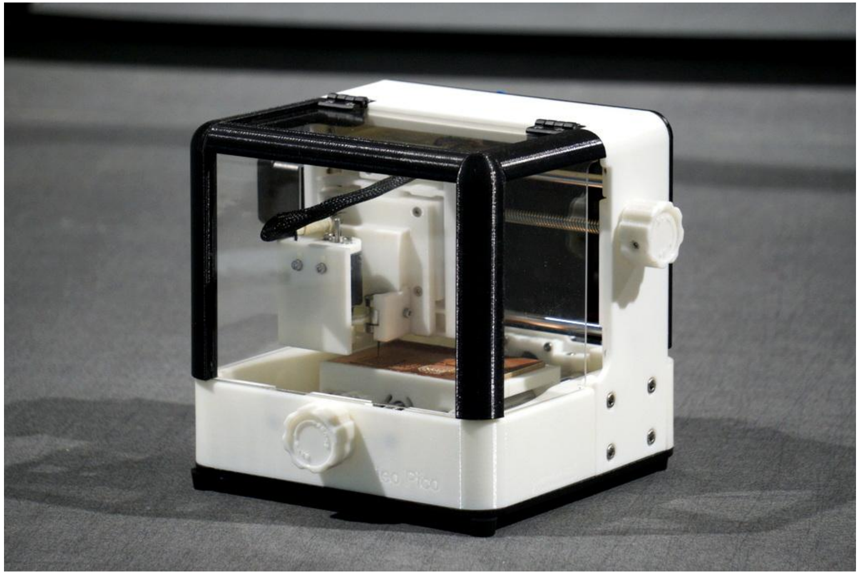


RepRap (2008)

Why 3D print?



OpenFlexure
laboratory-grade
open-source
microscope



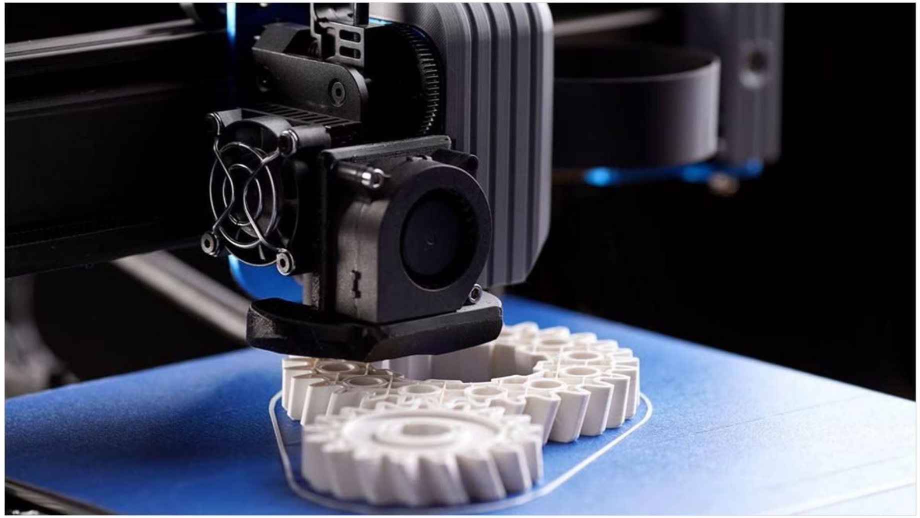
Pico CNC printed-circuit mill

People making things

Subtractive

Additive

Add a computer to move a machine to help

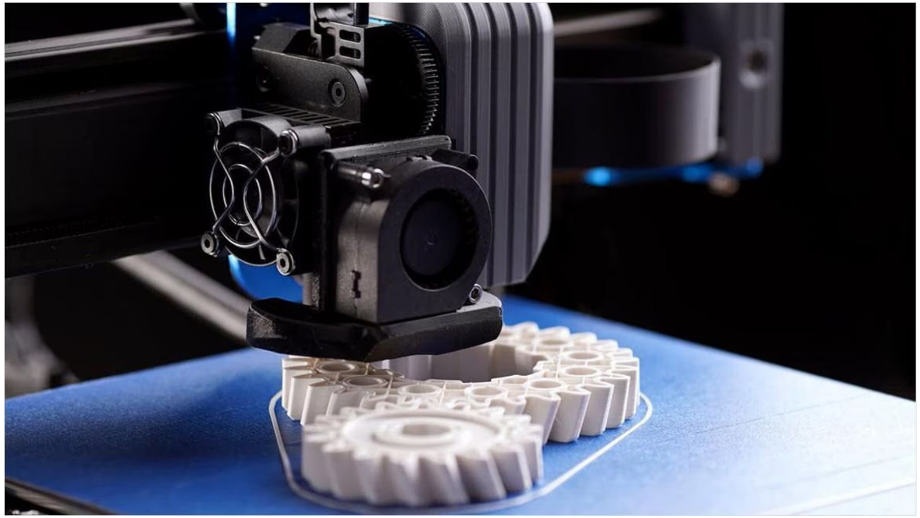


Subtractive –
Computer Numerically Controlled
(CNC) milling

Additive –
3D printing

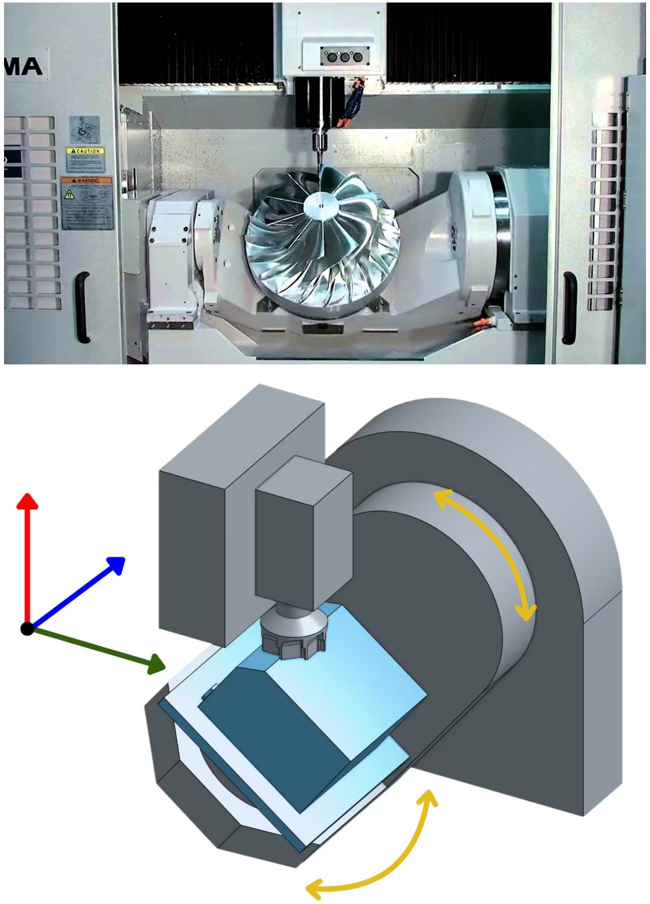
Why 3D print? – big forces vs. small forces

milling: 500N

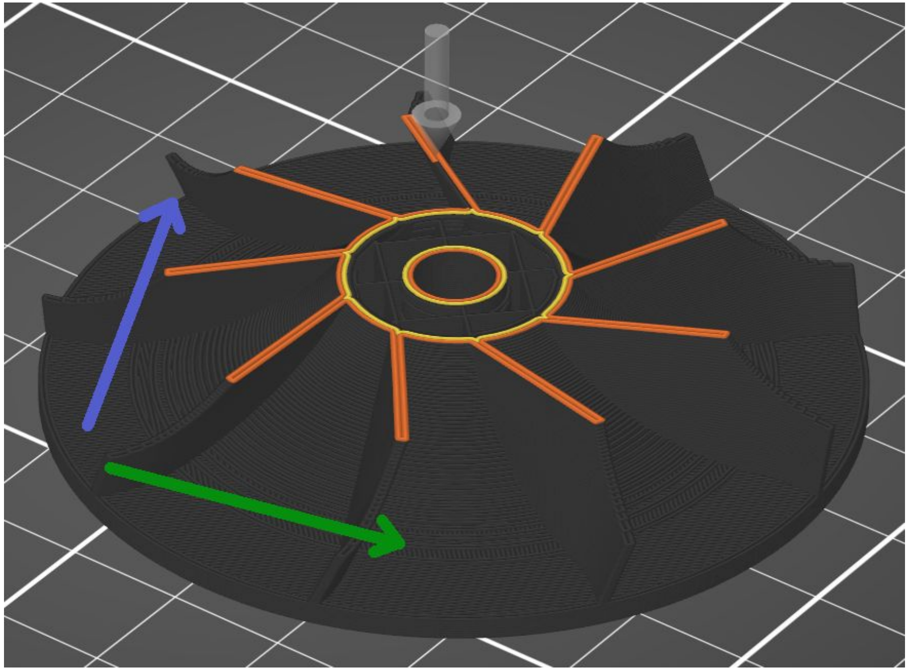


3D printing: 5N

Why 3D print? – 5 dimensions vs. 2 dimensions

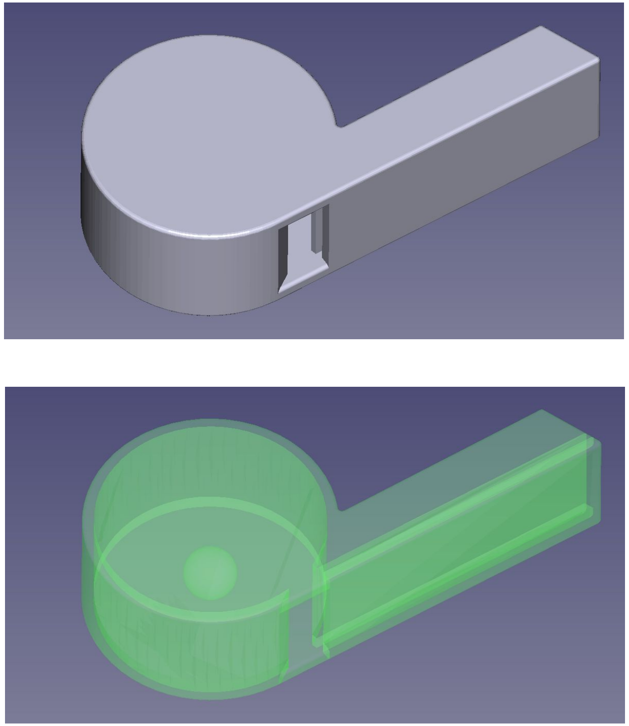


milling

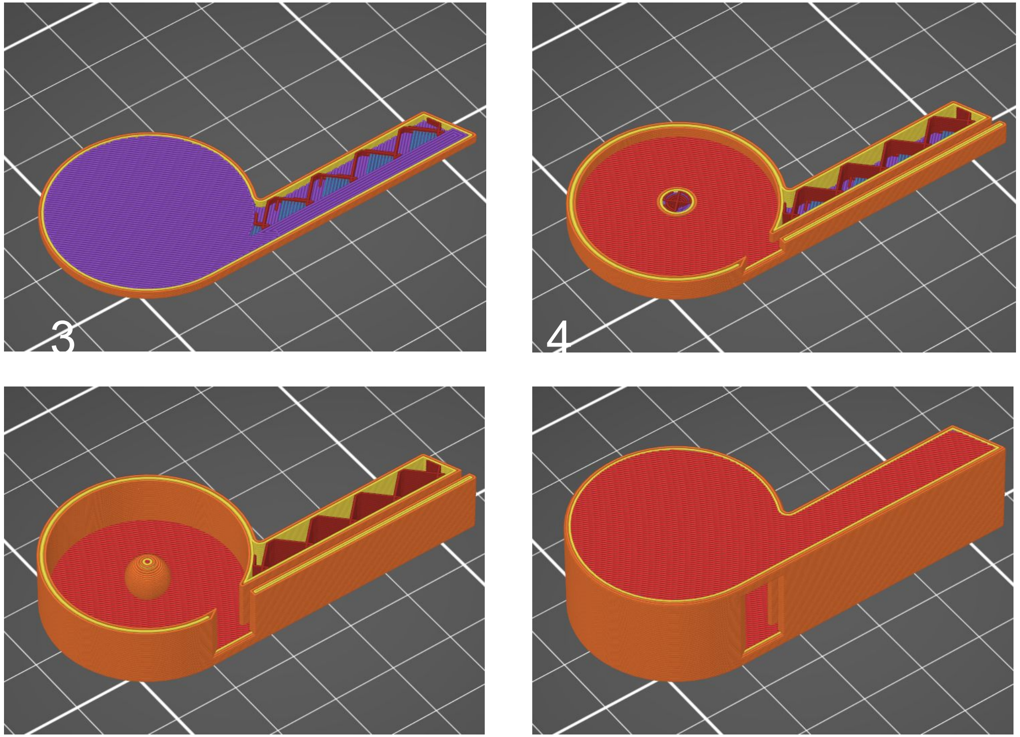


3D printing

Why 3D print? – can't make vs. can make



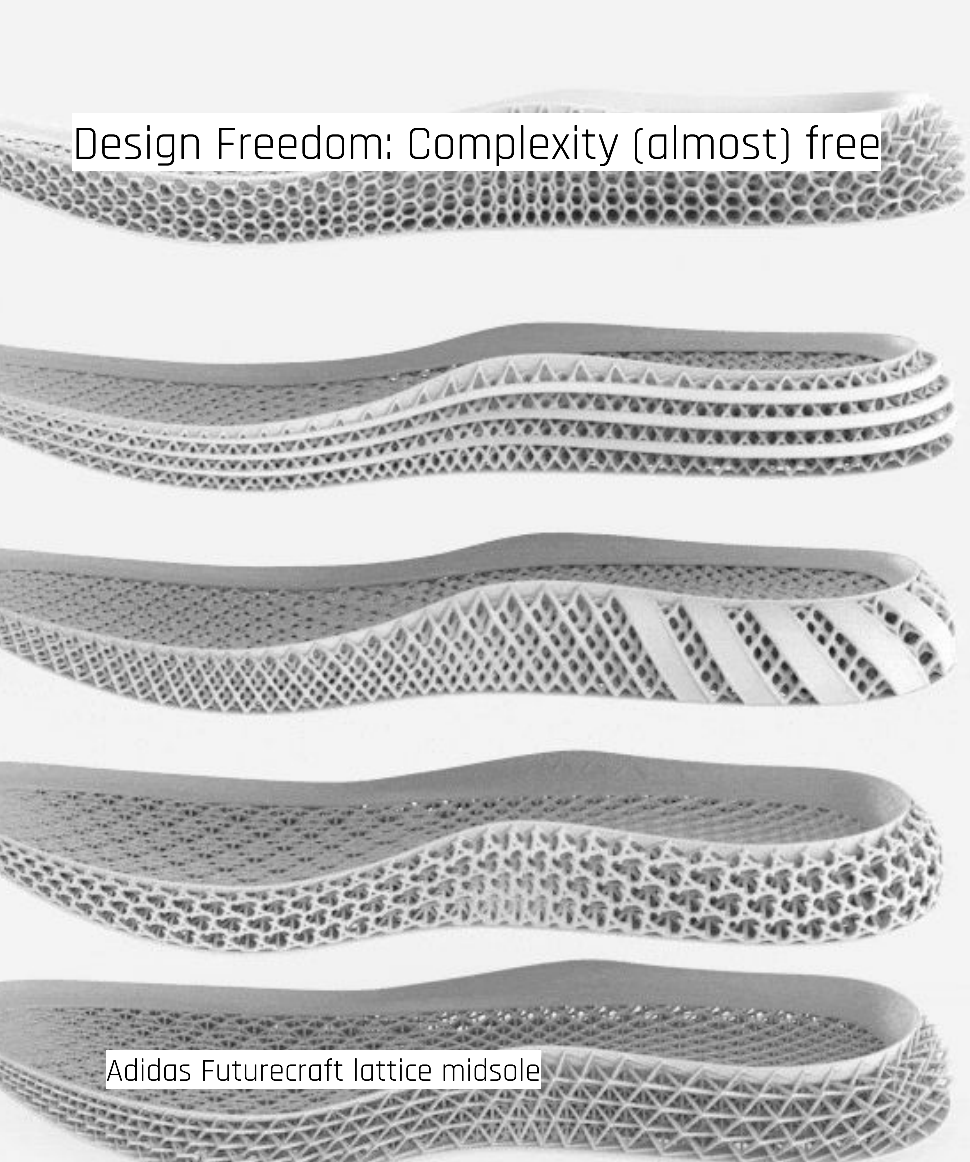
milling: can't



3D printing: can

Why 3D print? – complexity is (almost) free

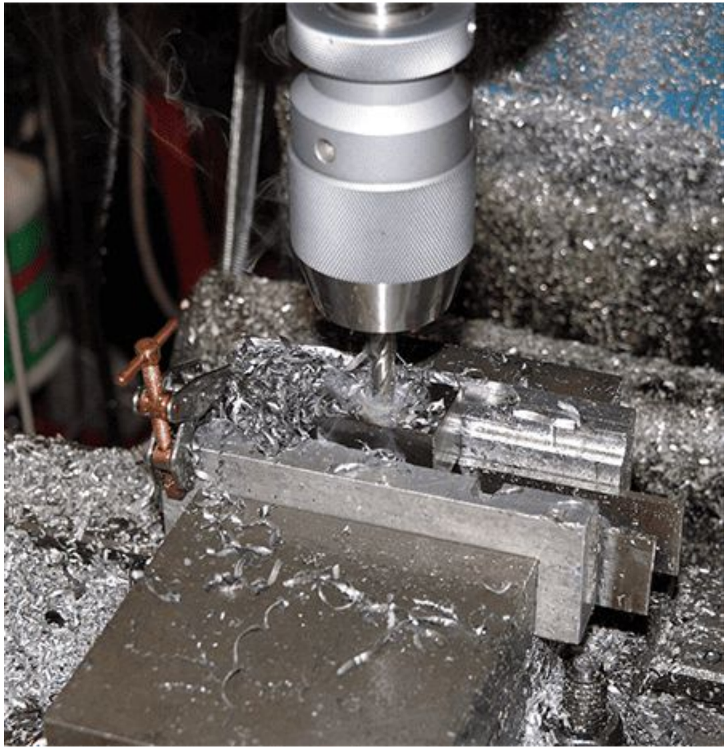
Design Freedom: Complexity (almost) free



Adidas Futurecraft lattice midsole

Thalassic Masks (2021) Filippo Nassetti and Vincenzo Reale

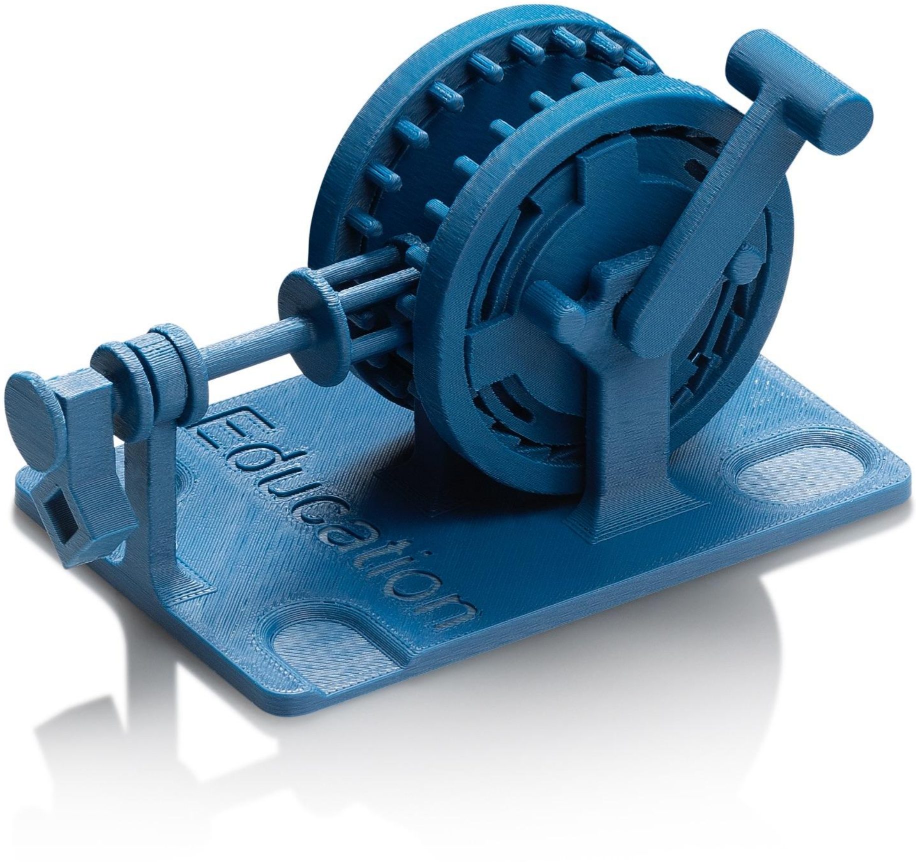
Why 3D print? – net shape and little waste

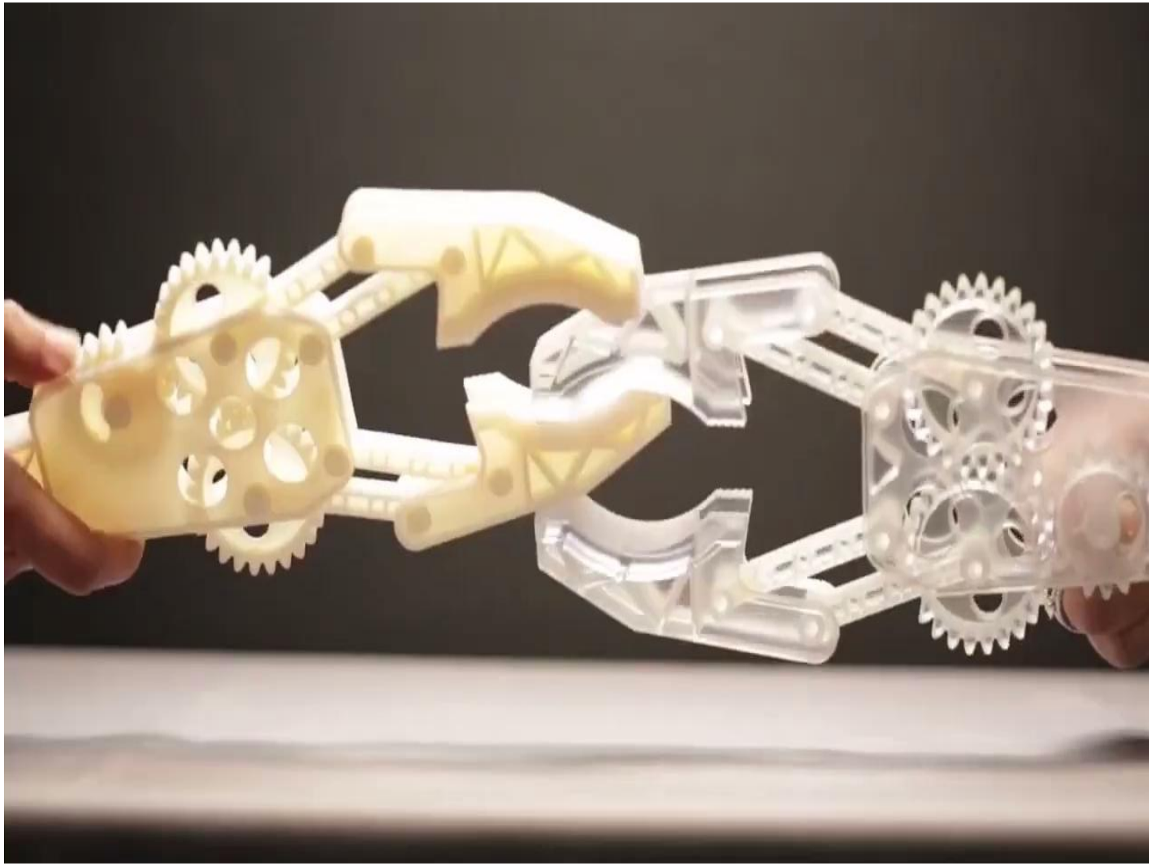


milling: waste material

3D printing: less waste material

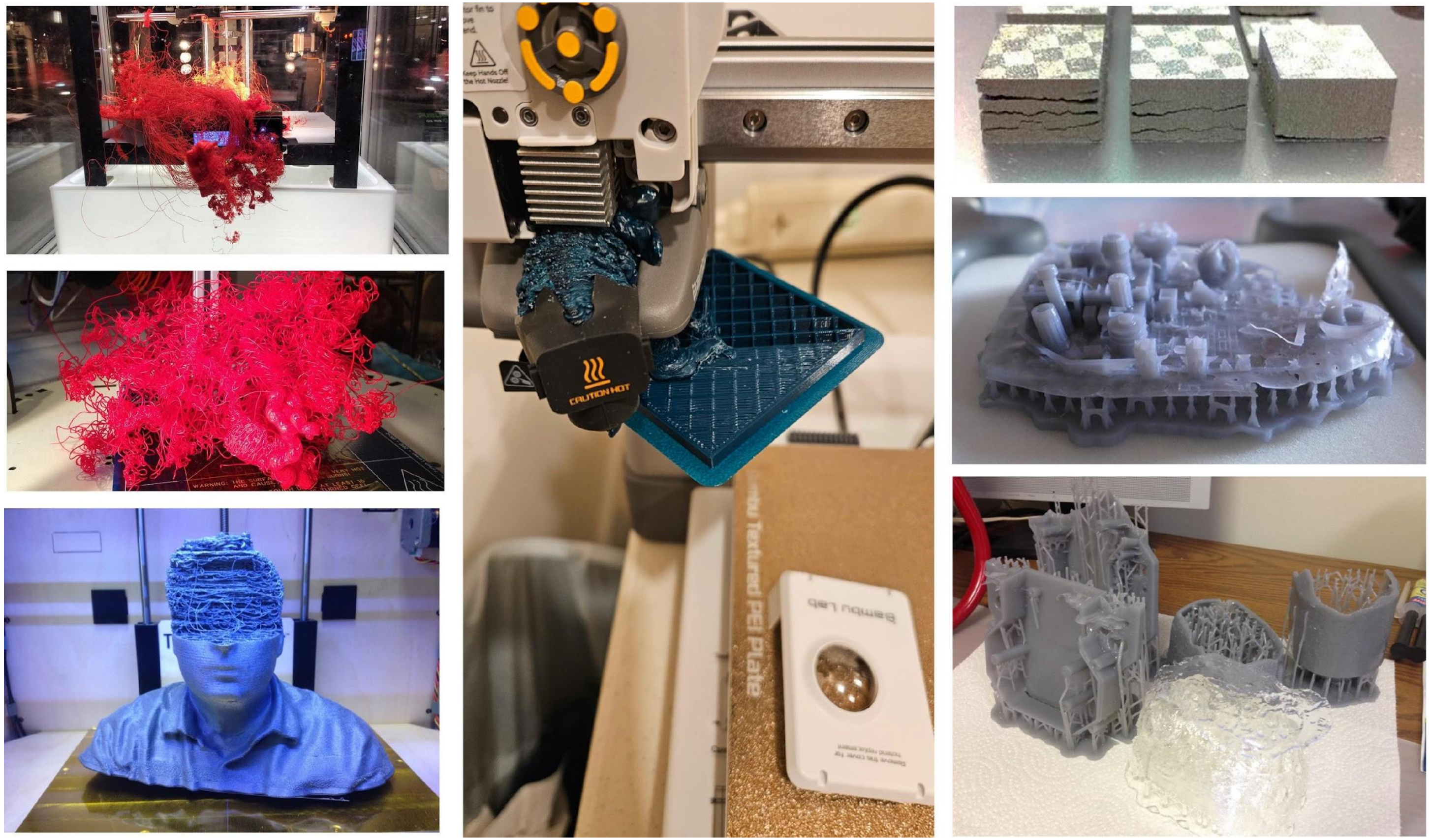
Print-in-place: Fully Functional Mechanisms in a Single Build





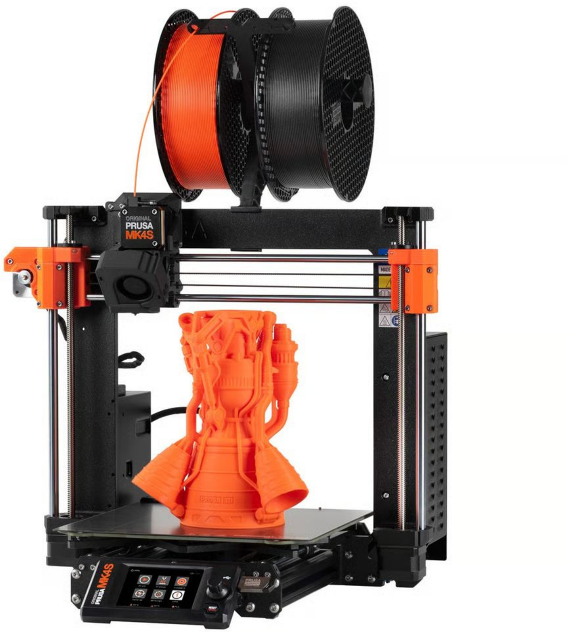
Stratasys Education - "Something That Moves Something" curriculum, developed by Ohad Meyuhas

3D Printing

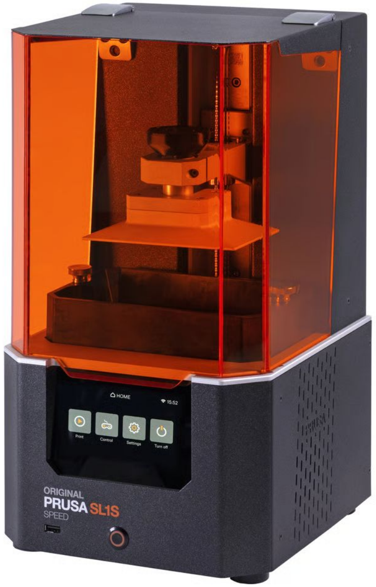


Sometimes it fails

3D printers likely to be found in FabLabs

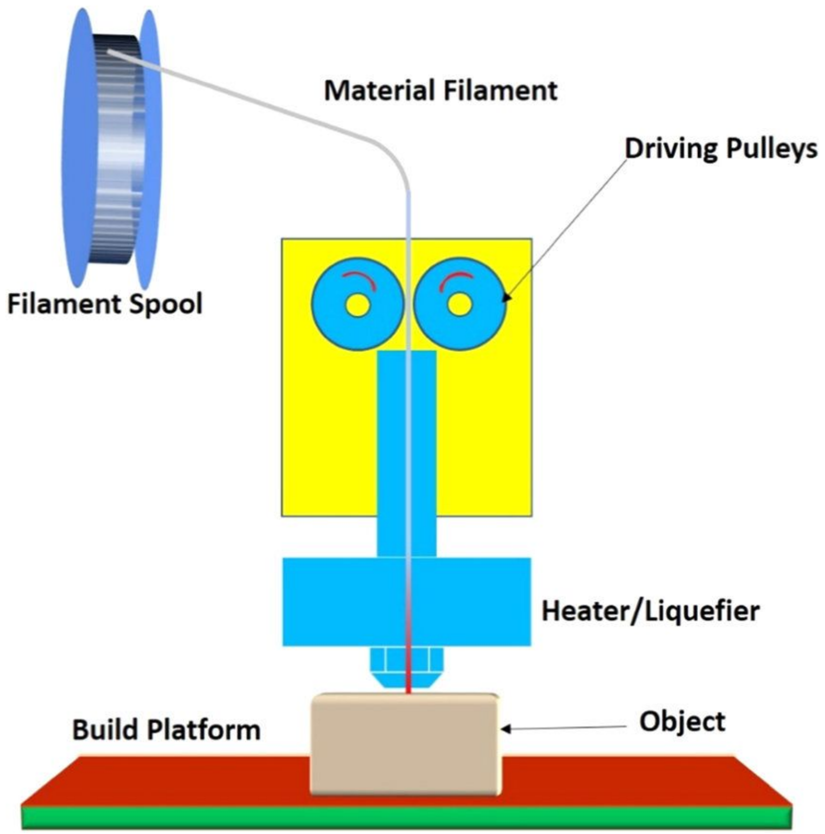


Fused Deposition Modelling (FDM)™
= Fused Filament Fabrication (FFF)

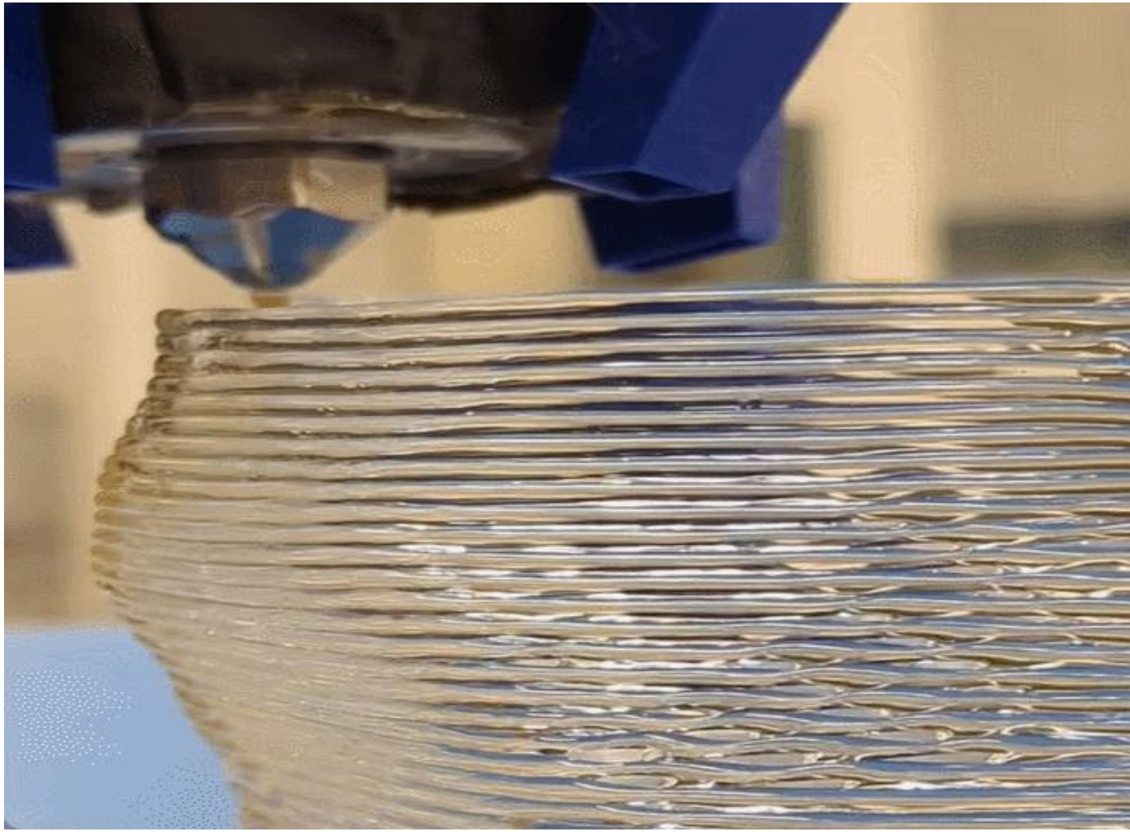


Masked StereoLithography Apparatus
(MSLA)

Fused Filament Fabrication (FFF) - Material Extrusion

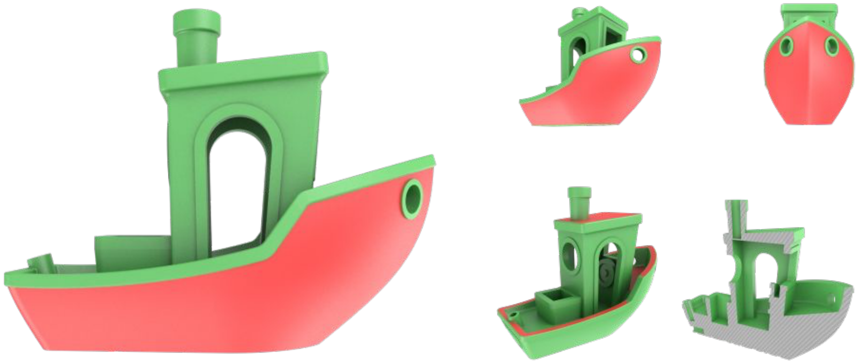


A computer-controlled hot glue gun



Fused Filament Fabrication is slow

(like most 3D printing)

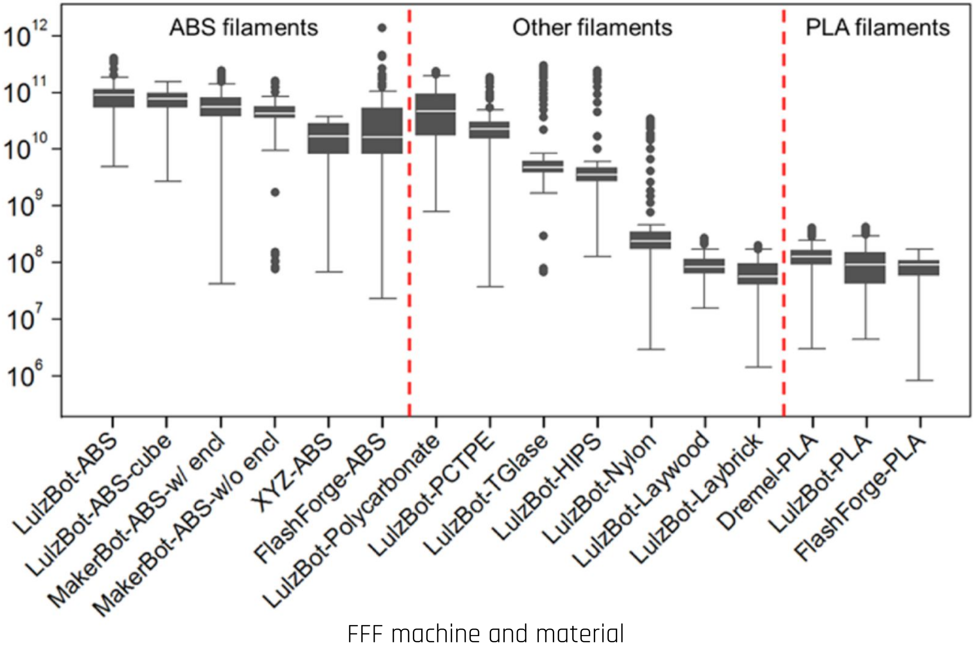


3DBenchy test model

Under 3-minute FFF print

Fused Filament Fabrication (FFF)

Ultra-Fine Particles
over time
NB: Log scale



Safety – particulates and volatile organic compounds (VOC)

Fused Filament Fabrication (FFF)

simplify3d.com

	 ABS	 Flexible	 PLA	 HIPS	 PETG	 Nylon
	Learn More	Learn More	Learn More	Learn More	Learn More	Learn More
Compare Selected	☐	☐	☐	☐	☐	☐
Ultimate Strength ?	40 MPa	26 - 43 MPa	65 MPa	32 MPa	53 MPa	40 - 85 MPa
Stiffness ?	5 / 10	1 / 10	7.5 / 10	10 / 10	5 / 10	5 / 10
Durability ?	8 / 10	9 / 10	4 / 10	7 / 10	8 / 10	10 / 10
Maximum Service Temperature ?	98 °C	60 - 74 °C	52 °C	100 °C	73 °C	80 - 95 °C
Coefficient of Thermal Expansion ?	90 µm/m-°C	157 µm/m-°C	68 µm/m-°C	80 µm/m-°C	60 µm/m-°C	95 µm/m-°C
Density ?	1.04 g/cm^3	1.19 - 1.23 g/cm^3	1.24 g/cm^3	1.03 - 1.04 g/cm^3	1.23 g/cm^3	1.06 - 1.14 g/cm^3
Price (per kg) ?	$10 - $40	$30 - $70	$10 - $40	$24 - $32	$20 - $60	$25 - $65

Filament material characteristics

Fused Filament Fabrication (FFF)

PLA

plant-based renewable polymer
low volatiles, fine particles
easiest to print
glass transition ~60C
more brittle

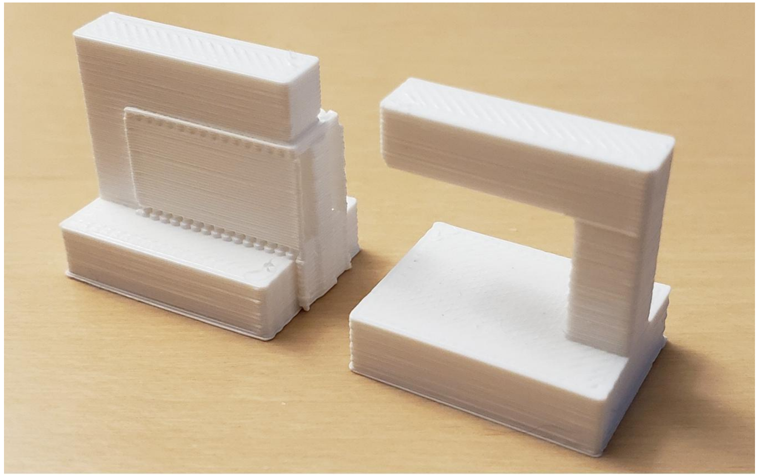
PETG

oil-based recyclable polymer
low volatiles, fine particles
glass transition ~80C
tougher, better UV resistance

store dry (silica gel sachets)

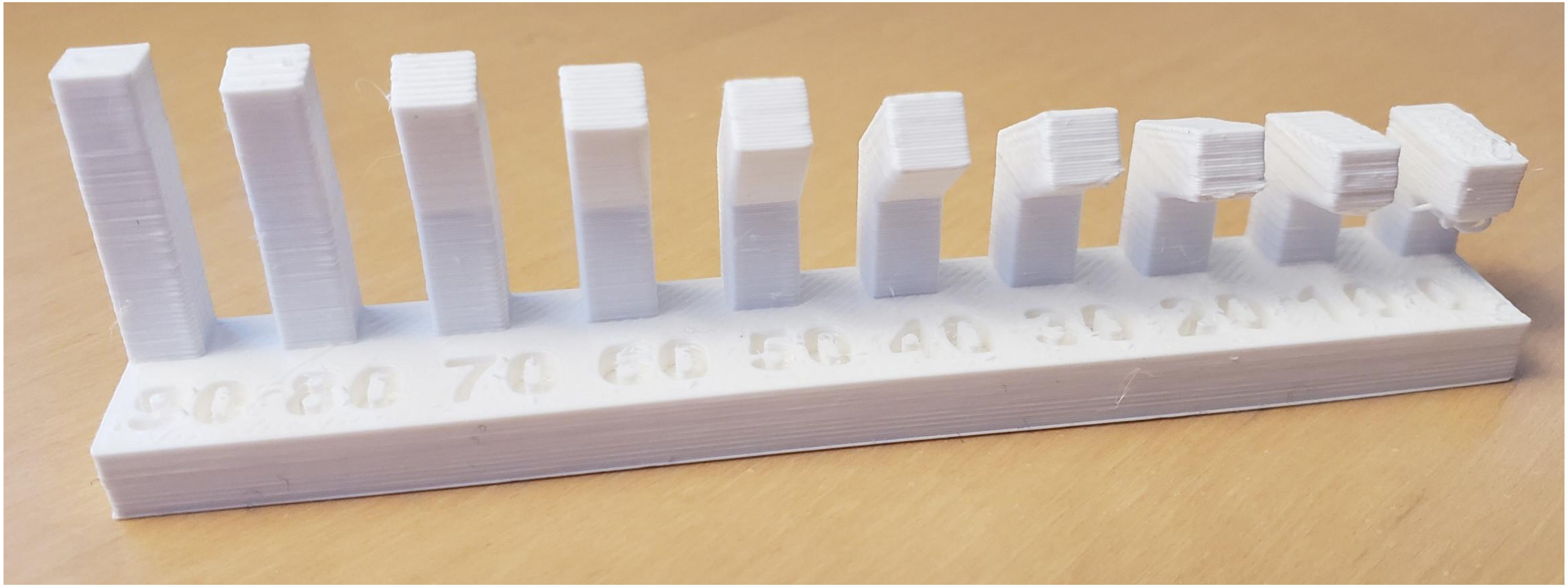
Filament material characteristics

Fused Filament Fabrication (FFF) Design Rules



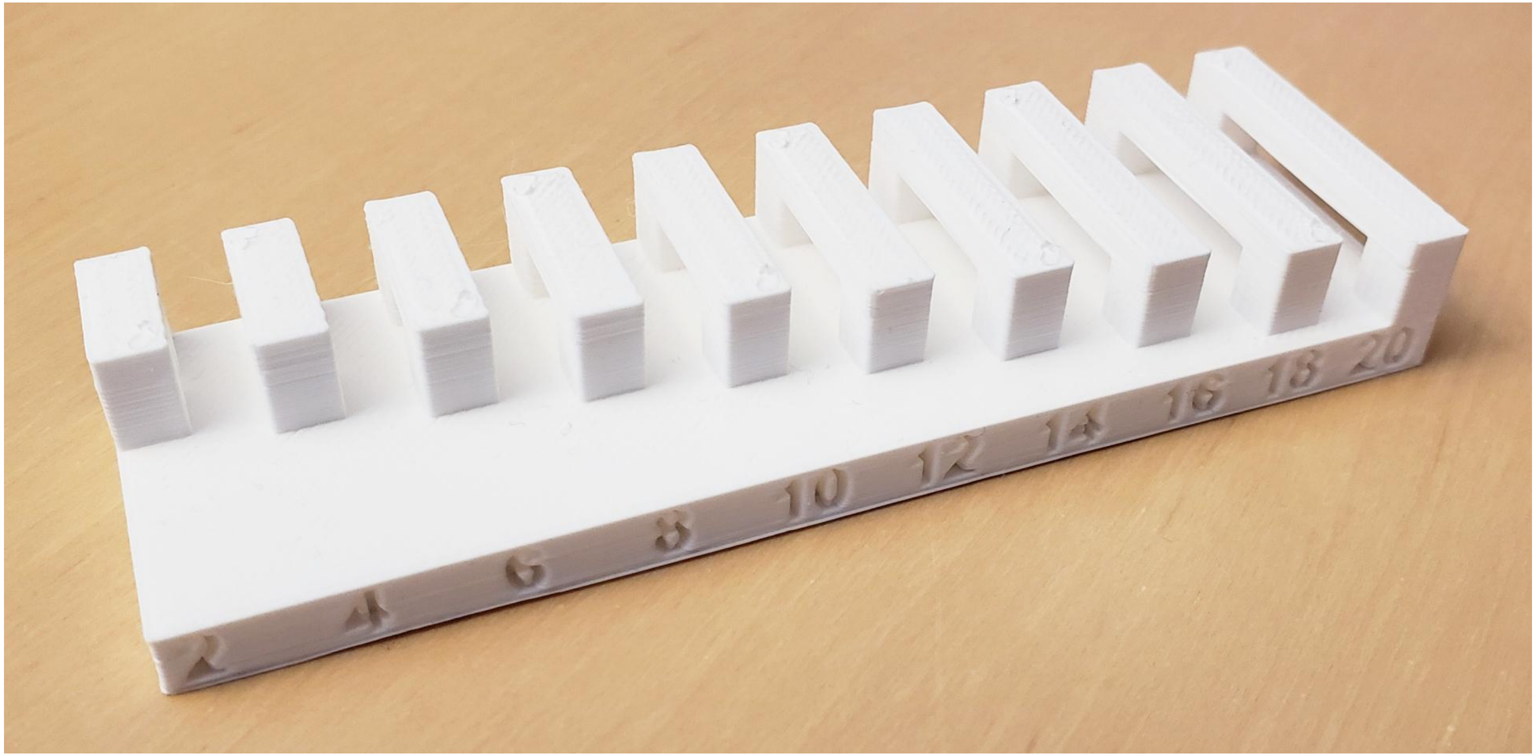
Overhangs need support

Fused Filament Fabrication (FFF) Design Rules



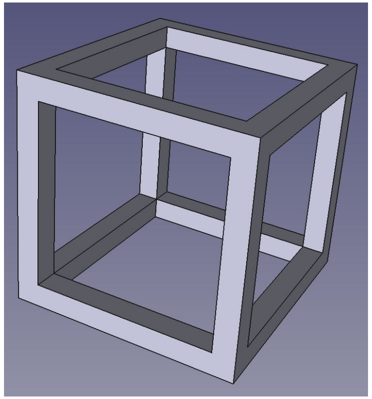
Overhangs sometimes need support - angle

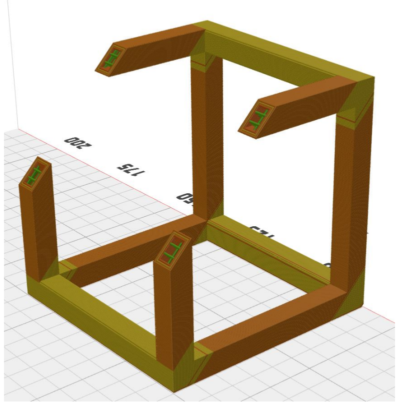
Fused Filament Fabrication (FFF) Design Rules

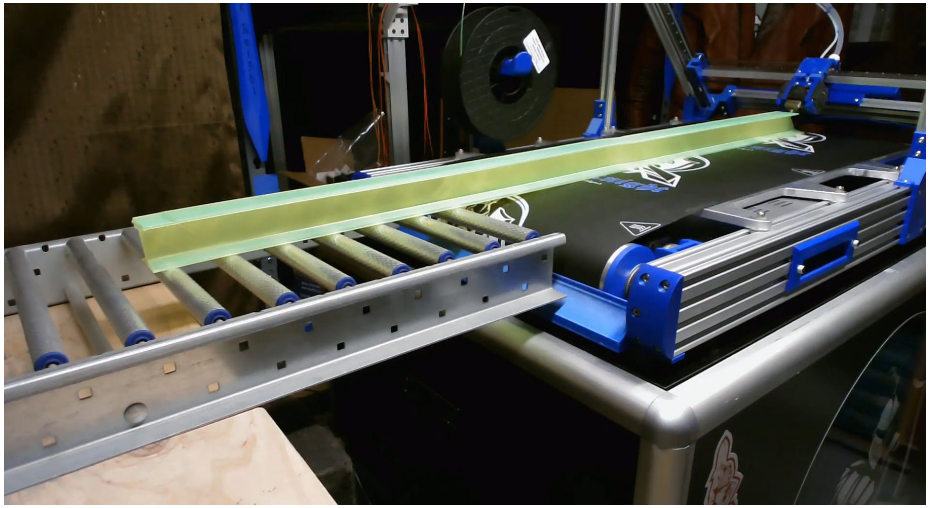


Overhangs sometimes need support - bridging

Fused Filament Fabrication (FFF)

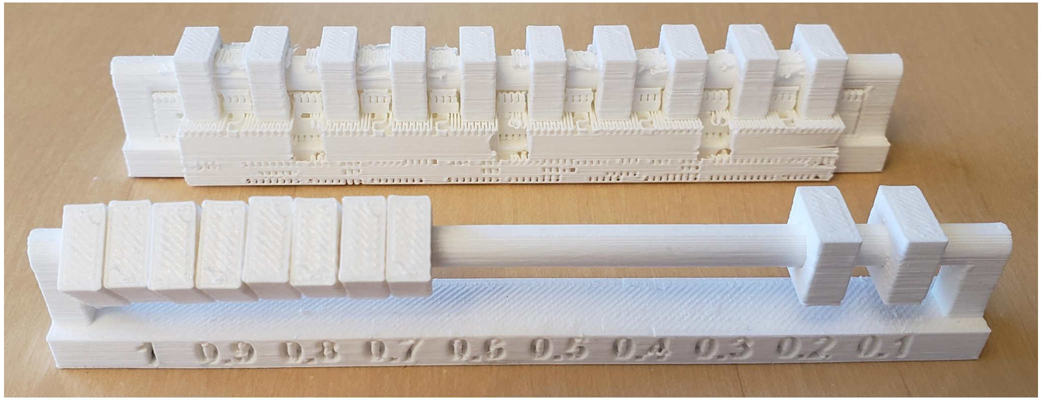


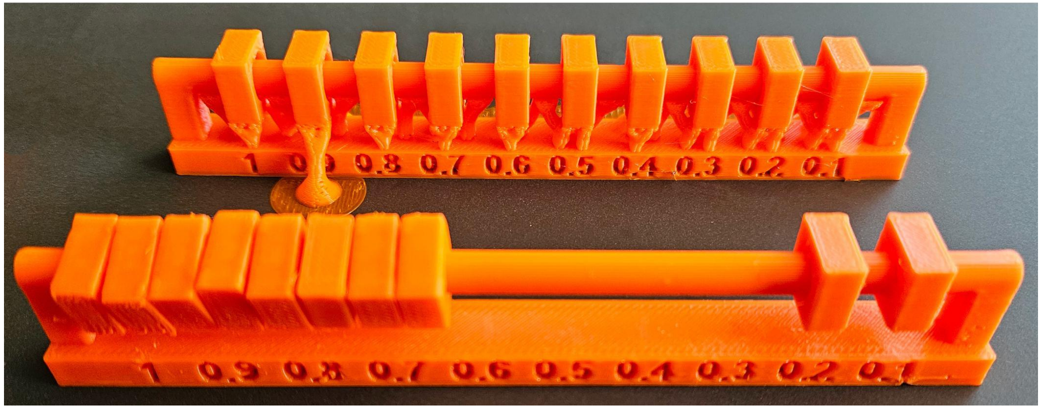




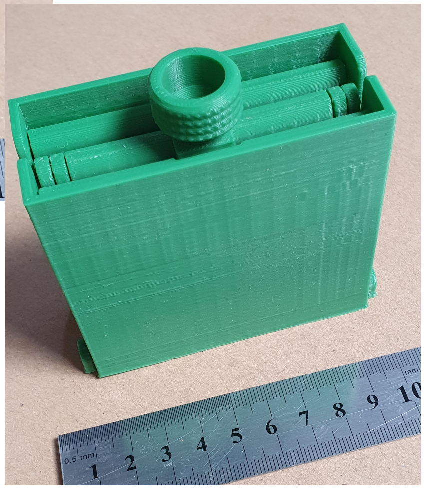
Thinking about overhangs and mass production gave a clever FFF 3D printer

Fused Filament Fabrication (FFF) Design Rules



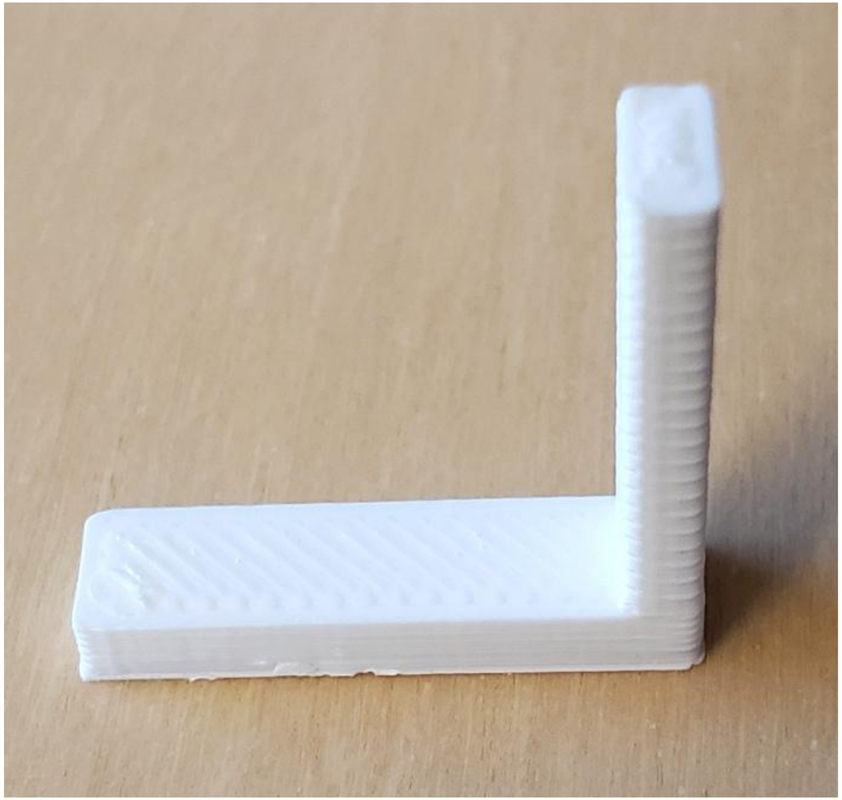


Clearances



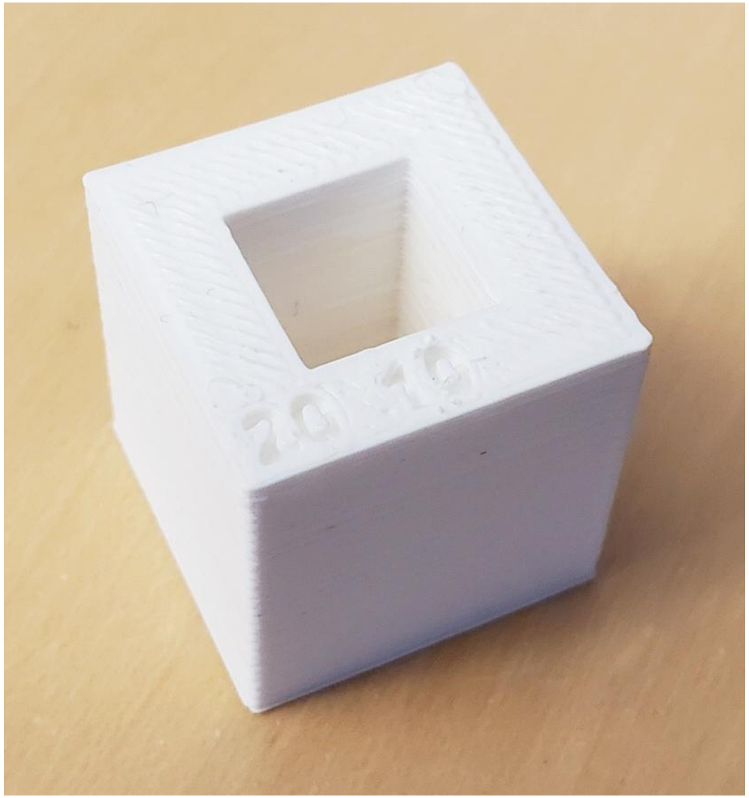
One shot

Fused Filament Fabrication (FFF) Design Rules



Anisotropy

Fused Filament Fabrication (FFF) Design Rules



Dimensional accuracy

Fused Filament Fabrication (FFF) Design Rules

Surface finish

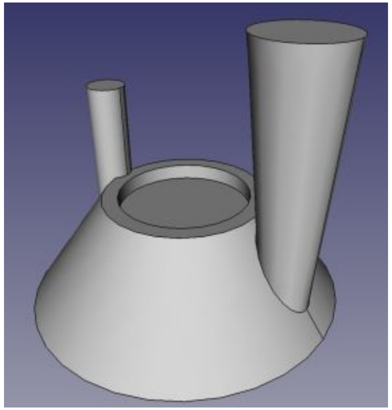
Fused Filament Fabrication (FFF) Design Rules

Infill

Fused Filament Fabrication (FFF)

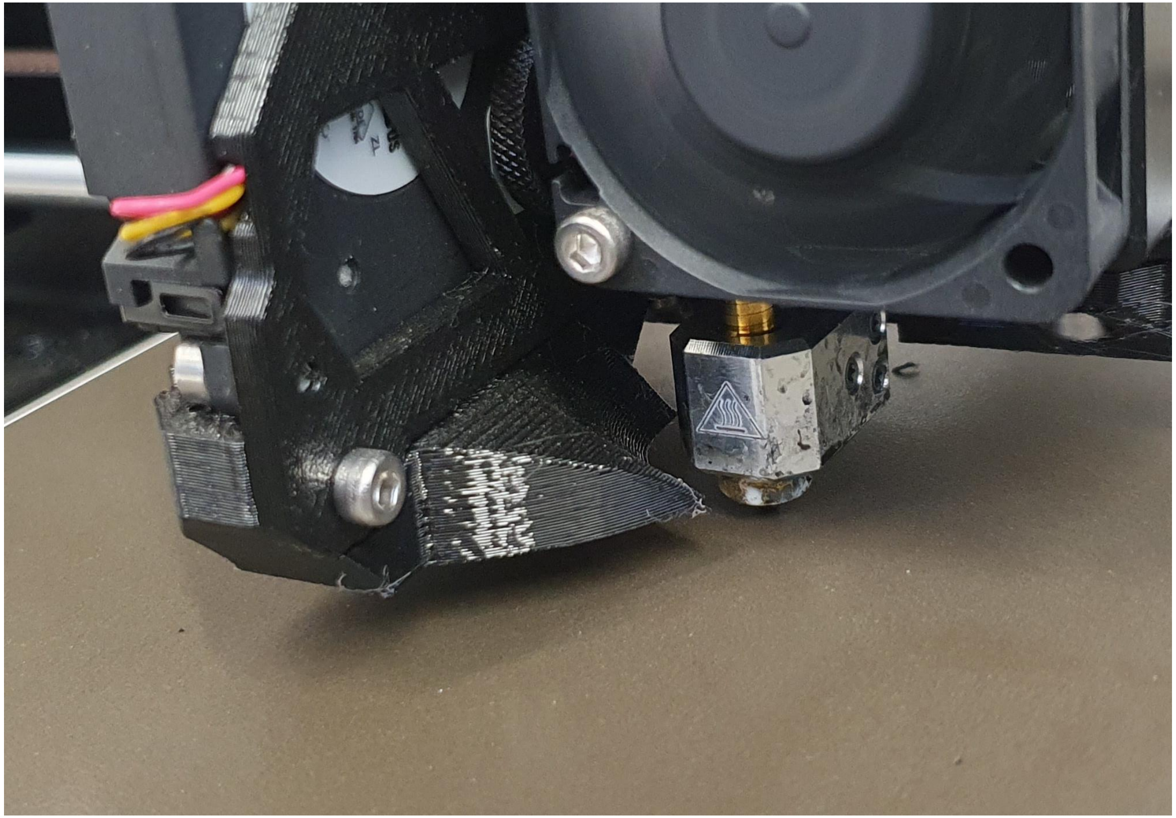
'cold' riser

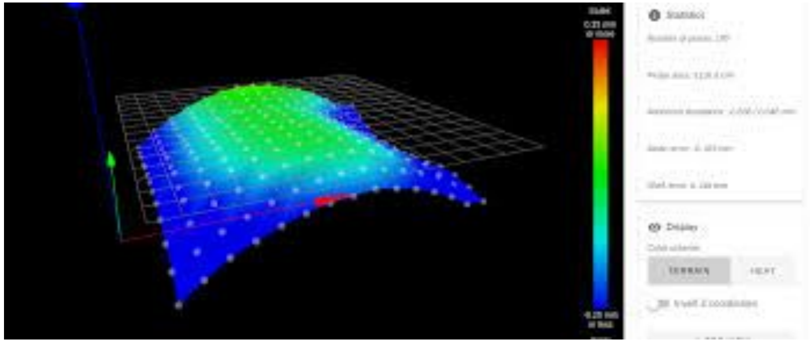
'hot' riser



Free-flow infill pattern and another clever idea

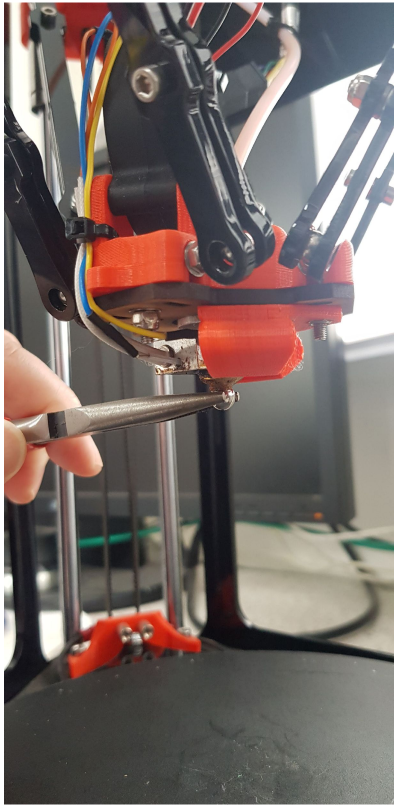
Fused Filament Fabrication (FFF)

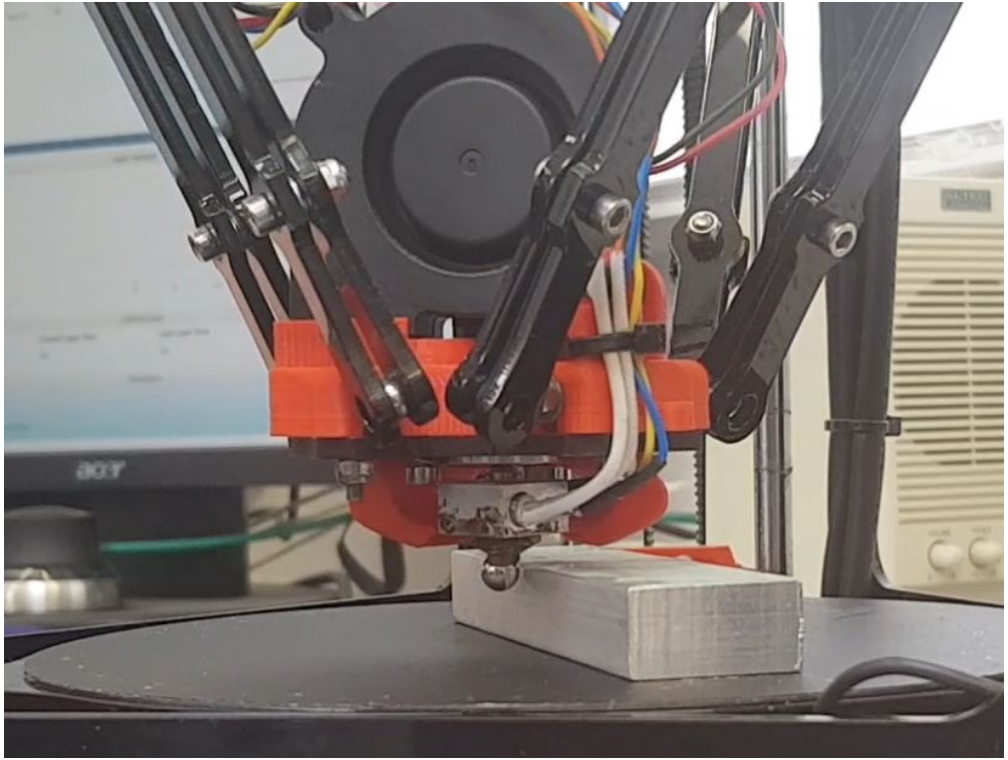




Bed levelling

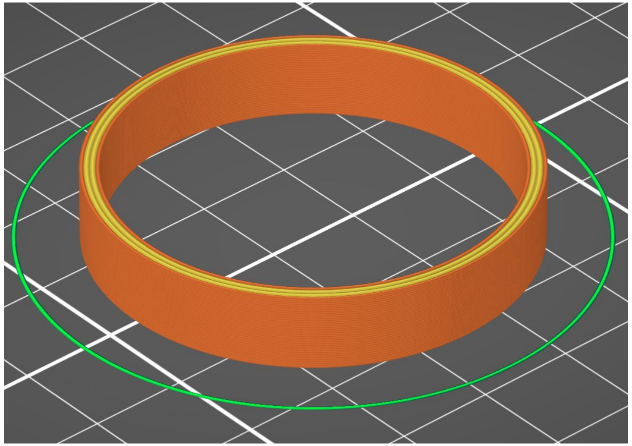
Scanning and probing



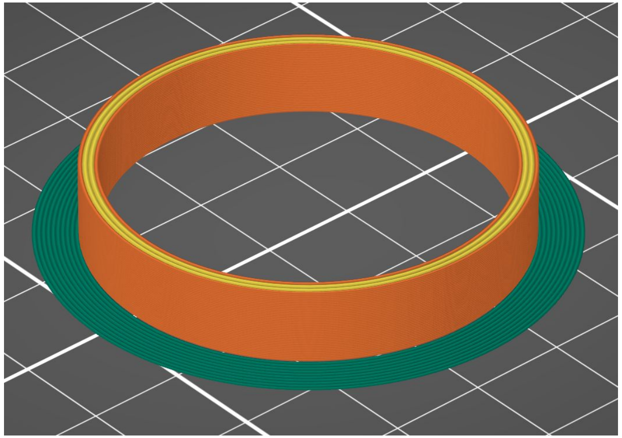


Turning a 3D printer into a coordinate measuring machine

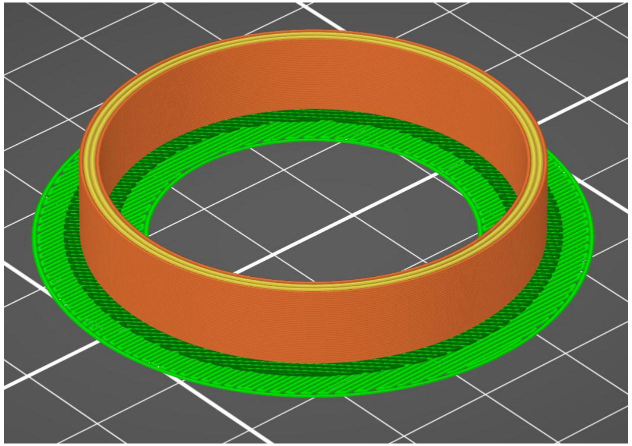
Fused Filament Fabrication (FFF)



skirt

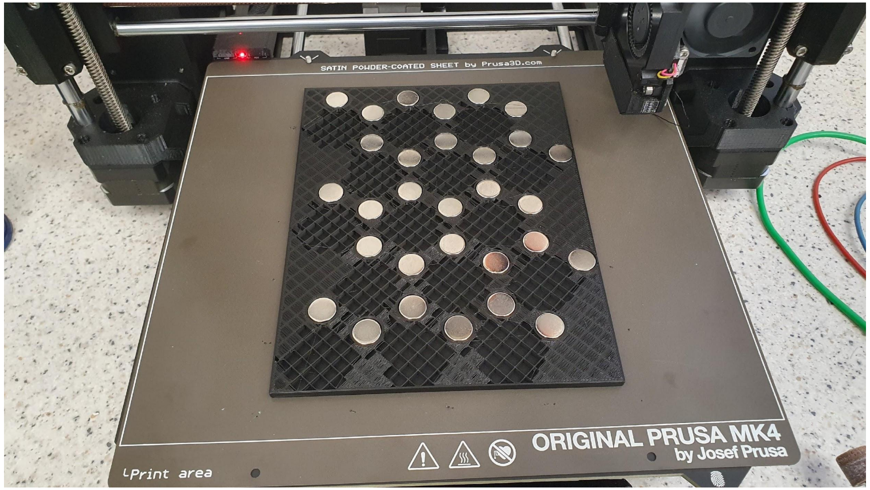


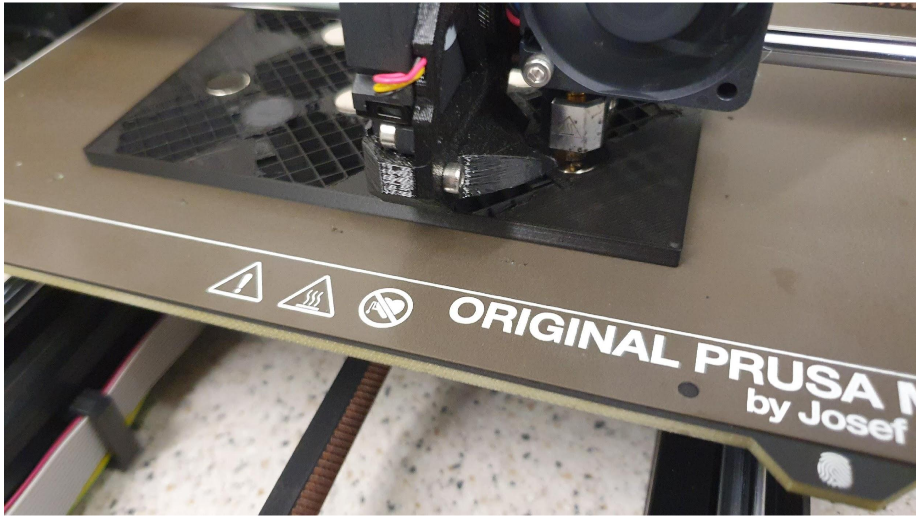
brim



raft

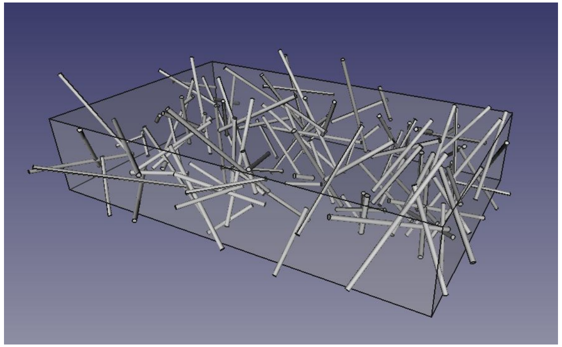
Fused Filament Fabrication (FFF)

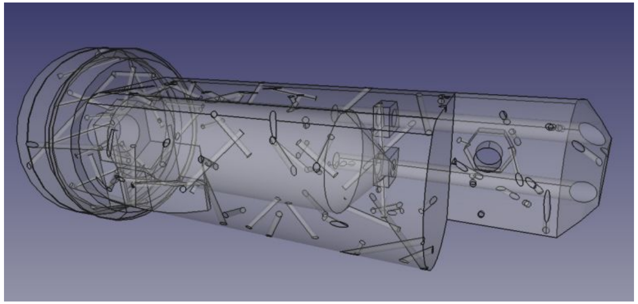


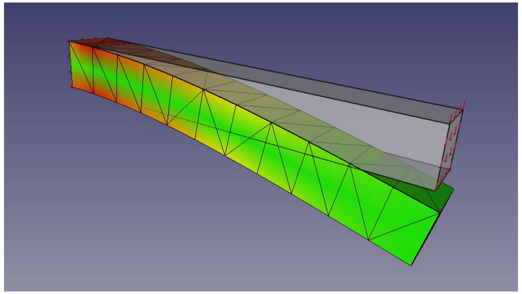


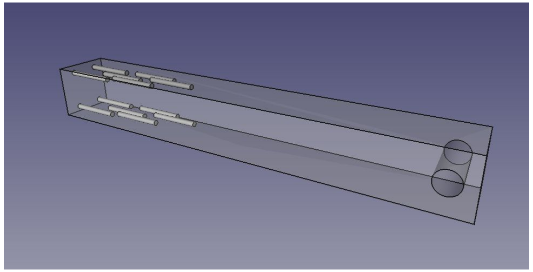
Pause and insert

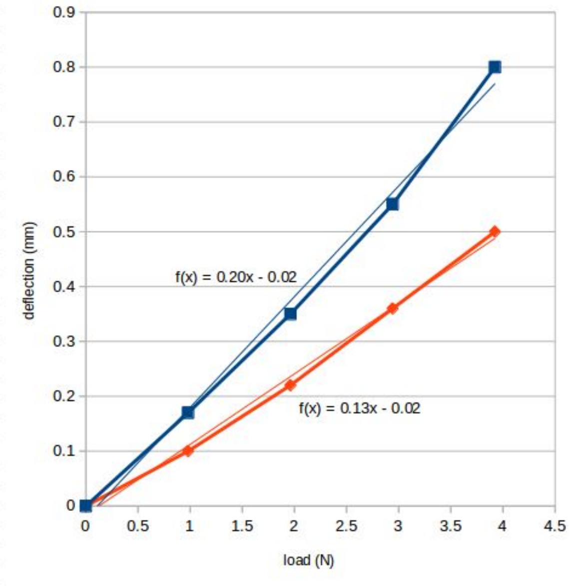
Fused Filament Fabrication (FFF)











Forcing internal structure within the infill

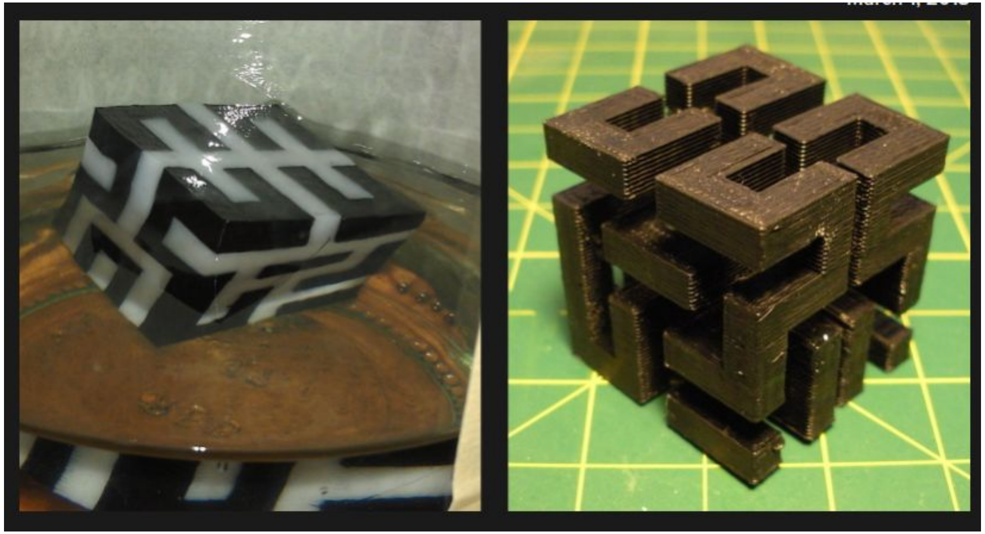
Multi-material Fused Filament Fabrication (FFF)

- Colours
- Hard plastic and rubber-like plastic
- Combine insulators (e.g. PLA) and conductors

Copper: $17 \times 10^{-7}\ \Omega \cdot cm$

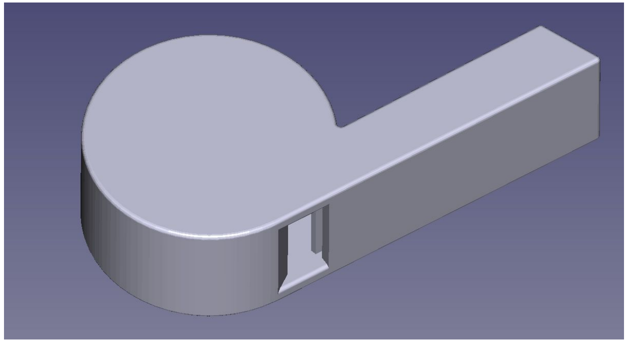
Conducting filament: $15\ \Omega \cdot cm$ (ten million times worse)

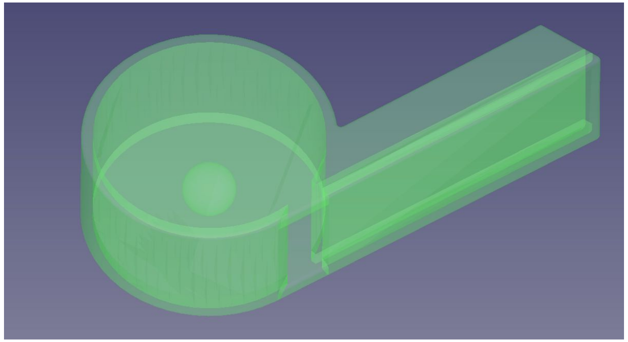
Multi-material Fused Filament Fabrication (FFF)

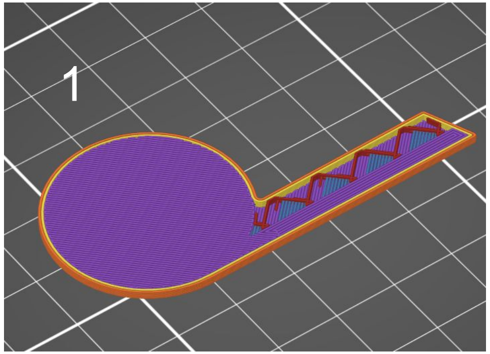


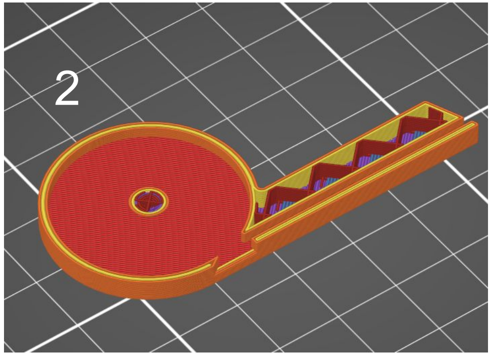
Soluble support

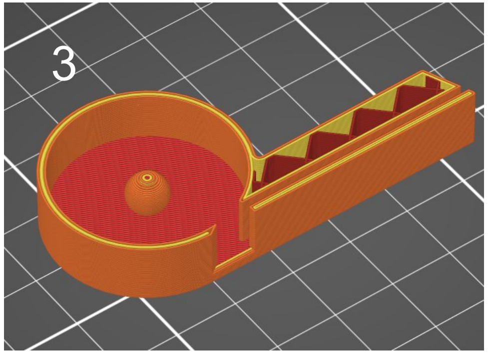
3D printing – slicing the *STL file** into layers

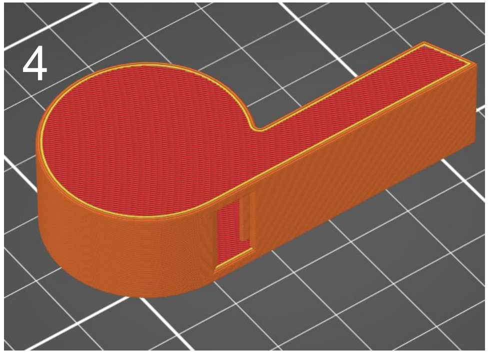








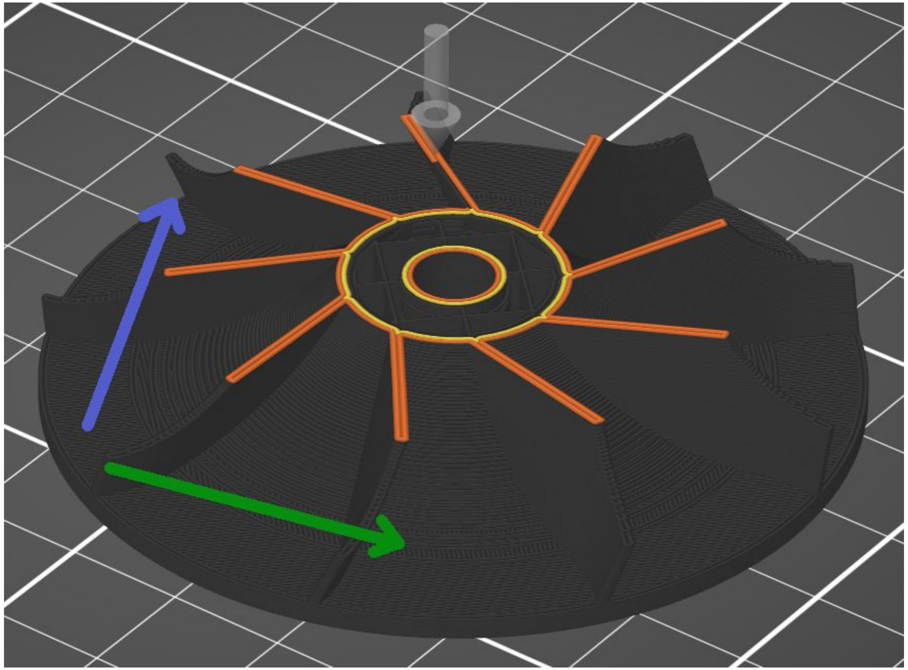




Generates *G-Code file* to control the printer

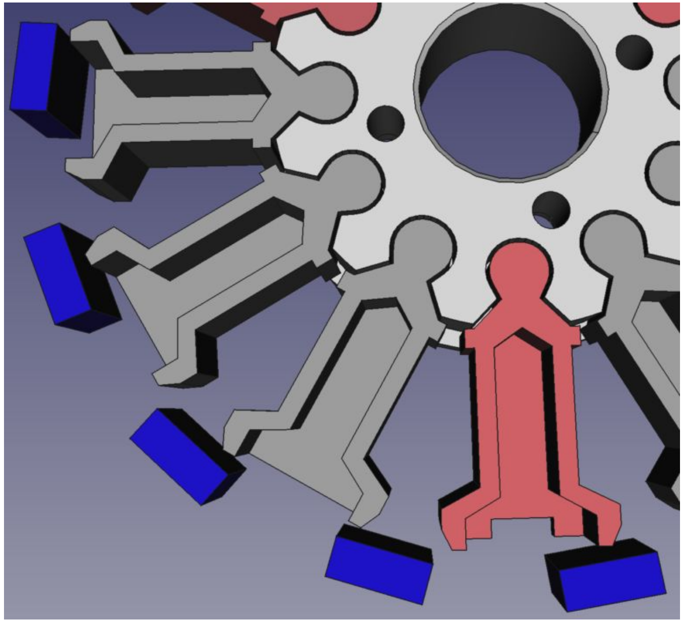
* later below

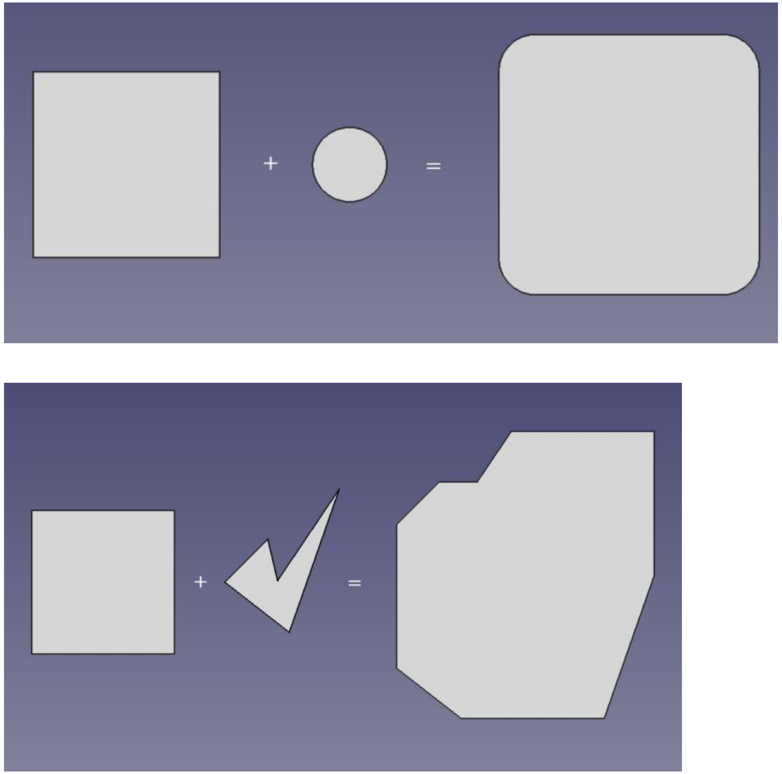
G-Code file to control an FFF printer



G1 X0 Y0 Z3 F2400 ; move to the X=0, Y=0, Z=3 position on the bed at a speed of 2400 mm/min
G1 Z0.2 F1200 ; move the Z-axis to Z=0.2mm at a slower speed of 1200 mm/min
G1 X30 E10 F1800 ; push 10mm of filament into the nozzle while moving to the X=30 position at the same time

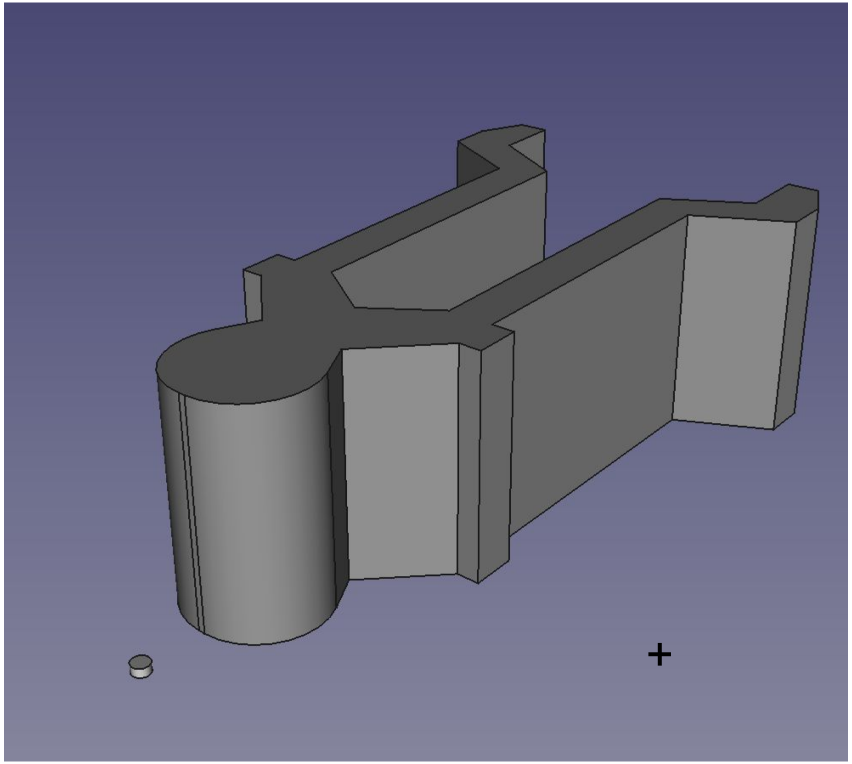
Fitting 3D printed parts together

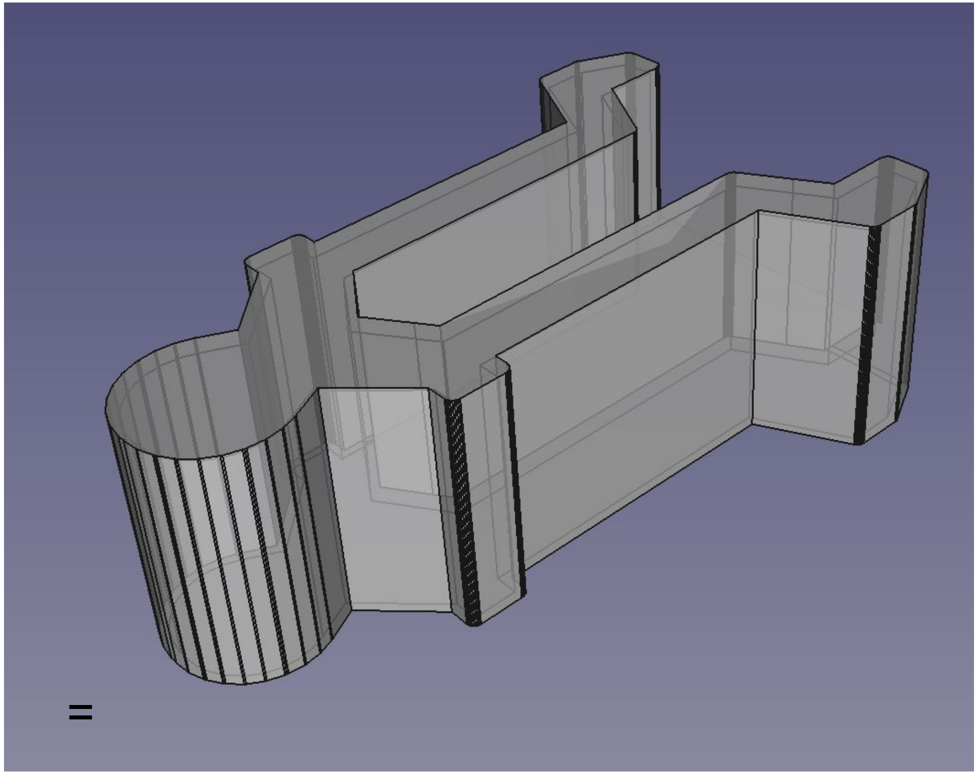




Minkowski sums

Fitting 3D printed parts together





Minkowski sums – OpenSCAD can do this (and it's in FreeCAD)

Keep the added shape AS SIMPLE AS POSSIBLE

Fused Filament Fabrication (FFF) post processing

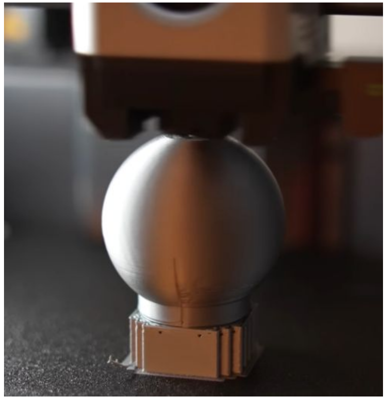
Painting - XTC-3D

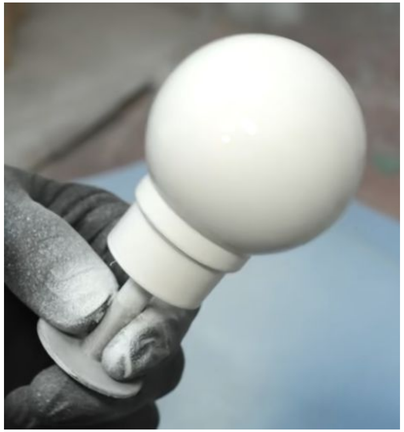
Fused Filament Fabrication (FFF) post processing

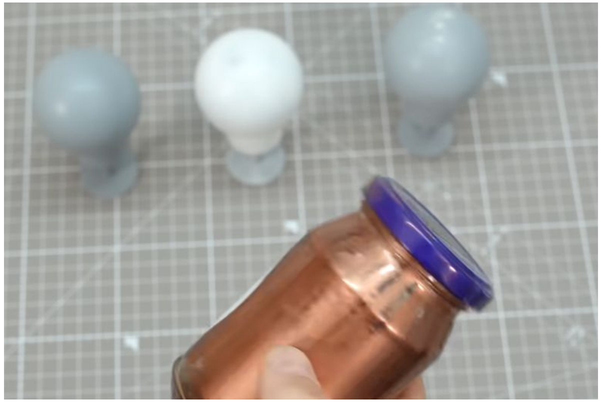
BEFORE **AFTER**

Solvent vapour

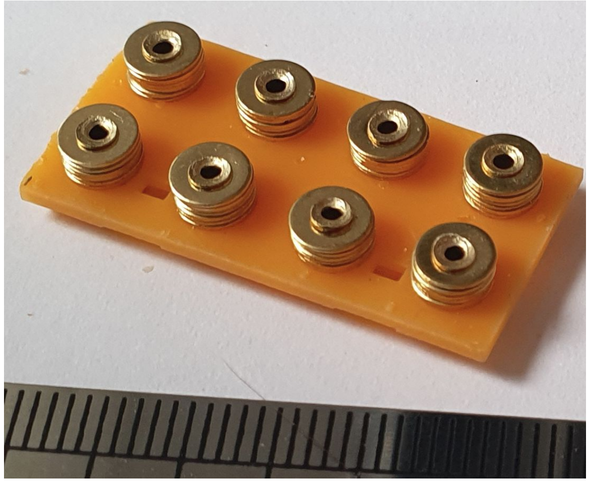
Fused Filament Fabrication (FFF) post processing





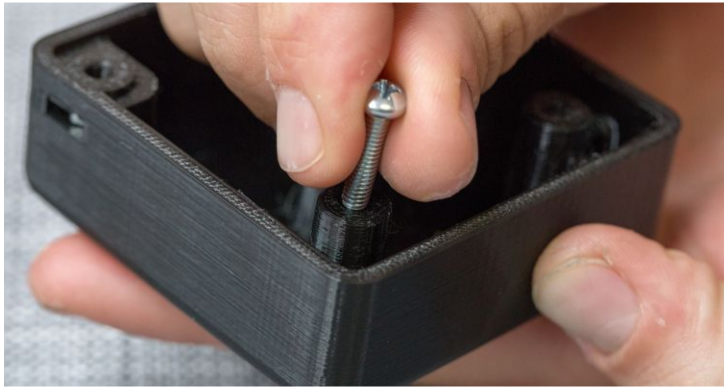


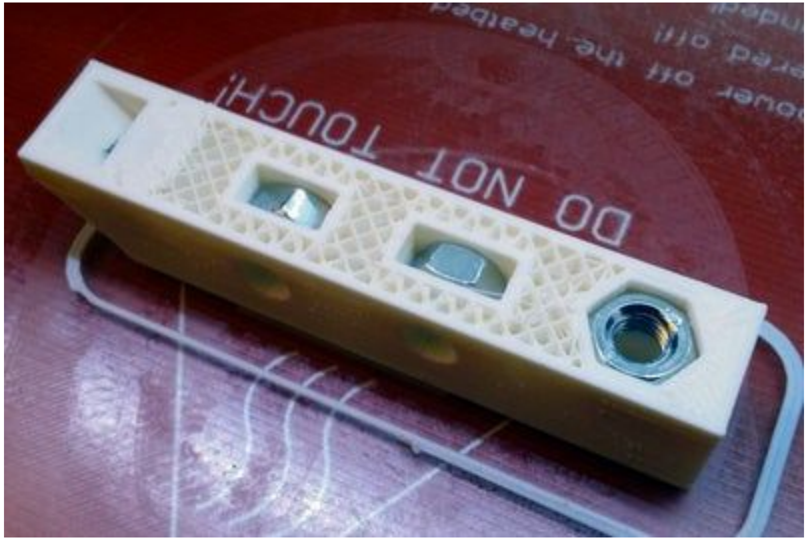
Electroplating



Fixings

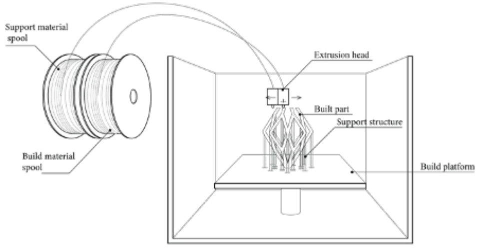
Rivets, screws and inserts



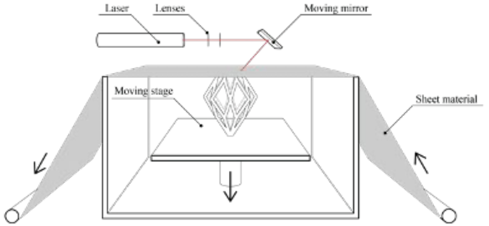


Additive Manufacturing Process Categories (ISO/ASTM)

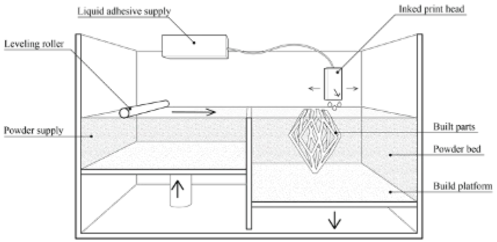
Material Extrusion



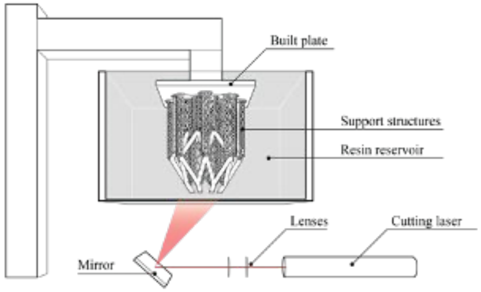
Sheet Lamination



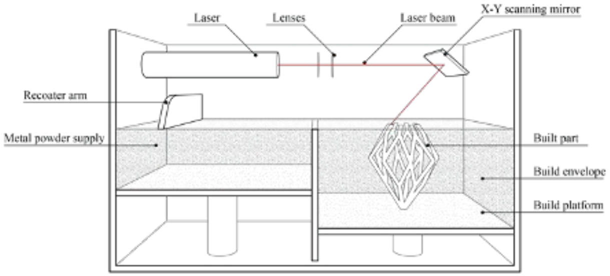
Binder Jetting



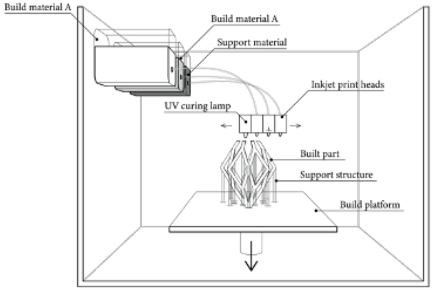
Vat Photopolymerization



Powder Bed Fusion



Material Jetting



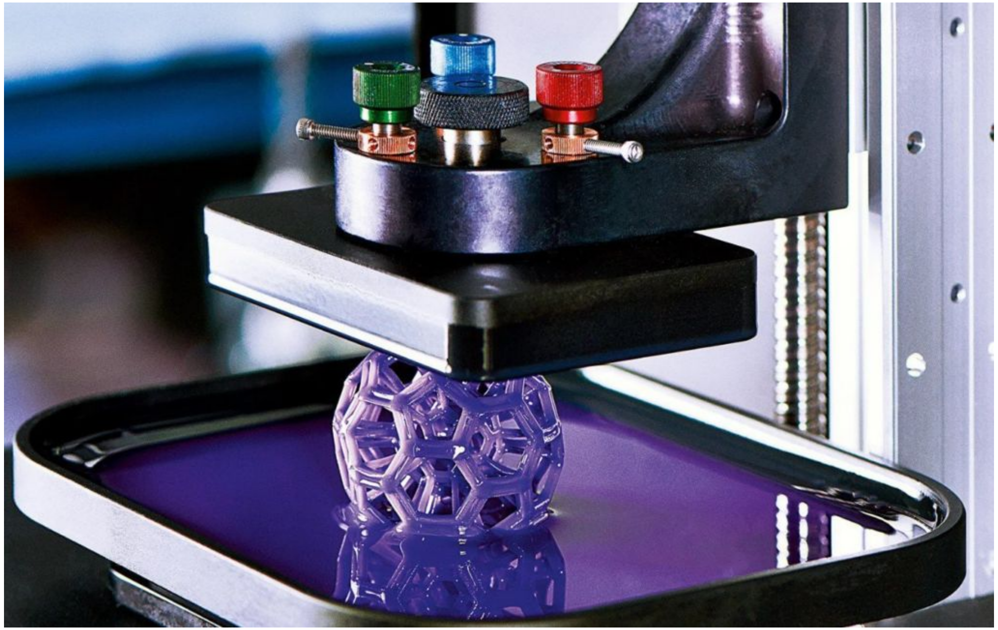
Classification based on ISO/ASTM 52900. illustration by Ohad Yaacov Meyuhas, Technion - Israel Institute of Technology (PhD research)

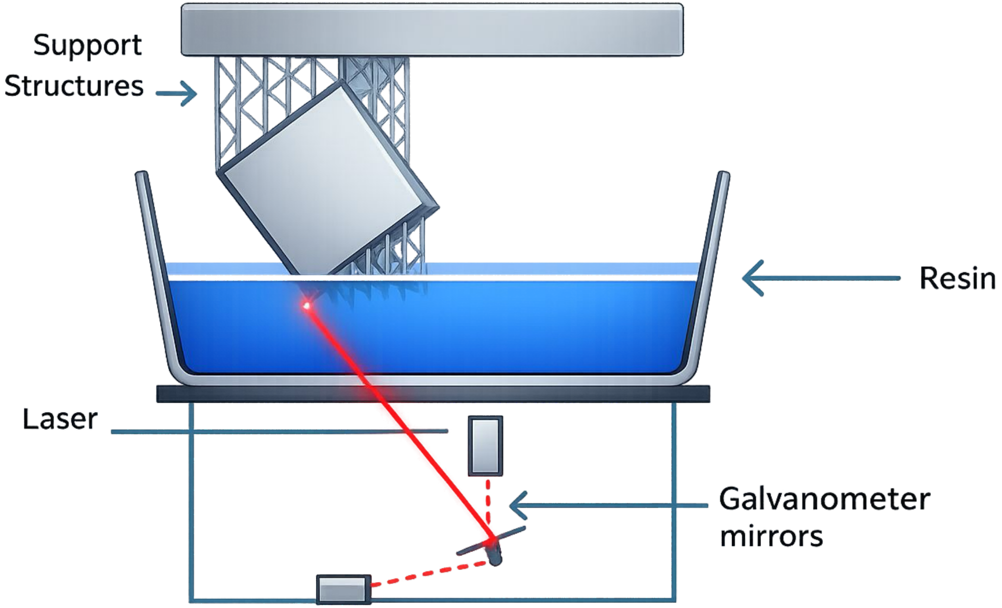
Thermoplastic vs. Thermoset

Thermoplastic pellets

Photopolymer resin

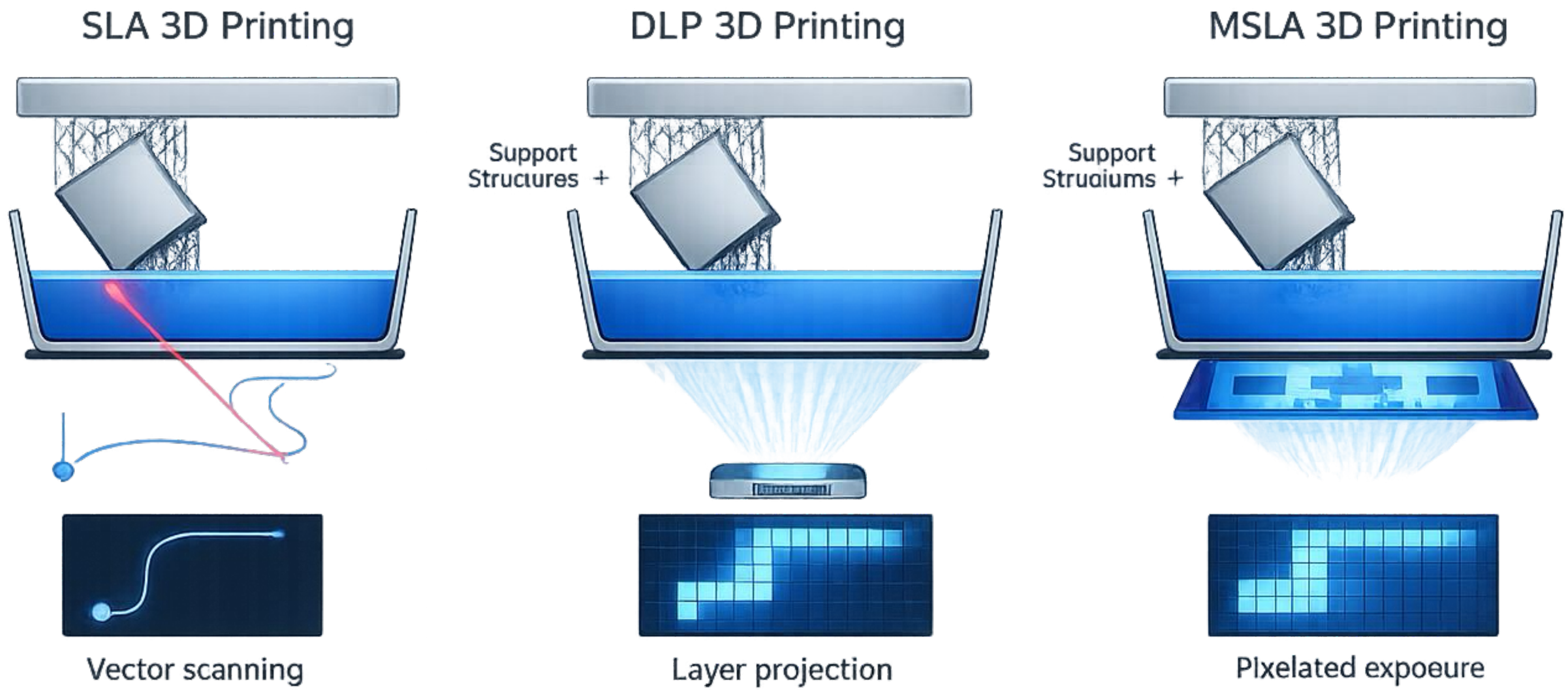
Stereolithography (SLA)





Resin is cured by a UV laser steered by galvanometer mirrors

Vat Photopolymerization SLA vs DLP vs MSLA



SLA maximizes accuracy, while DLP and MSLA enable faster layer exposure depending on system design.

Vat Photopolymerization Post-processing Workflow

IPA Ultrasonic wash

Rinse and Dry

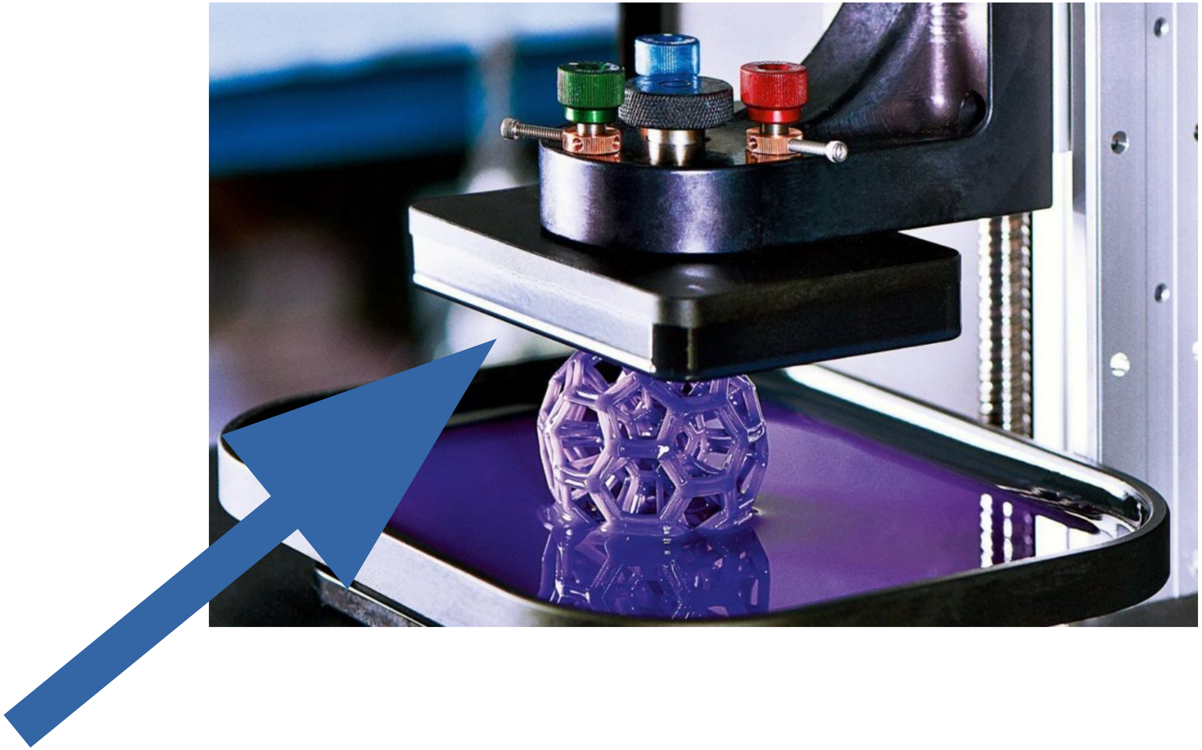
UV Cure

SLA maximizes accuracy, while DLP and MSLA enable faster layer exposure depending on system design.

Vat Photopolymerization Post-processing Workflow

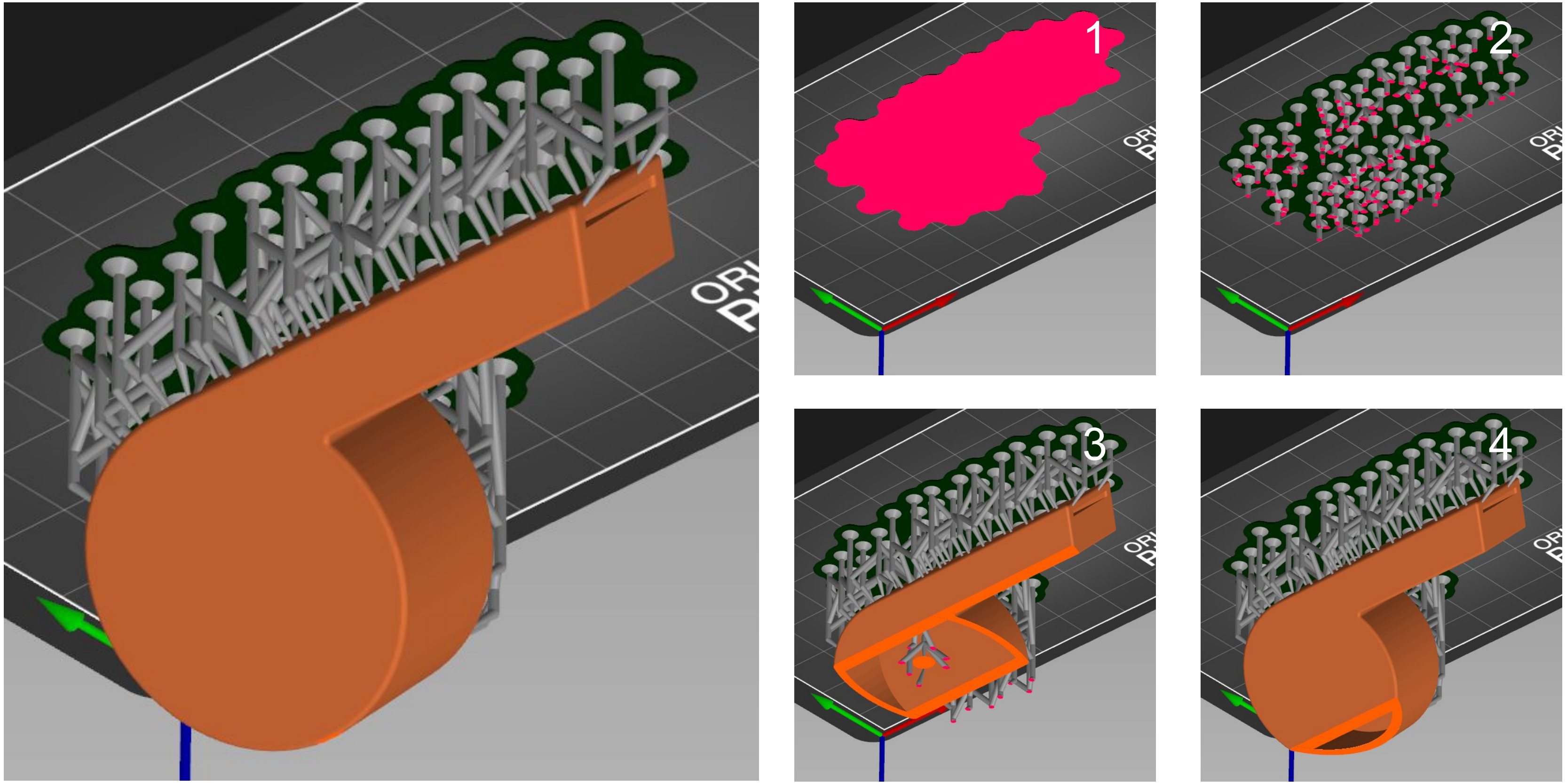
Post-processing is essential to remove uncured resin and achieve full material properties

Part Orientation and Support Strategy in Vat Photopolymerization



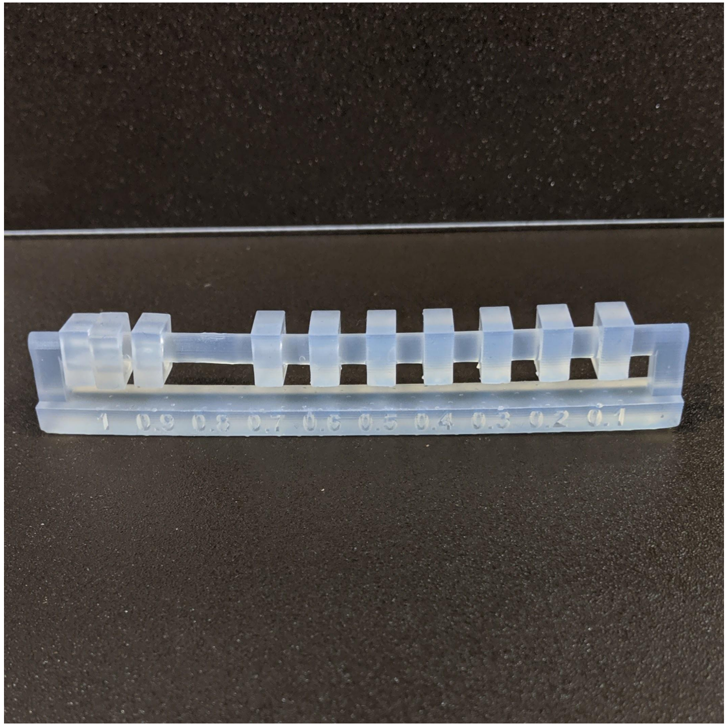
Imagine looking up at the build plate

Part Orientation and Support Strategy in Vat Photopolymerization



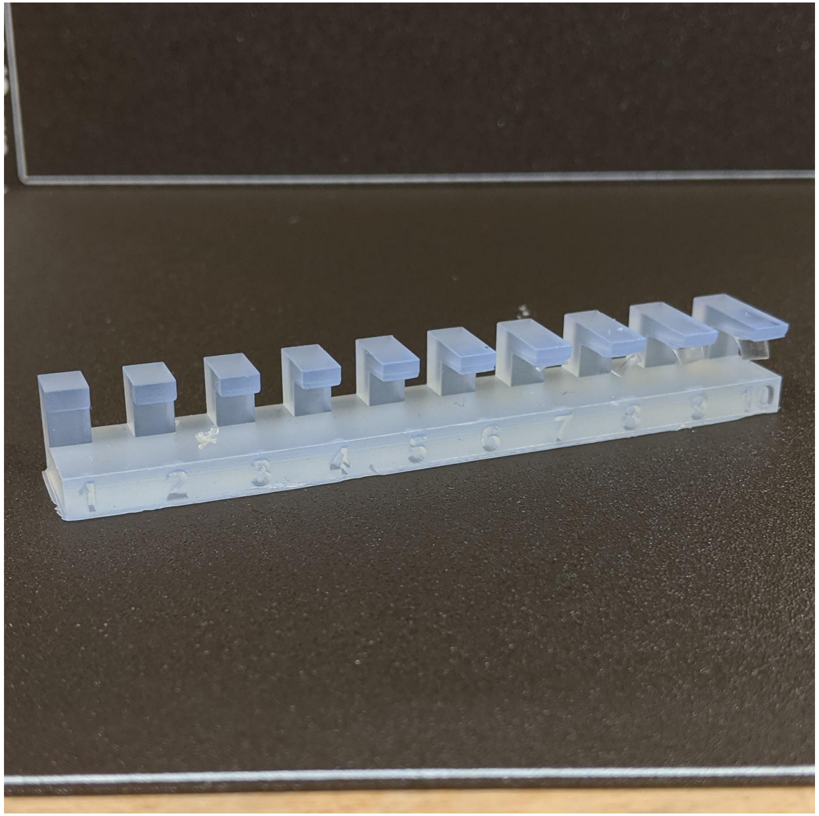
Orient the part (~30°-45°) to reduce peel forces, generate supports for overhangs, then slice

Stereolithography (SLA)



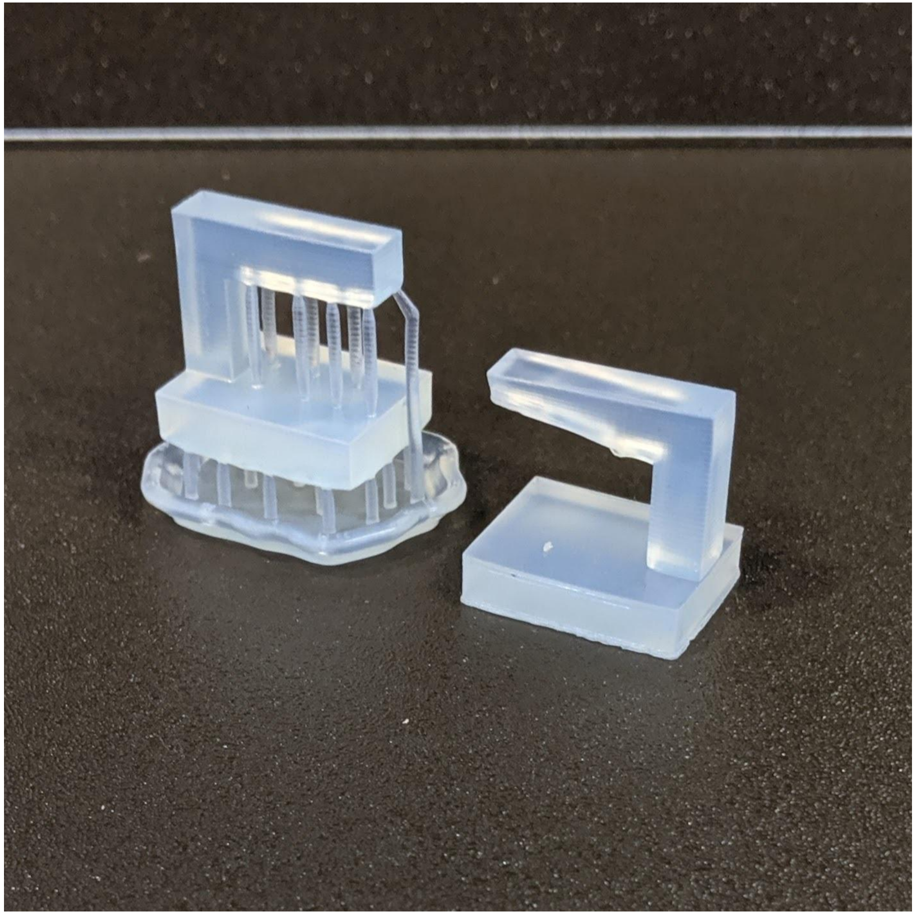
Clearance and support

Stereolithography (SLA)



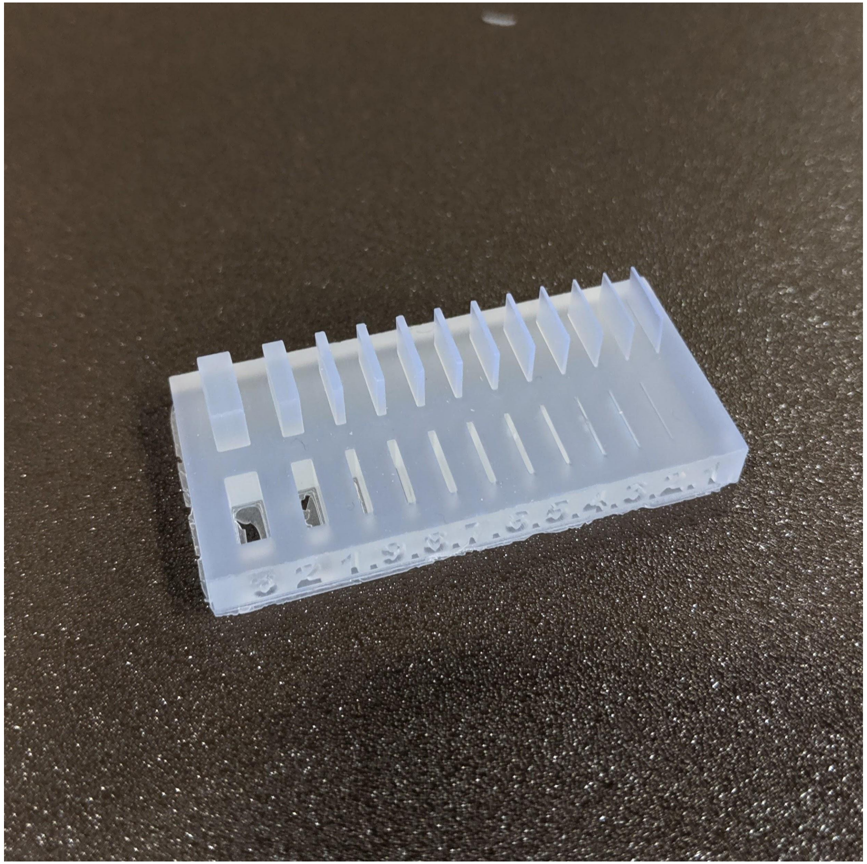
Support

Stereolithography (SLA)



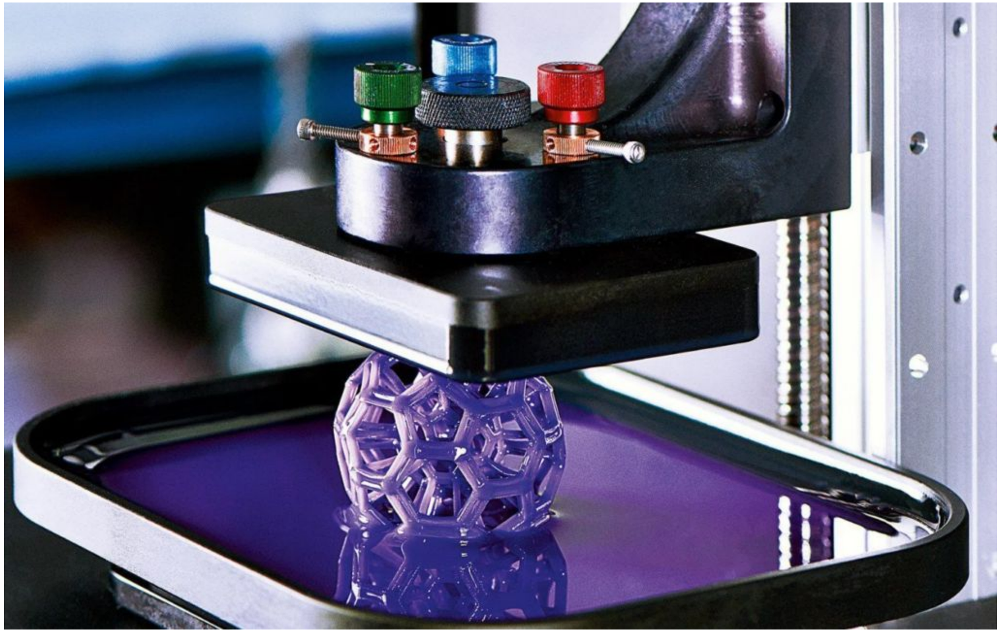
Support

Stereolithography (SLA)



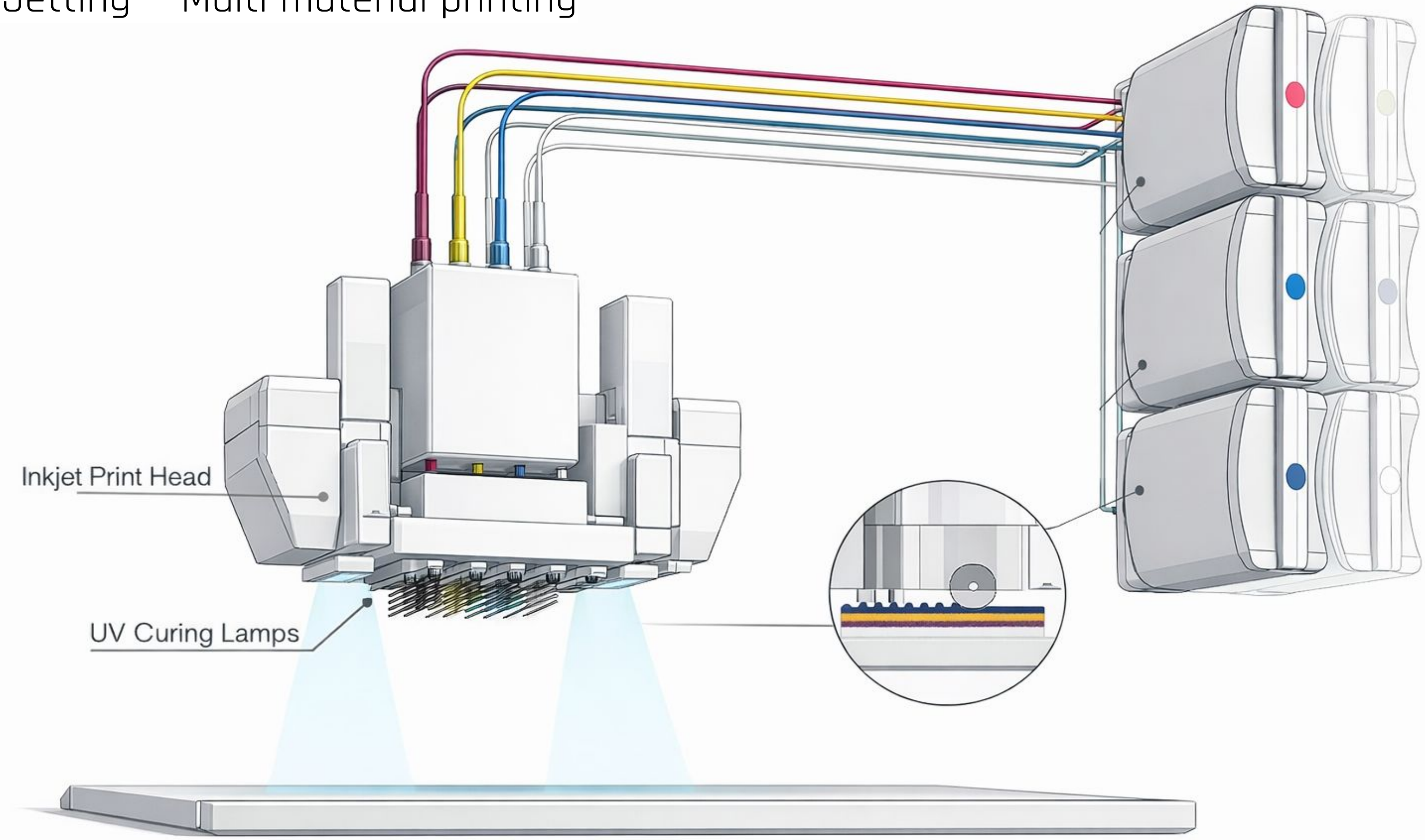
Detail and thickness

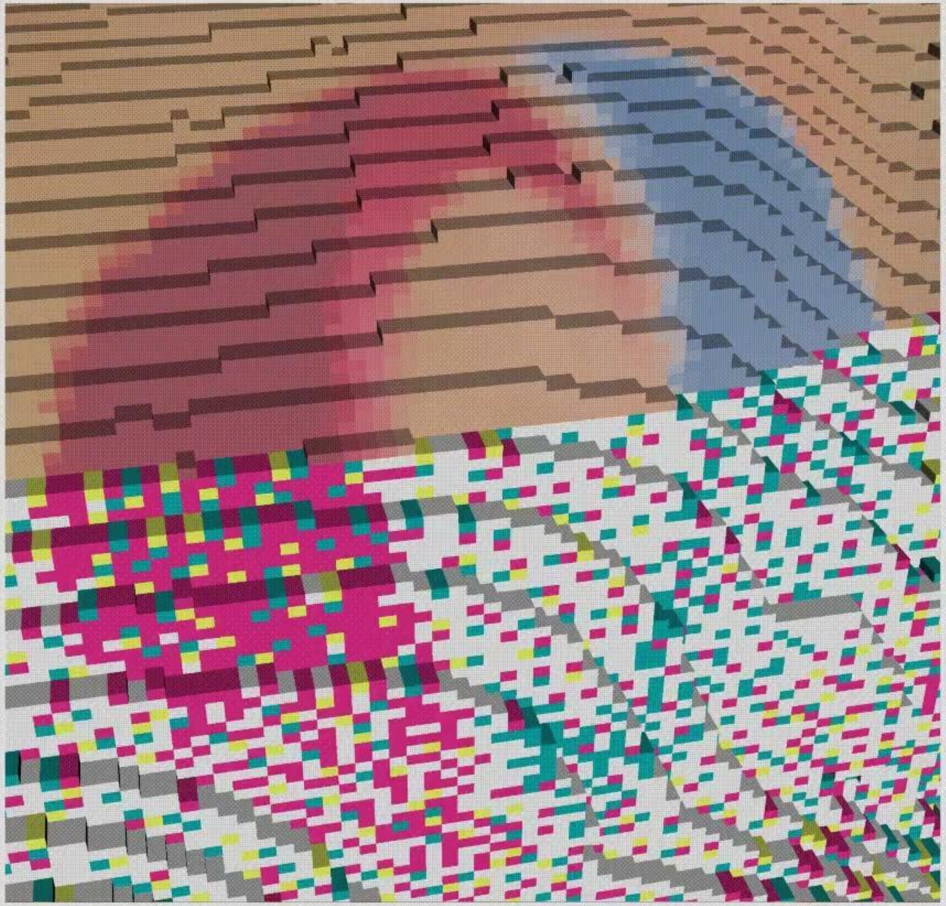
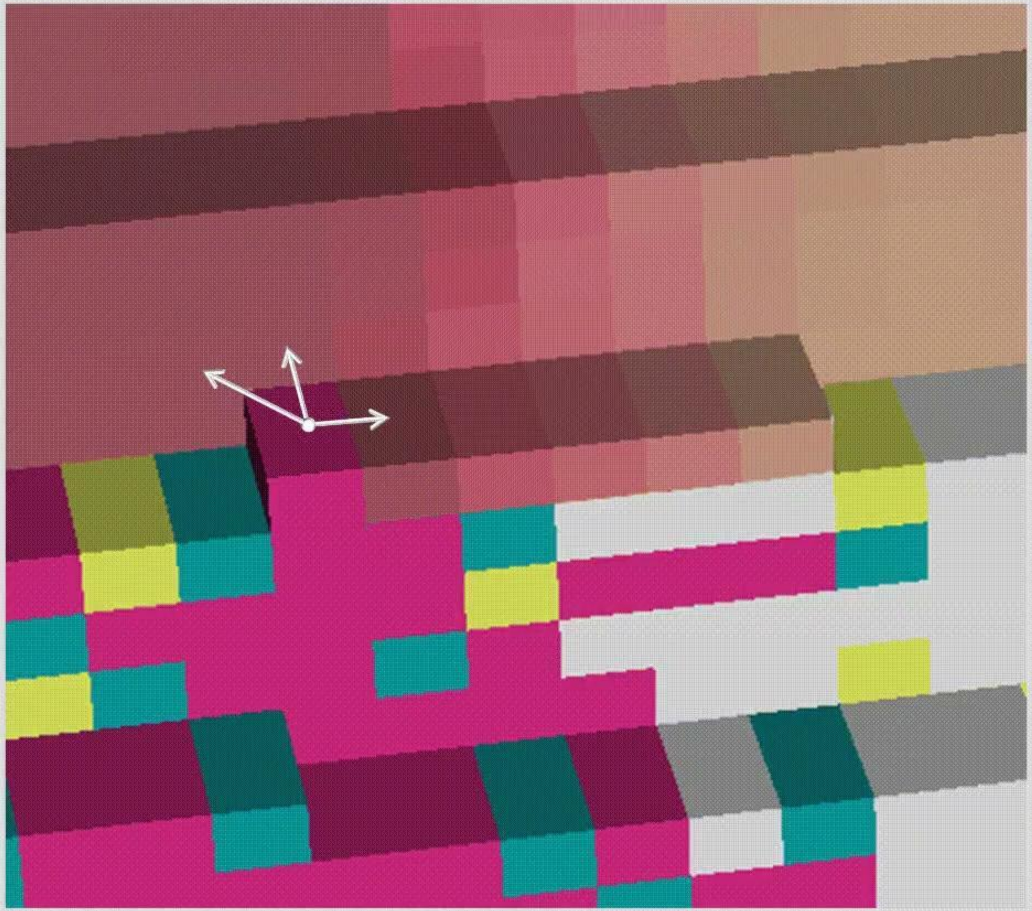
Vat Photopolymerization vs. Fused Filament Fabrication (FFF)



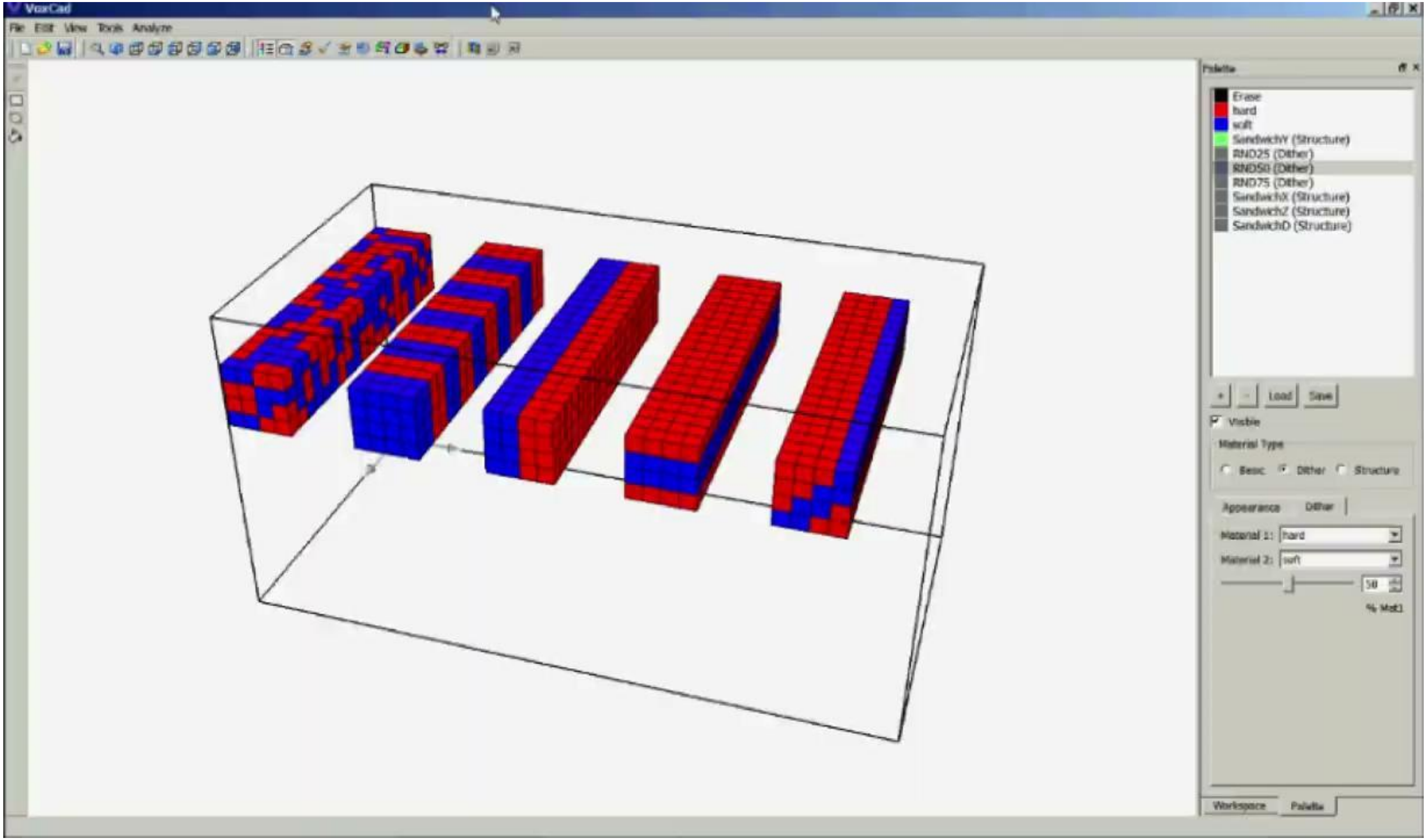
- Fine details and smooth surface finish
- Higher accuracy than most FFF prints
- High-temperature and specialty resins available
- Mono-material process
- Requires post-processing
- Internal cavities must be designed to avoid trapped resin
- Not recyclable

Material Jetting - Multi material printing



Error Diffusion with Translucent Materials | Fraunhofer Institute for Computer Graphics Research IGD | Dr. Philipp Urban



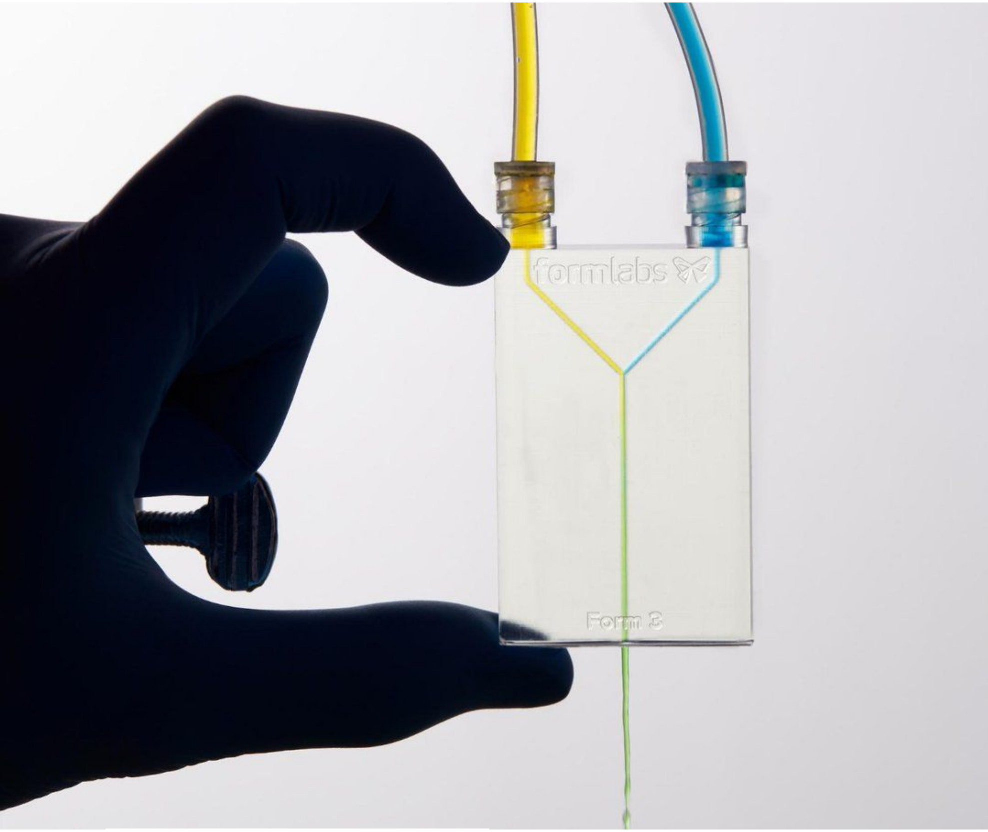
http://www.voxcad.com/ Mixtures of 50:50 (%) – Materials A & B -> different behavior

Medical applications

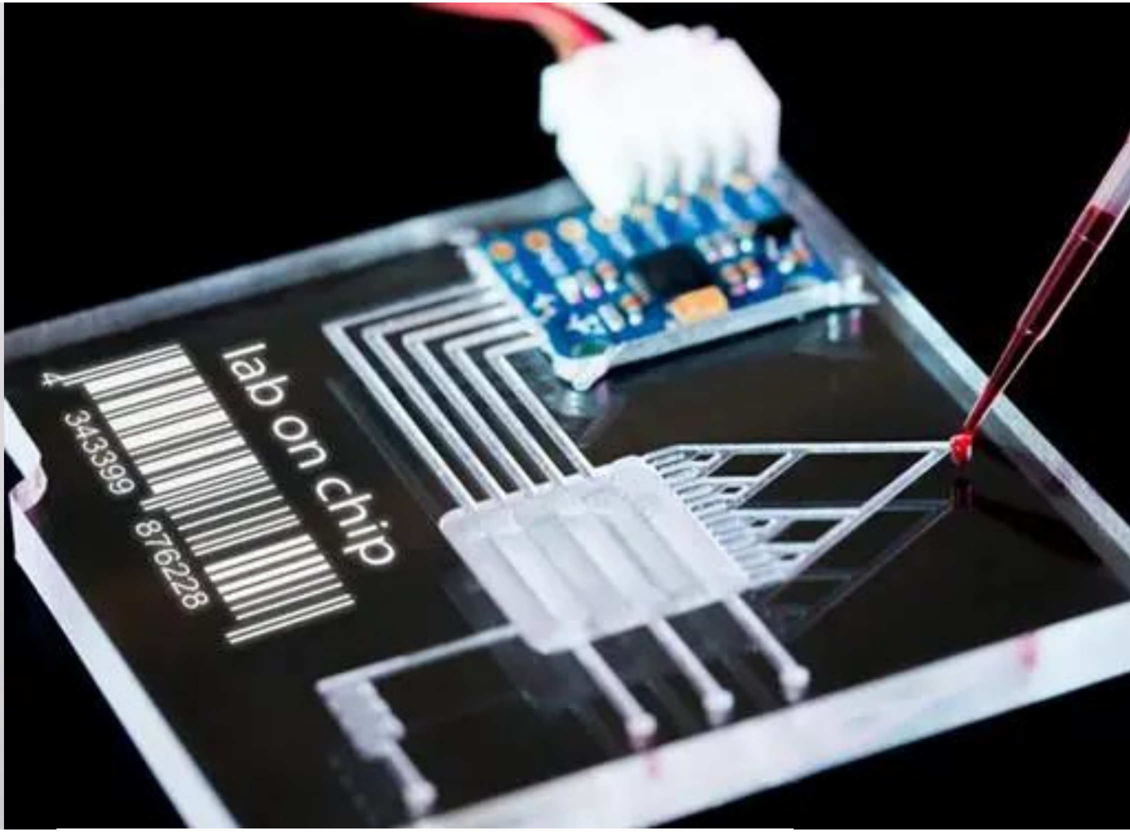
Pediatric heart model printed in tissue-like materials

Clinical case study: Sant Joan de Déu Hospital Barcelona, Stratasys

Beyond Prototyping: Functional AM

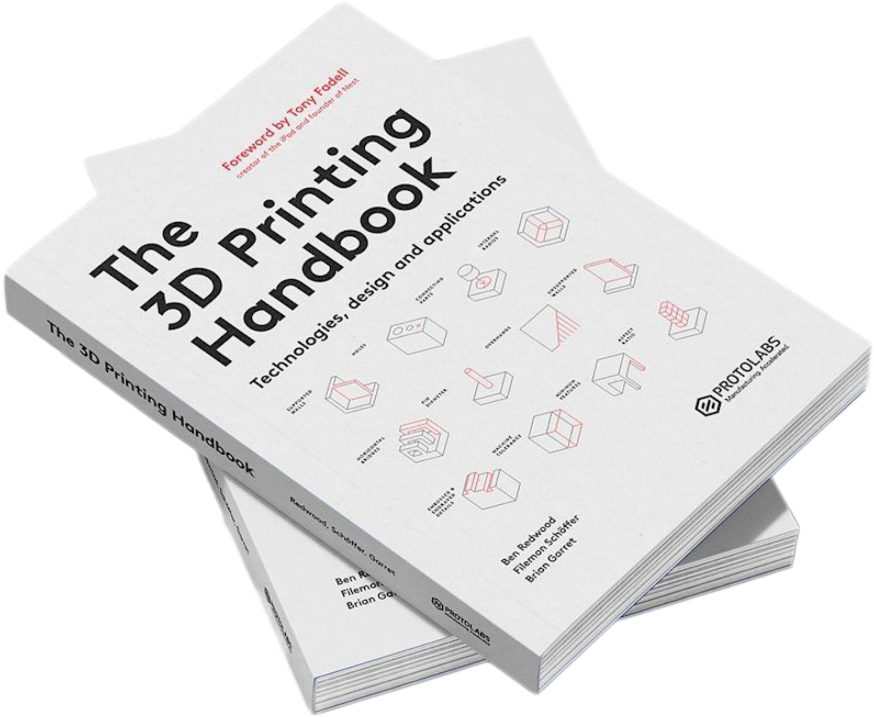


Formlabs, Desktop Millifluidics



Science / AAAS, Biosensors and Microarrays Come to Life

The 3D Printing Handbook:



The 3D Printing Handbook: Technologies, Design and Applications Book by Ben Redwood, Brian Garret, and Filemon Schöffer

File format

Feature	STL	OBJ	AMF	3MF
Primary Geometry	Triangular mesh	Polygon mesh	Mesh (curved support)	Mesh (extensible)
Supports Units	✖	✖	✔	✔
Color Support	✖	✔	✔	✔
Texture Support	✖	✔ (External MTL)	⚠️ Limited	✔
Multi-material	✖	⚠️ Limited	✔	✔
Material Definitions	✖	⚠️ External (MTL)	✔	✔
Metadata	✖	✖	✔	✔ (Rich)
Build Information	✖	✖	⚠️ Limited	✔
Compression	✖	✖	✔ (ZIP container)	✔ (ZIP container)
File Size Efficiency	⚠️ Medium (Binary)	✖ Large	⚠️ Medium (if Zipped)	✔ Small
Toolpath / G-code	✖	✖	✖	⚠️ Possible*

* 3MF supports toolpaths and G-code through specific extensions (like the Slice Extension).

Assignments

Group assignment:

- test the design rules for your 3D printer(s)

Individual assignment:

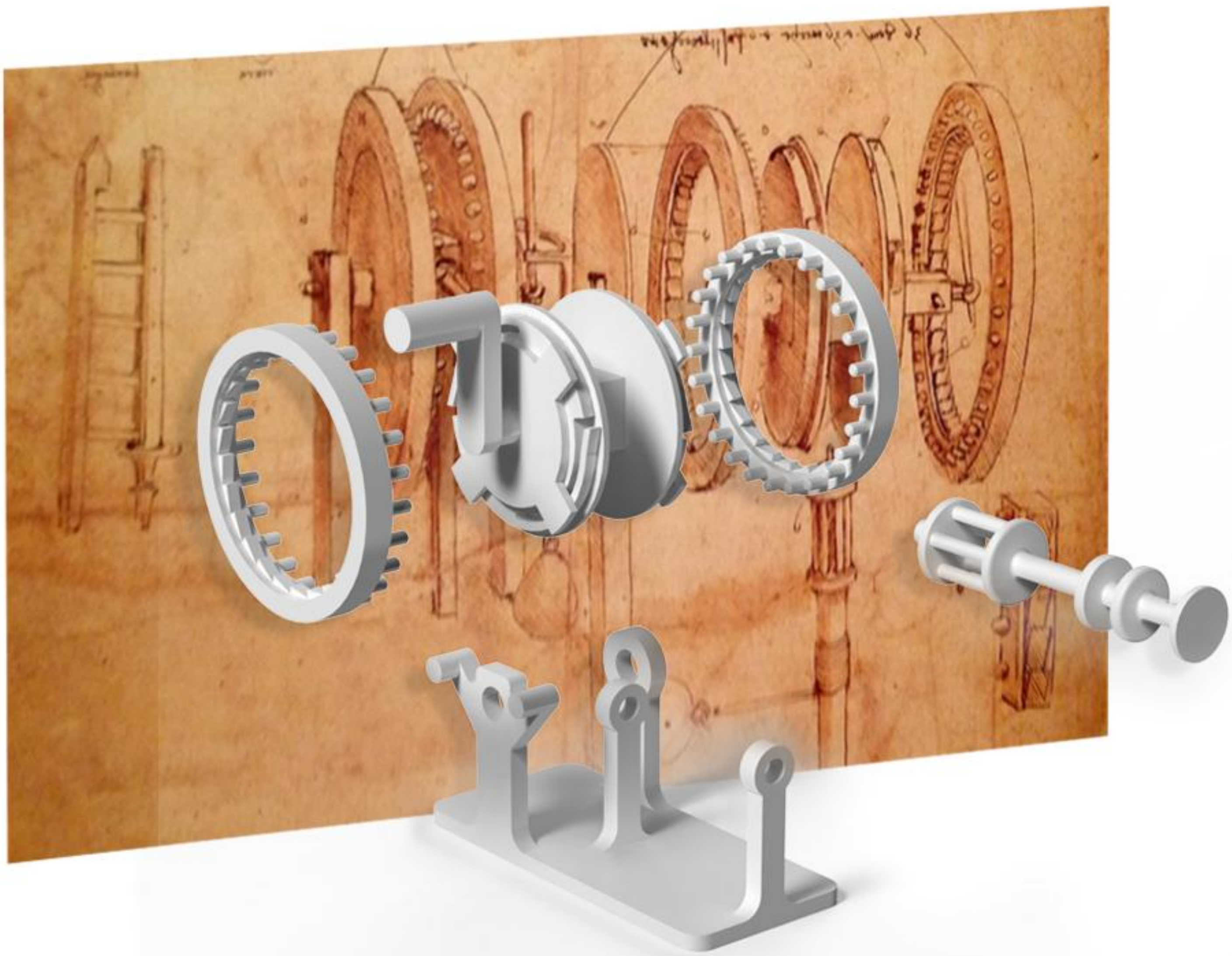
- design, document, and 3D print an object
  that could not be made subtractively
  (small, few cm^3, limited by printer time)
- 3D scan an object (and optionally print it)

Understanding Printer Limits: Support Structures

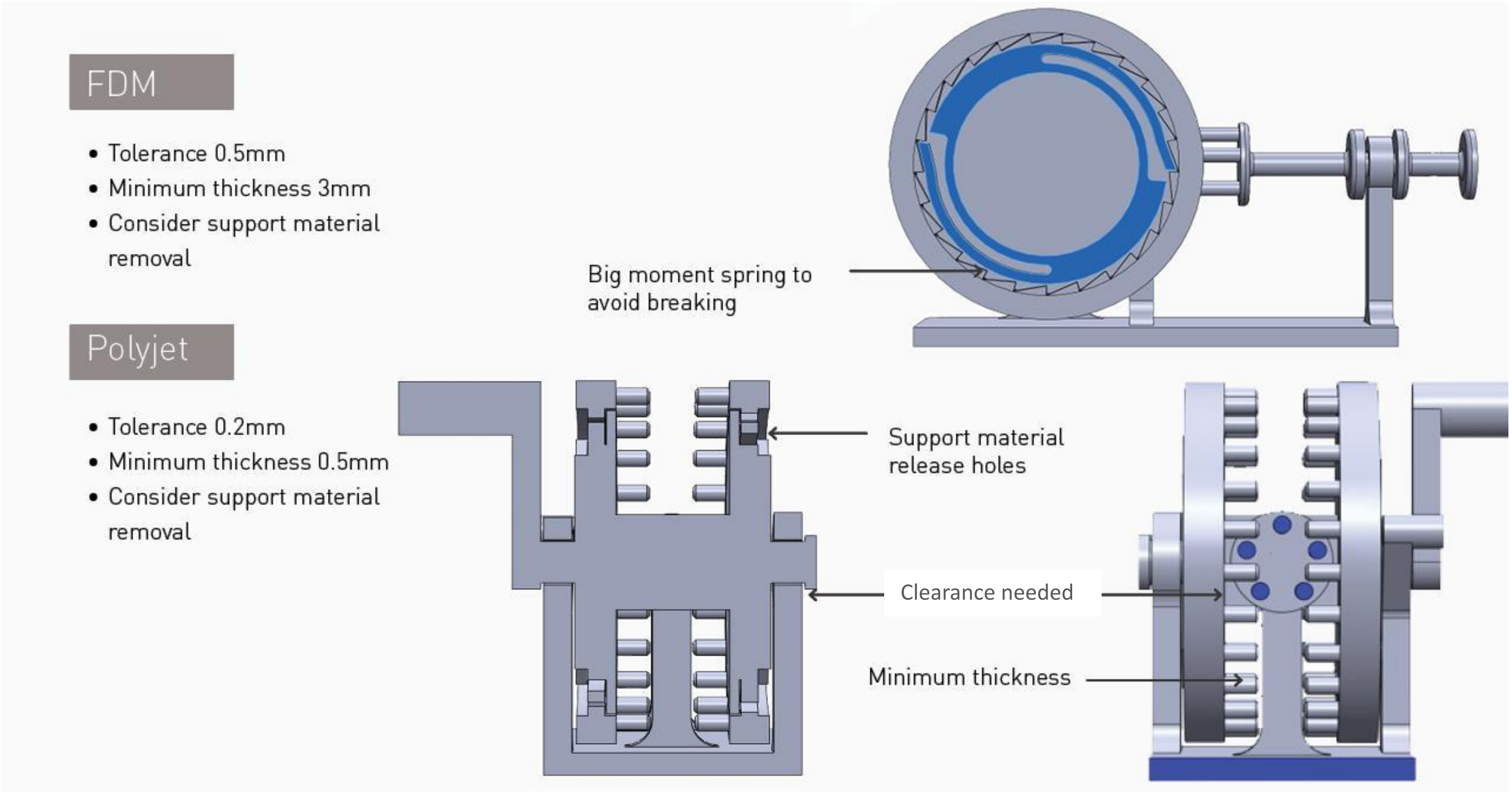
https://www.hubs.com/knowledge-base/supports-3d-printing-technology-overview/

Design and Print a 3D Calibration Ruler

Makerbot A/B test print



Know your printer before designing



Stratasys Education - “Something That Moves Something” curriculum, developed by Ohad Meyuhas

Make design decisions

Wall Thickness
Wall thickness is the distance between surfaces of a solid part

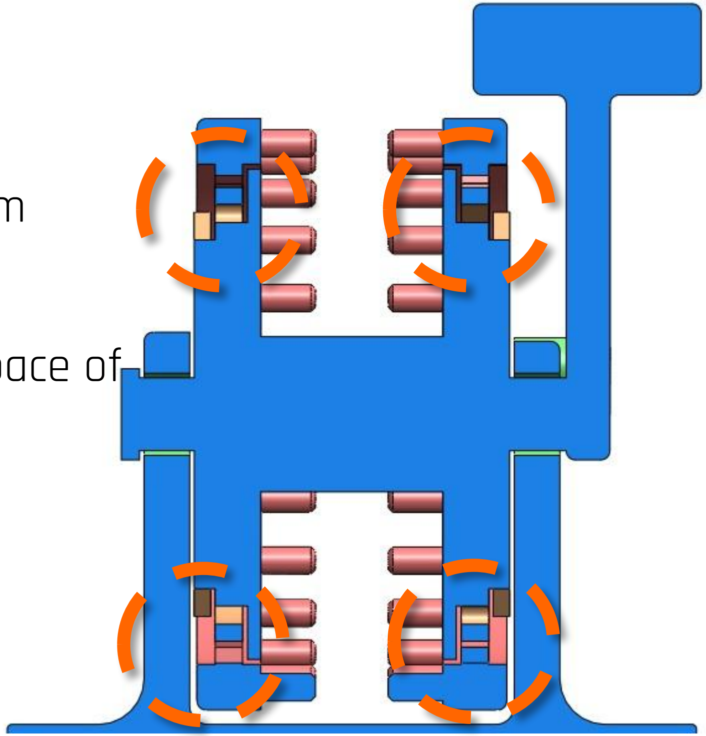
Clearance
The gaps between parts

Supports & Support Removal
Design for less and understand how to remove support from hard-to-reach places

Infill
The density of the solid. Material population within inner space of the solid model

File conversion
Converting a file format to adapt with CAM software

Post Processing
Finishing, sealing, sanding, cleaning



Bounos: Design and print soluble support removal ruler