ISDN2400 Physical Prototyping

Additive Manufacturing I

By Rob Scharff

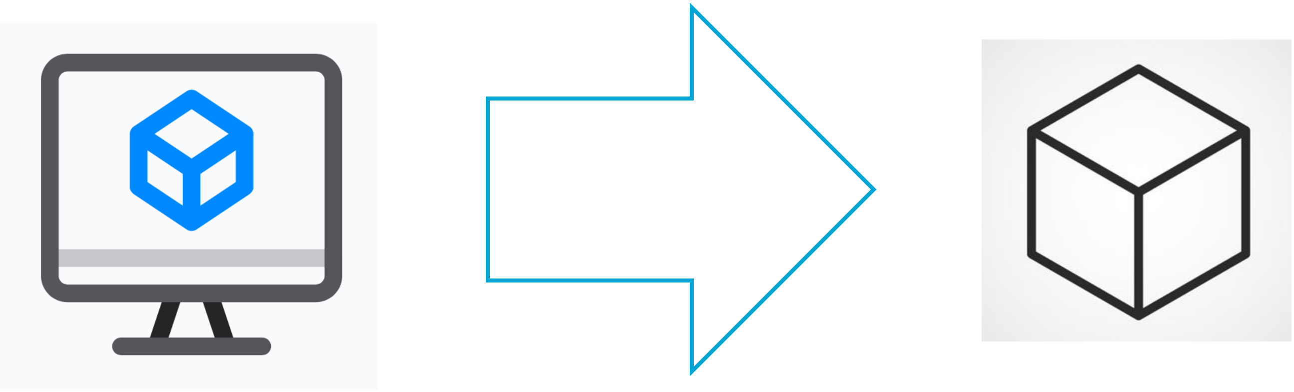
February 2025

Today's lecture

- Introduction to Additive Manufacturing
- Fused Deposition Modelling
  - Hardware
  - Workflow

Additive Manufacturing or 3D-Printing

"A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies"



CAD Design

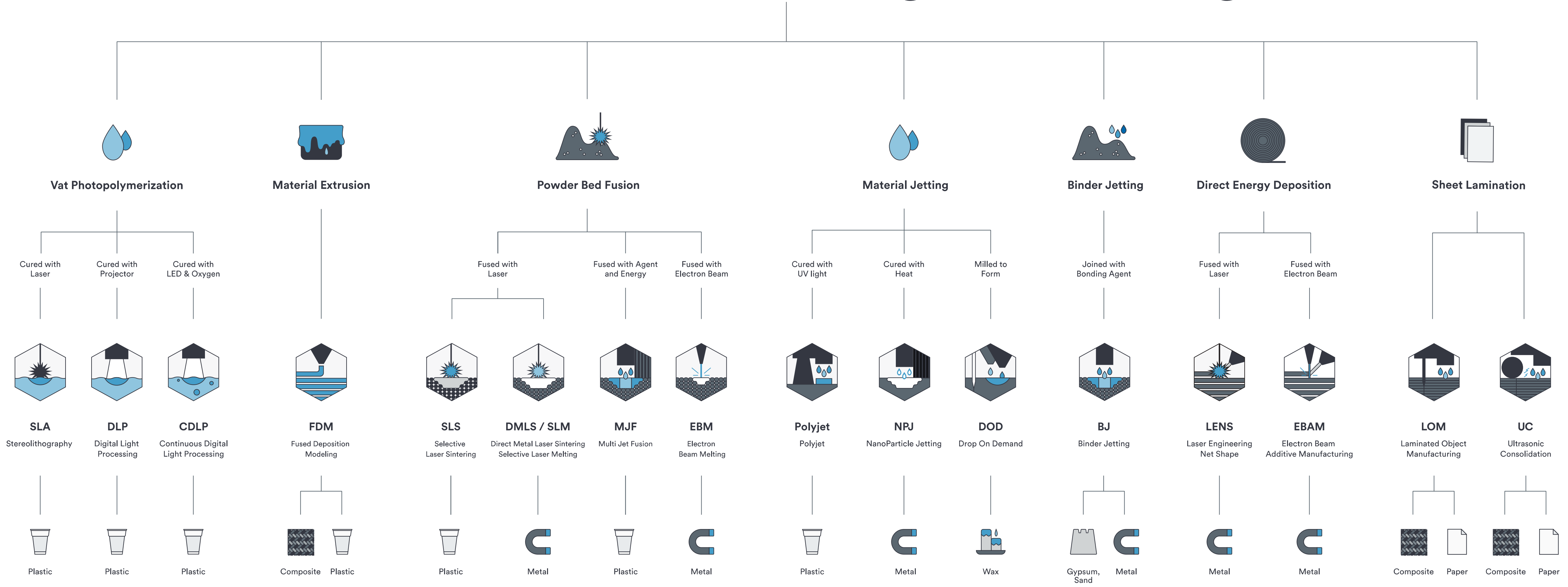
Printed part

Doubrovski 2023

Additive Manufacturing technologies

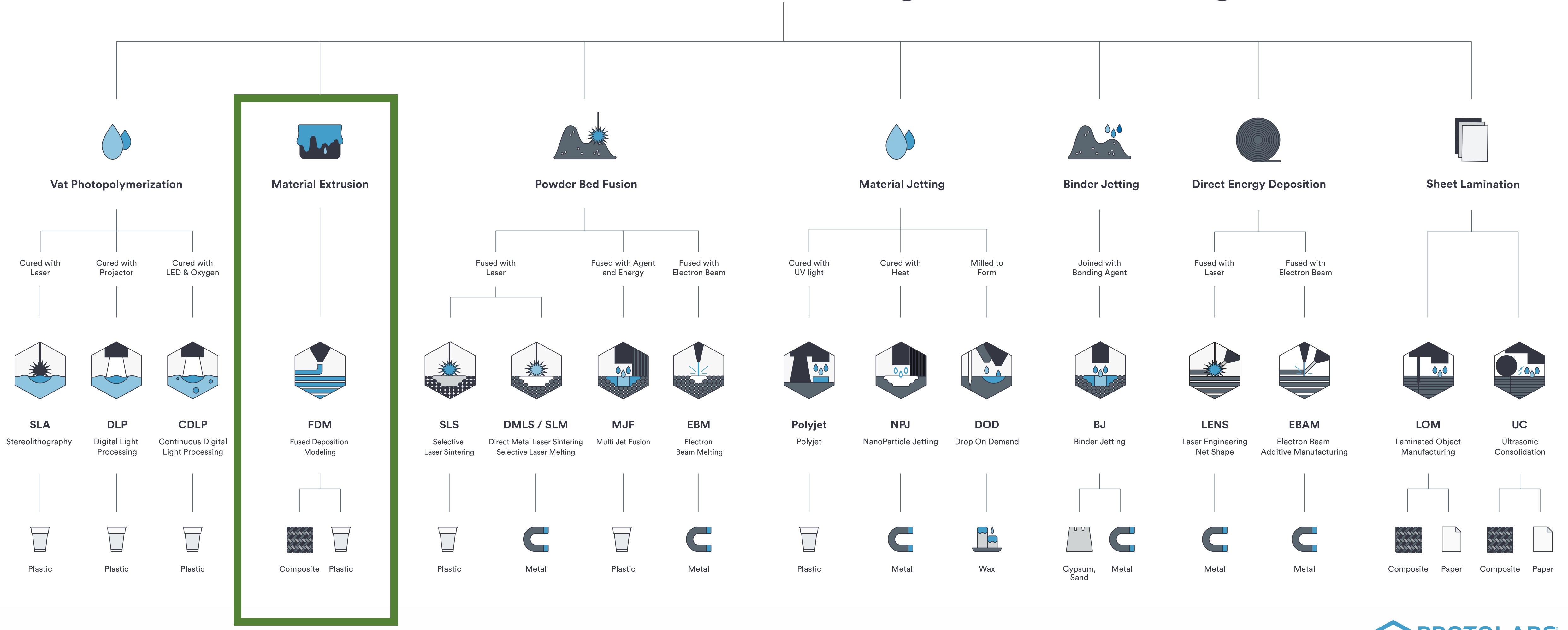
- Material Extrusion
- Material Jetting
- Binder Jetting
- Powder Bed Fusion
- Direct Energy Deposition
- Vat Photopolymerization
- Sheet Lamination

Additive Manufacturing Technologies



PROTOLABS
Manufacturing. Accelerated.

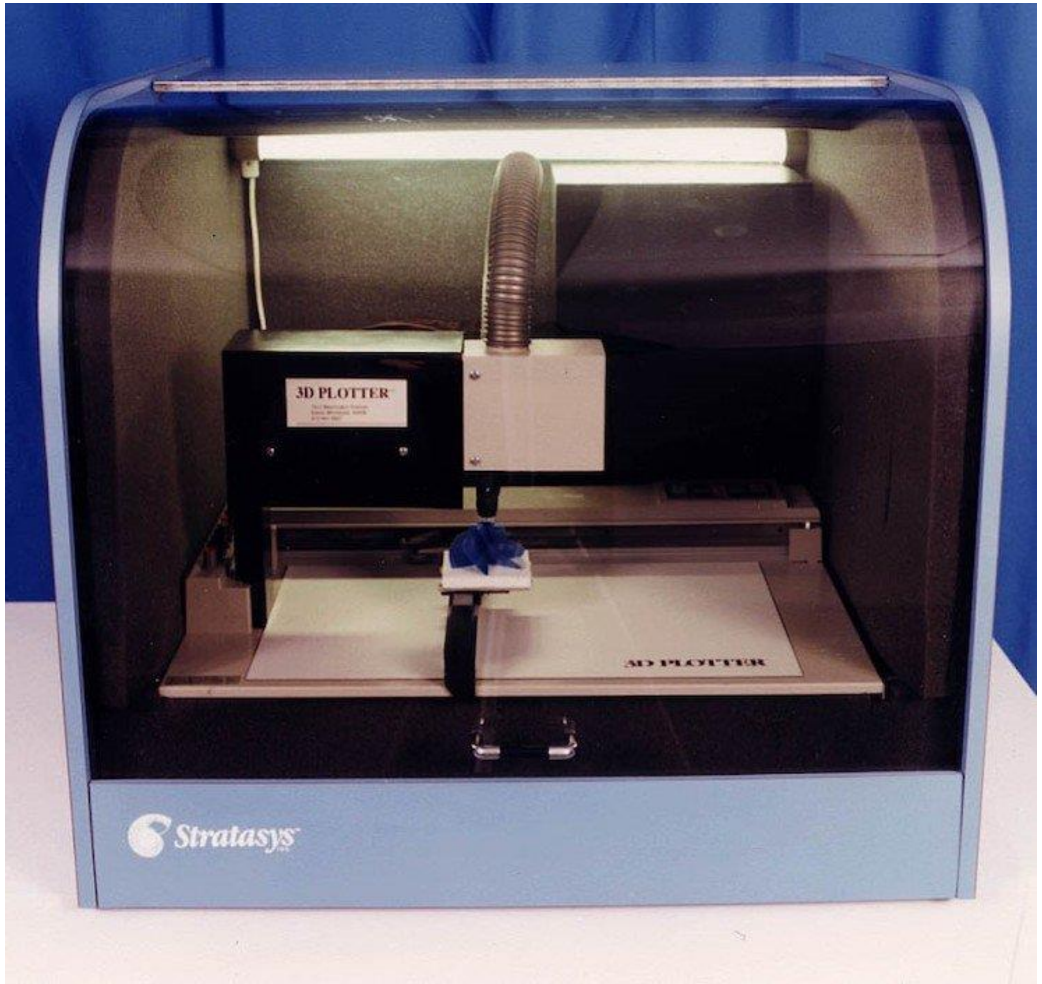
Additive Manufacturing Technologies



PROTOLABS
Manufacturing. Accelerated.

History of Fused Deposition Modelling

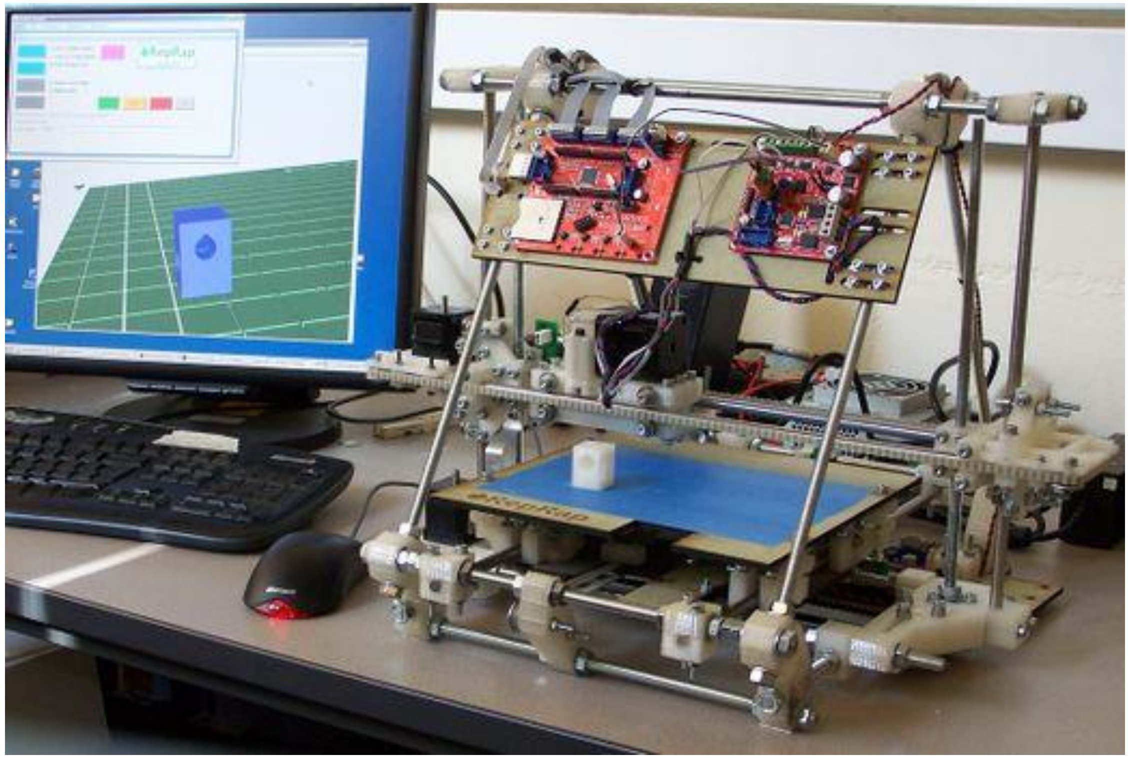
- Created in 1988 by Scott and Lisa Crump (founders of Stratasys)Material Jetting
- Patented in 1989 as a technology for 3D printing where a material is extruded out of a nozzle and creates a 3D object layer by layer



www.tctmagazine.com/additive-manufacturing-3d-printing-news/exclusive-stratasys-scott-crump-3d-printing-legacy/

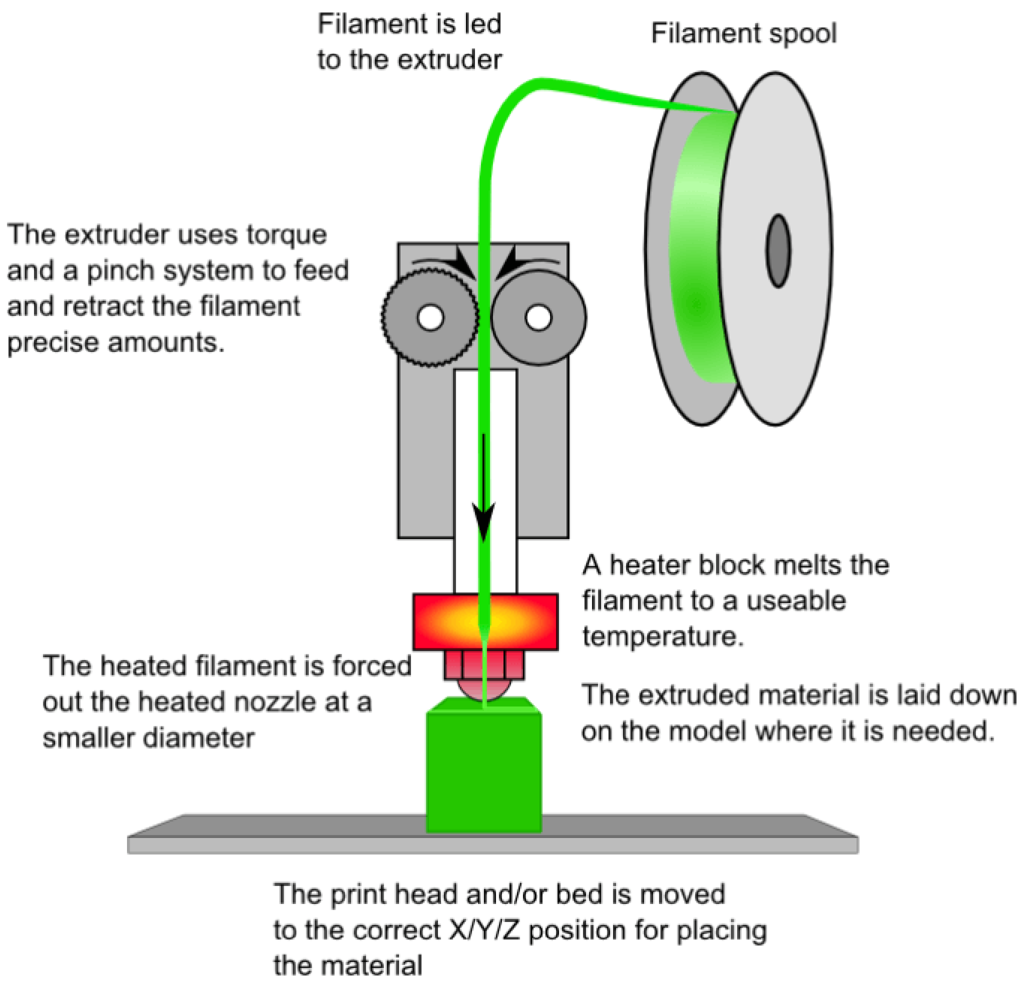
History of Fused Deposition Modelling

- FDM patent expired in 2009, igniting mainstream consumer 3D printing via the opensource RepRap project and startups like Ultimaker and Prusa
- Fused Filament Fabrication (FFF) was coined as an alternative to the trademarked term FDM

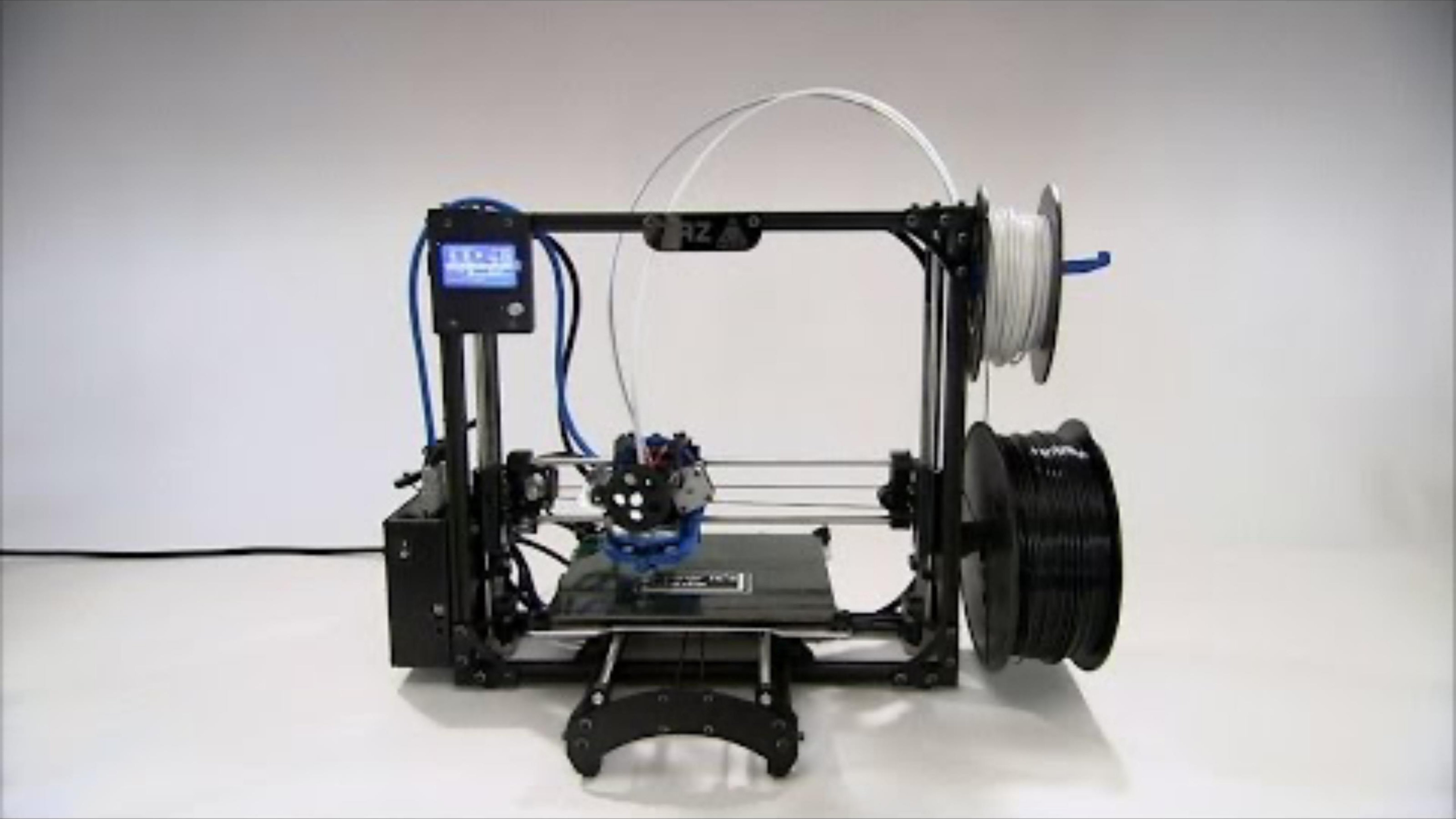


www.reprap.org/wiki/Mendel

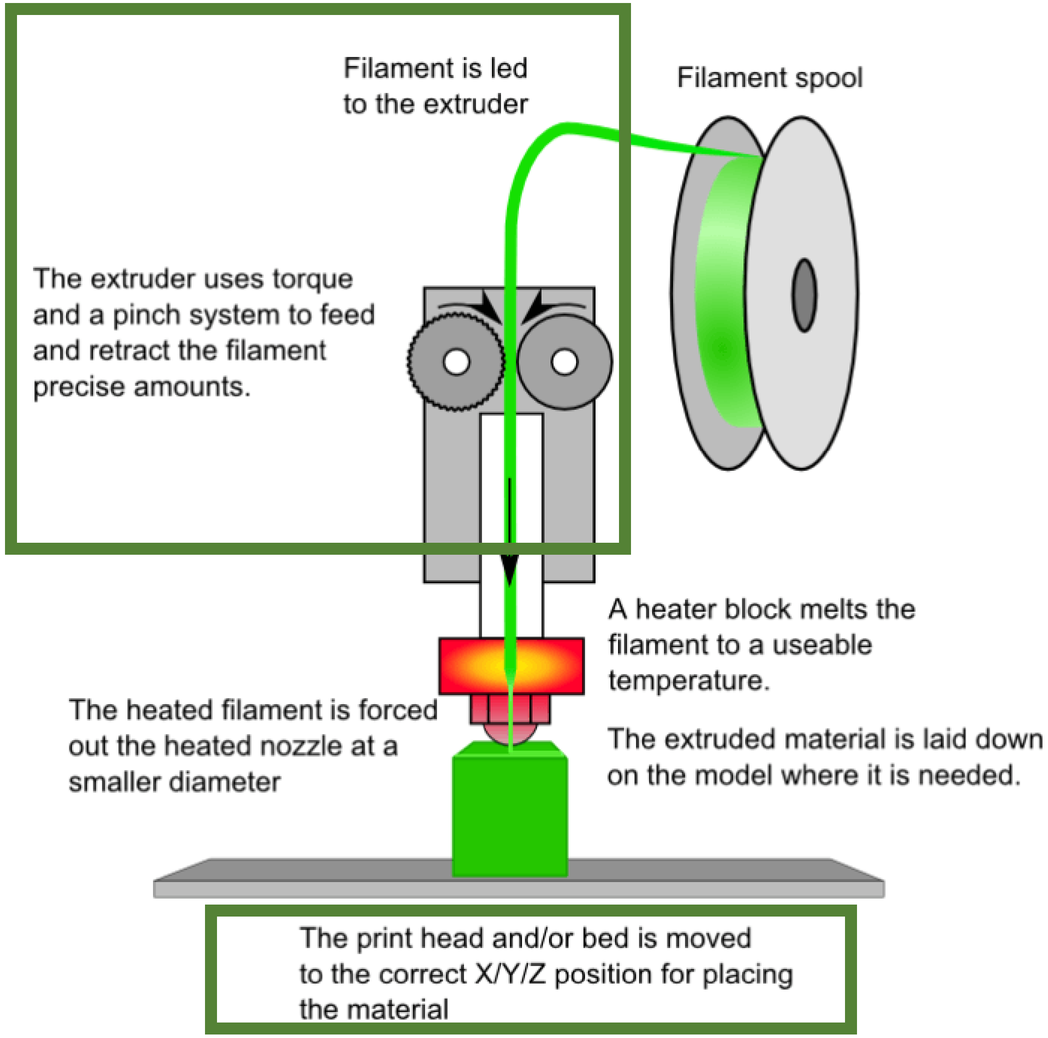
How does FDM work?



www.kywoo3d.com/blogs/3d-printer-news/basic-introduction-of-fdm-3d-printer



Motion system (gantry)

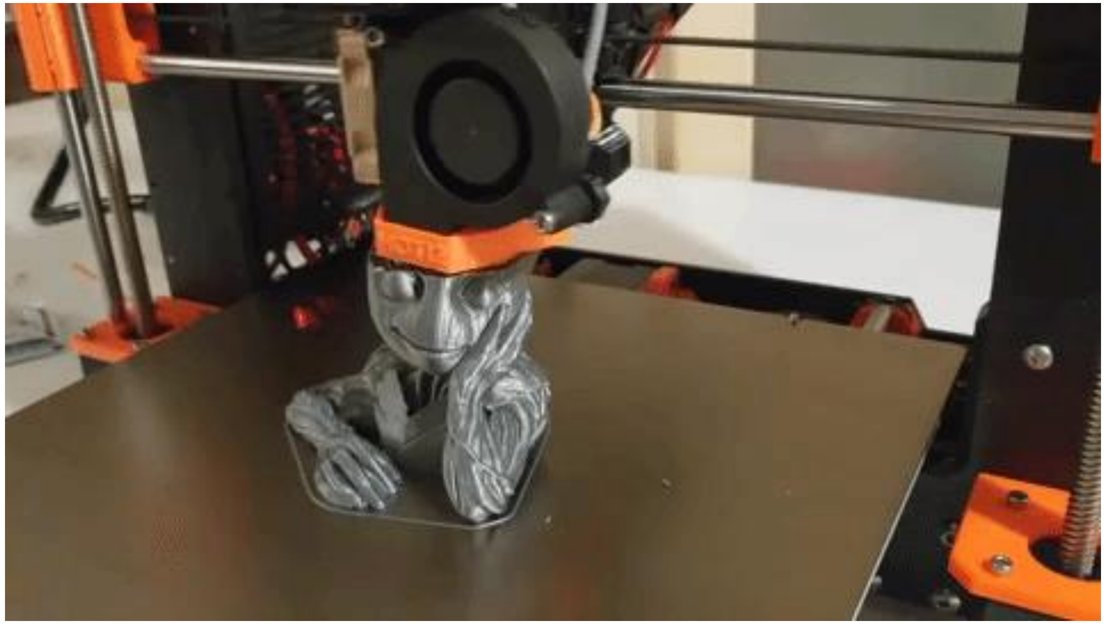


www.kywoo3d.com/blogs/3d-printer-news/basic-introduction-of-fdm-3d-printer

Cartesian rectilinear: XZ-head

- Y-axis: buildplate
- X- and Z-axis: printhead
- Straightforward control
- Stepper motors for X-axis and extruder are moving
  - Heavy moving mass: slower printing
- Example: Prusa MK4

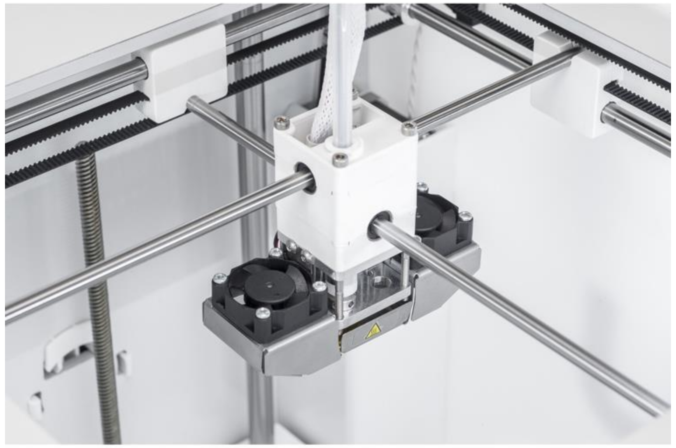
www.prusa3d.com



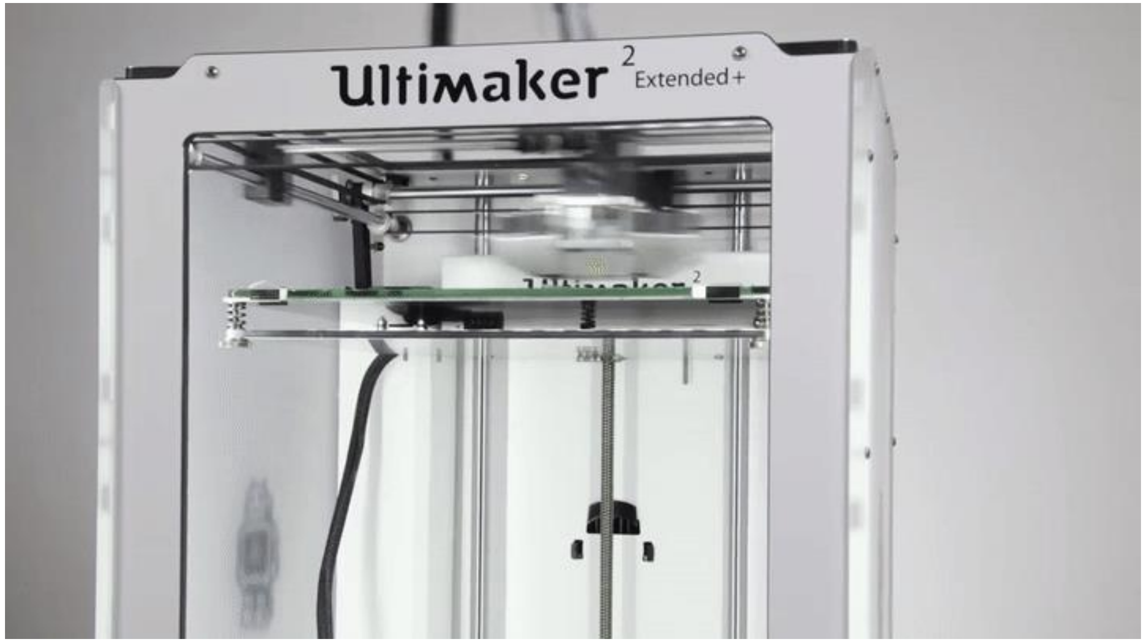
www.reddit.com/r/mechanical_gifs/comments/87imzw/1st_print_on_prusa_i3_mk3/

Cartesian rectilinear: crossed

- Z-axis buildplate
- X- and Y-axis printhead
- External stepper motors for XYZ-axes and extruder (Bowden tube)
- Light printhead for faster printing
- Example: Ultimaker 2



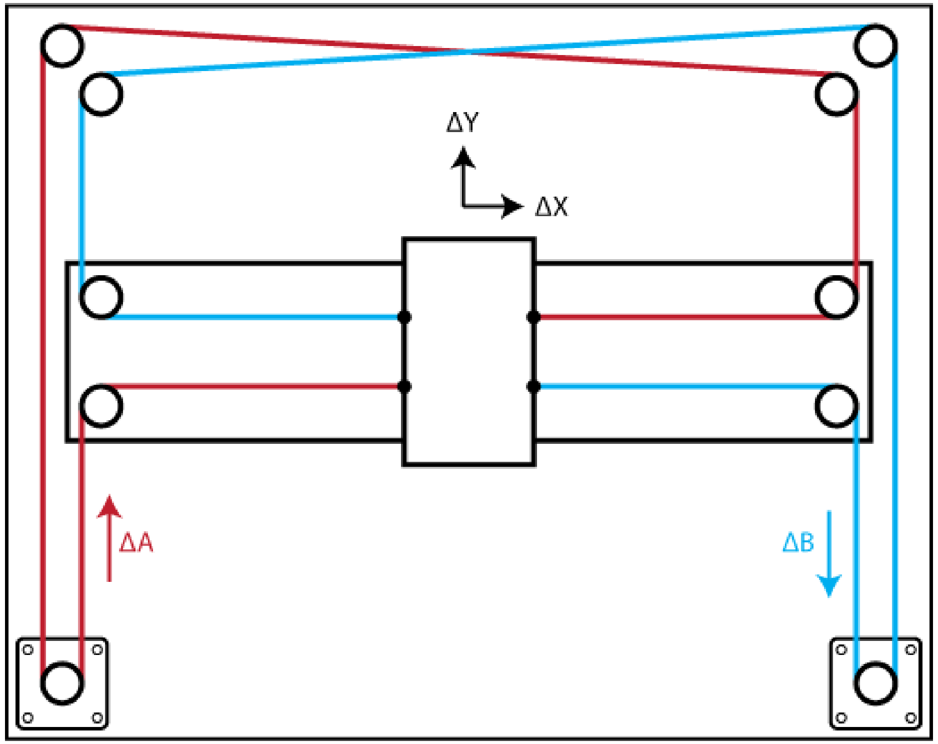
www.mtb3d.com



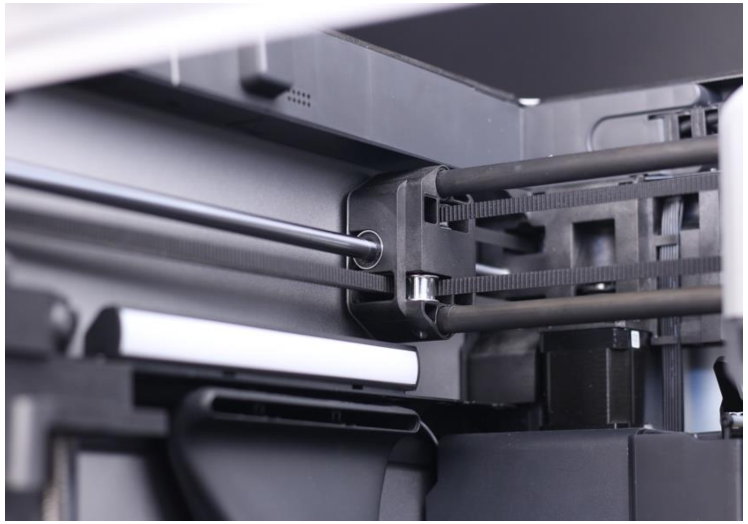
www.makeagif.com/gif/wind-turbine-by-valcrow-ultimaker-3d-printing-timelapse-DAoPmJ

Core-XY

- Both motors move clockwise:
  - carriage moves left
- Both motors move counterclockwise:
  - carriage moves right
- Both motors move in opposite directions:
  - up and down
- One motor moves:
  - diagonal
- Example: Bambu Lab X1



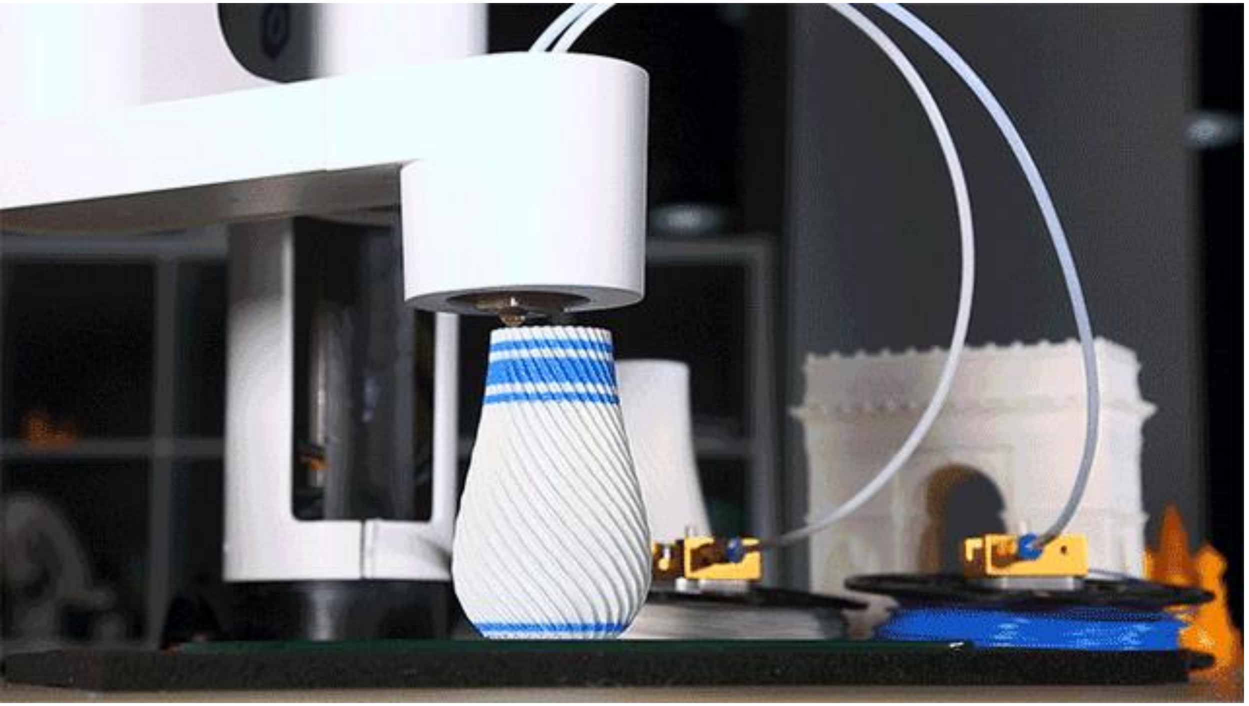
www.corexy.com/theory.html



www.3dprintbeginner.com/bambu-lab-x1-carbon-review/

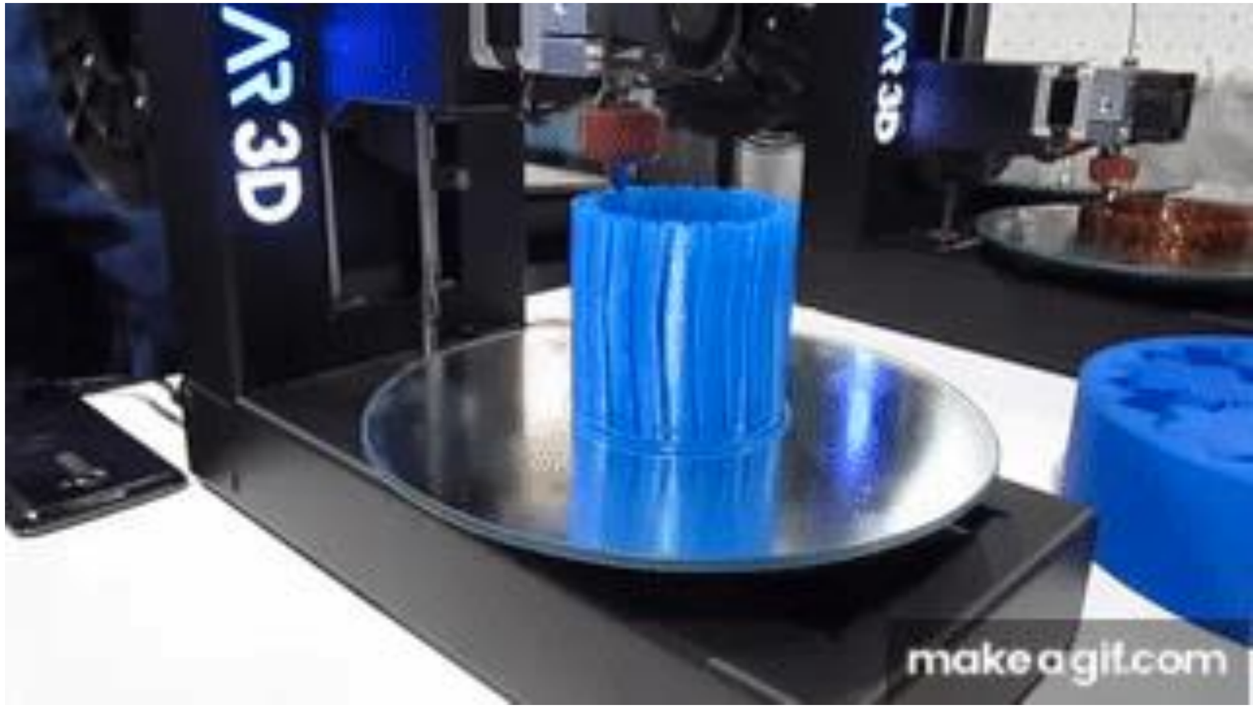
Other types

SCARA



https://www.engineering.com/story/is-it-possible-to-sell-an-industrial-desktop-robot-for-under-2000

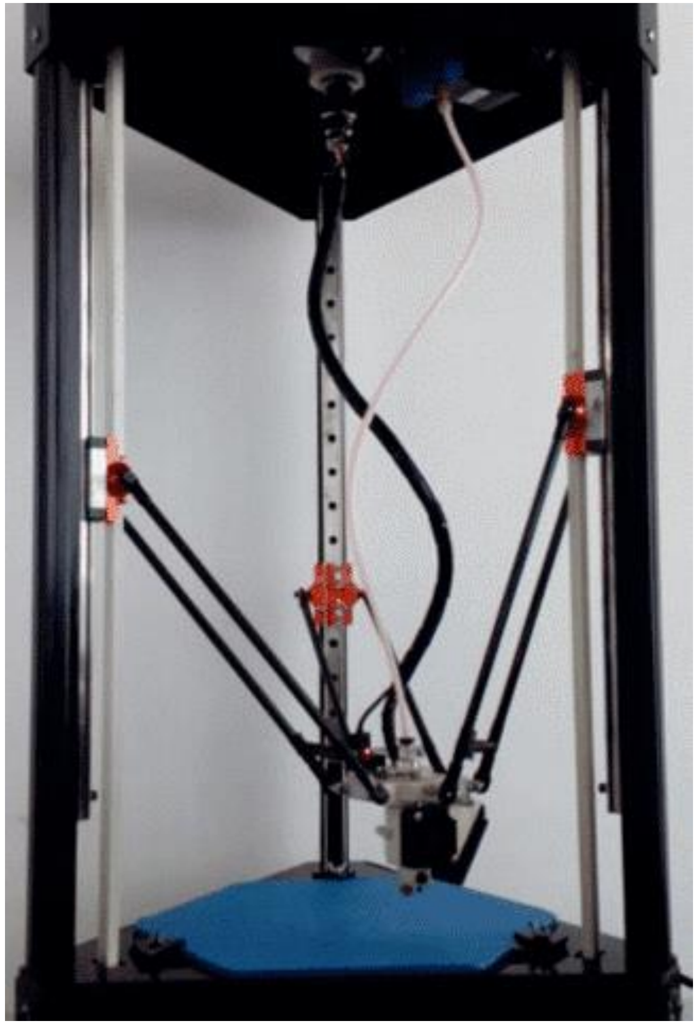
Polar



www.makeagif.com/gif/polar-3d-printer-in-operation-eBs9yn

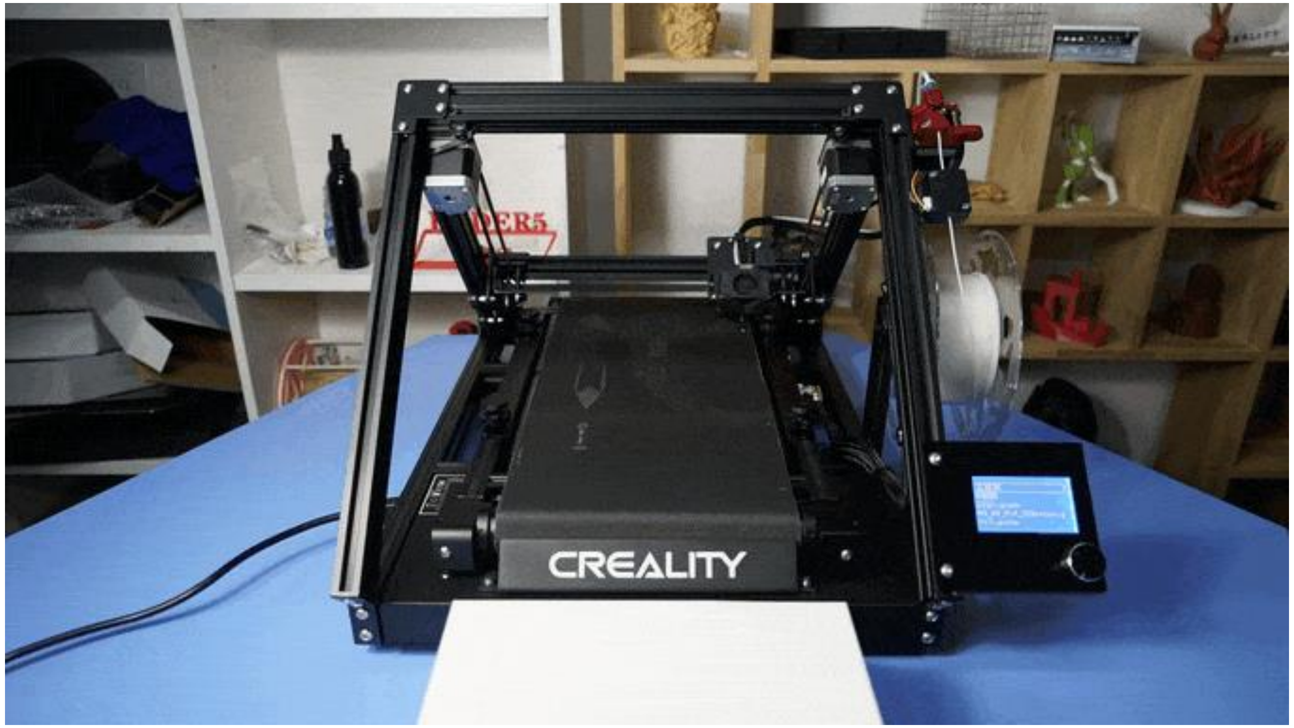
Other types

Delta



www.3dprint.com/75339/ares-all-in-one-3d-printer/

Conveyer belt



www.3dnatives.com/en/creality-3dprintmill-conveyer-belt-231120204/

Other types

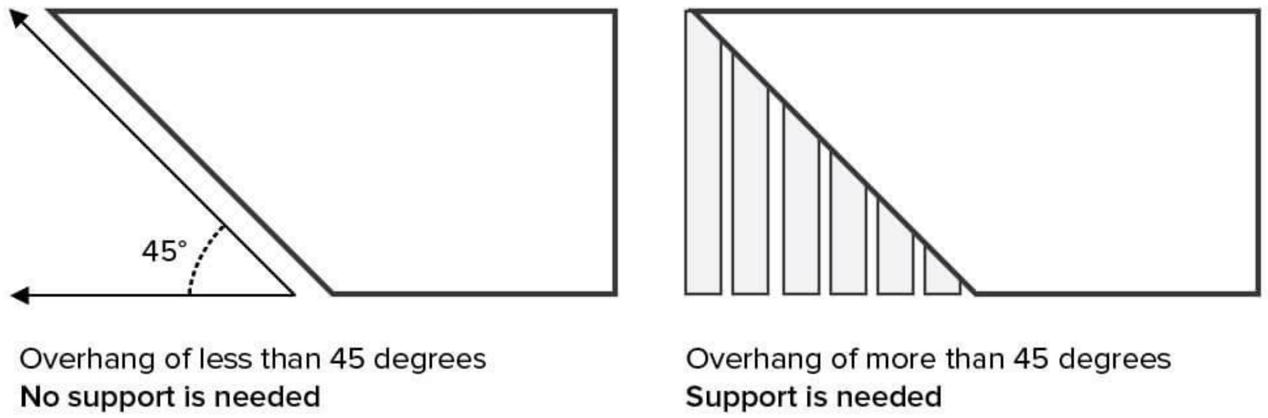
Multi-axis (>3)

www.roboticgizmos.com/ai-build

- Why would you want more than three axes for FDM?
- Printing orientation considerations

Support material

- Cannot print in air
- Maximum overhang angle around 45 degrees
- More overhang requires a supporting structure



https://www.gambody.com/blog/main-types-3d-printing-supports-tips-for-beginners/

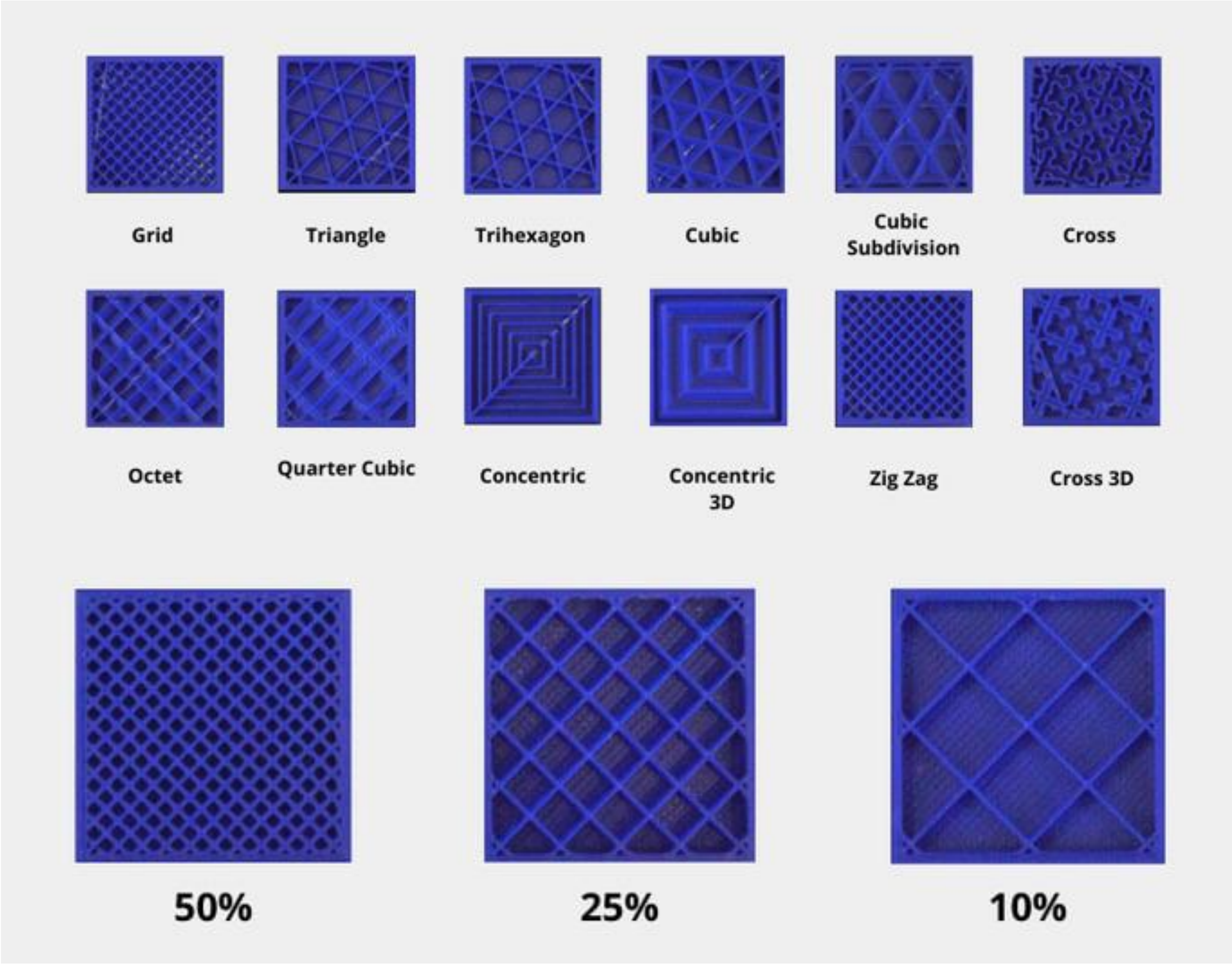
Disadvantages of Support Material

- More material usage
- Non-smooth contact surface
- Post-processing required
- Extra printing time

https://support.makerbot.com/s/article/1667411595840

Internal Support: Infill

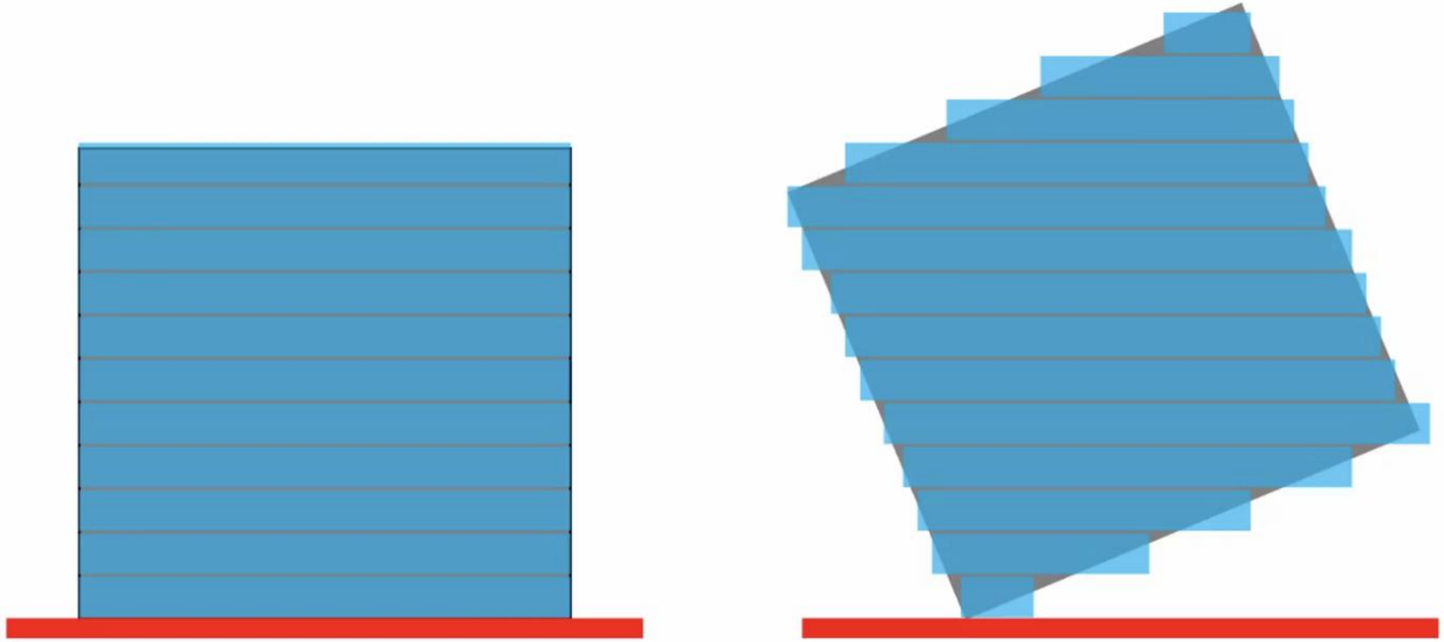
- Printing solid parts is slow
- Print internal structure for support, strength, and weight



www.support.bcn3d.com/knowledge/infill

Surface Quality

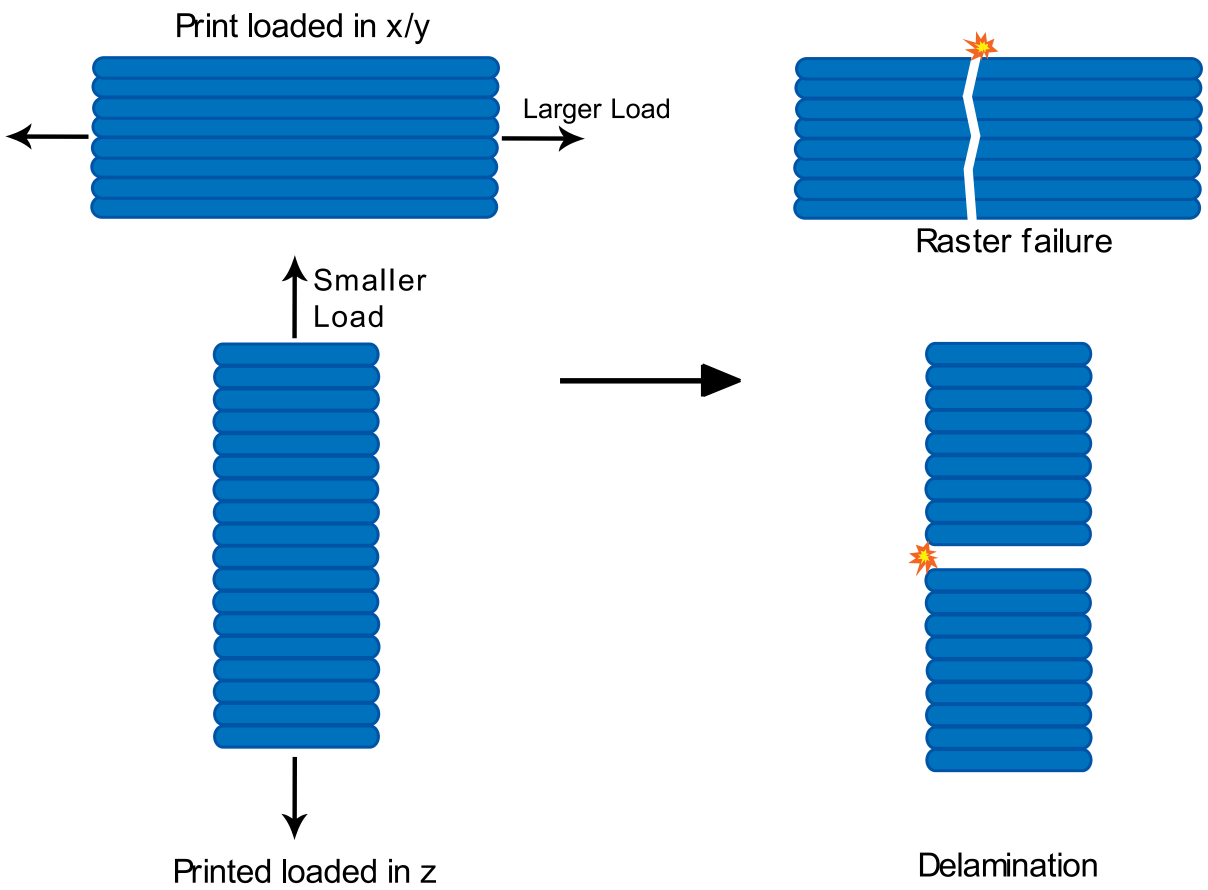
- Stair-stepping effect



Yeung, 2021

Anisotropic properties

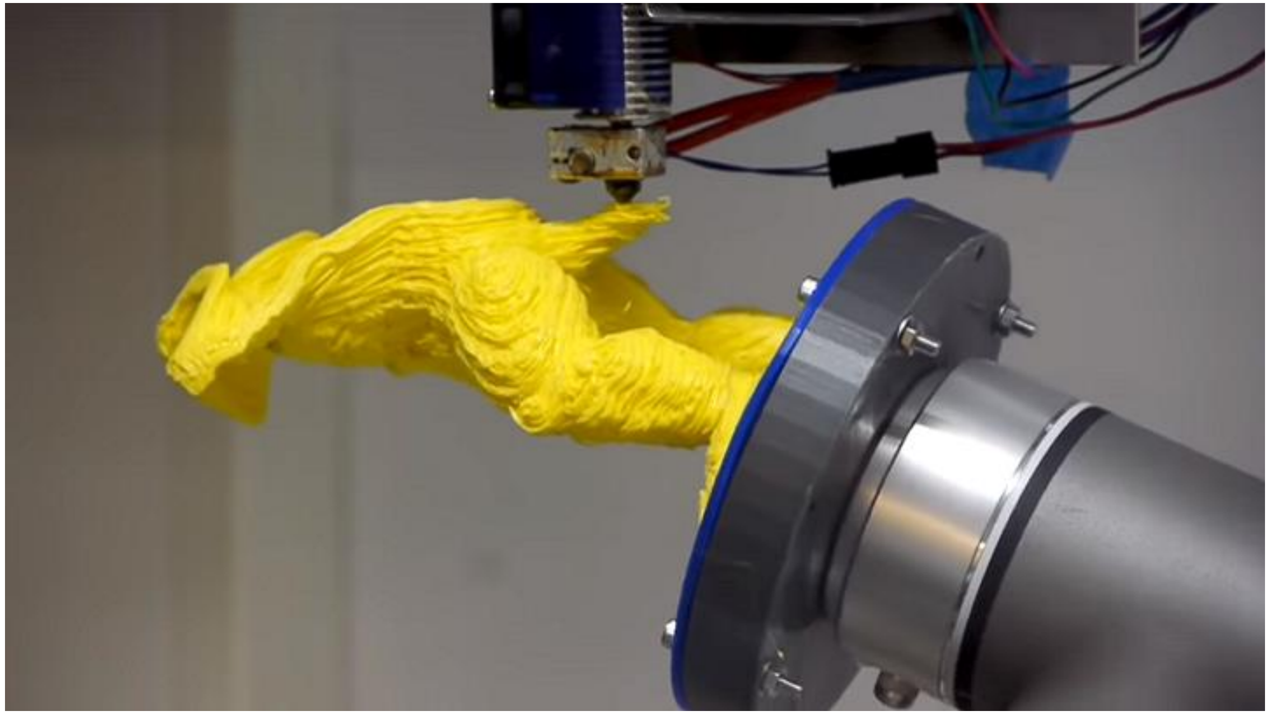
- Mechanical properties are different along each axis
- Strength/stiffness larger in the direction of the fibers
- Bonding between layers is weaker



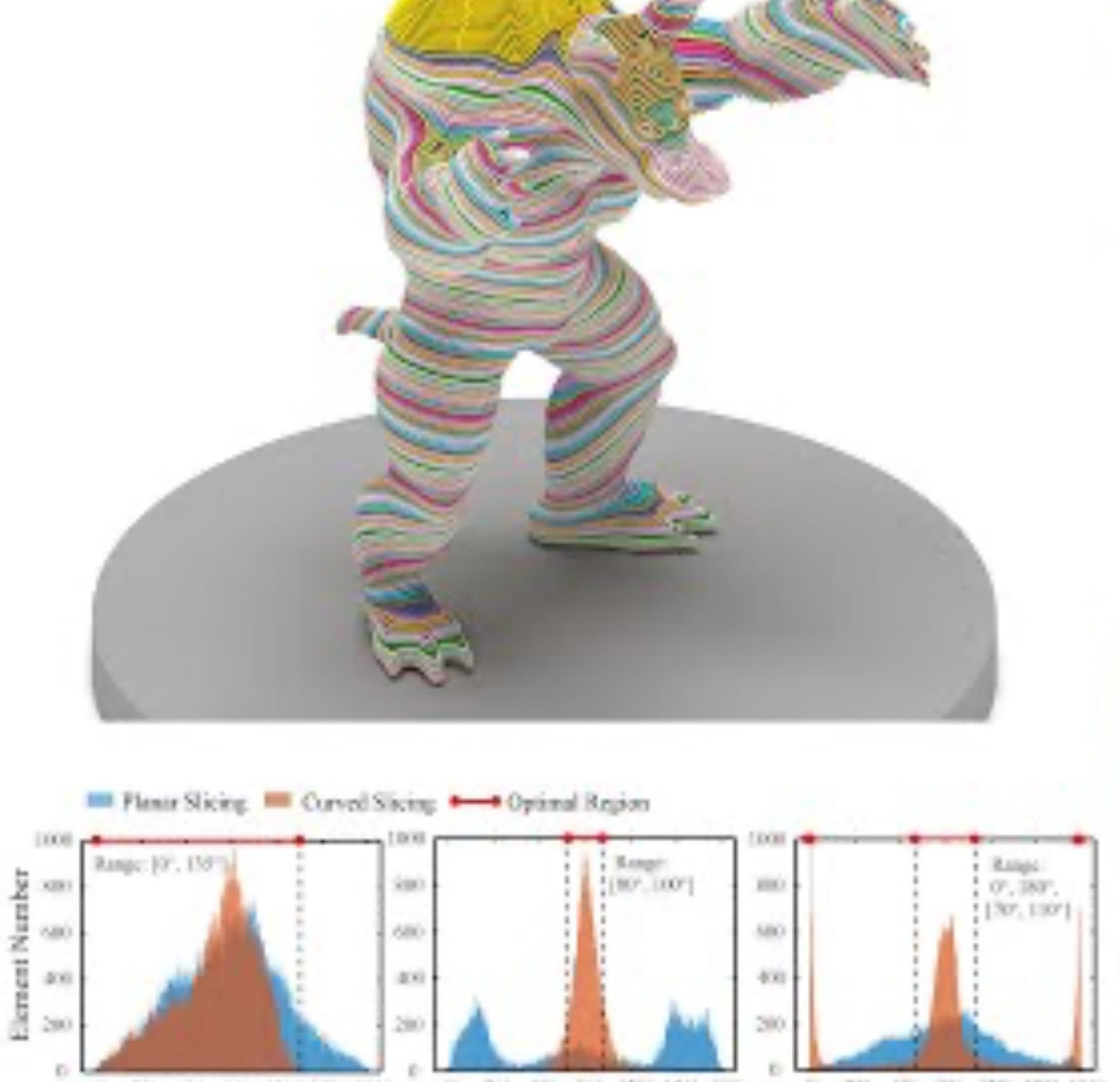
https://www.doitpoms.ac.uk/tlplib/add_manuf/fdm.php

Advantages of multi-axis Additive Manufacturing?

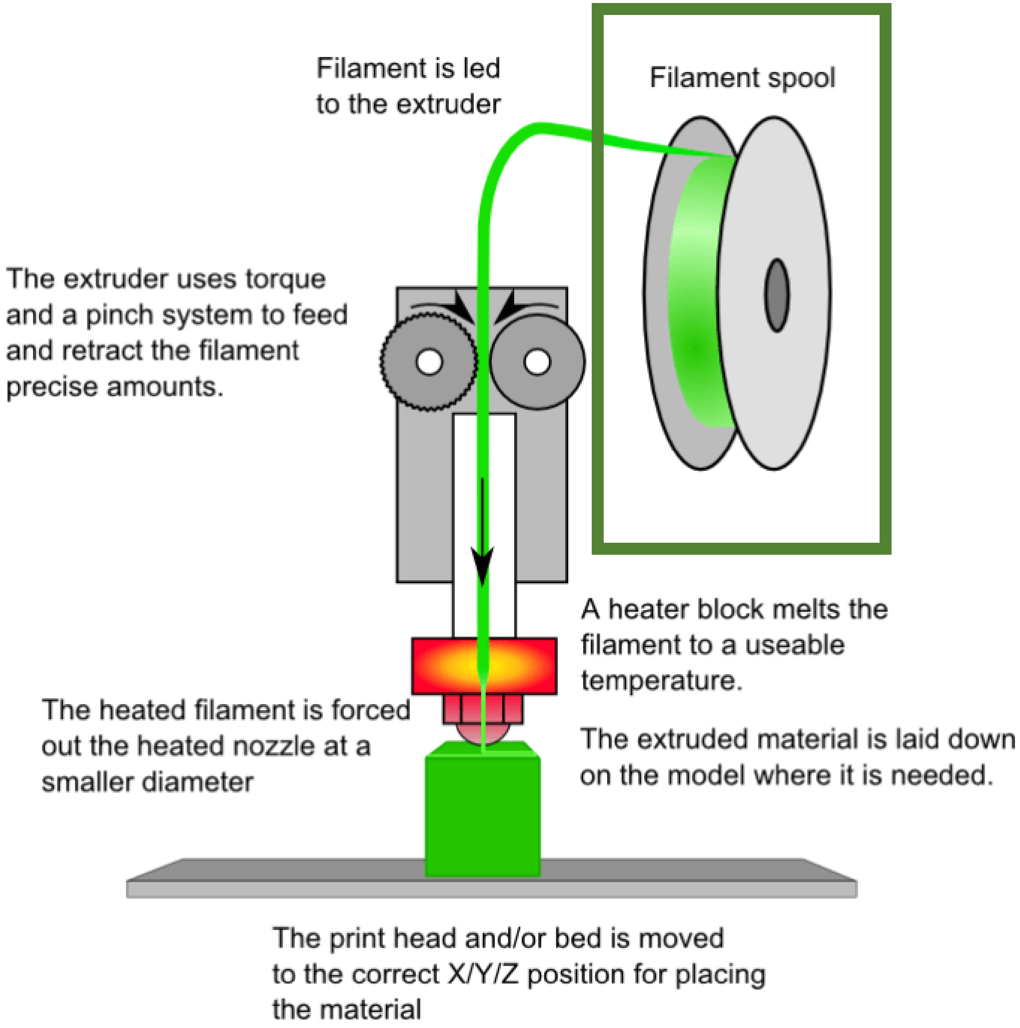
- Support-free printing
- Strength enhancement
- Better surface quality



www.3dprint.com/215803/multi-axis-robotic-3d-printer/


Planar Slicing
Curved Slicing
Optimal Region
Element Number
1000
800
600
400
200
0

Materials



www.kywoo3d.com/blogs/3d-printer-news/basic-introduction-of-fdm-3d-printer

Filament

- Thermoplastics of 1.75mm or 2.85mm in diameter
- Most printers use 1.75mm filament
  - Less torque required
  - less power required to heat the filament
- Some printers (e.g. Ultimaker) use 2.85mm filament
  - Why?

https://www.ankermake.com/blogs/printing-tips/how-to-dry-filament

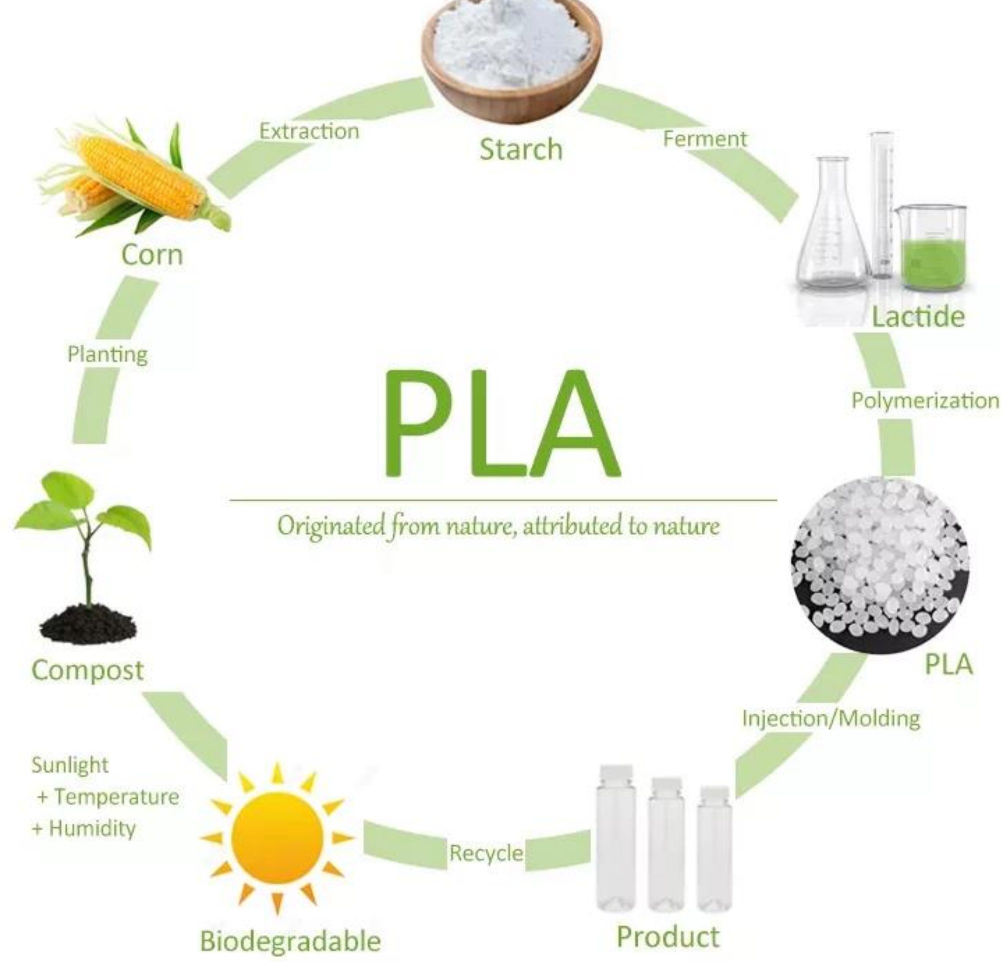
Answer

- Pushing filament through the Bowden tube

www.support.makerbot.com/s/article/1667337580379

Polylactic acid (PLA) filament

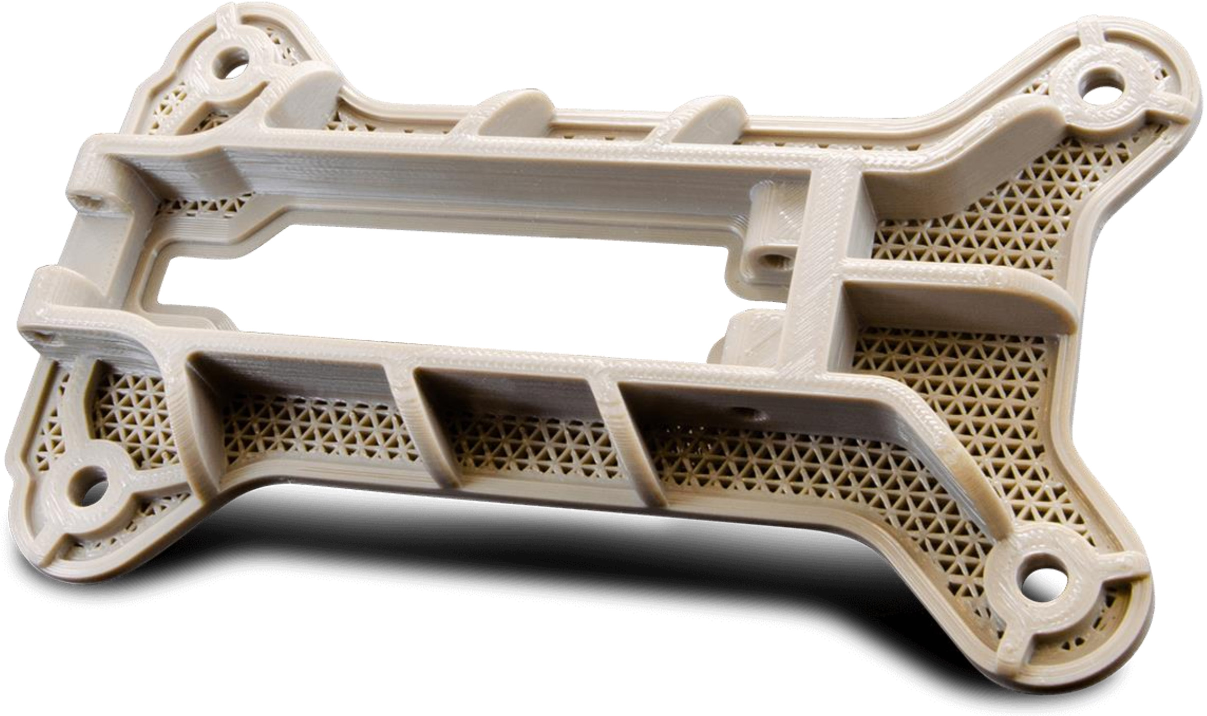
- Made from fermented plant starch from corn, cassava, maize, sugarcane or sugar beet pulp
- Low melting temperature (170-180 °C)
- Easy to print
- Low hardness and toughness
- Inexpensive
- Made from renewable materials
- Compostable
- Lower carbon footprint



https://www.plasticbottlesupplier.com/news/pla.html

Engineering plastics

- PEEK (PolyEtherEtherKetone)
- ABS (Acrylonitrile Butadiene Styrene)
- PP (PolyPropylene)
- PETG (PolyEthylene Terephthalate Glycol)
- And many others...



www.minifactory.fi/technology/peek-3d-printing/

Flexible materials

- TPU (thermoplastic polyurethane)
- Shore hardness typically in the range of 50A-95A

www.3dnatives.com/en/tpu-3d-printing-040620204/

Which printer is better for flexible materials?

www.tomsguide.com/us/ultimaker-2-3d-printer,review-2556.html

www.prusa3d.com

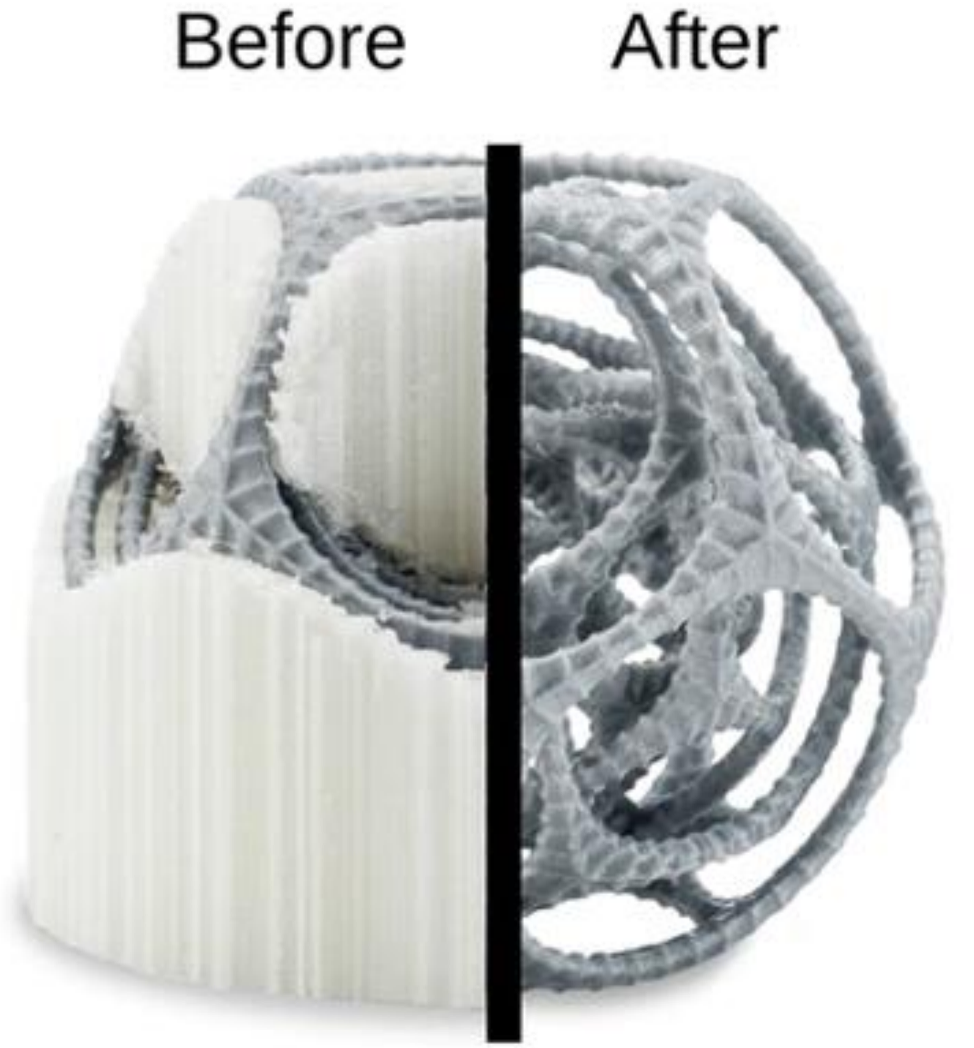
Answer

- Friction when pushing a flexible filament through the bowden tube leads to underextrusion
- Direct-drive extruder better for 3D printing flexible materials

www.support.makerbot.com/s/article/1667337580379

Support material

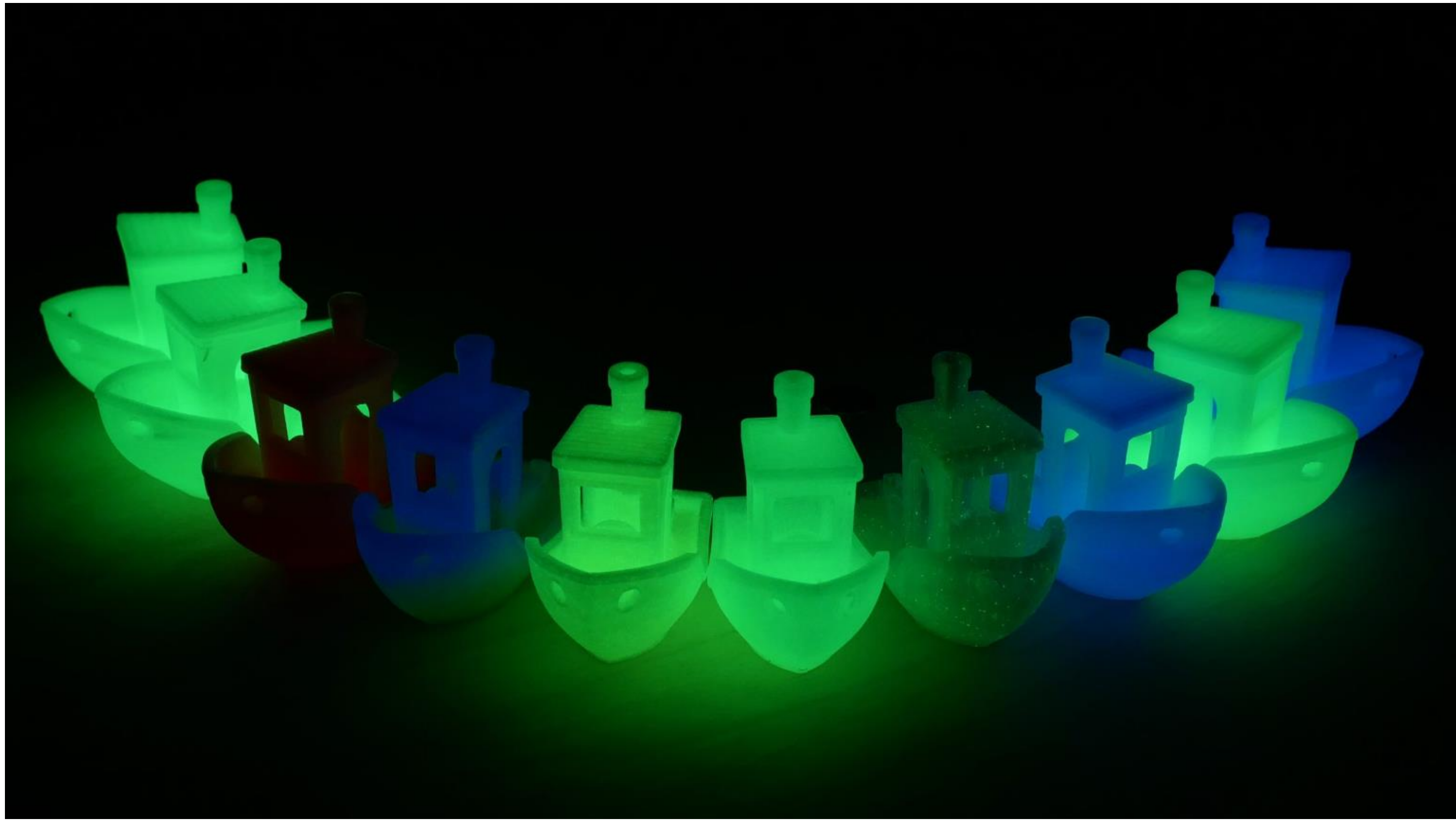
- PVA (polyvinyl alcohol): dissolves in water)
- HIPS (high impact polystyrene): dissolves in limonene
- Dual extrusion required



www.3dnatives.com/en/all-you-need-to-know-about-pva-for-3d-printing-270520224/

Special filaments

- Magnetic
- Conductive
- Ceramic-filled
- Metal-filled
- Glow-in-the-dark
- Glitter
- Color-changing
- PoroLay
- Ultrafuse
- And many more…



www.cnckitchen.com/blog/which-glow-in-the-dark-filament-is-the-best


UltiMaker
3D print functional steel parts
Ultimaker
UltiMaker
Metal Expansion Kit

Fiber-reinforced composites

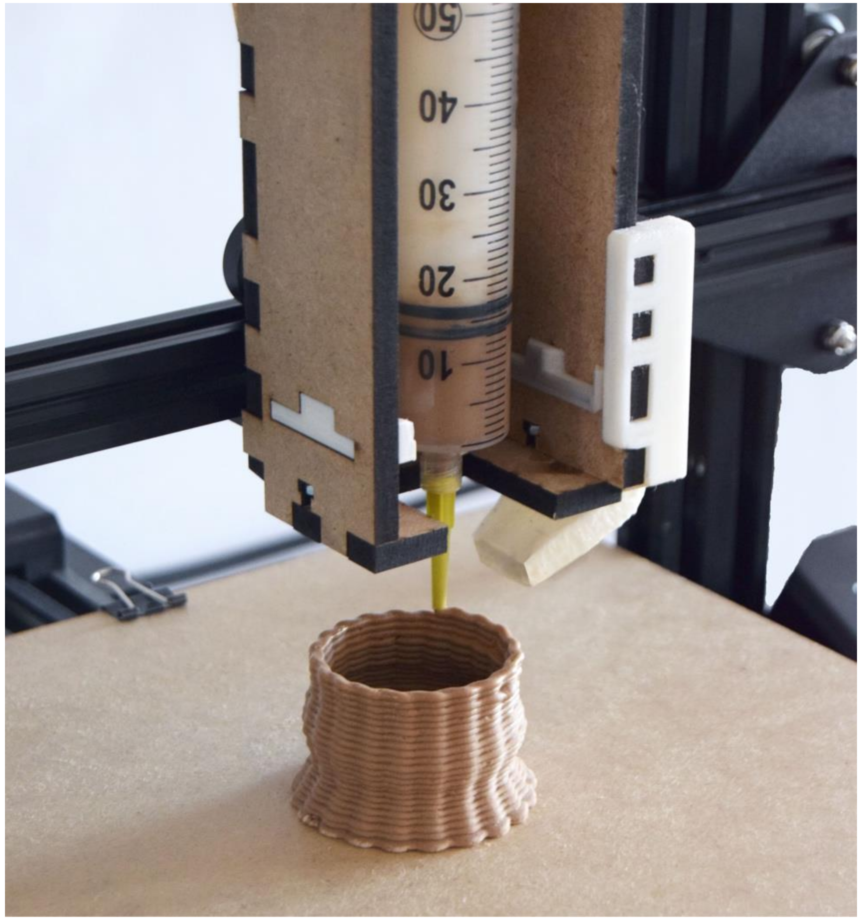
- Carbon fiber
- Aramid fiber
- Fiberglass

https://www.3dpeople.uk/3dpeopleuk-blog/discontinue-continuous-fiber-fabrication-cff


PROCESS EXPLANATION
How Continuous Carbon Fiber Reinforcement Works
Markforged

Non-filaments

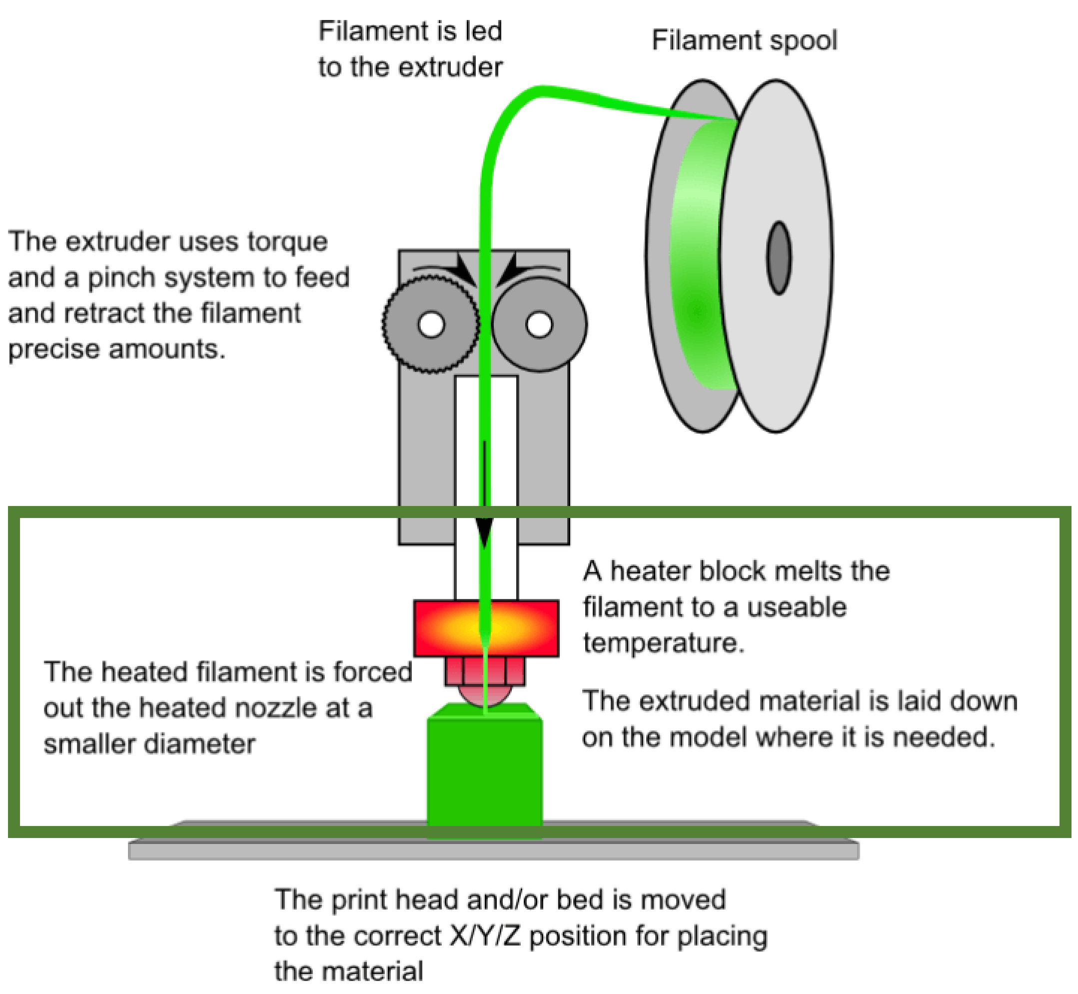
- Granular plastic (pellet printers)
- Paste extrusion
- Silicone/Glass/Concrete



https://3dprinting.com/news/transform-your-3d-printer-into-a-versatile-paste-extrusion-add-on/

Temperature management

- Nozzle
- Heated bed/chamber
- Fan



www.kywoo3d.com/blogs/3d-printer-news/basic-introduction-of-fdm-3d-printer

Issues related to temperature management

- Delamination
- Warping
- Oozing/stringing
- Pillowing
- Underextrusion
- Overextrusion
- Nozzle clogging
- And many others...

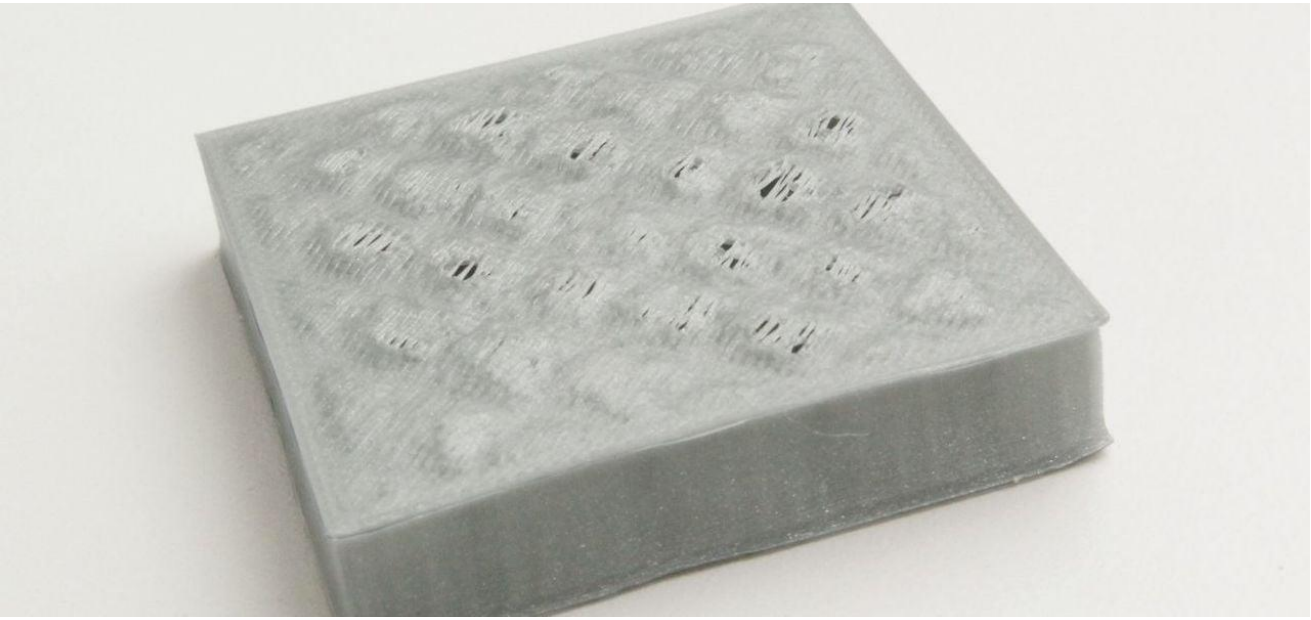
Delamination

- Poor layer-to-layer adhesion
- Increase the nozzle temperature
- Decrease the printing speed

www.facfox.com/docs/kb/5-tips-to-avoid-layer-delamination-in-3d-printing

Pillowing

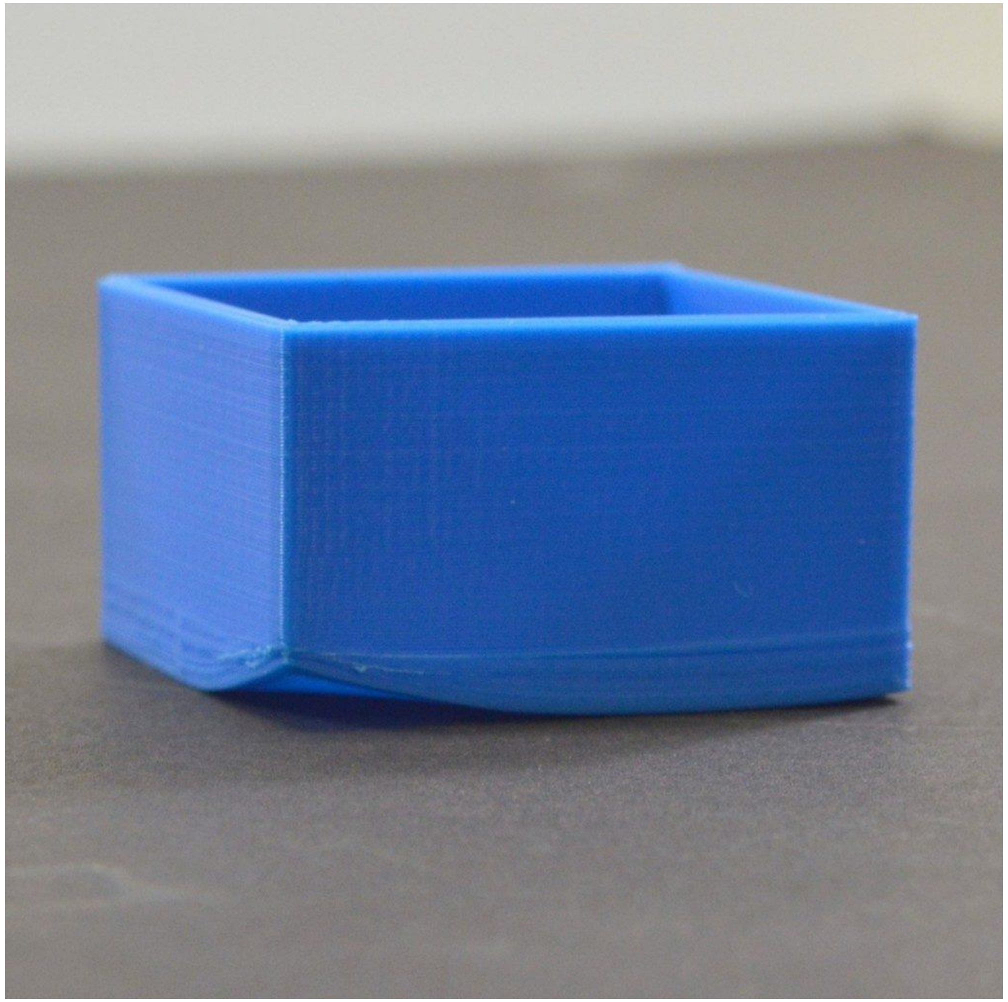
- Warping around infill structure
- Too hot: turn on fan for the top layers



www.all3dp.com/2/3d-printing-top-layer-problems-easy-fixes-for-pillowing/

Warping

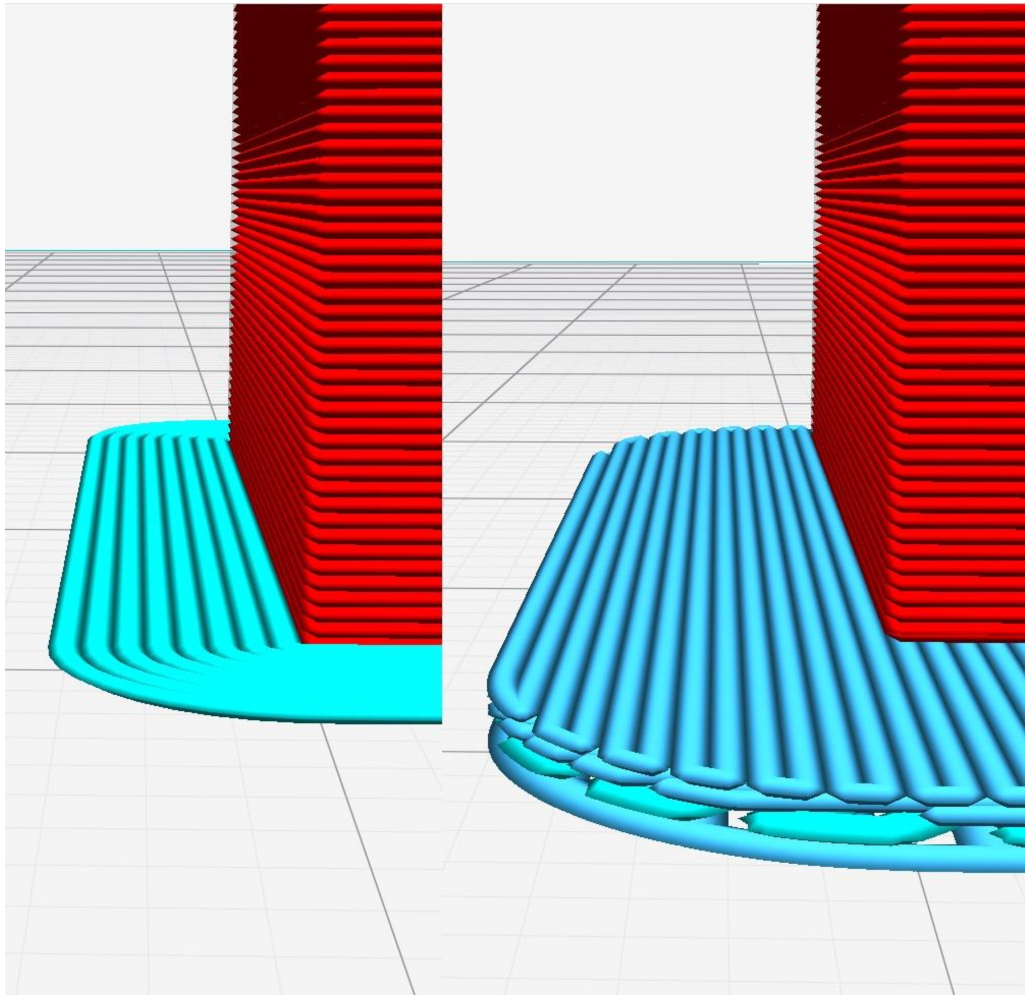
- Uneven cooling and thus shrinking of extruded filament
- Solutions?



www.simplify3d.com/resources/print-quality-troubleshooting/warping/

Warping: solutions

- Heated bed/enclosure
- Fan off
- Use low-temperature materials
- Print slow (~35mm/s)
- Reduce infill density
- Use a brim/raft/adhesive
- Avoid sharp corners (prone to uneven cooling)



www.stampa3d-forum.it/articoli/guide/skirt-brim-raft-cosa-sono/

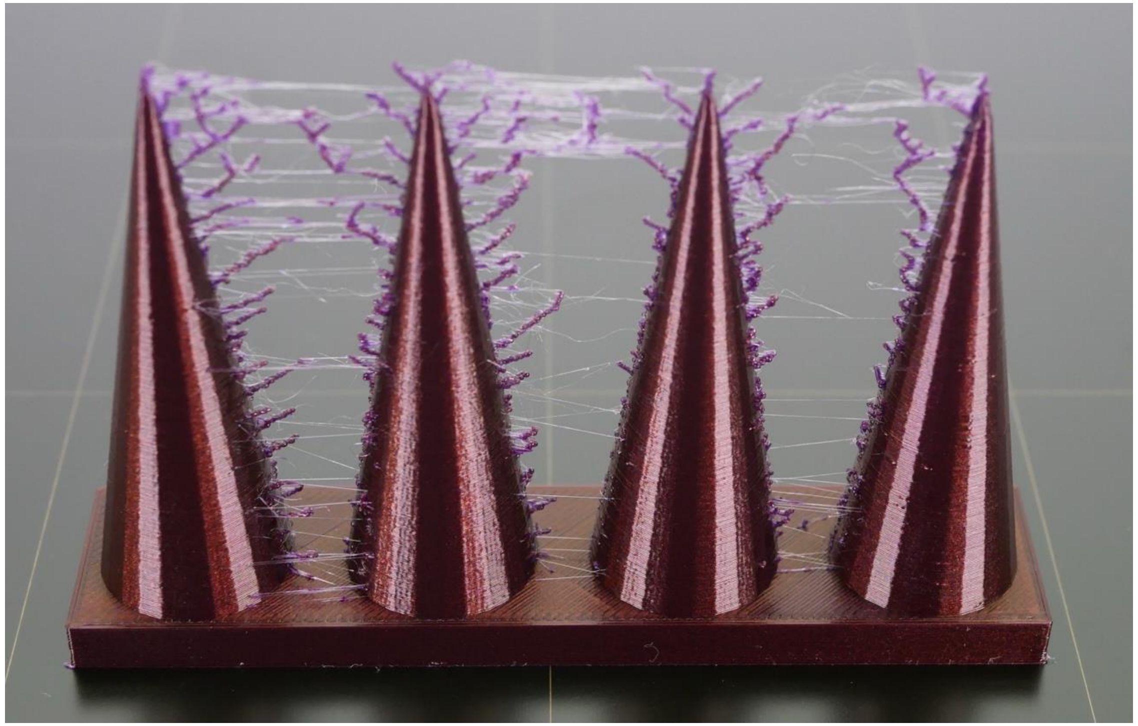
Raft

- Horizontal latticework of filament located underneath your part
- Delamination as a feature

www.zortrax.com/blog/3d-printed-rafts-guide/

Oozing/stringing

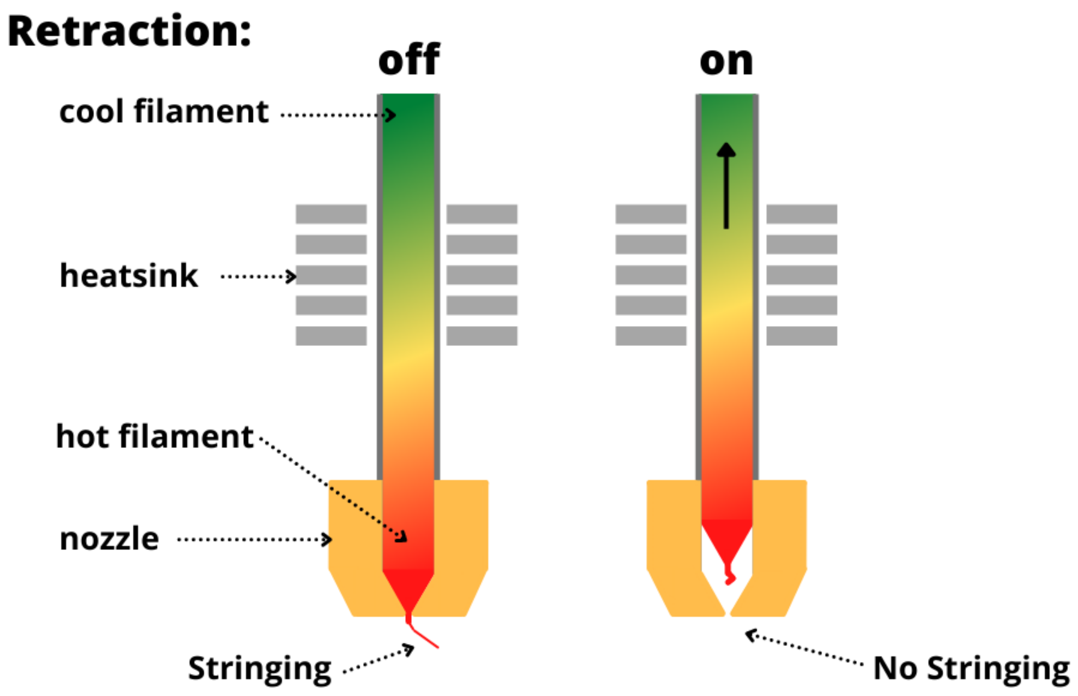
- Plastic oozing out of the nozzle when the extruder is moving to a new location
- Solutions?



https://help.prusa3d.com/article/stringing-and-oozing_1805

Oozing/stringing: solutions

- Retraction of the filament during travelling
  - Not possible for soft filaments
- Reduce travelling of the nozzle without printing



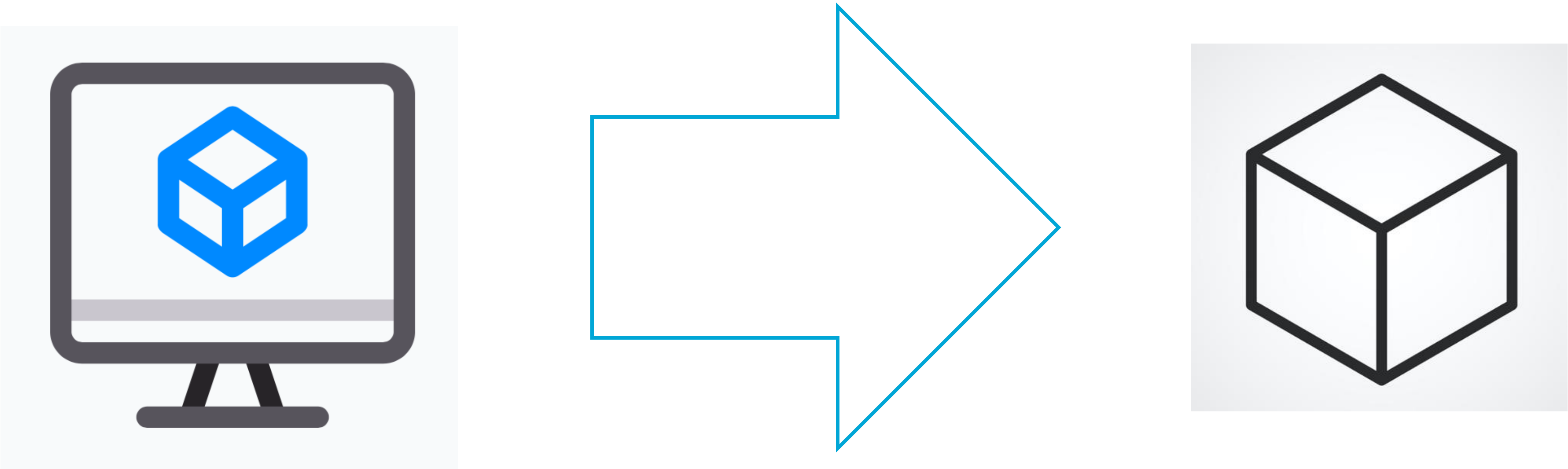
www.the3dprinterbee.com/stringing-guide-3d-printing/

Solving printing issues

- Change hardware settings
- Change the printing strategy
- Change the CAD model

www.sculpteo.com/blog/2018/07/16/mastering-fdm-3d-printing-in-your-school-lab/

3D-printing workflow



CAD Design

Printed part

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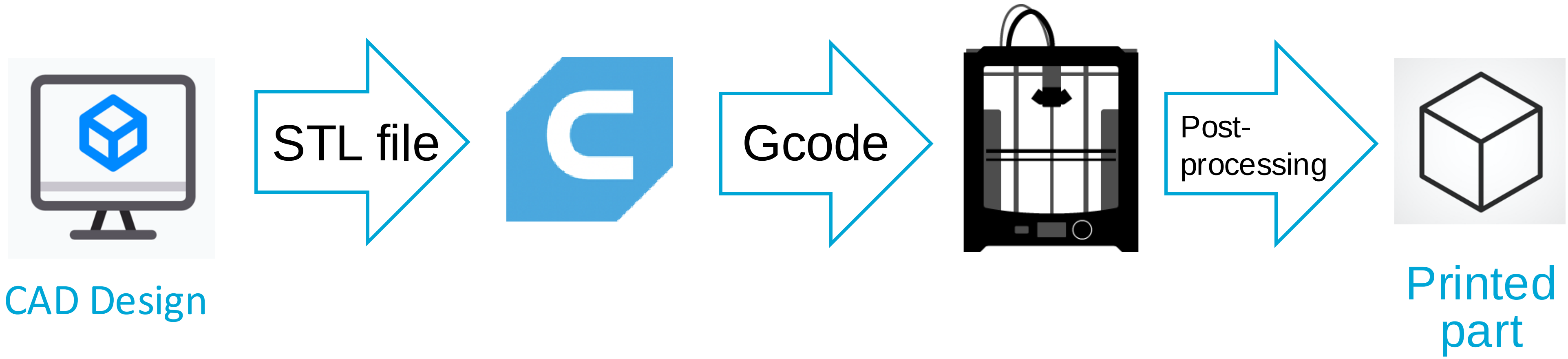

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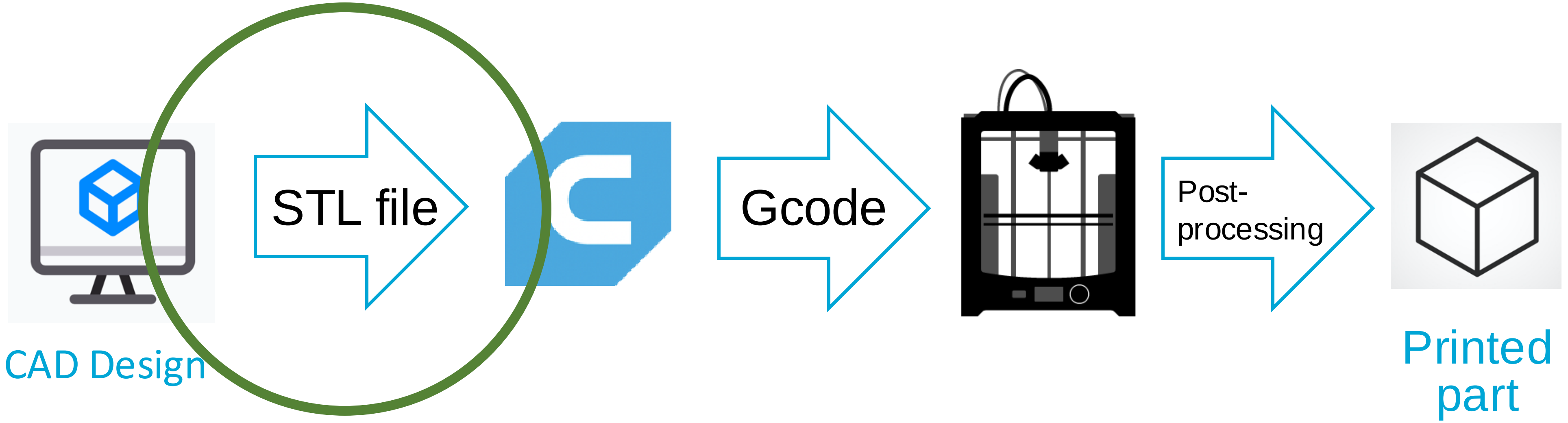
Export settings



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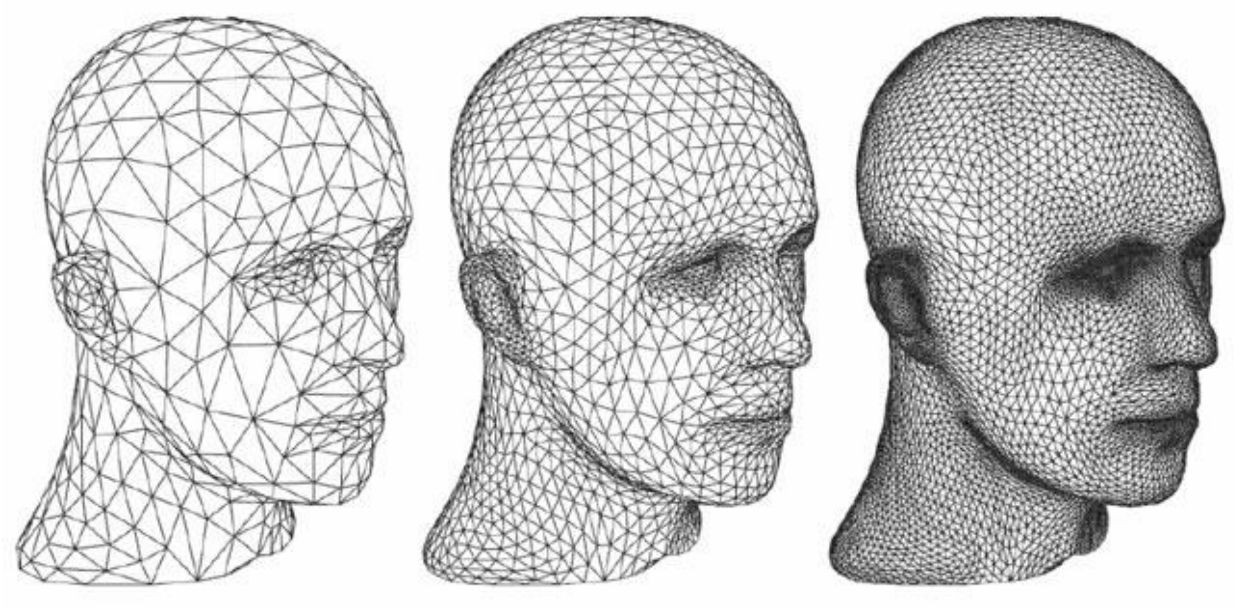
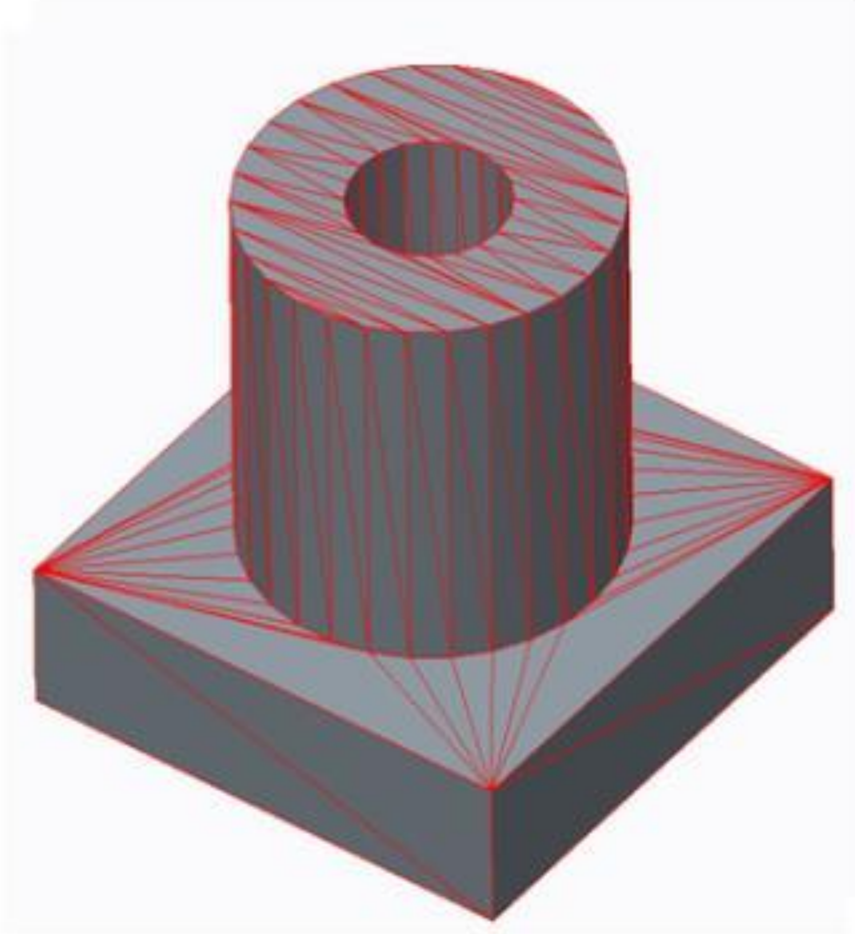
Export your CAD model to an STL-file

- STL: Standard Tessellation Language
- An STL file describes the surface geometry of a 3D model by breaking it down into small triangles (facets)



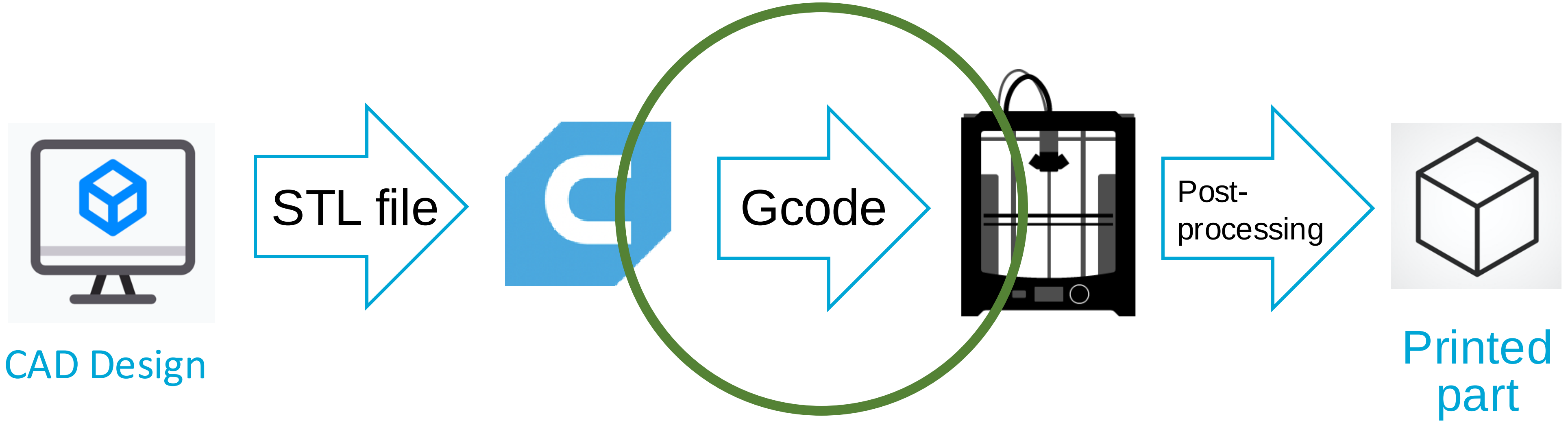
www.sculpteo.com/en/3d-learning-hub/create-3d-file/what-is-an-stl-file/

```
solid CREO STL
 facet normal 0.000000e+00 0.000000e+00 -1.000000e+00
  outer loop
   vertex 5.000000e+01 -5.000000e+01 0.000000e+00
   vertex -5.000000e+01 5.000000e+01 0.000000e+00
   vertex 5.000000e+01 5.000000e+01 0.000000e+00
  endloop
 endfacet
 facet normal 0.000000e+00 1.000000e+00 0.000000e+00
  outer loop
   vertex 5.000000e+01 5.000000e+01 6.000000e+00
   vertex 5.000000e+01 5.000000e+01 0.000000e+00
   vertex -5.000000e+01 5.000000e+01 0.000000e+00
  endloop
 endfacet
......
......
endsolid CREO STL
```



Ding et al., 2015

Slicer settings



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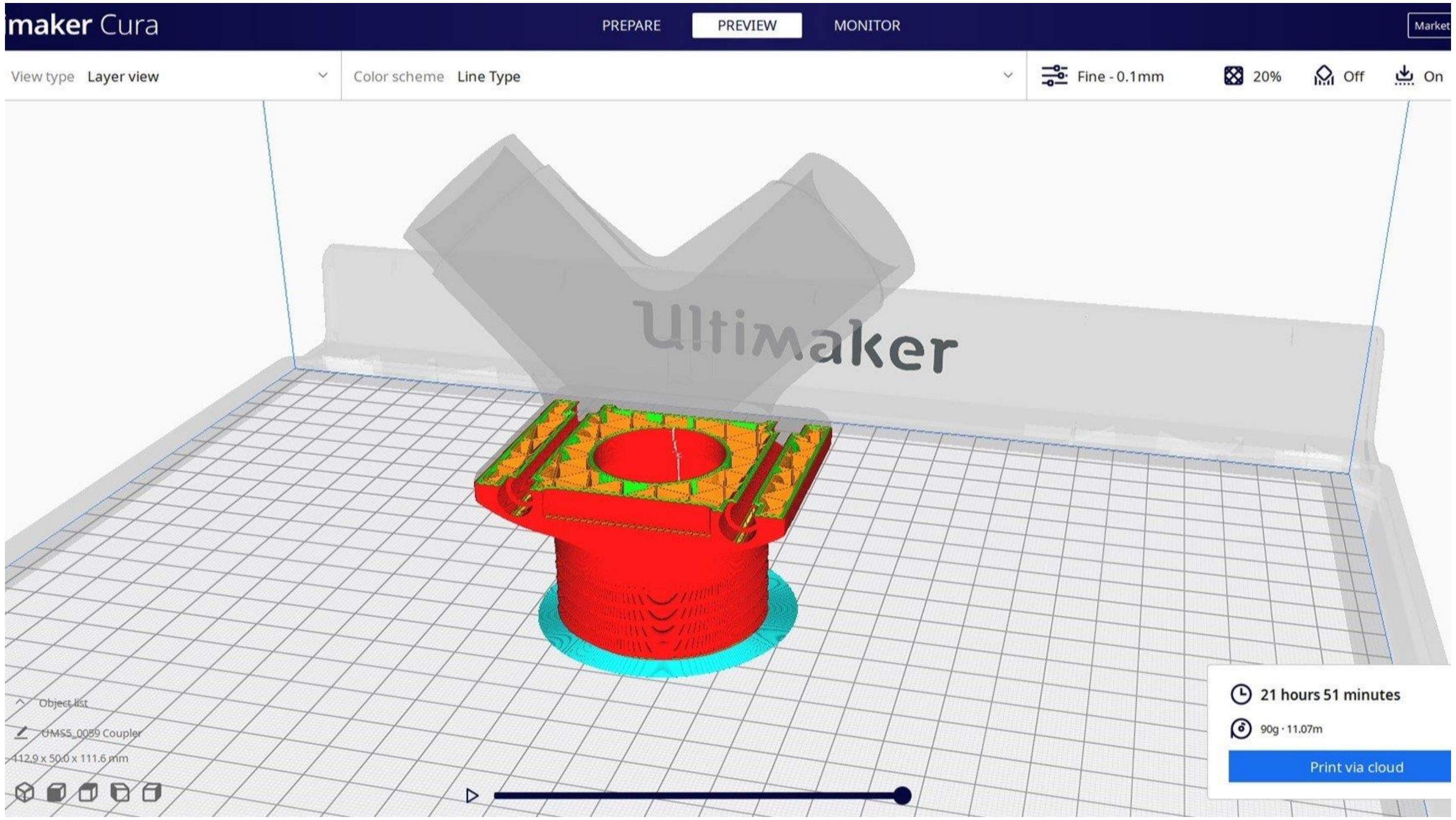
Converting an STL-file into a G-code file

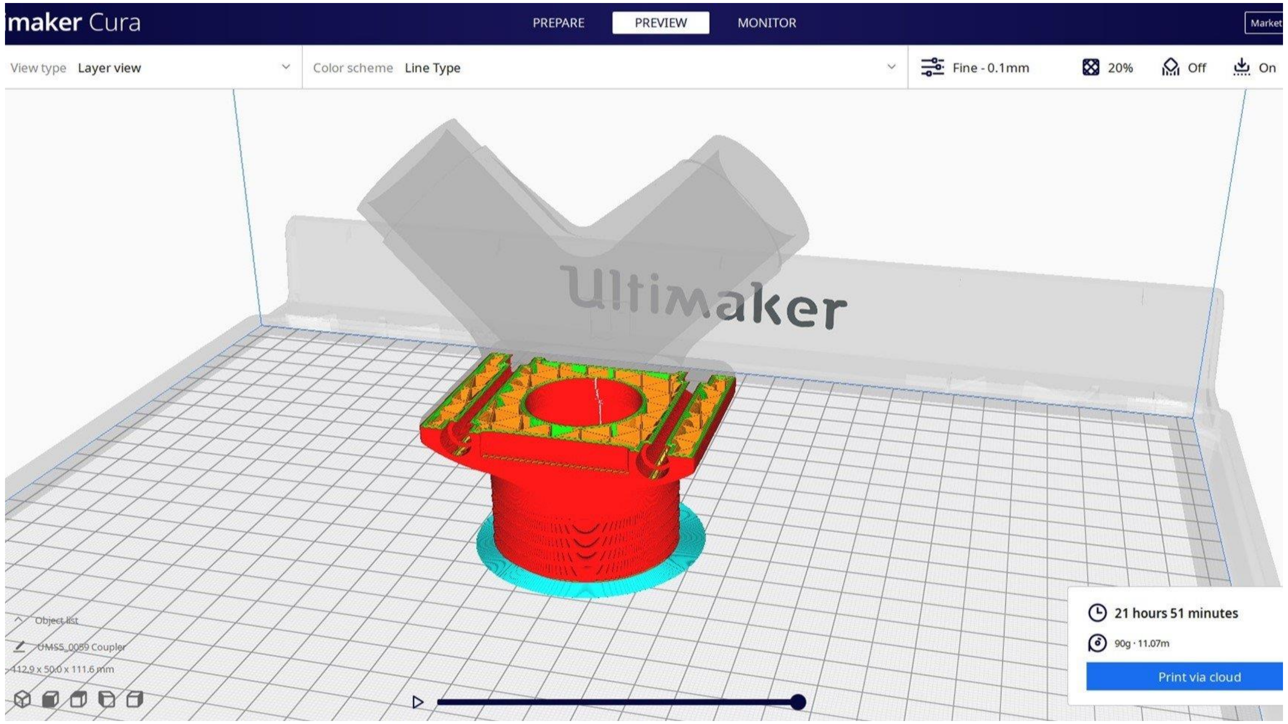
- Instructing machine tool movement to fabricate a model
  - G-code
- Slicer software
  - Cura
  - Bambu Studio



www.all3dp.com/2/best-cura-plugins/

Decisions made in the slicer

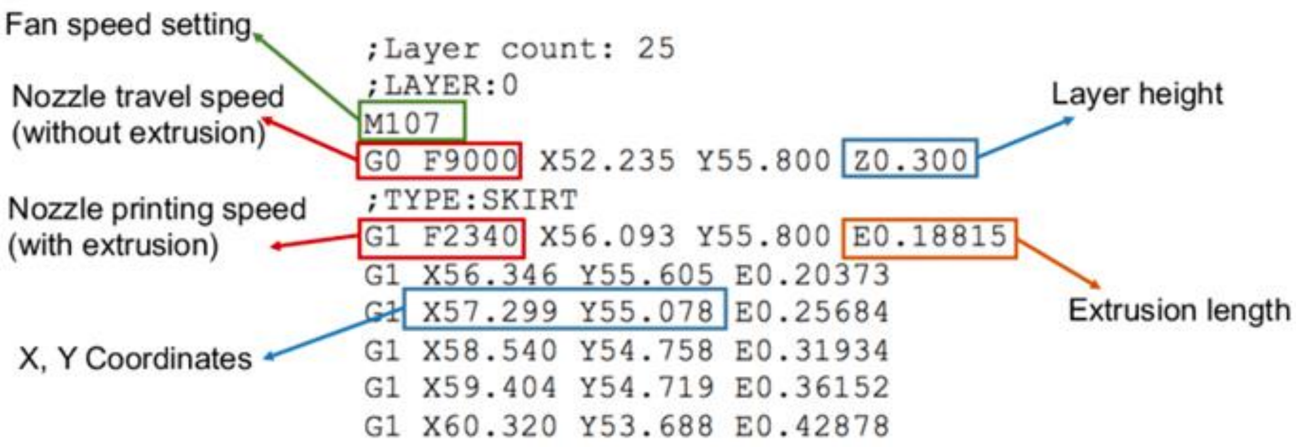
- Orientation
  - Affects strength
  - Affects printing time
  - Affects surface quality
  - Affects the amount of support material required
- Support structure/infill
- Path planning



www.all3dp.com/2/best-cura-plugins/

G-code

- Computer numerical control programming language
- Originally used for CNC milling machines
- Developed by MIT in the 1950s
- Now the standard for 3D-printing

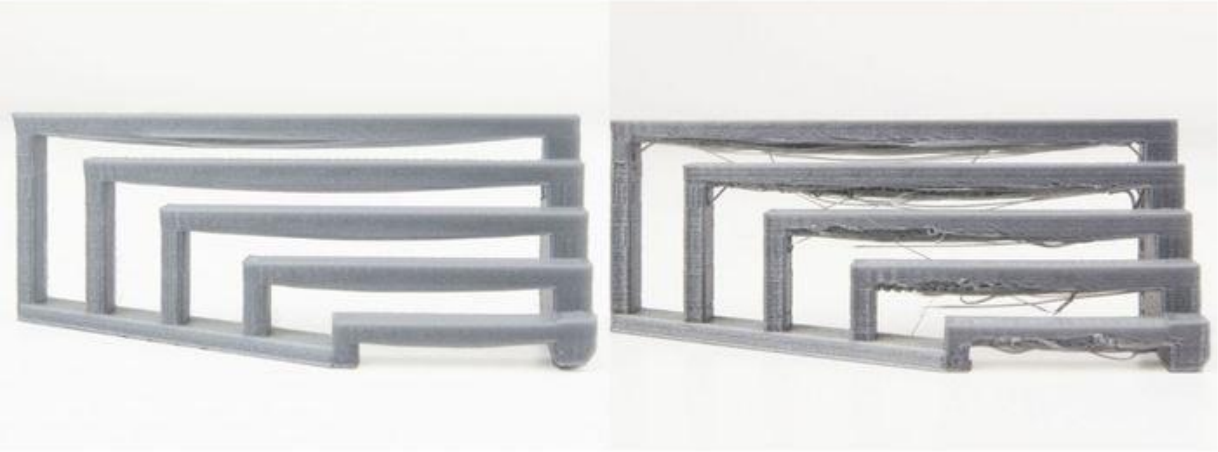


Unconventional printing modes

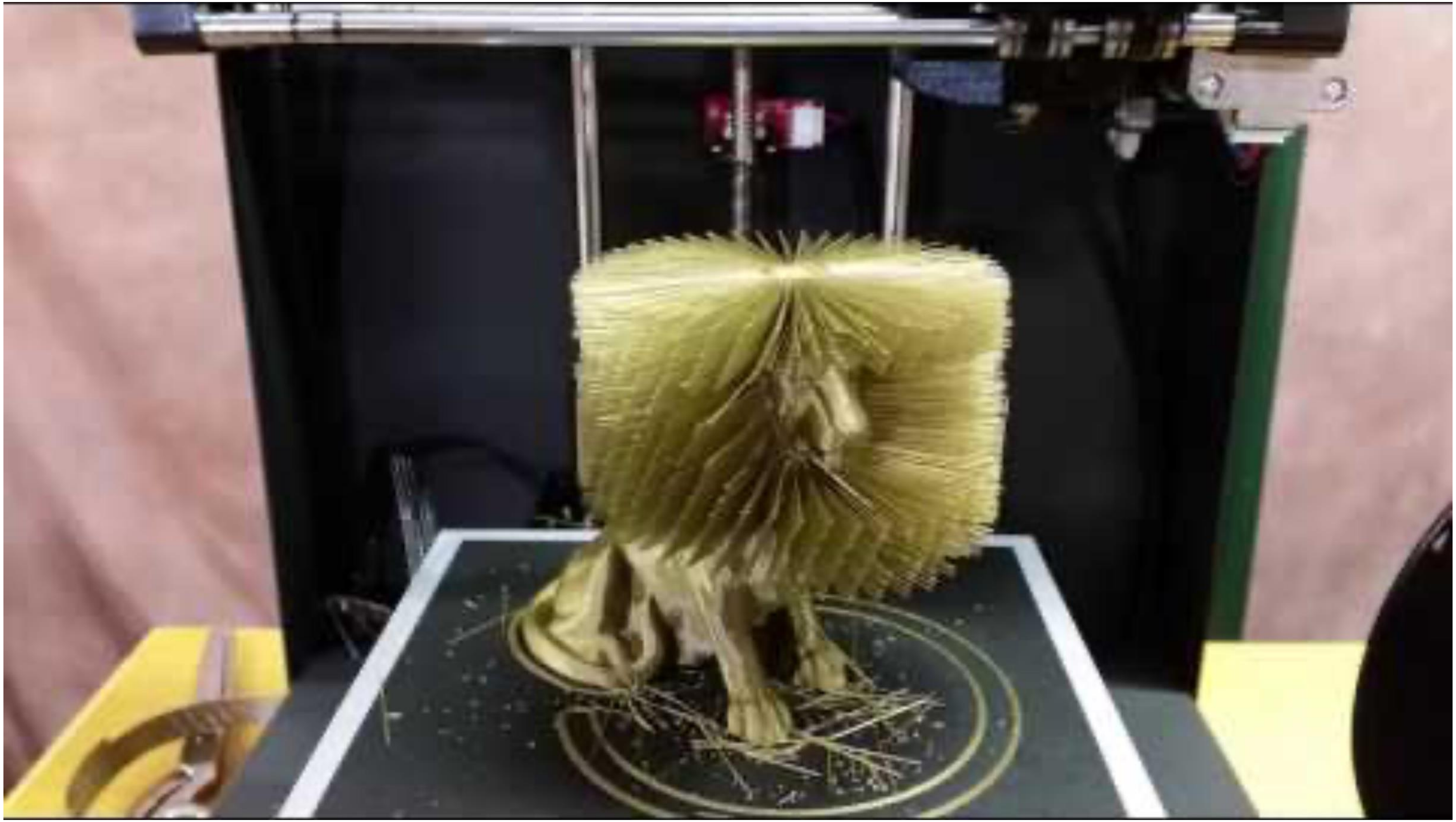
- Push the boundaries of FDM printer’s capabilities
- Understanding of the hardware enables new possibilities

Bridging

- Span a line across a gap
- Cura feature

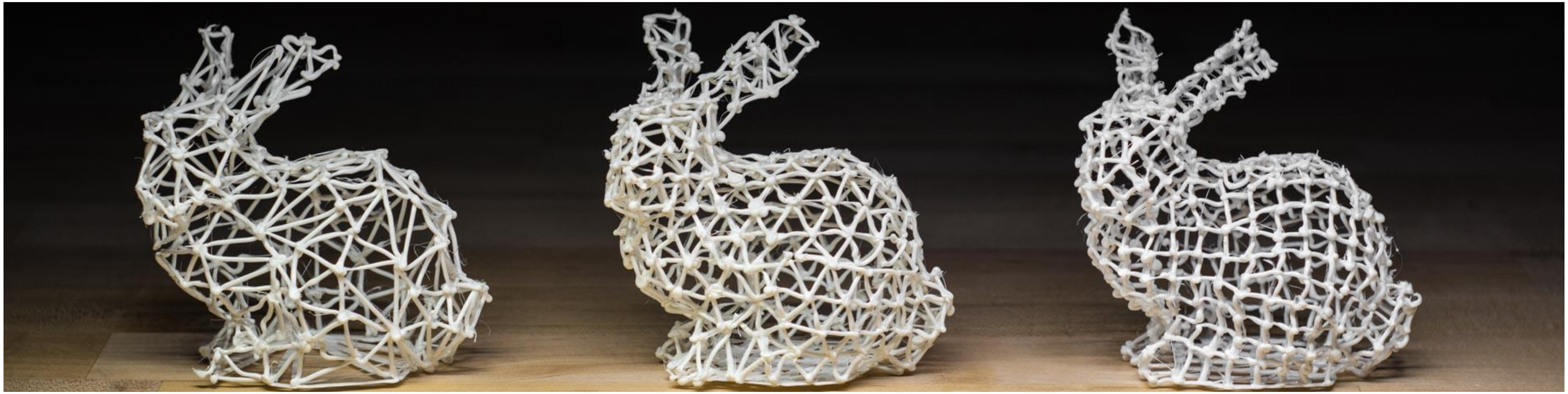


www.3dnatives.com/en/how-to-avoid-briding-in-3d-printing-2107234/



Wire printing

- Solidify mid-air
- Print slow with fan on
- Cura feature



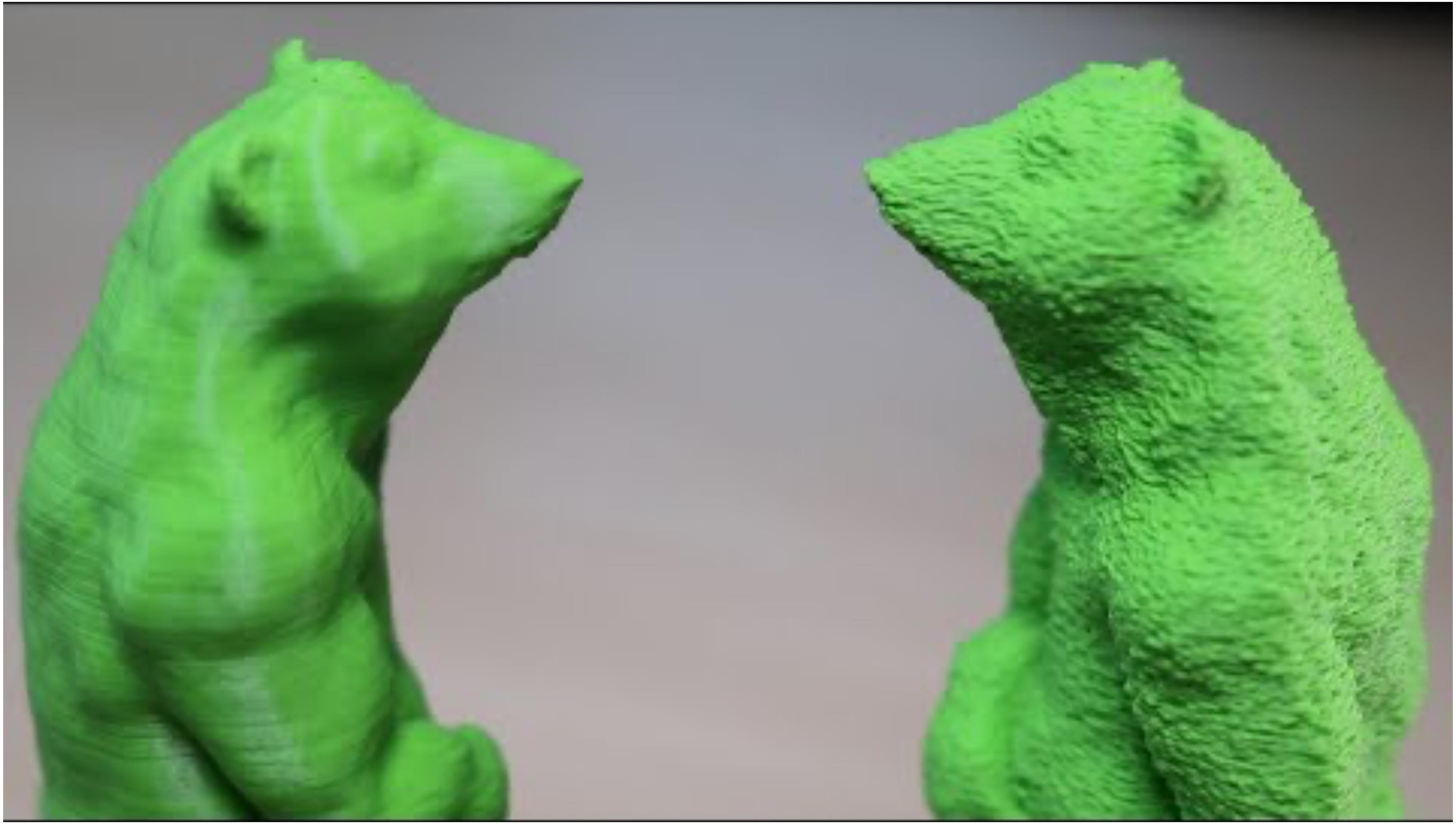
www.cs.cornell.edu/projects/wireprint/


WIRE
PRINTING

Fuzzy skin

- Jitter the printhead on the outer contour
- For a rough surface and hiding layer lines
- Cura feature

www.reddit.com/r/3Dprinting/comments/arrhnl/so_i_tried_curas_fuzzy_skin_mode_yeahits_like/



Ironing

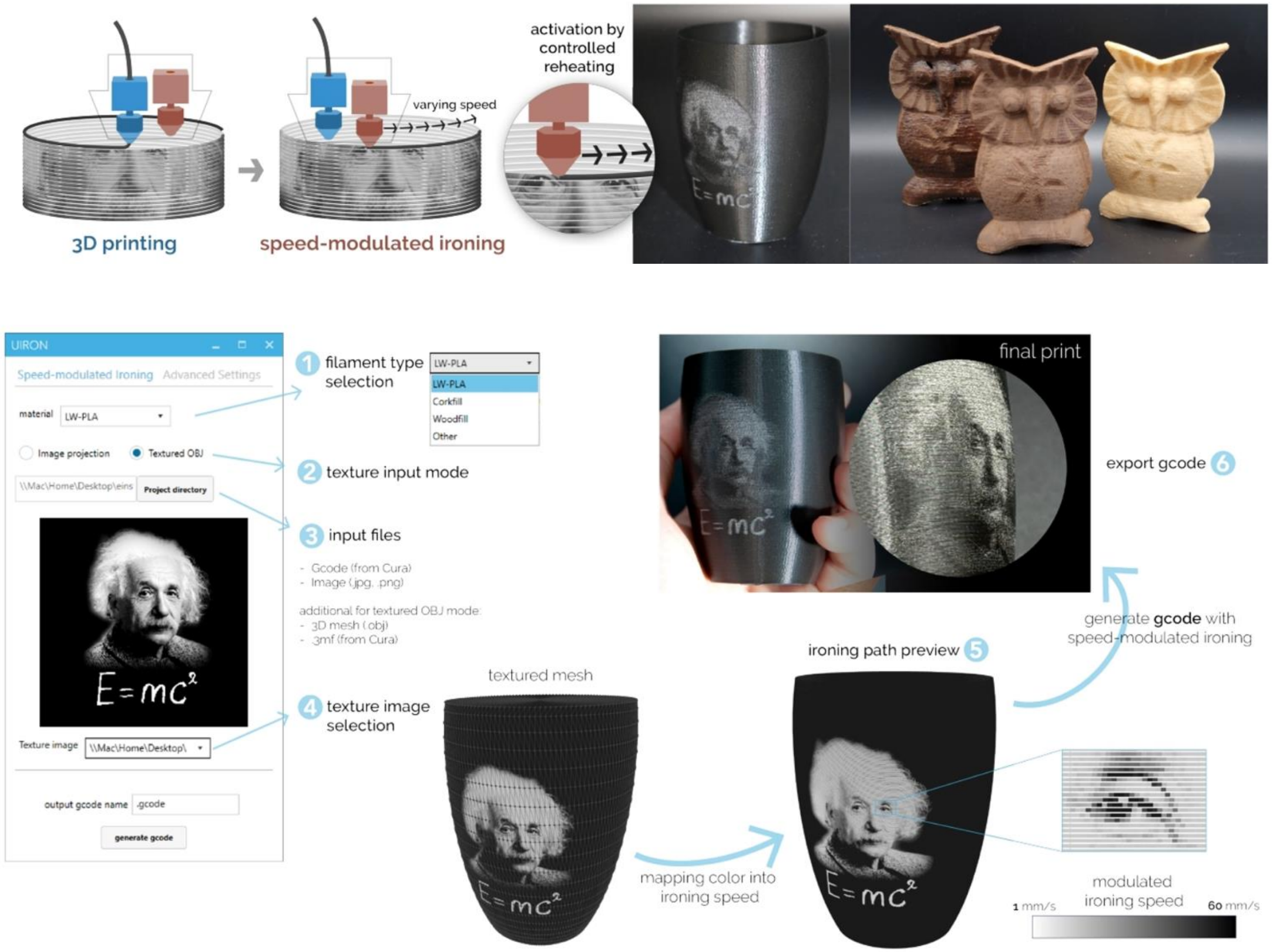
- Moving the nozzle back and forth over the top layer
- Small amount of extrusion to fill gaps
- Cura feature

www.youtube.com/watch?app=desktop&v=gh5wC4Ti95s&ab_channel=CHEP

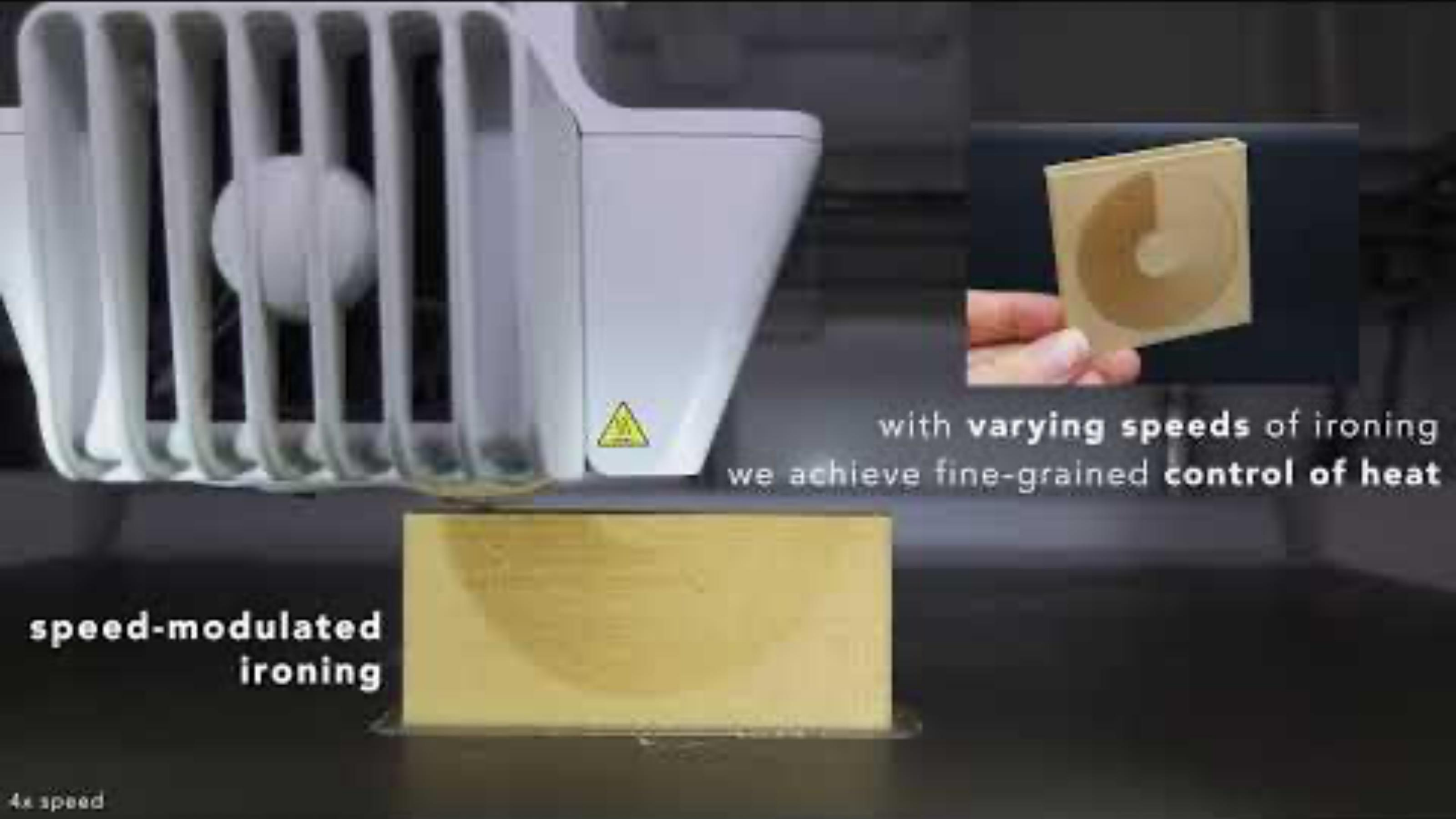

URA
SMOOTH
TEXTURED

Speed-modulated Ironing

- One nozzle to 3D print and a second nozzle to reheat printed areas at varying speeds, controlling the material's temperature-response
- The rapid adjustments of speed allow for fine-grained reheating, enabling high-resolution color and texture variations



Demonstrating Speed-Modulated Ironing: High-Resolution Shade and Texture Gradients in Single-Material 3D Printing, Ozdemir et al., 2024


with **varying speeds** of ironing
we achieve fine-grained **control of heat**
speed-modulated ironing
4x speed

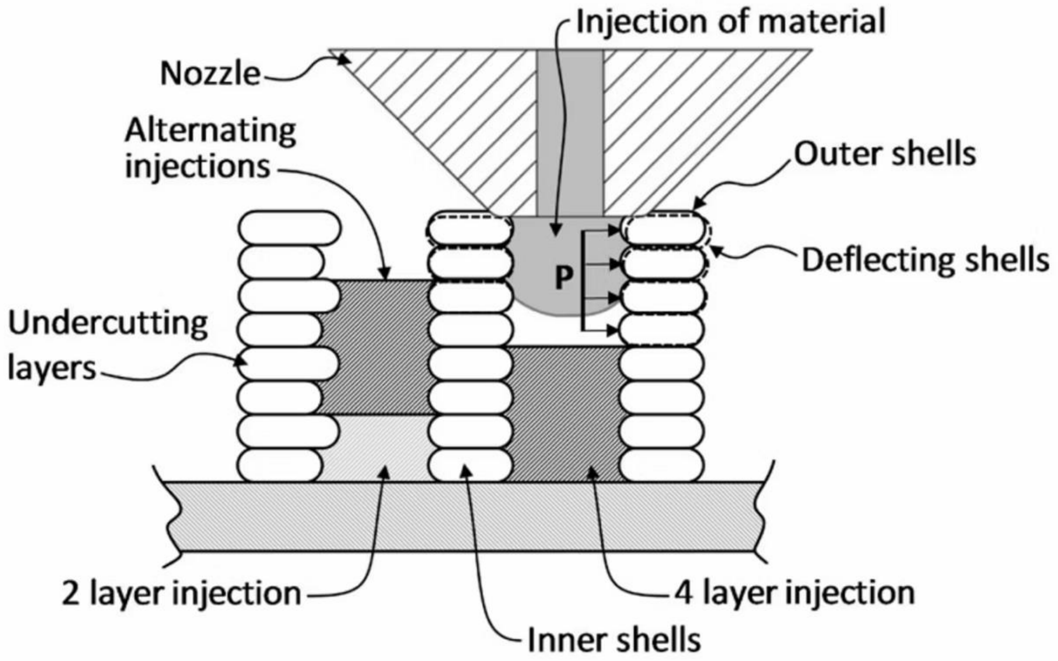
Sagging

- Print black and white layers in an alternating way
- Hatching for halftoning (simulating continuous tone)

Hatching for 3D prints, Kuipers et al., 2017

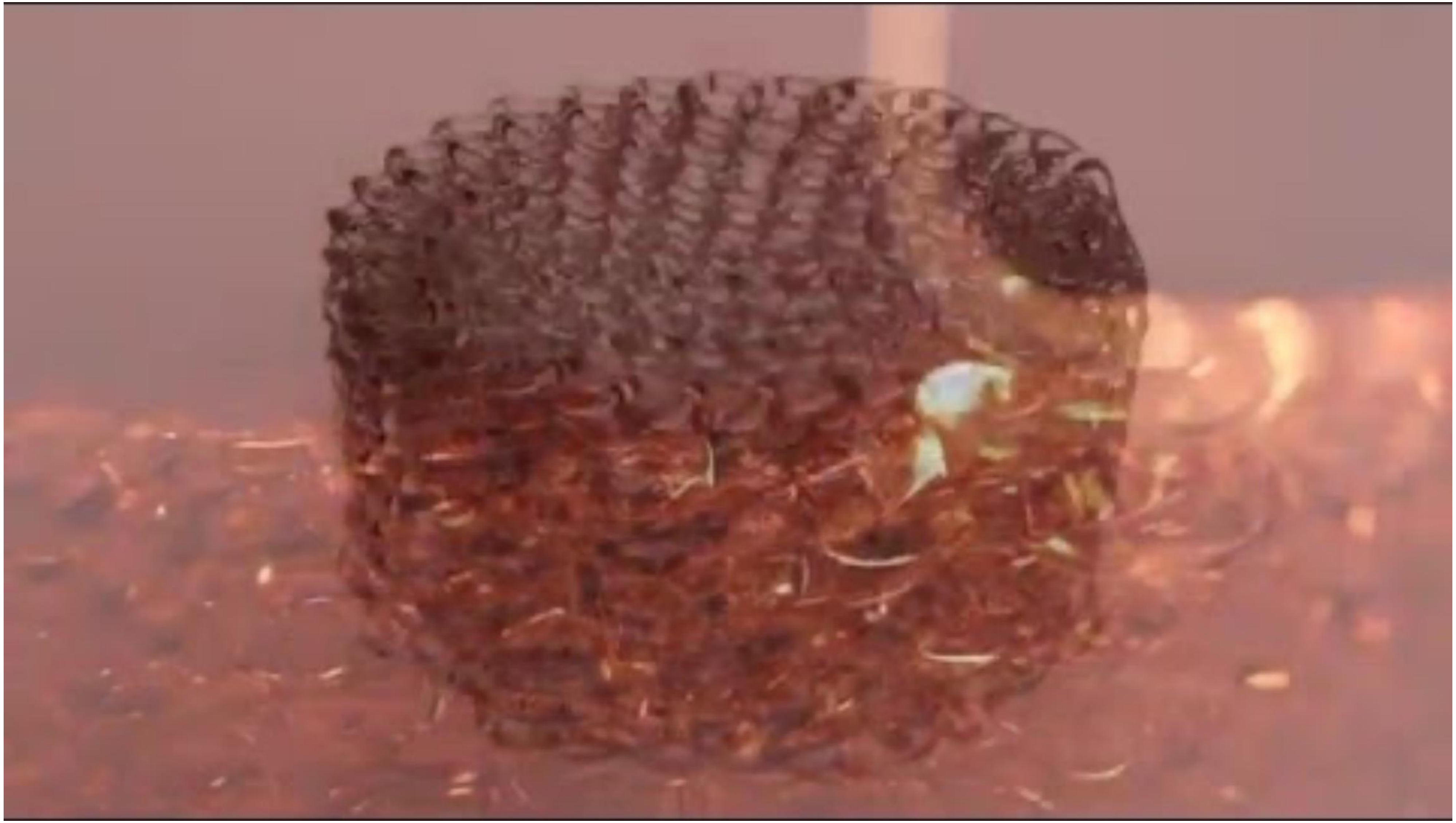
Drooping

Injection



Kazmer & Colon, 2020

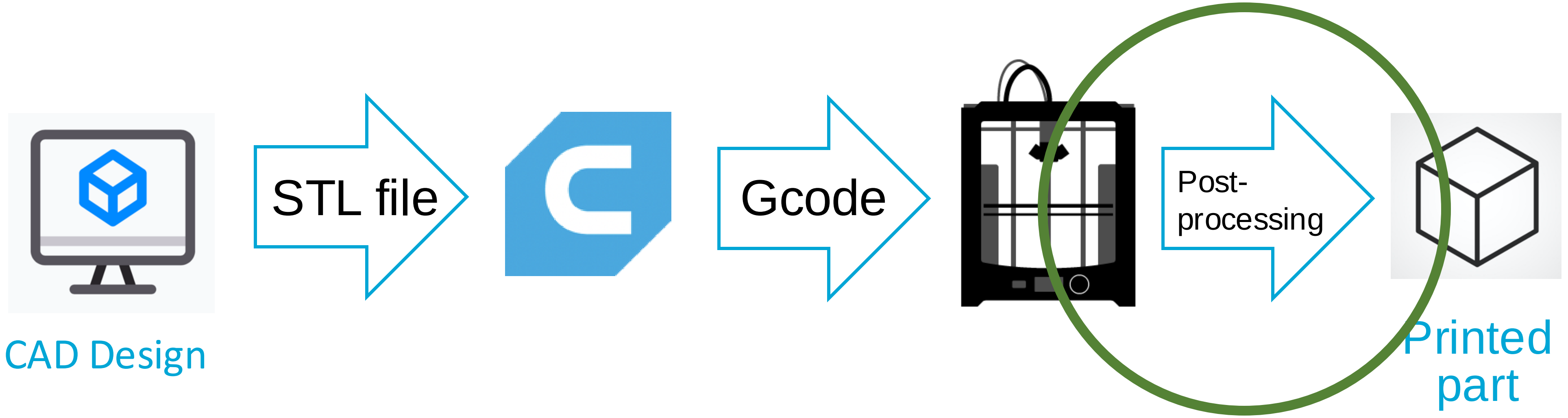
Rope coiling



Other extrusion modes

- Spaghettification
- Mid-air printing
- Fusing
- Laying
- Blobbing
- Piling
- Underextrusion
- Engraving
- And many more…

Post-processing



Doubrovski 2023

Post-processing

- Support removal
- Sanding
- Smoothening
- Drilling
- Painting
- Polishing
- Hydro-dipping
- Electroplating
- Epoxy coating
- Welding
- And many more…

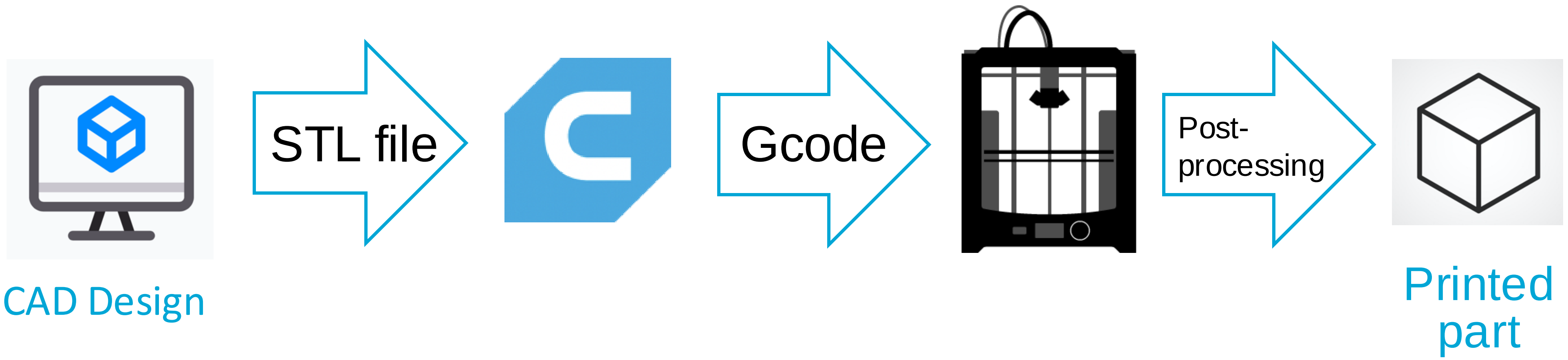
https://manufactur3dmag.com/8-techniques-for-post-processing-of-fdm-3d-printed-parts/

Smoothening

- Acrylonitrile Butadiene Styrene (ABS)
  - ABS is soluble in ketones
  - Aceton can be used to smoothen part
  - Difficult to print (warping)
- Polyvinyl butyral (PVB)
  - Easier to print
  - Put in mist of IPA to smoothen part

https://www.geeetech.com/blog/2018/02/heres-how-you-can-get-smooth-and-shiny-abs-prints-at-home/

Where does design end?



Doubrovski 2023

Questions?

Next week's lab

- Slicing and FDM-printing of the mold for silicone casting of the fish tail
  - 1 mold per group
- Teams need to be determined before the start of the lab