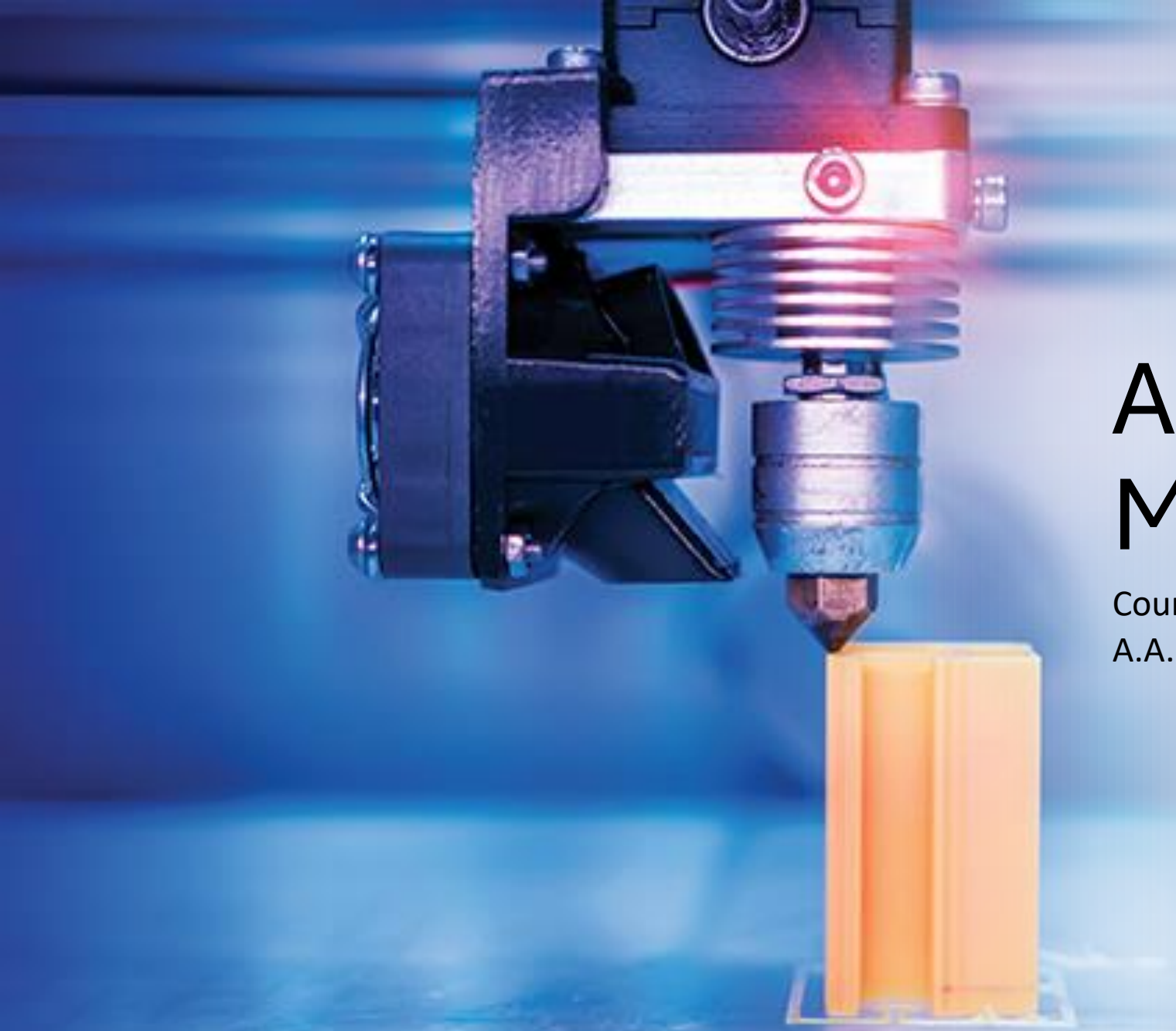


Università di Pisa

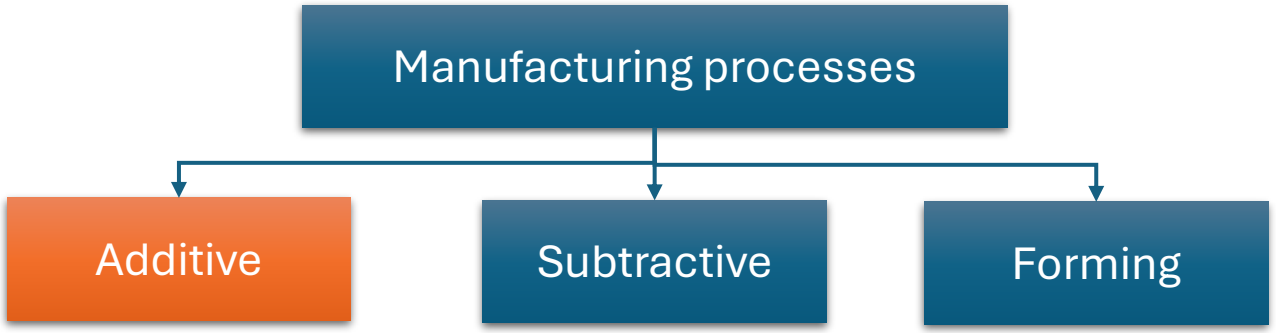
Additive Manufacturing

Course: Tecnologia Meccanica

A.A. 2023-2024

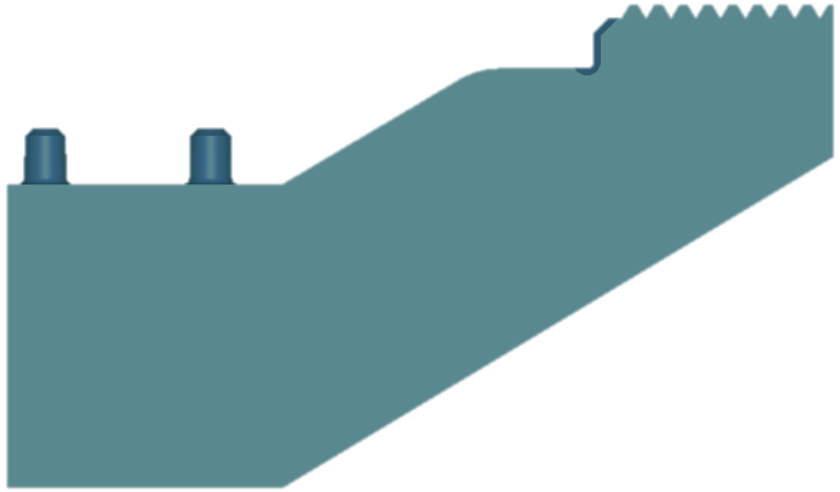
Ing. Alessio Pacini, PhD student

Additive Manufacturing (AM)



Additive Manufacturing (AM)

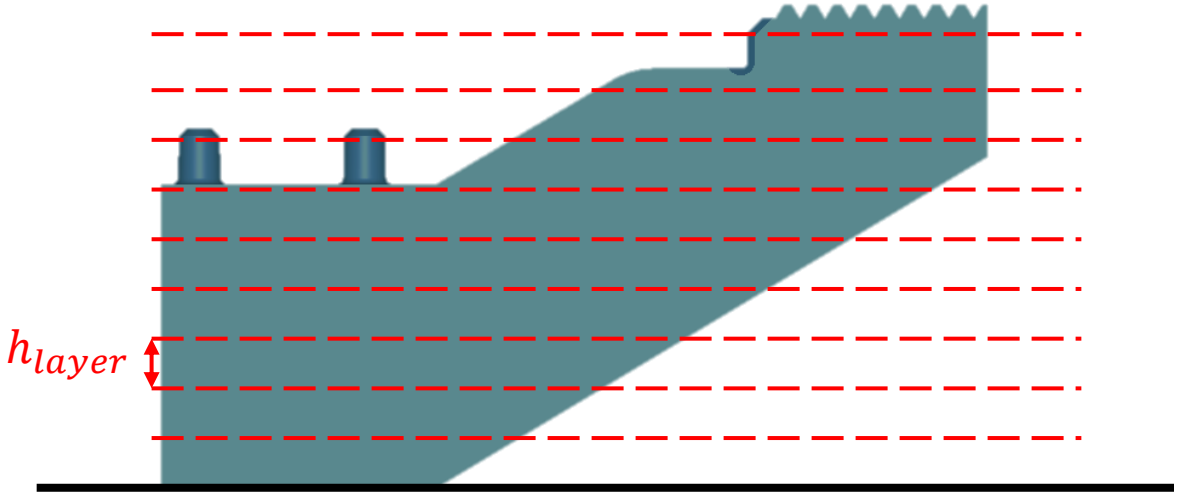
1. Creation of a digital model through Computer-Aided Design (CAD)



Additive Manufacturing (AM)

1. Creation of a digital model through Computer-Aided Design (CAD)

2. The 3D model is divided into a series of 2D cross-sectional layers (slicing)



Additive Manufacturing (AM)

1. Creation of a digital model through Computer-Aided Design (CAD)

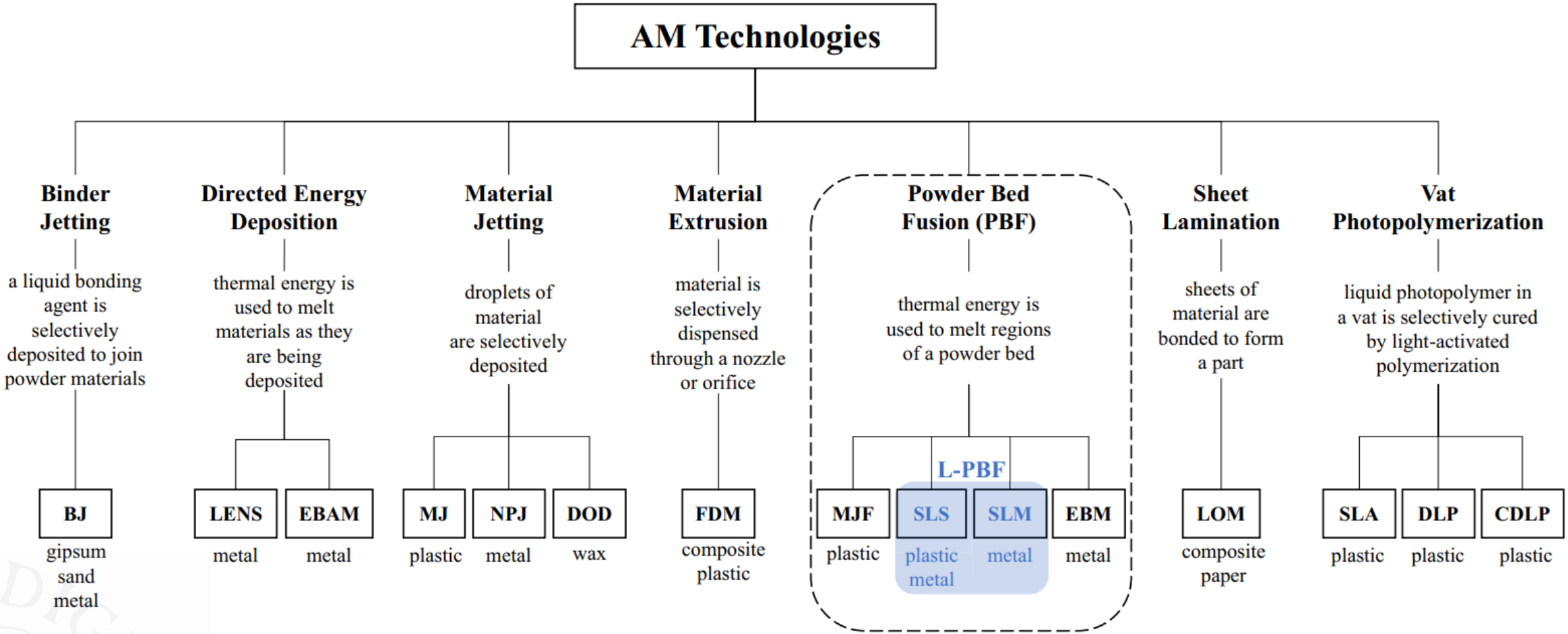
2. The 3D model is divided into 2D cross-sectional layers (slicing)

3. The AM machine uses an additive process where successive layers of material are deposited on top of one another

Materials

- Thermoplastic polymers
- Thermosetting polymers
- Resins
- Metals and alloys
- Composites
- Ceramics
- Biological materials

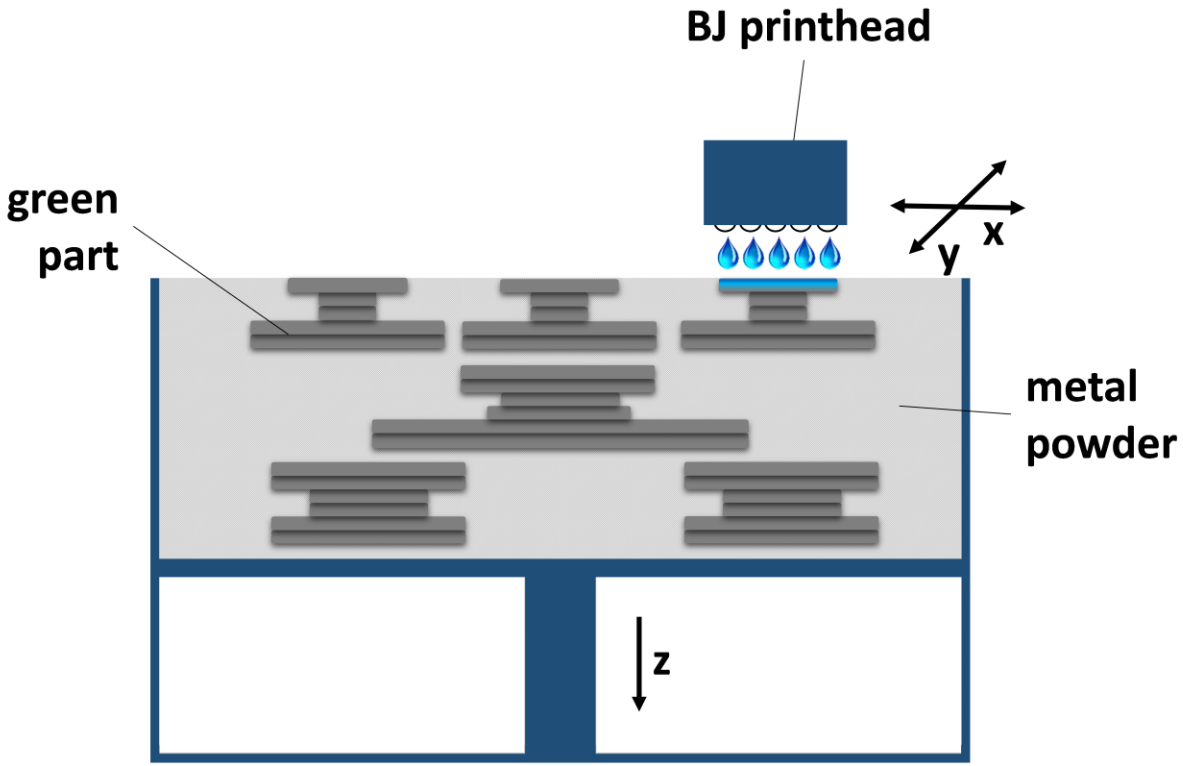
Principali processi (ASTM/ISO 52900)



Lupi et al. (2023) Laser powder bed additive manufacturing: A review on the four drivers for an online control Journal of Manufacturing Processes 103(4):413-429. DOI 10.1016/j.jmapro.2023.08.022

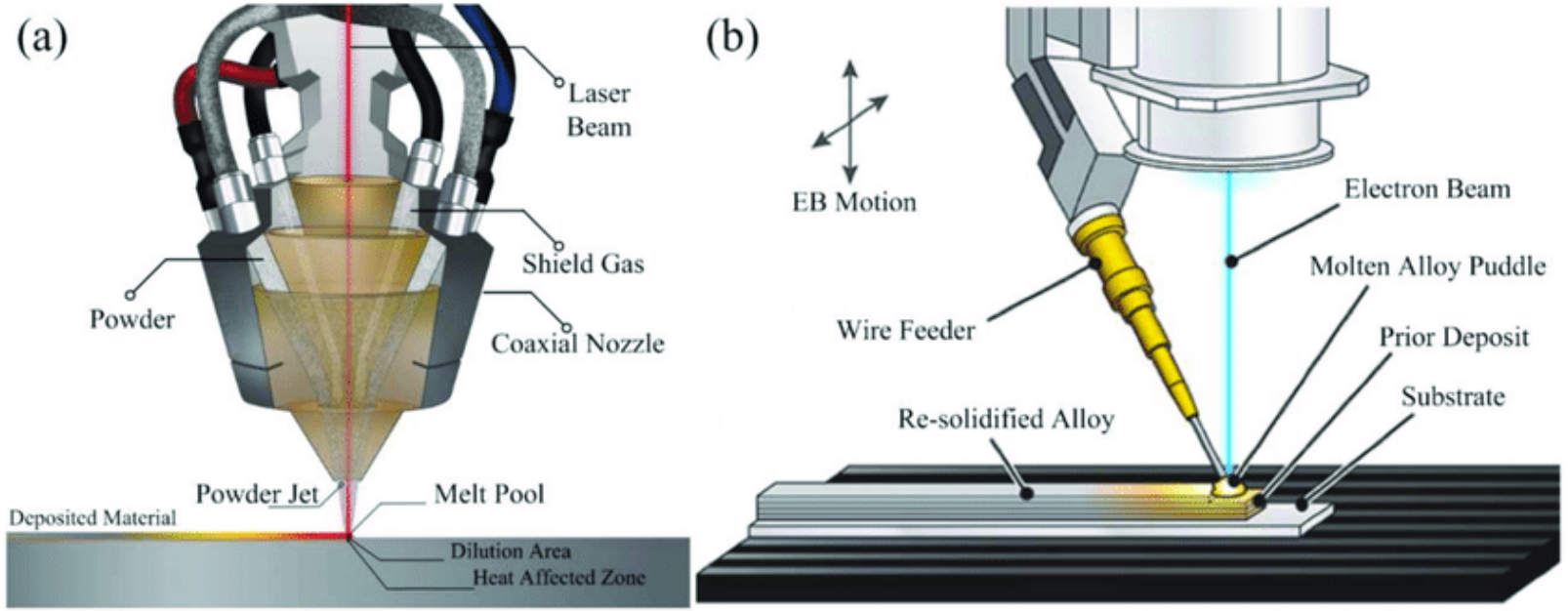
Main processes (ASTM/ISO 52900)

- **Binder jetting**: AM process in which a liquid bonding agent is selectively deposited to join powder materials



Main processes (ASTM/ISO 52900)

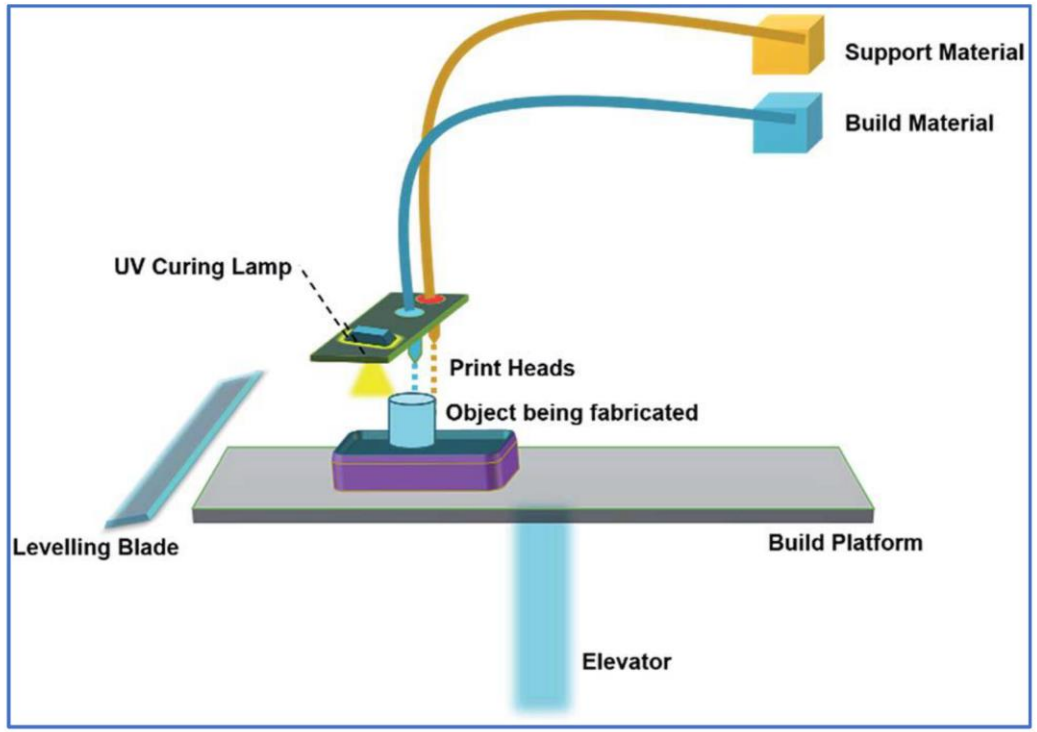
- **Directed energy deposition** : AM process using focused thermal energy (e.g., laser, electron beam, or plasma arc) to fuse materials by melting as they are deposited.



Metal Additive Manufacturing for Electrical Machines: Technology Review and Latest Advancements - Scientific Figure on ResearchGate.

Main processes (ASTM/ISO 52900)

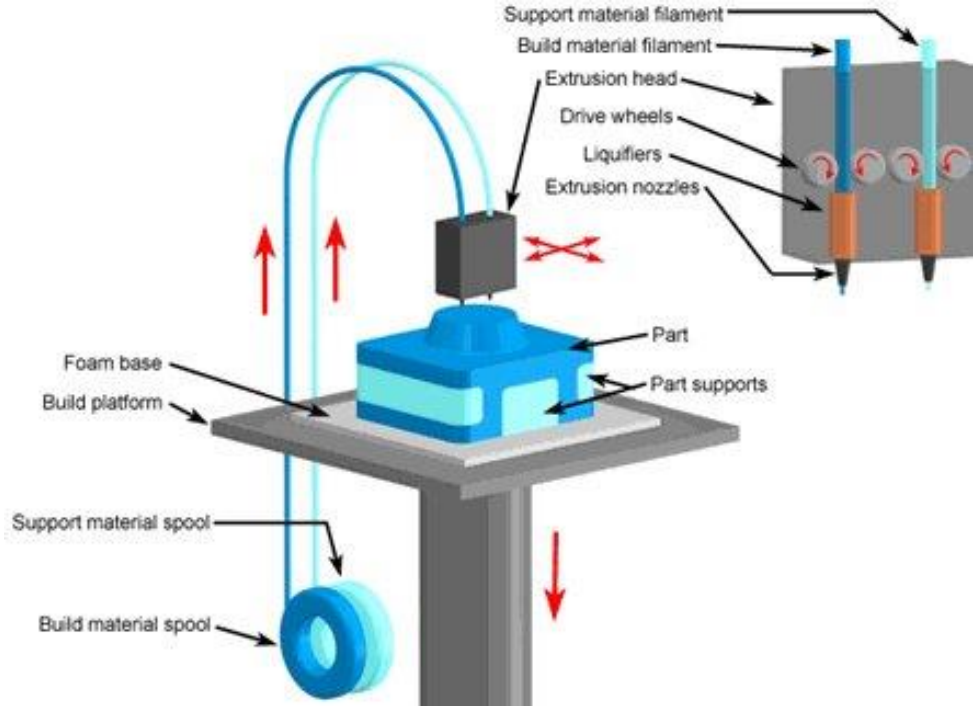
- **Material jetting** : AM process in which material is selectively dispensed through a nozzle or orifice.



Gülcan, O.; Günaydın, K.; Tamer, A. The State of the Art of Material Jetting—A Critical Review. *Polymers* **2021**, *13*, 2829. https://doi.org/10.3390/polym13162829

Main processes (ASTM/ISO 52900)

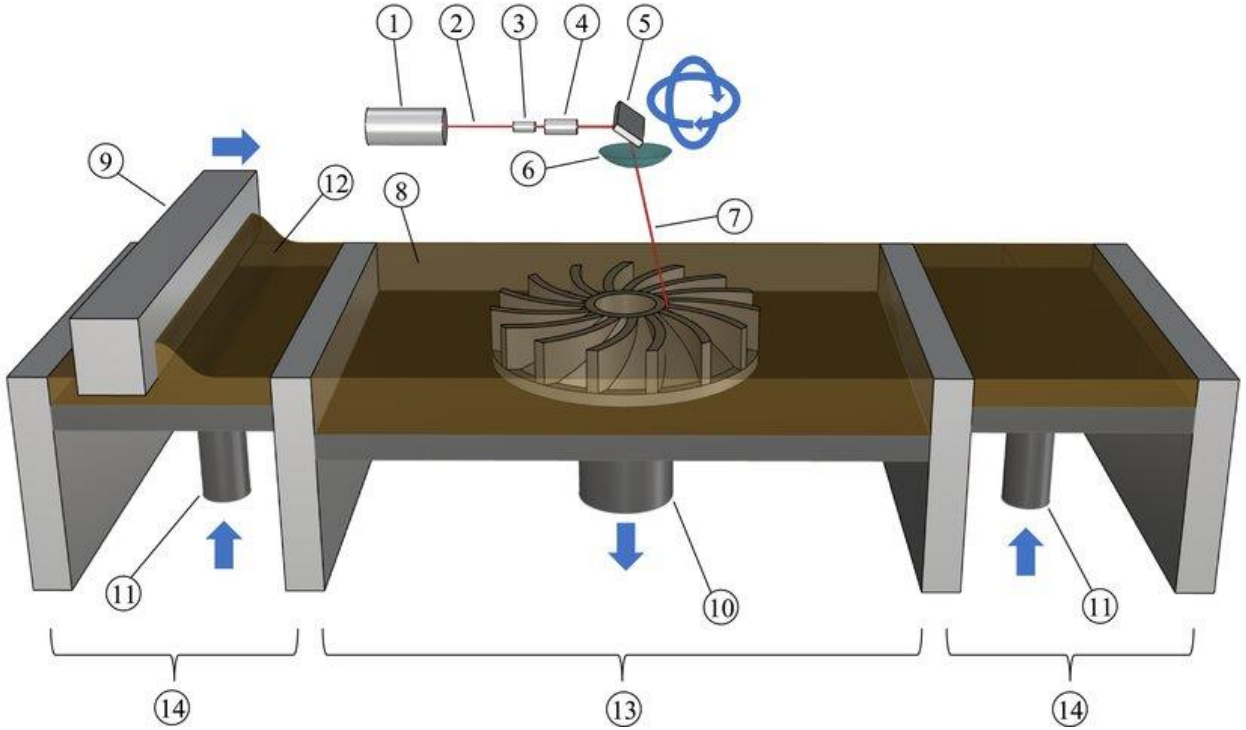
- **Material extrusion**: AM process in which droplets of build material are selectively deposited (e.g., photopolymer and wax)



Polymers | Free Full-Text | The State of the Art of Material Jetting—A Critical Review (mdpi.com)

Main processes (ASTM/ISO 52900)

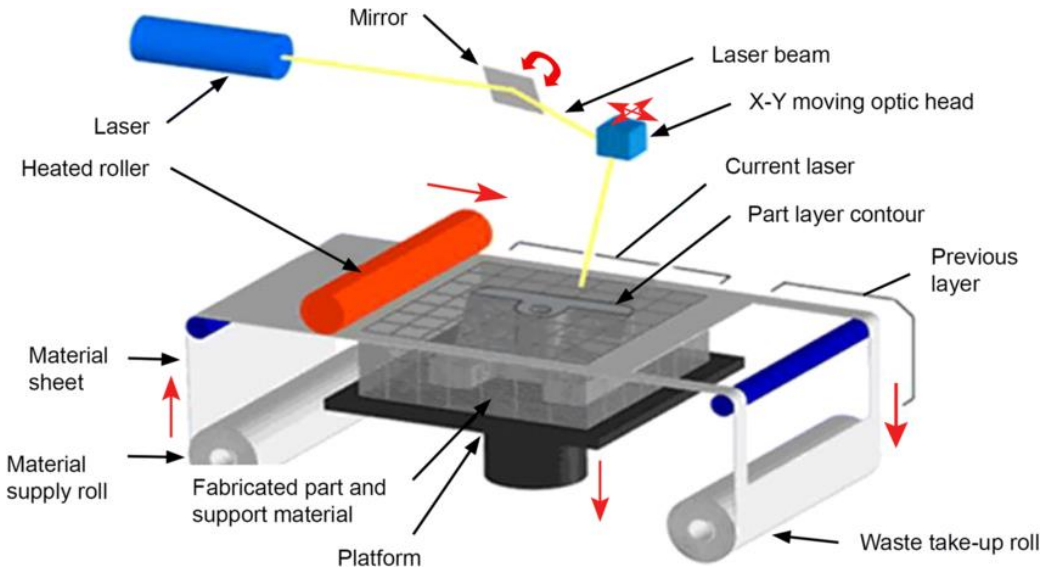
- **Powder bed fusion** : AM process in which thermal energy selectively fuses regions of a powder bed.



Lupi et al. (2023) Laser powder bed additive manufacturing: A review on the four drivers for an online control Journal of Manufacturing Processes 103(4):413-429. DOI 10.1016/j.jmapro.2023.08.022

Main processes (ASTM/ISO 52900)

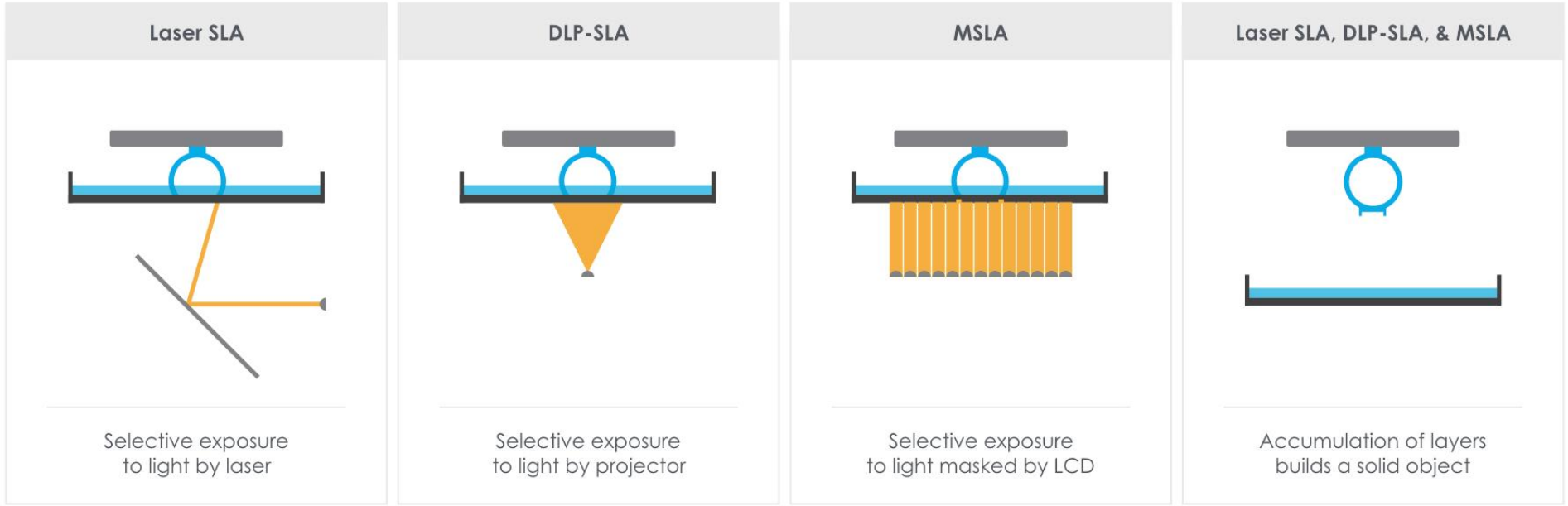
- **Sheet lamination** : AM process in which sheets of material are bonded to form a part.



Additive manufacturing methods: techniques, materials, and closed-loop control applications - Scientific Figure on ResearchGate.

Main processes (ASTM/ISO 52900)

- **Vat photopolymerization** : AM process where liquid photopolymer in a vat is selectively cured by light-activated polymerization.



Advantages

Net-shape
Reduced tie to market
Reduction of waste
customization

- Creation of complex geometries
- Just-in-time production
- Reduction in storage and transport costs
- Flexibility
- Customized parts for medical applications
- Simplification of production processes
- Reduction in material waste (use of recyclable materials)
- Topological optimization
- Equipment cost lower than traditional machine tools
- Mechanical Technology

Additive vs subtractive

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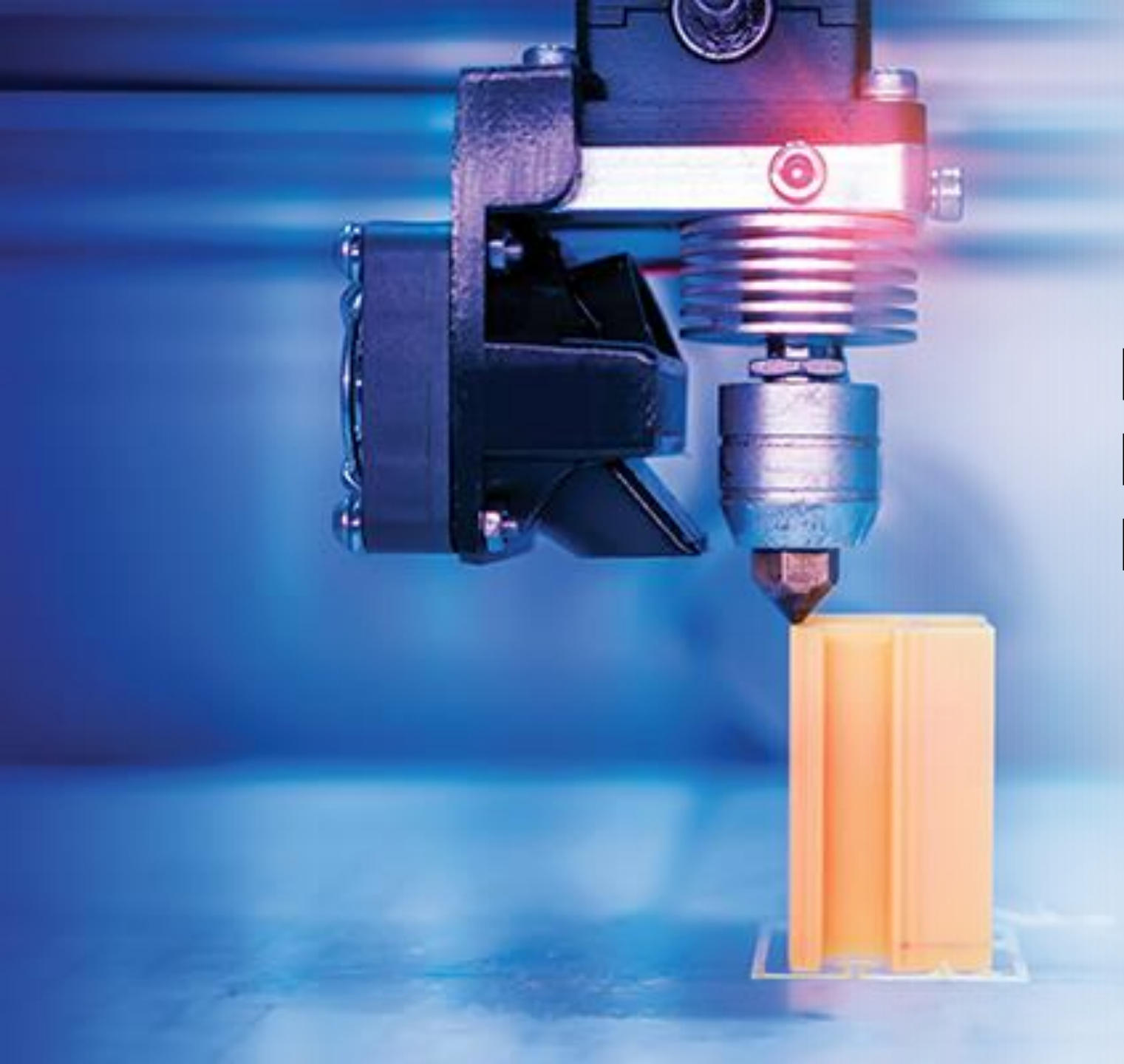
Civile e Industriale

Cost comparison forming, additive and subtractive. Constant vs decreasing…

Comparison of geometrical complexity, precision, mechanical resistance, fabrication time and material choice

Limitations

- Lower dimensional accuracy compared to traditional machine tools
- Inferior surface finish
- Post-processing often required
- Limited material availability
- Lower production volumes
- Constraints on product size
- High training and development costs
- Anisotropic material properties; some residual porosity remains



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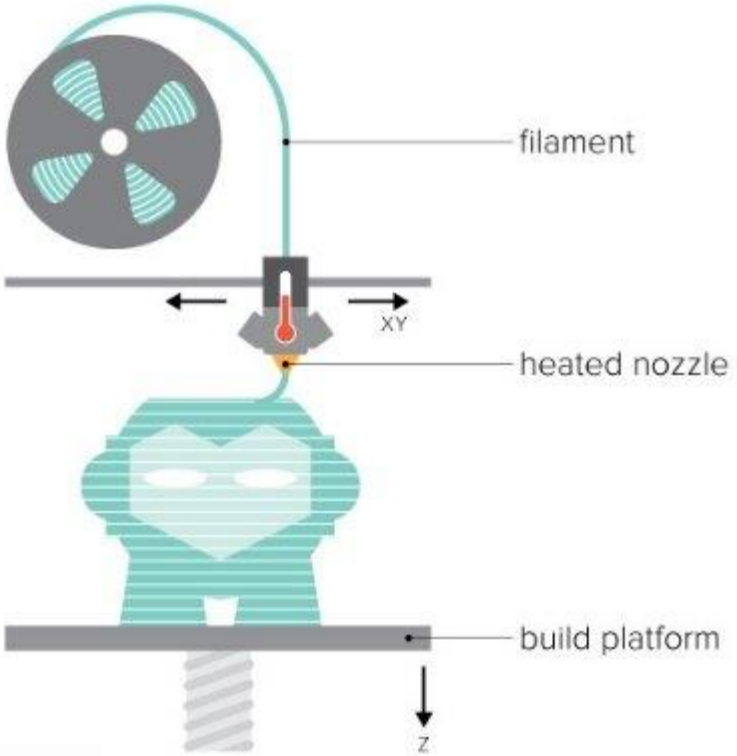
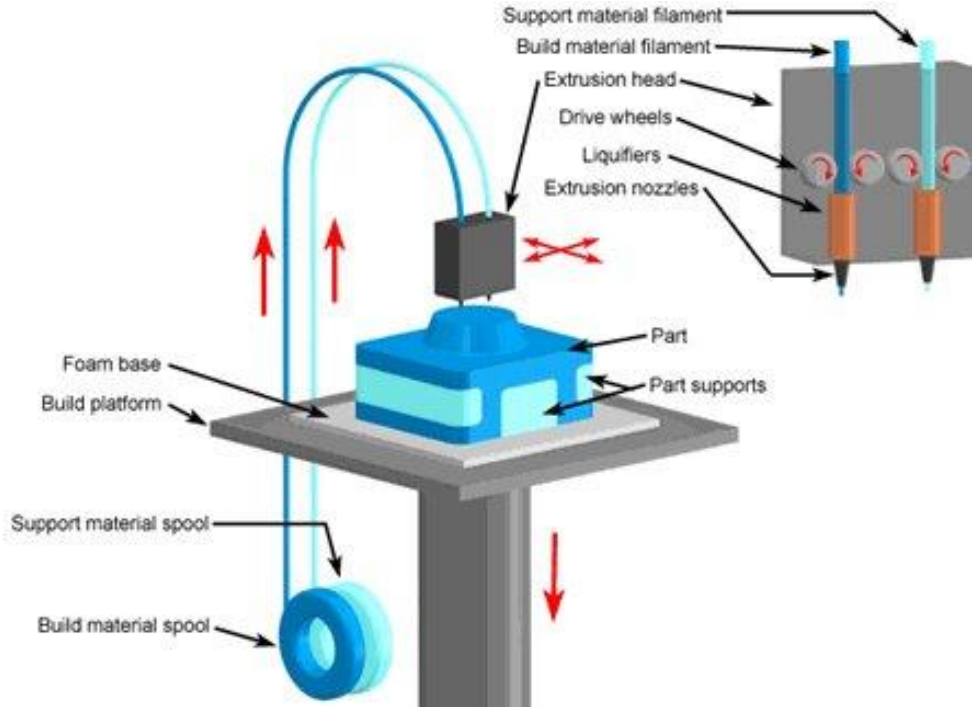
Filament Deposition Modelling (FDM)

FDM: process

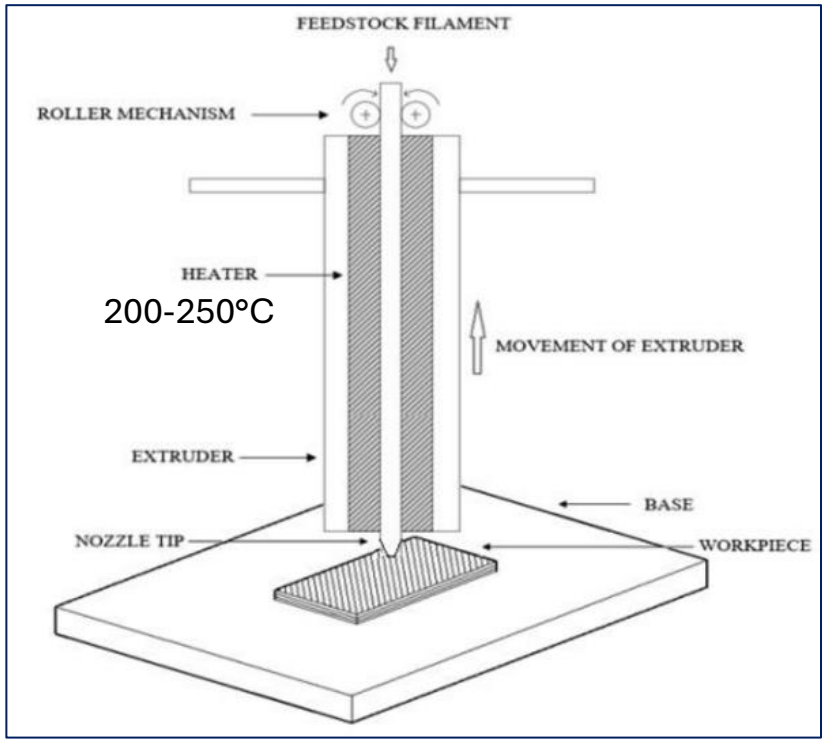


Banjanin et al. (2018). PRODUCTION FACTORS INFLUENCING MECHANICAL AND PHYSICAL PROPERTIES OF FDM PRINTED EMBOSSING DIES. 225-236. 10.24867/GRID-2018-p28.

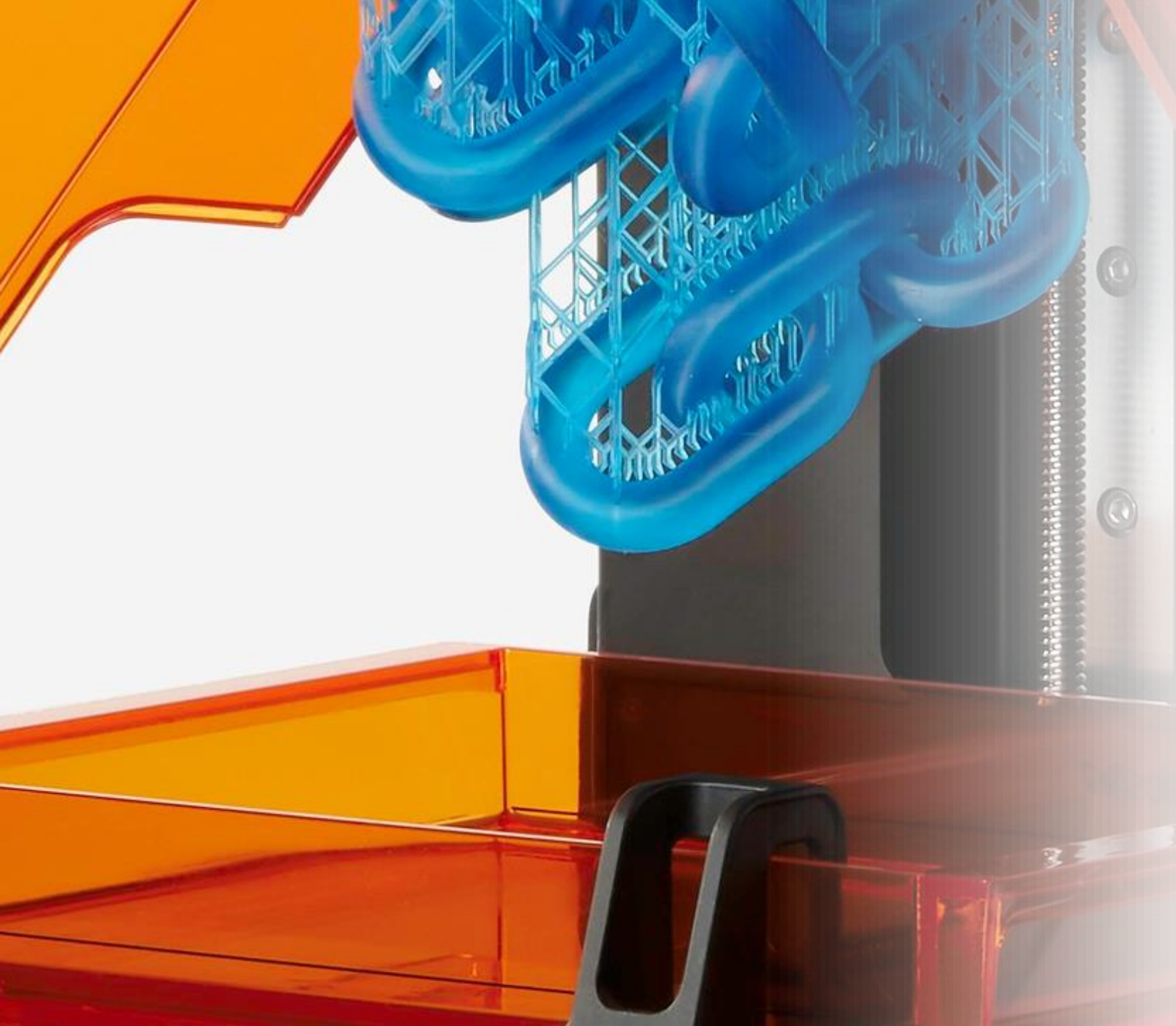


A Review paper on 3D-Printing Aspects and Various Processes Used in the 3D-Printing - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Fused-deposition-modeling_fig4_350374850 [accessed 21 Mar, 2024]

FDM: process



Vyavahare et al. (2020), "Fused deposition modelling: a review", *Rapid Prototyping Journal*, Vol. 26 No. 1, pp. 176-201. https://doi.org/10.1108/RPJ-04-2019-0106



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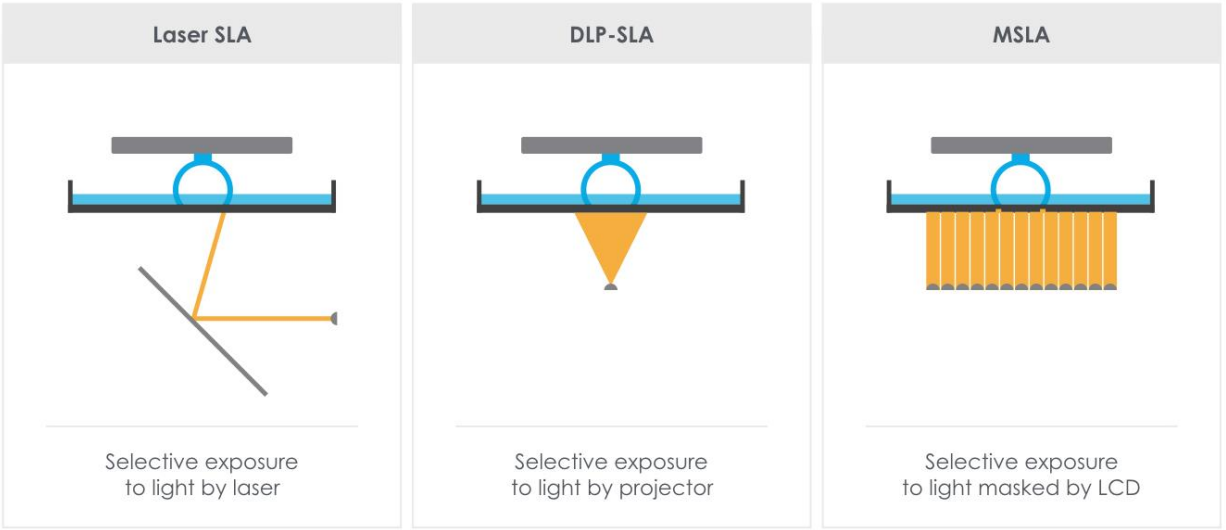
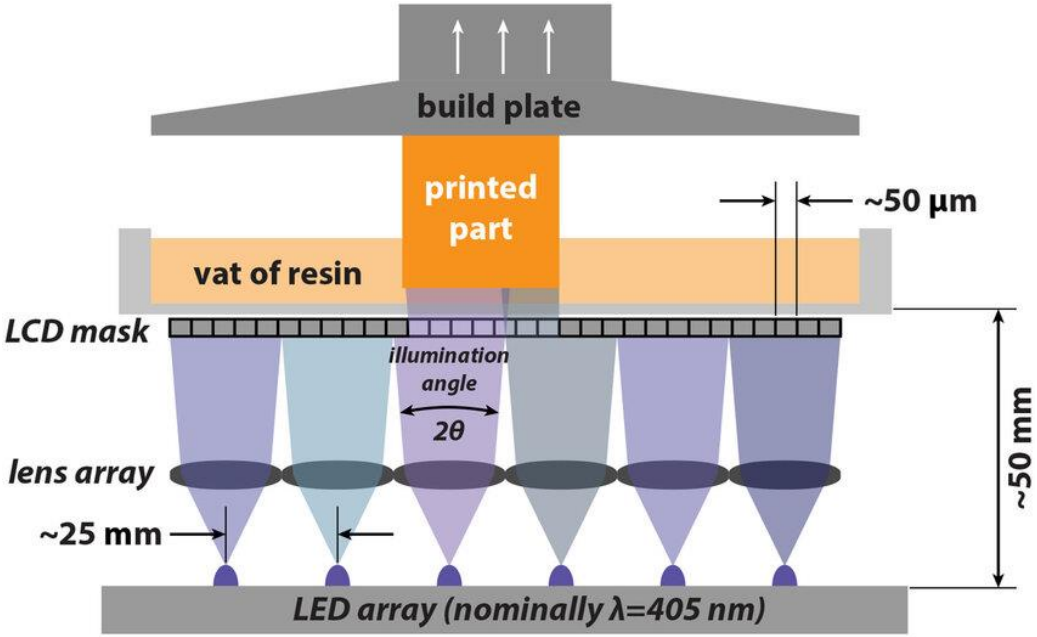
Masked Stereolithography Apparatus (MSLA)

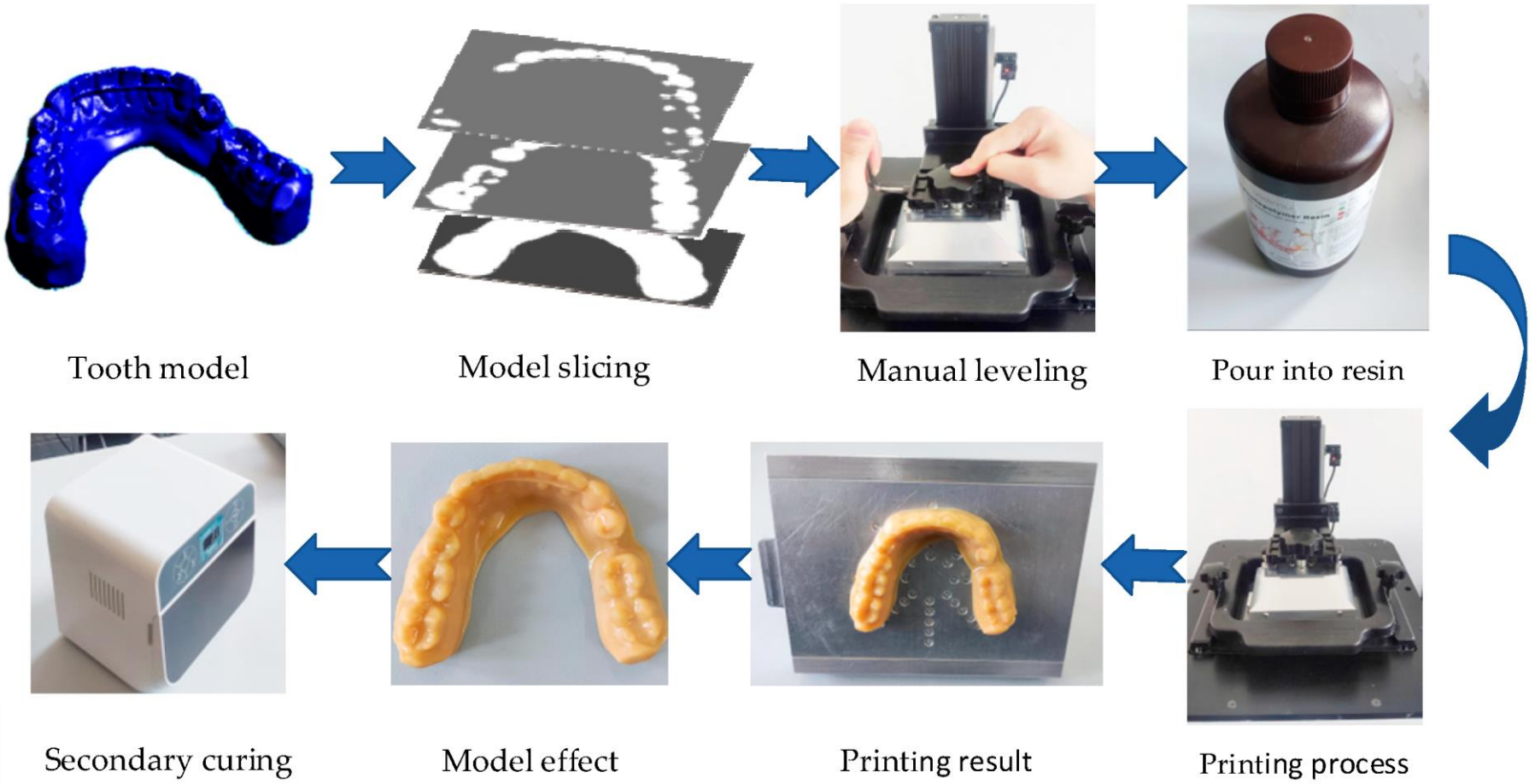
MSLA: processs





Characterizing light engine uniformity and its influence on liquid crystal display based vat photopolymerization printing - Scientific Figure on ResearchGate

MSLA: process



Jiang, T.; Yan, B.; Jiang, M.; Xu, B.; Xu, Y.; Yu, Y.; Ma, T.; Wang, H. Enhanced Adhesion—Efficient Demolding Integration DLP 3D Printing Device. *Appl. Sci.* **2022**, *12*, 7373. https://doi.org/10.3390/app12157373

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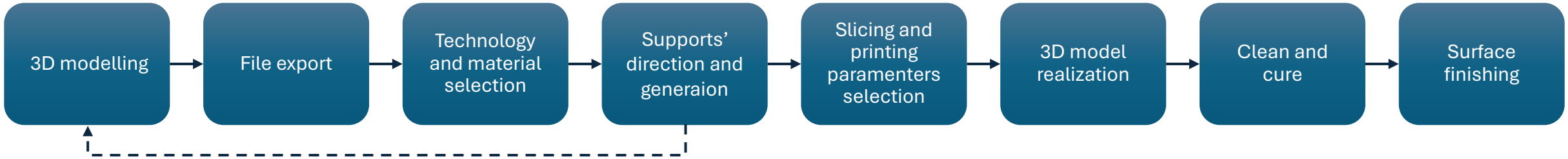
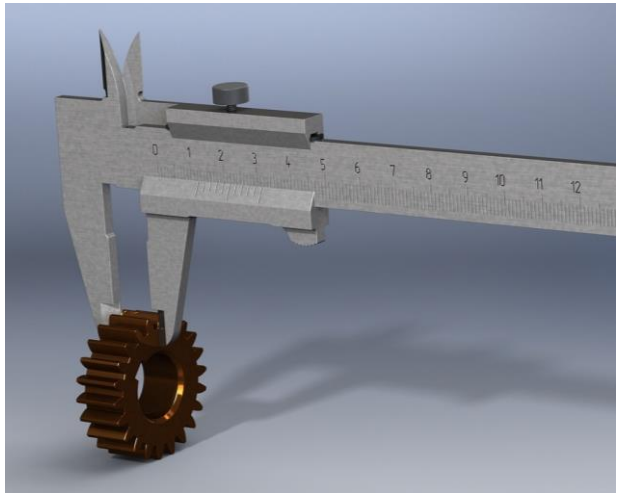
Progetto di una parte realizzata per AM

Design of AM parts



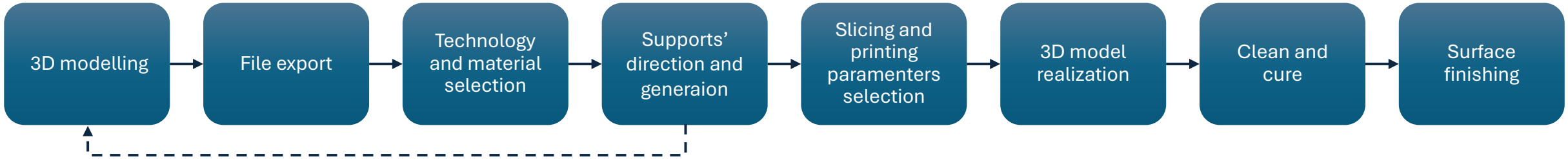
Calibration and setup of the bed

- During or after printing, polymers and resins tend to shrink (shrinkage).
- This occurs due to heating/cooling (FDM) or curing (MSLA).The final model will be smaller than the nominal model.
- The original model must be scaled to compensate.

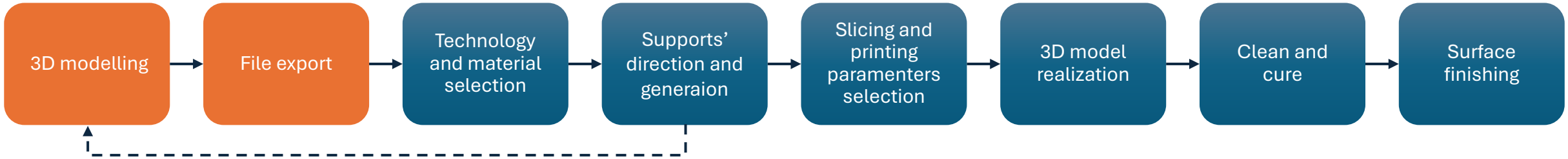


- The calibration process involves measuring the actual dimensions of the printed part and subsequently deriving scaling factors to be applied in each of the three directions (x, y, z).

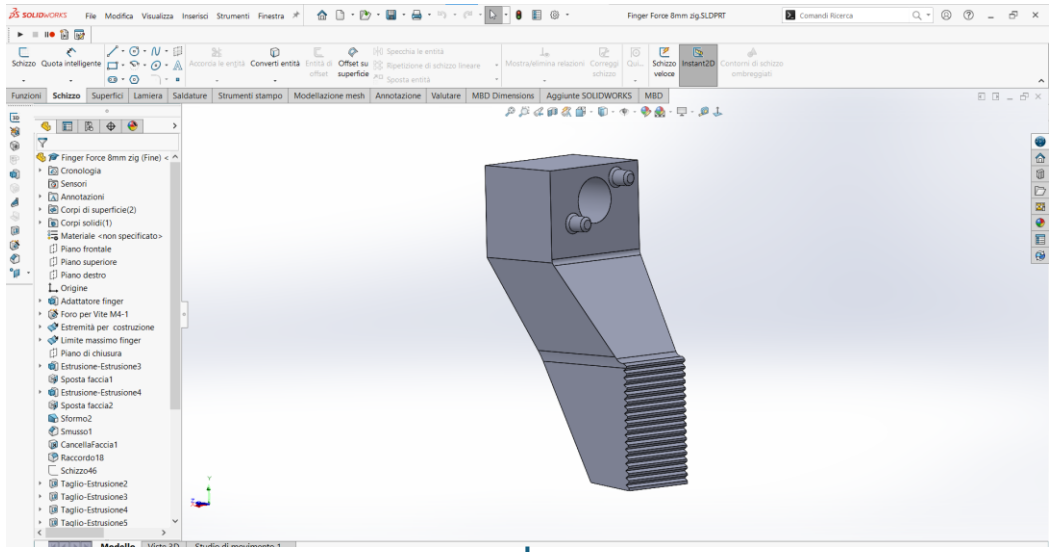
Design of AM parts

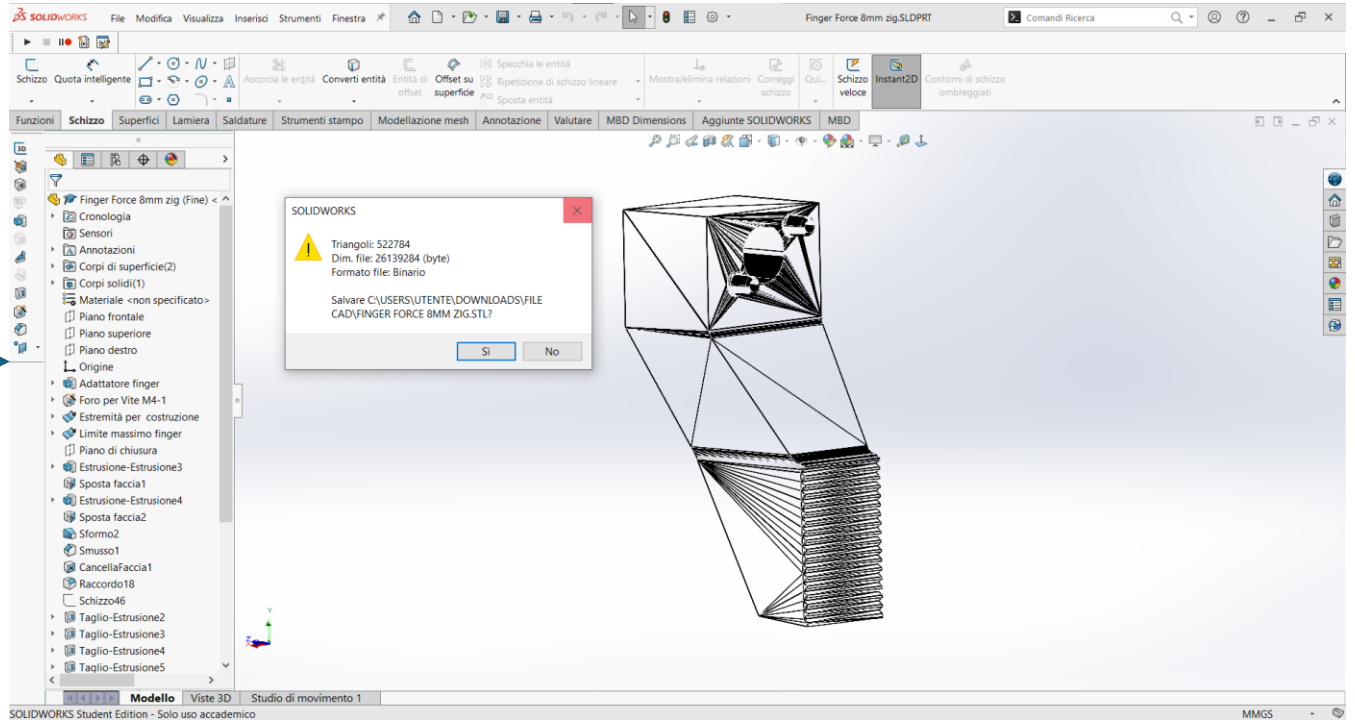


Design of AM parts



3D model creation and export





Polygon-based representation

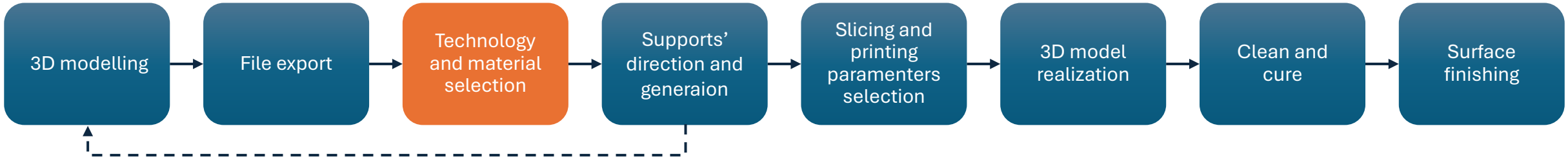
(STL, AMF, 3MF, OBJ, PLY)

Be careful of export quality!

raw

high

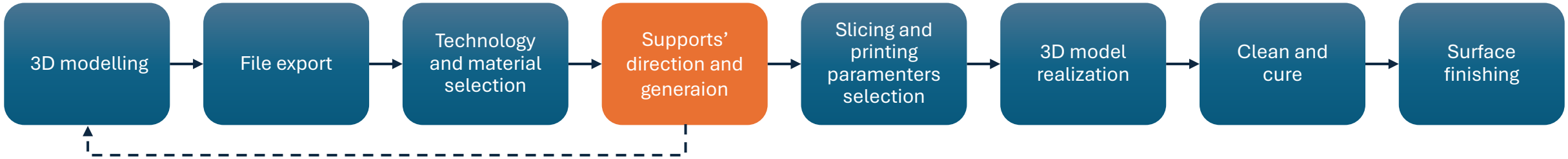
Design of AM parts



Process and material selection

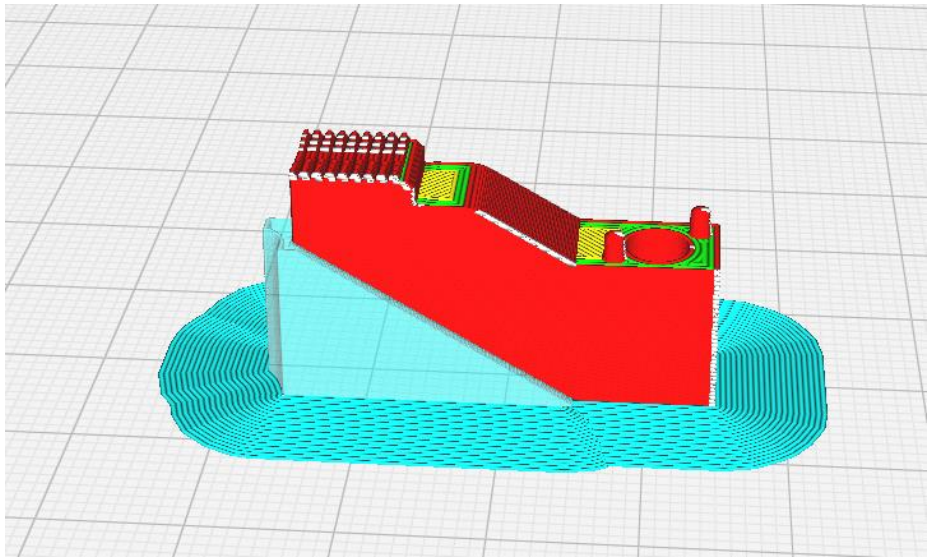
	FDM	MSLA
Material	Materials-3D Guide – Snapmaker (example)	Resins for 3D Printing: How to Choose a Right 3D Printed Resin – ELEGOO Official (example)
Height layer	0,08 – 0,3 mm	0,01-0,2 mm
Multi – material	Available	/
Printing time	Limited by head speed	Limited by bed movements and expousure time
Workspace	Generally higher, at the same price, compared to MSLA	

Design of AM parts



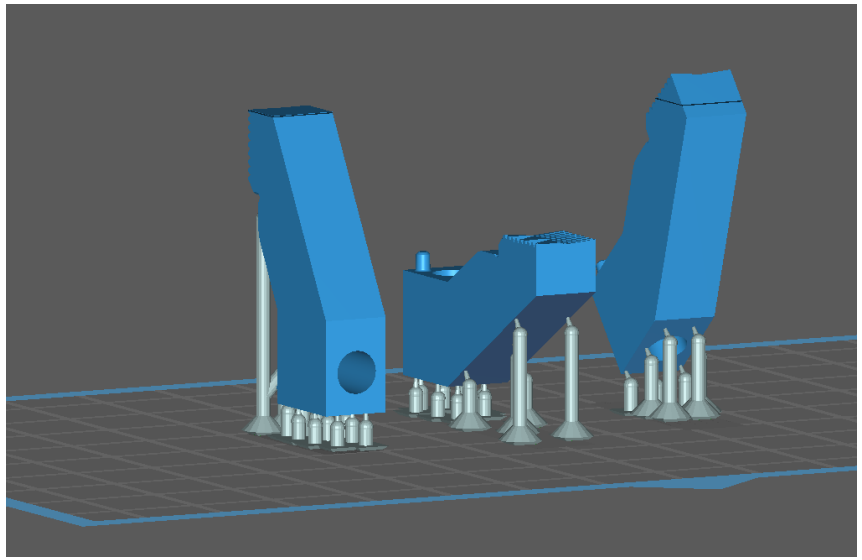
Support type and direction

FDM



UltiMaker Cura - UltiMaker

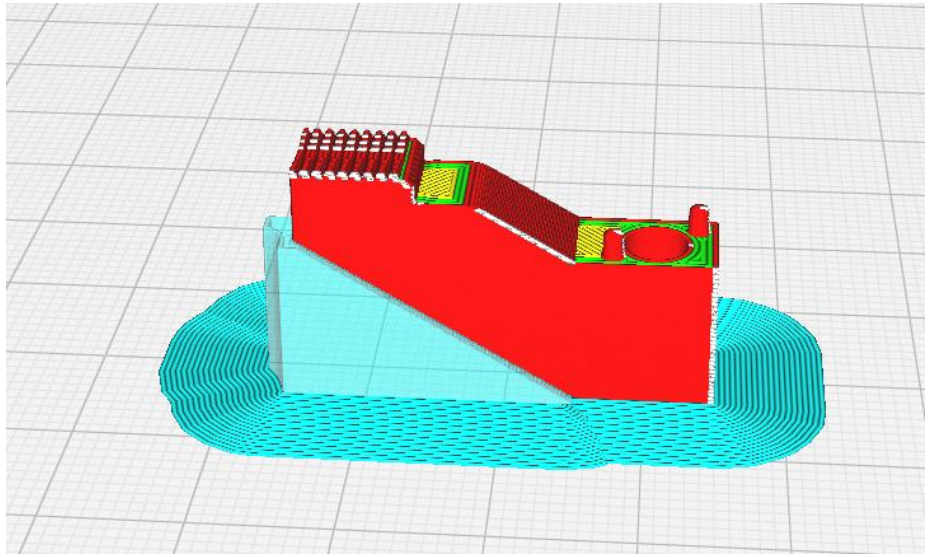
MSLA



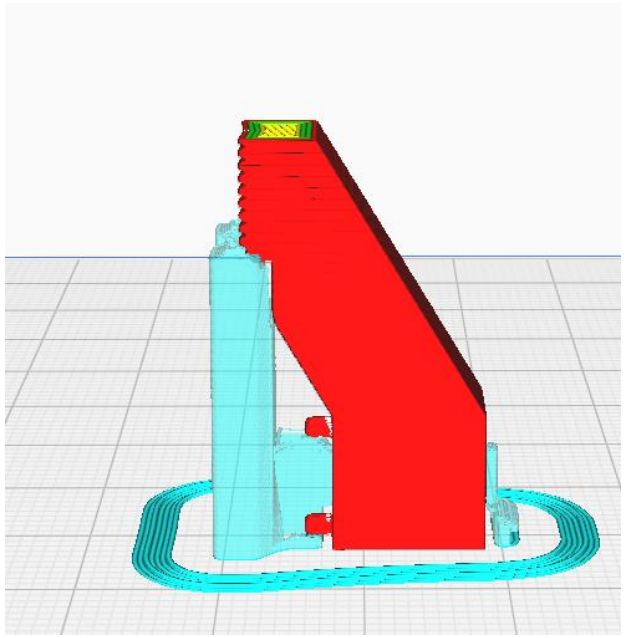
CHITUBOX SLA/DLP/LCD 3D Slicer Software

FDM orientation example

FDM



a



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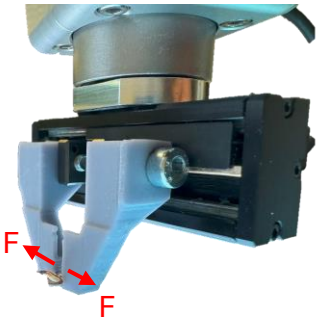
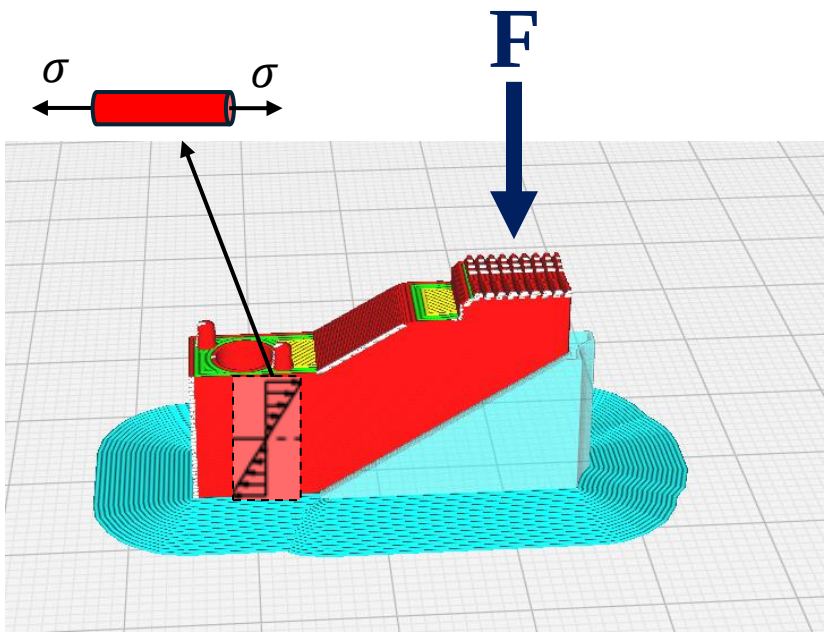


FDM orientation example

FDM

Solution: a (better mechanical resistance)



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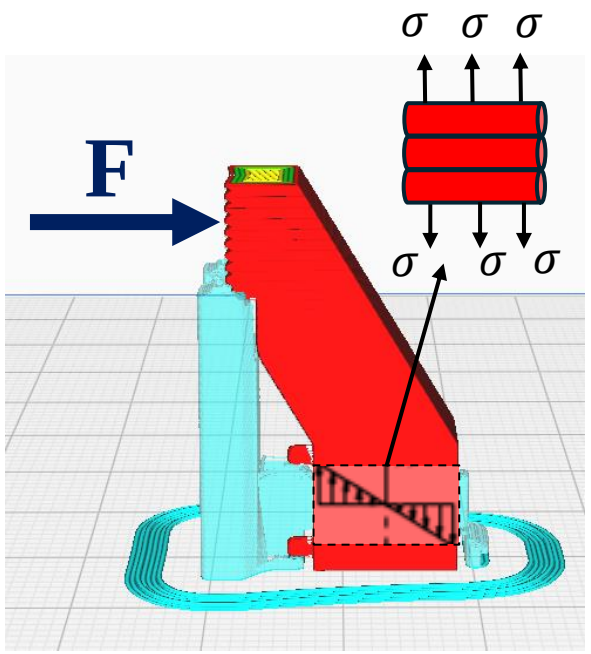

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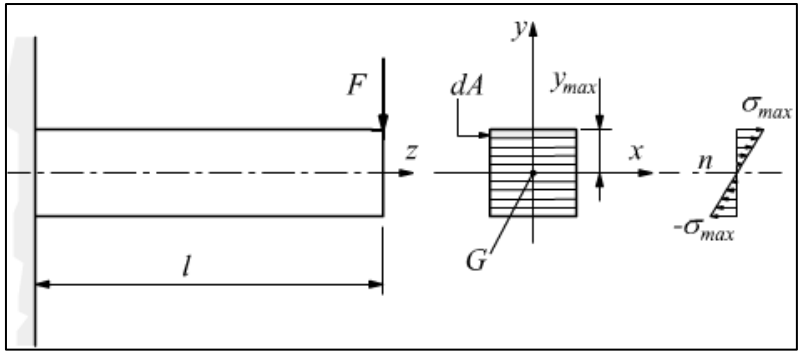
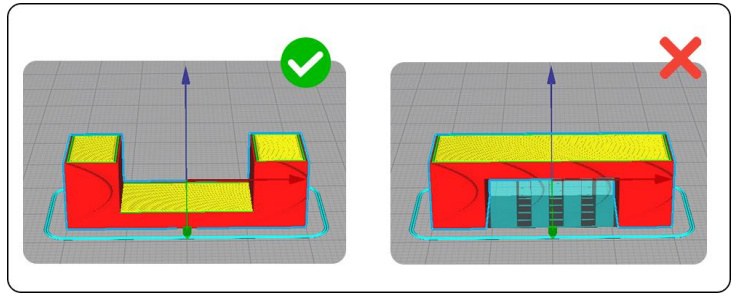
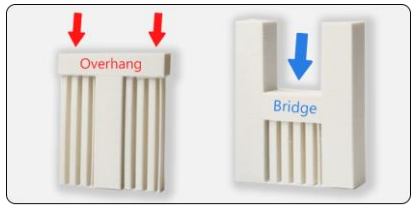


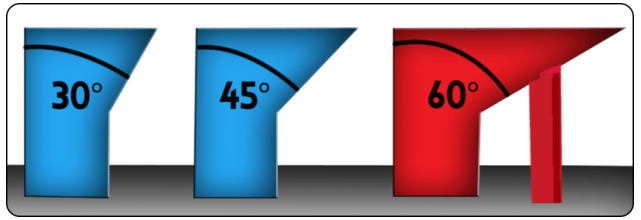
Other considerations for FDM

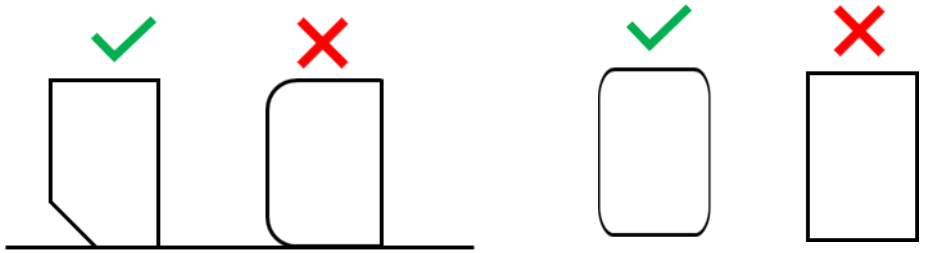
FDM

- Minimize the number of supports
- Adopt specific supports for «*overhang*» > 45°
- Printing time not influenced by the product's position
- Consider multi-material prints
- Avoid sharp edges
- Prefer chamfers on the base structure









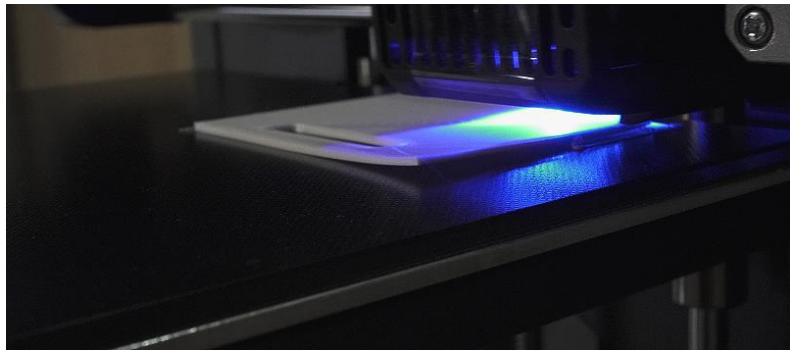
Others FDM considerations: warping

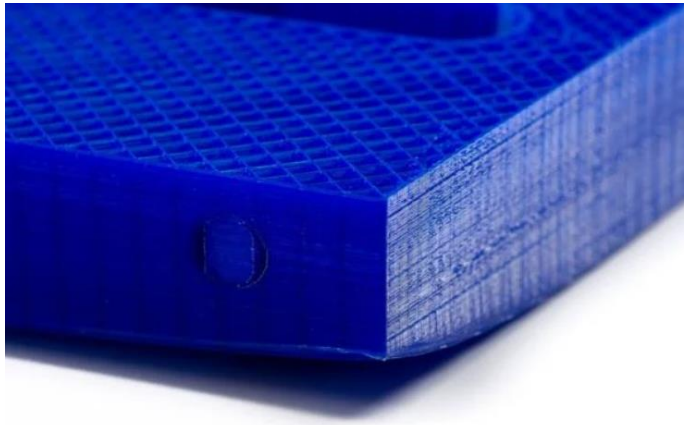
FDM

- Warping occurs when the printing material, typically thermoplastic such as PLA or ABS, cools down

- This phenomenon can cause the printed part to detach from the print bed or create internal stresses that may lead to deformation, unwanted curvatures, or even breakage.

- To mitigate warping, several strategies and techniques can be employed:
  - **Heating the print bed**
  - **Using adhesives or specialized substrates**
  - **Optimizing printing parameters (extrusion temperature, print speed, and cooling)**
  - **Using a heated print chamber**
  - **Increasing the adhesion surface to the print bed**





Others FDM considerations: supports

FDM

- Pay close attention to the choice of support geometry and material.
- In the case of a single extruder, the supports will be made of the same material as the printed part and must be removed manually. Their geometry should allow for easy detachment.
- In the case of a dual extruder, the following can be used:.
  - **Breakaway materials:** Materials that facilitate removal and ensure better dimensional accuracy.
  - **Soluble supports:** Materials that dissolve when immersed in an appropriate liquid. These are useful for creating complex and intricate geometries but require more time for the cleaning process.

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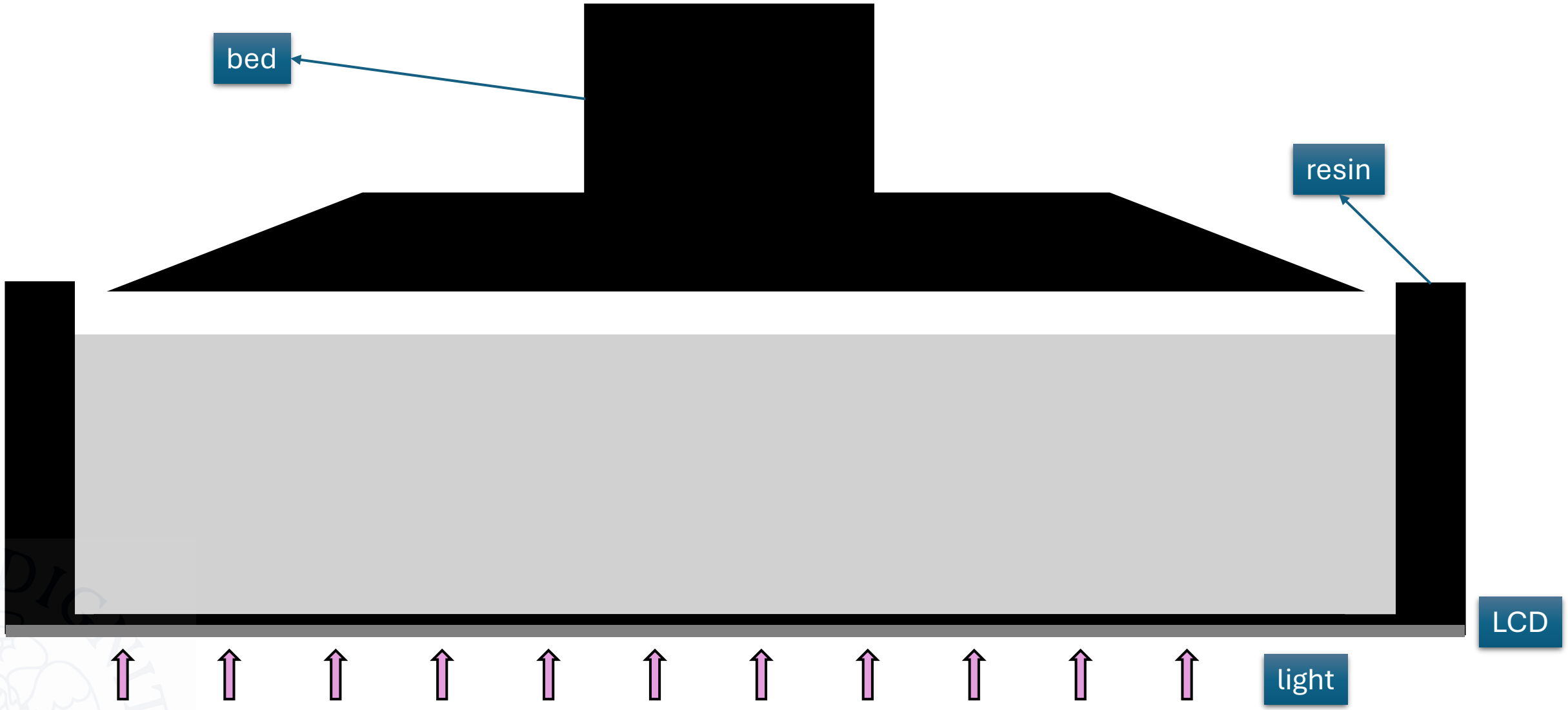

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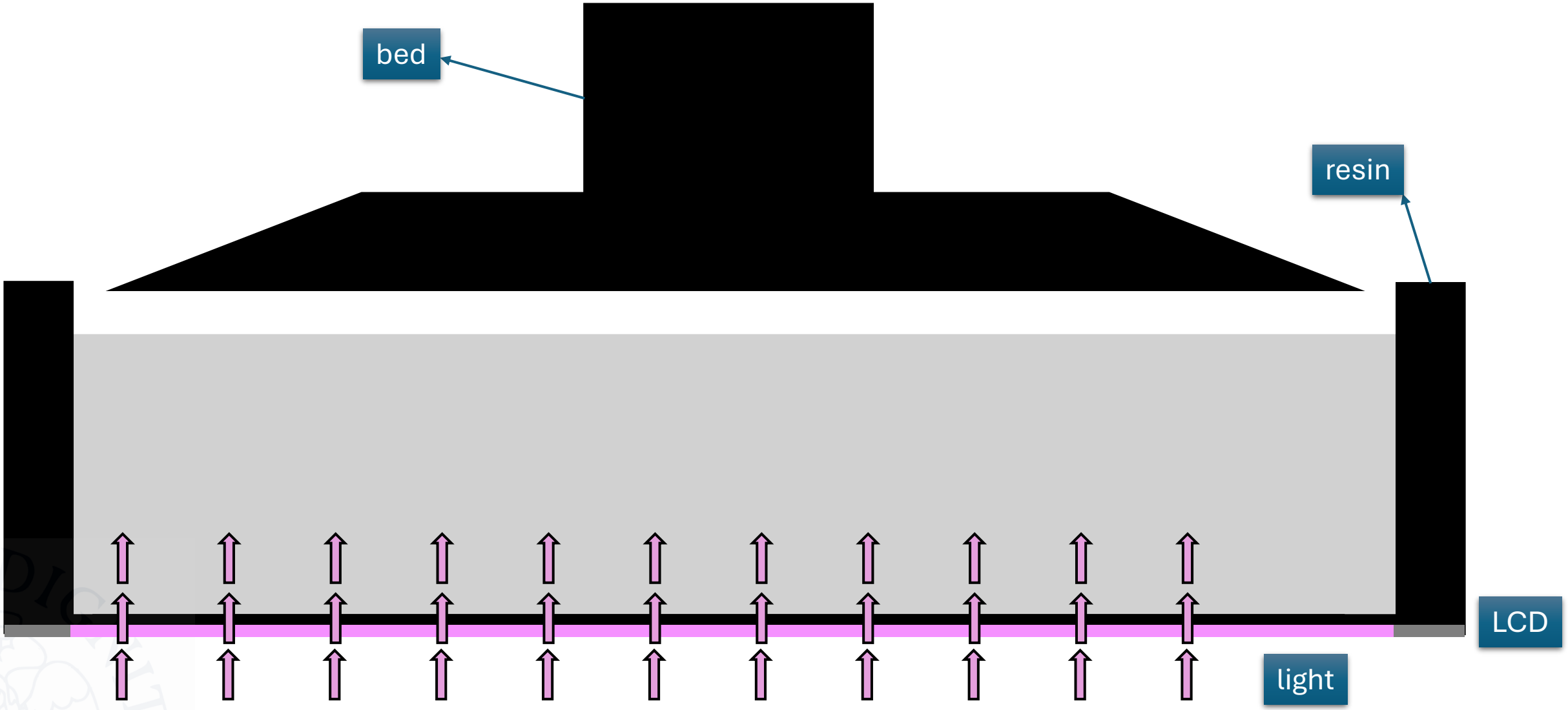
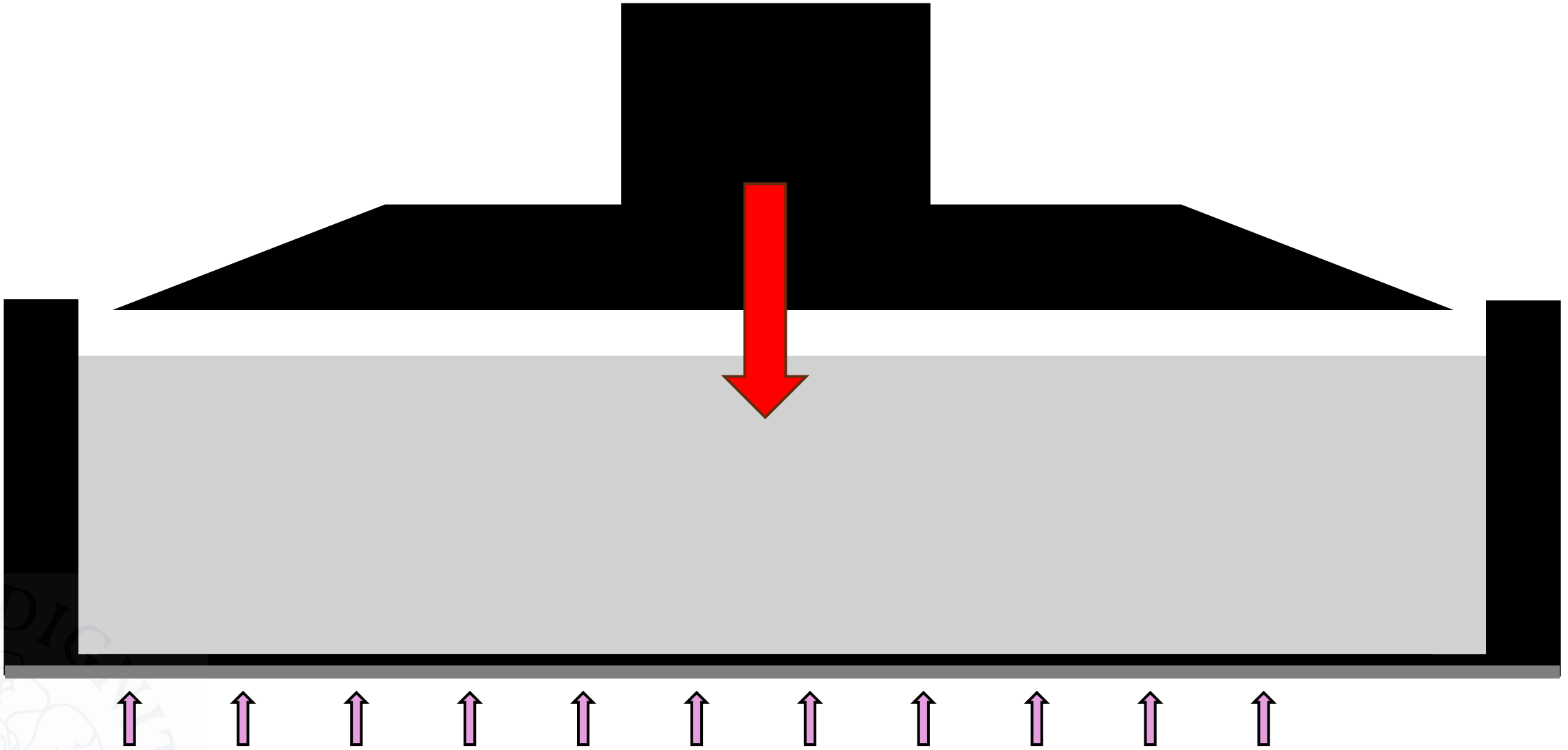


MSLA: drenaggio della resina



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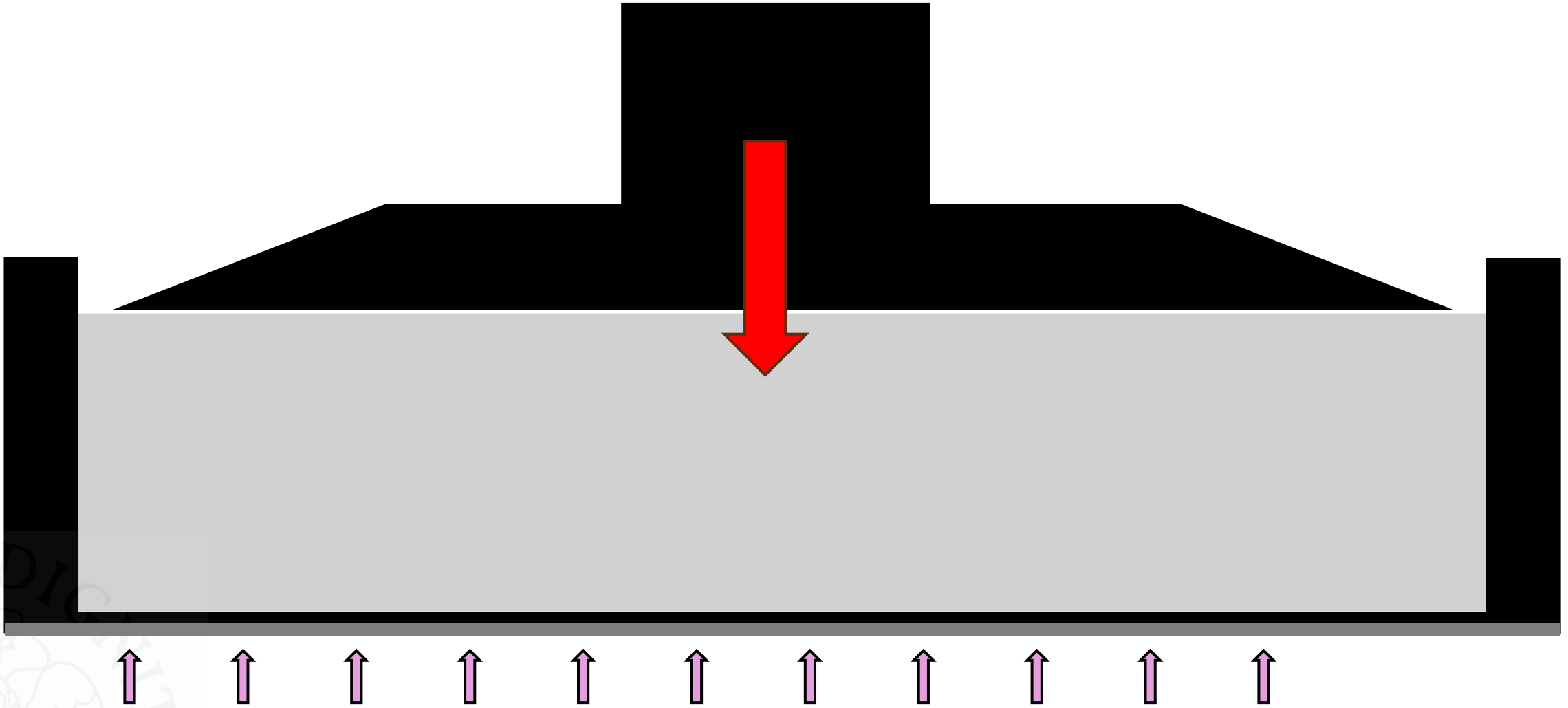

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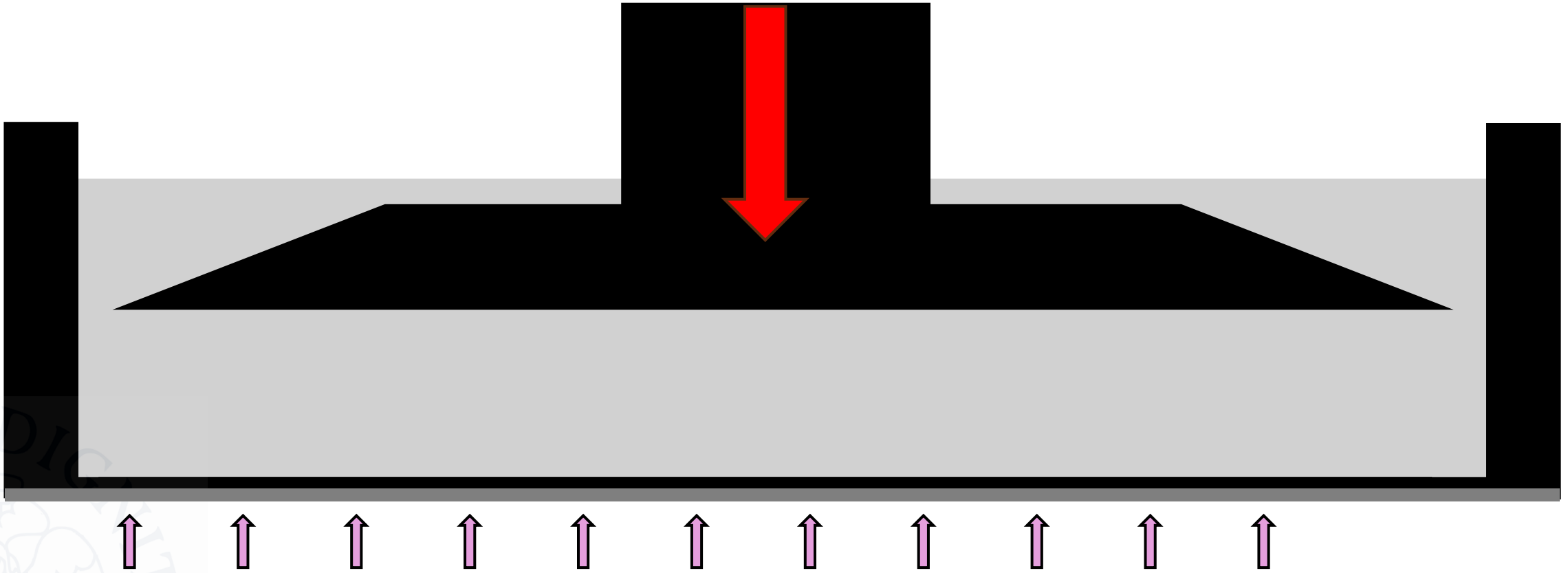

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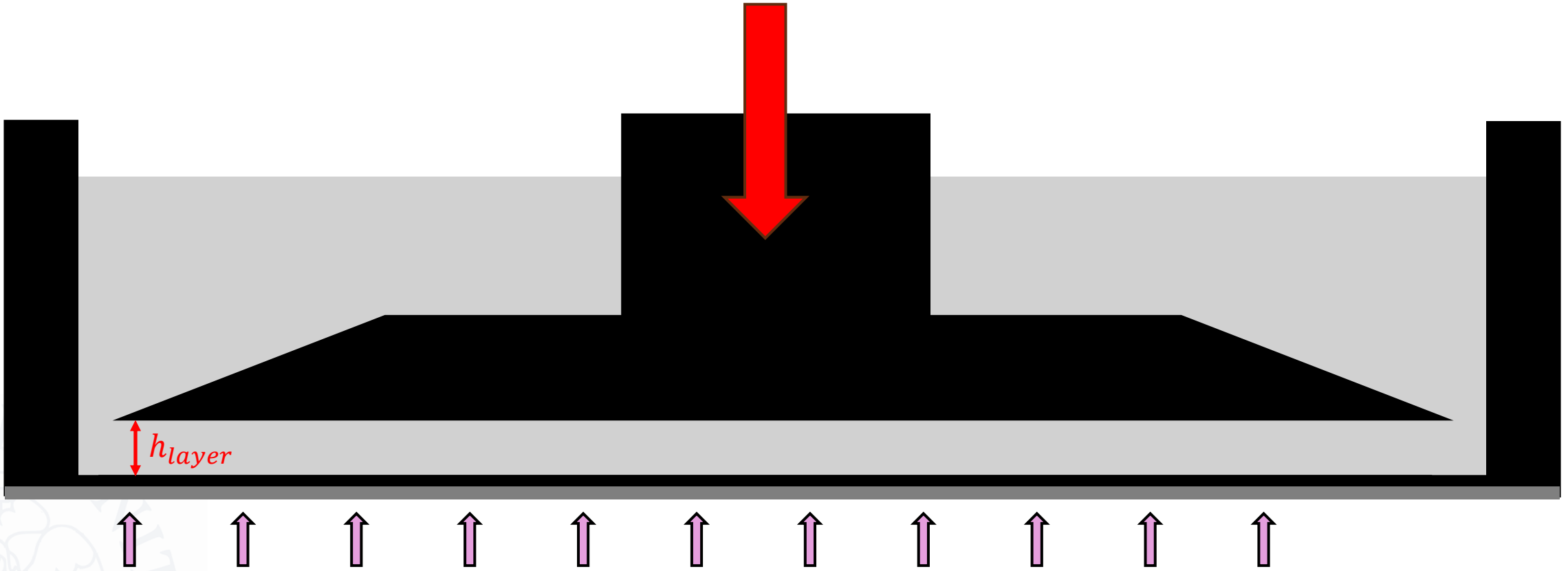

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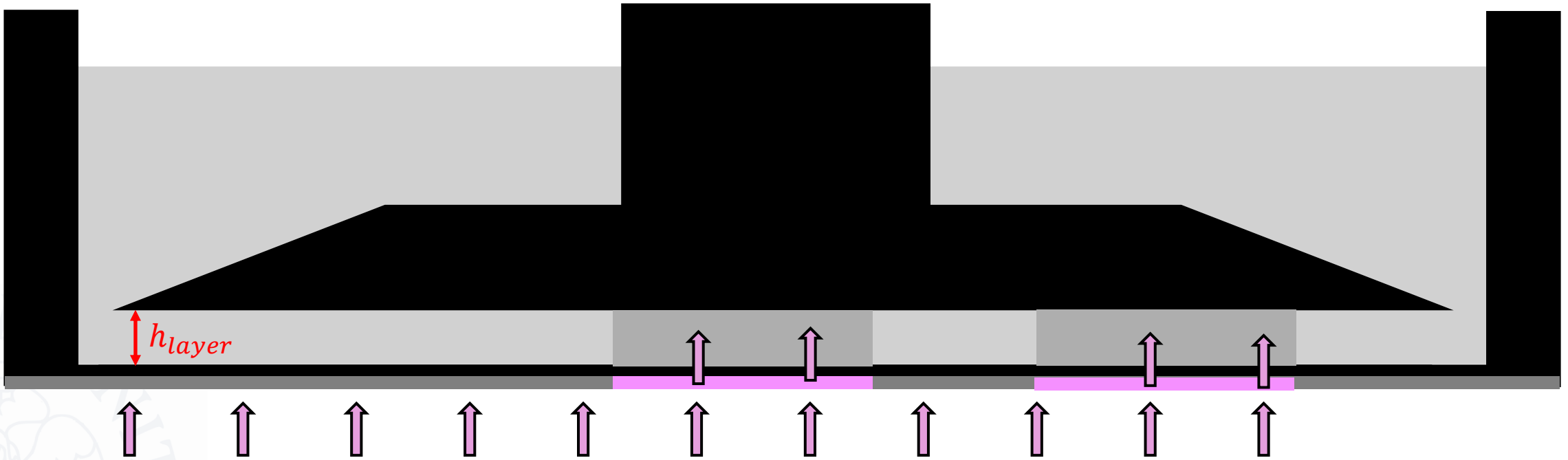

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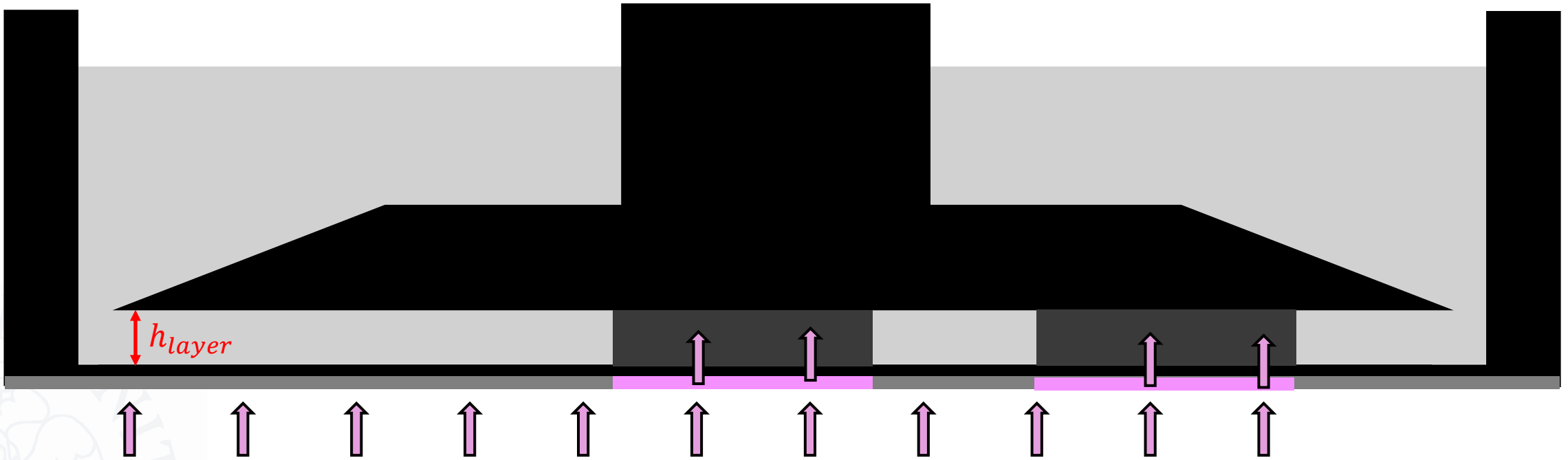

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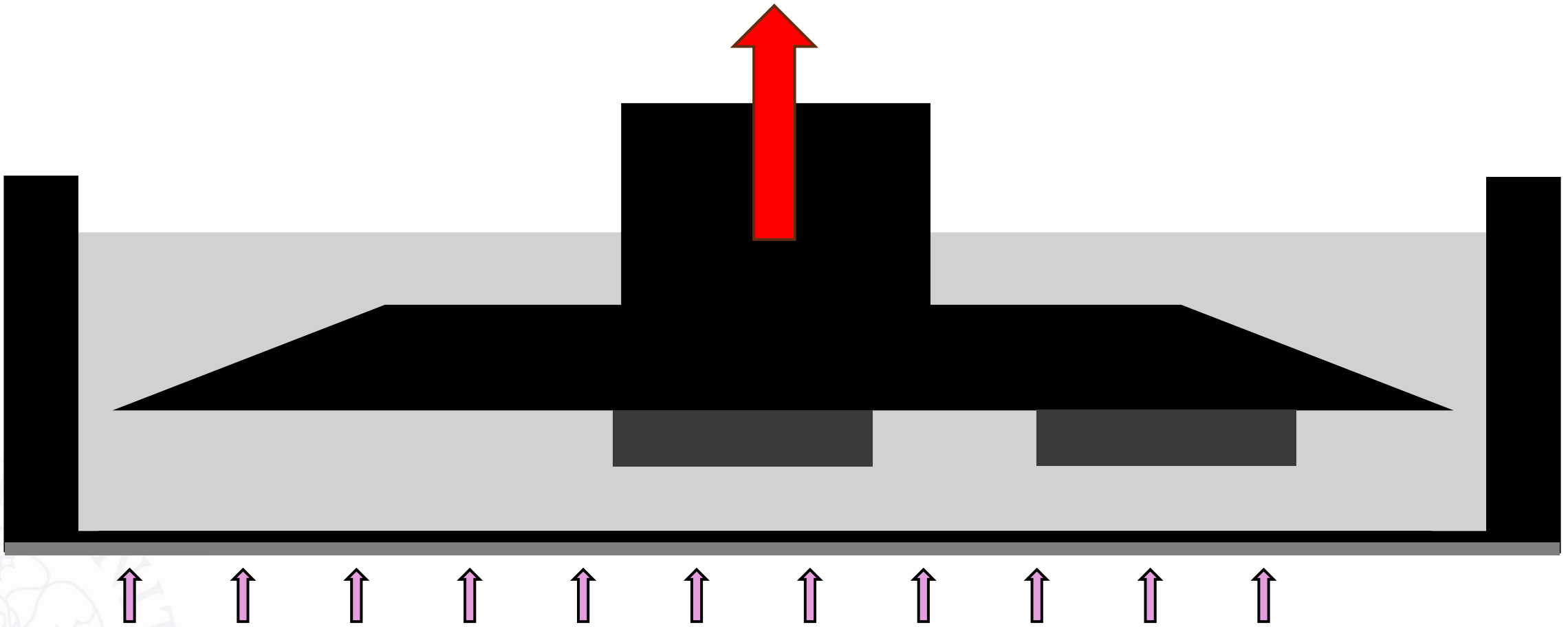
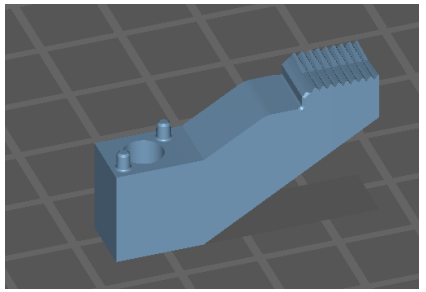
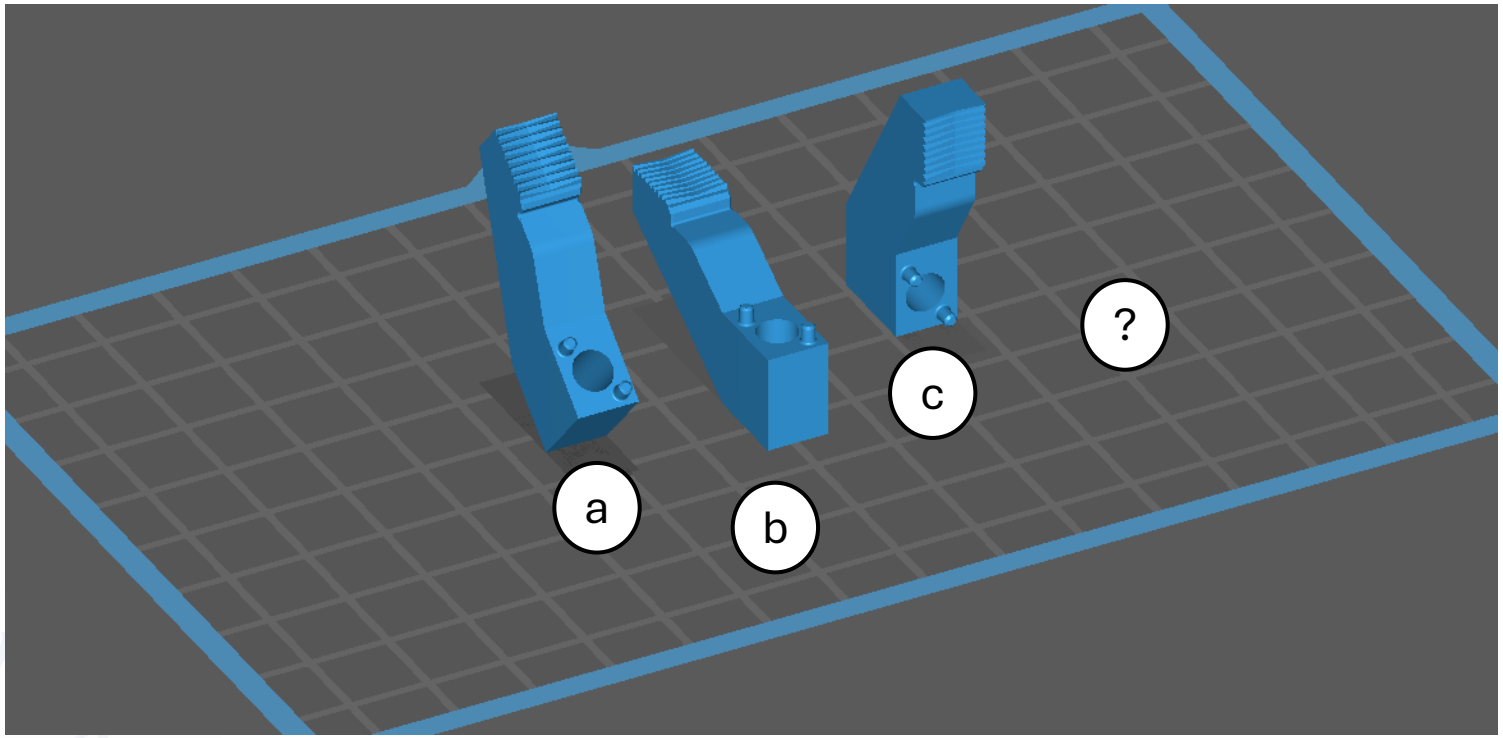
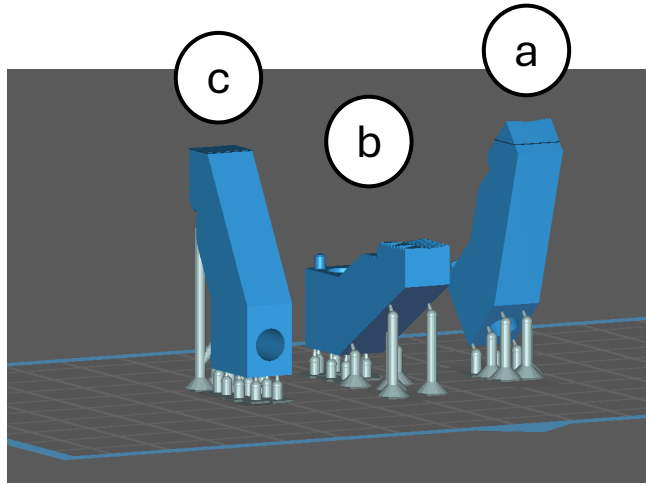


How to position the product in MSLA?

MSLA

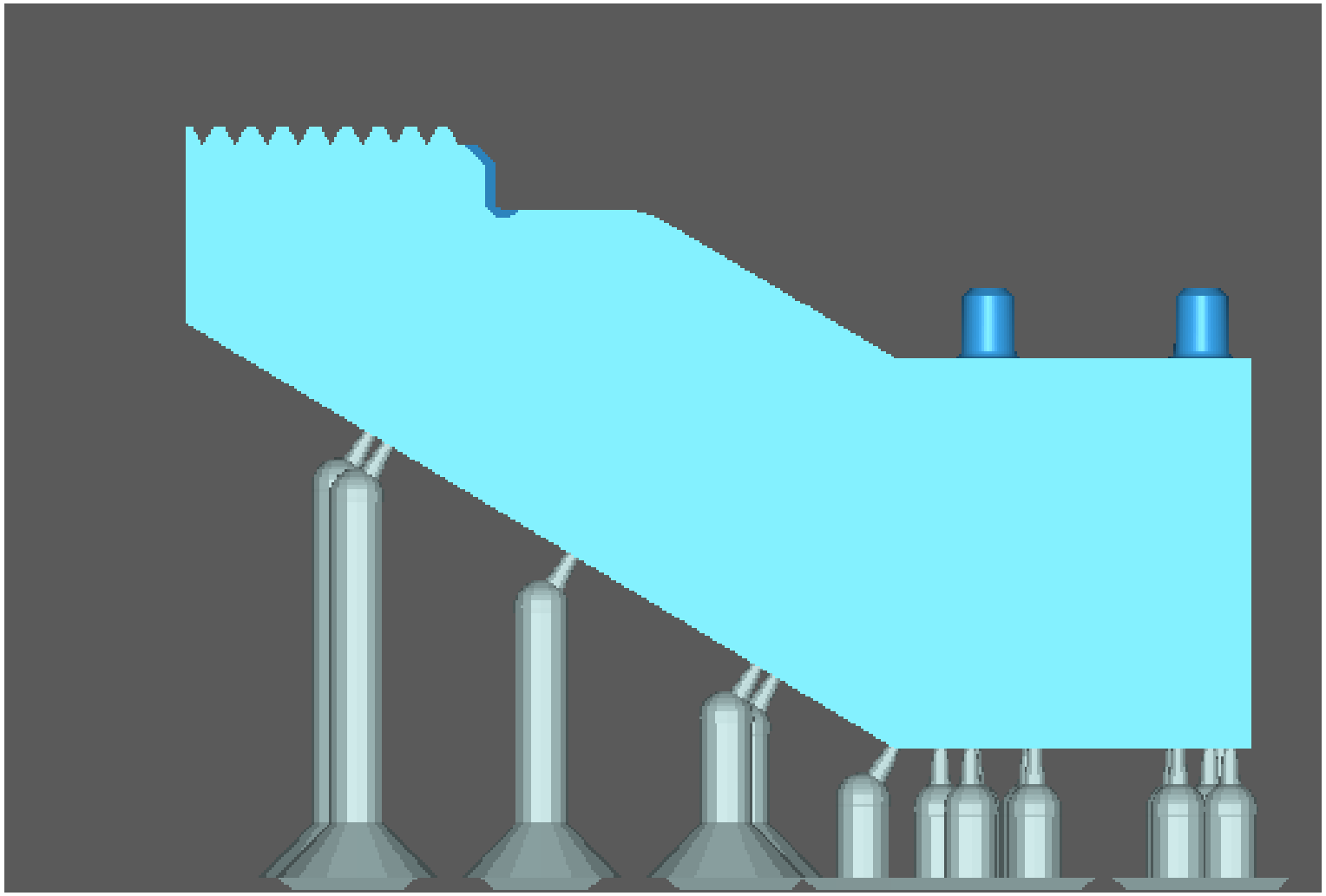




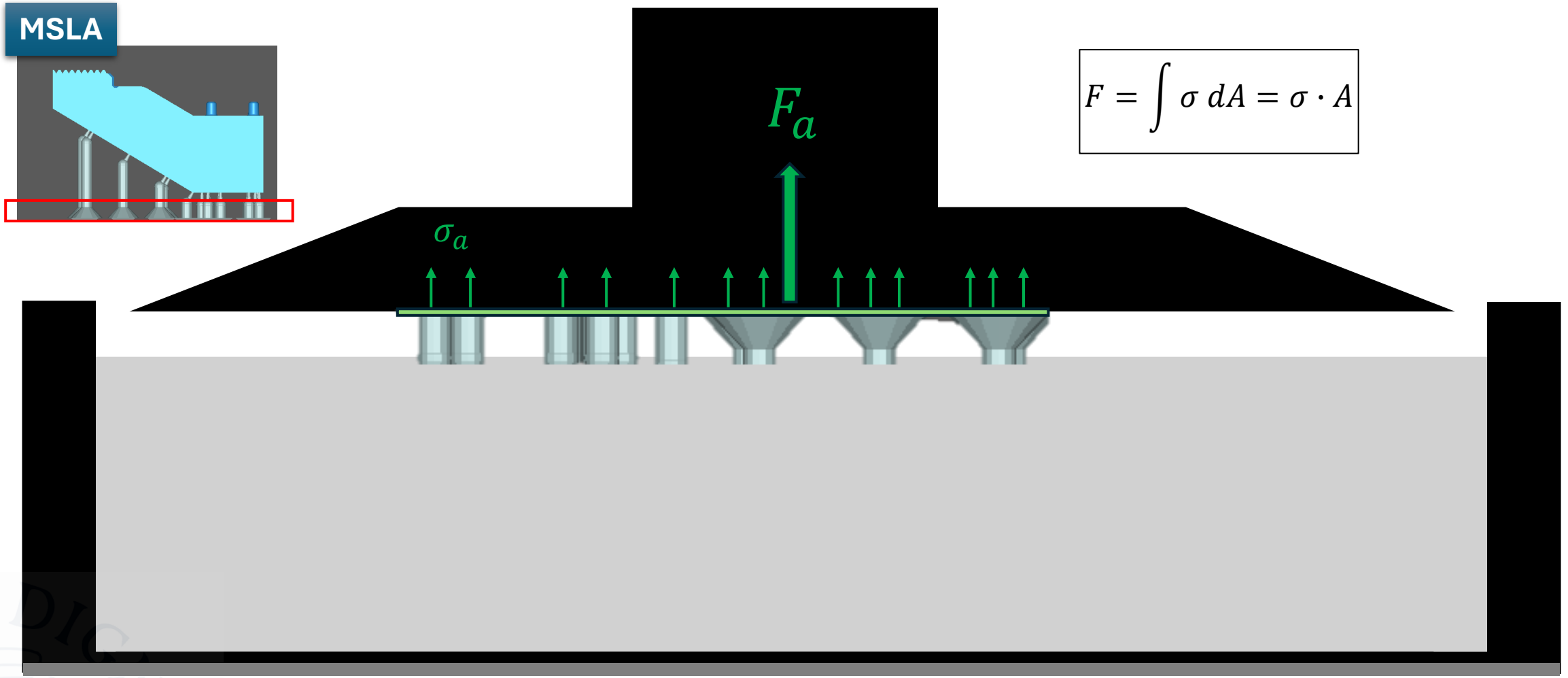


Solution b

MSLA

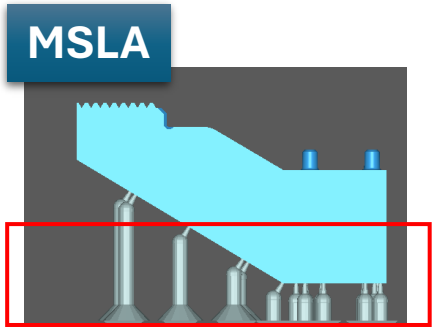


MSLA: sticking

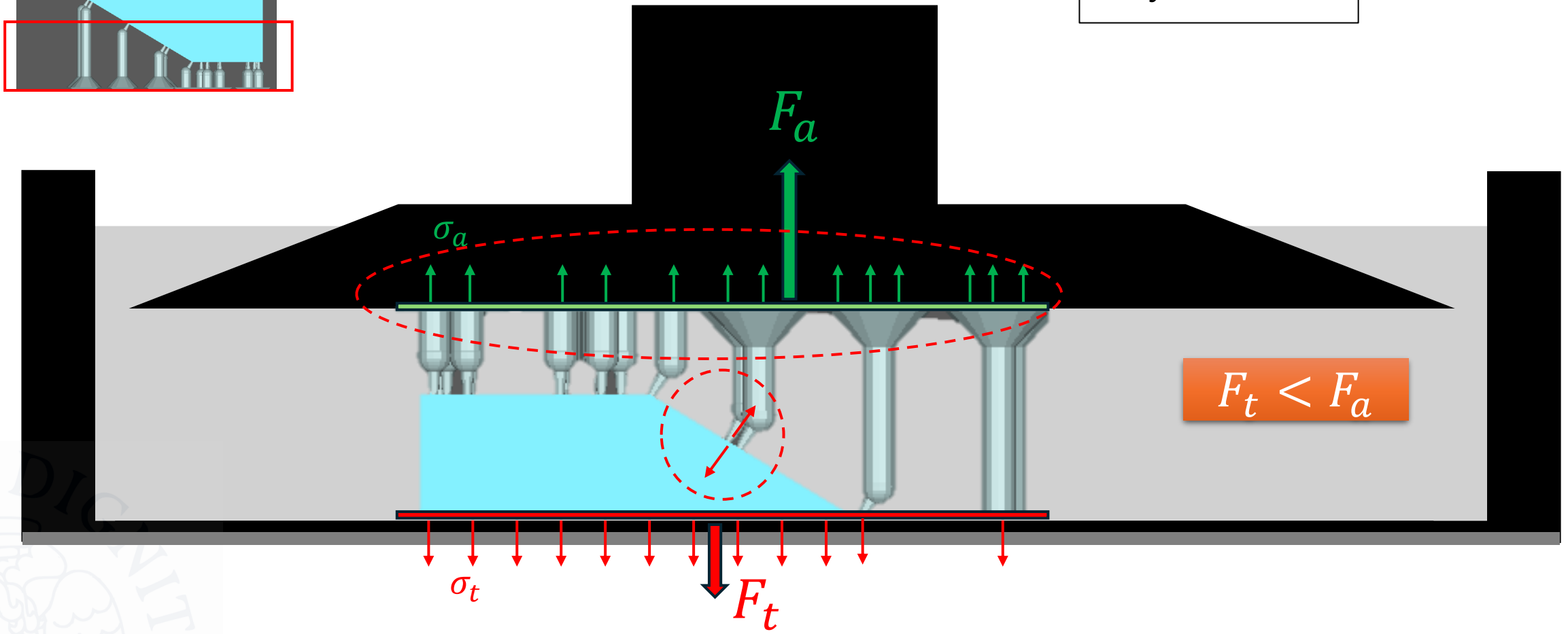


$$F = \int \sigma \, dA = \sigma \cdot A$$

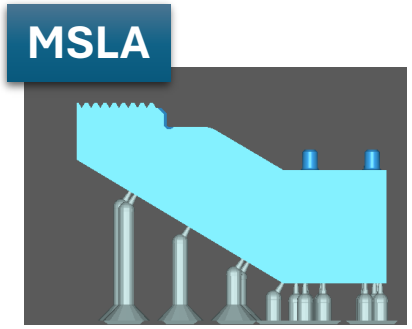
MSLA: sticking

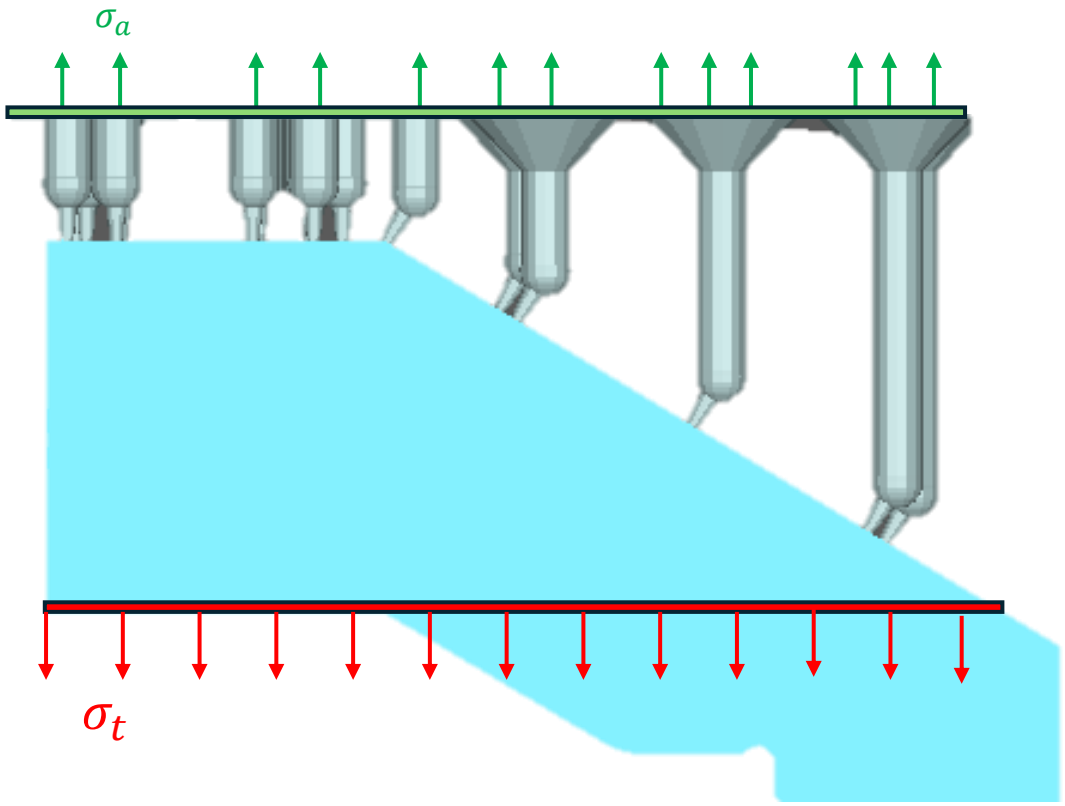


$$F = \int \sigma \, dA = \sigma \cdot A$$



MSLA: sticking



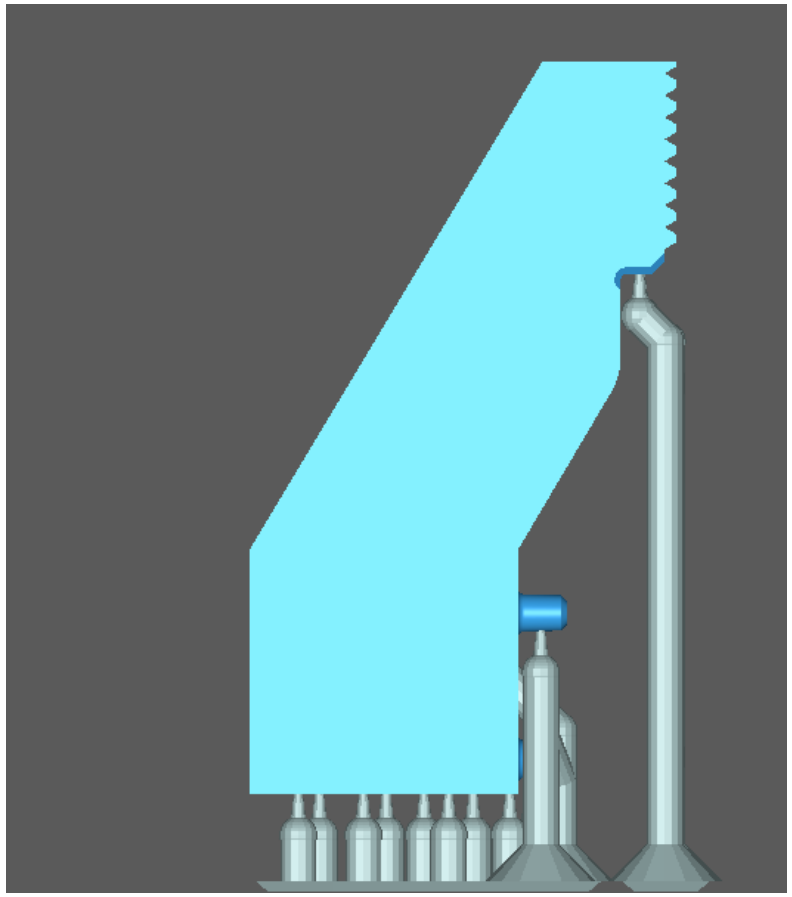


$$F = \int \sigma \, dA = \sigma \cdot A$$

Minimize the area of contact (*sticking*)

Soluzione c

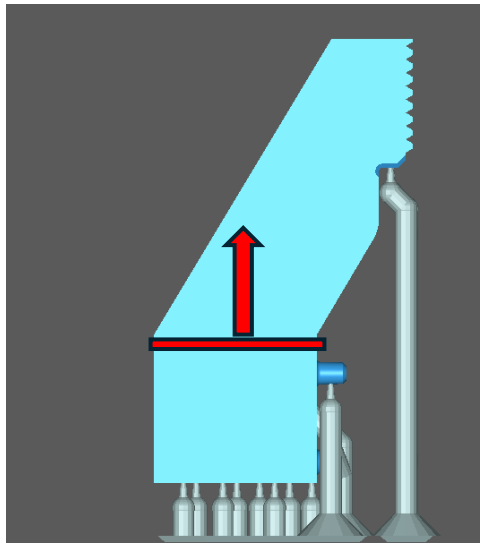
MSLA



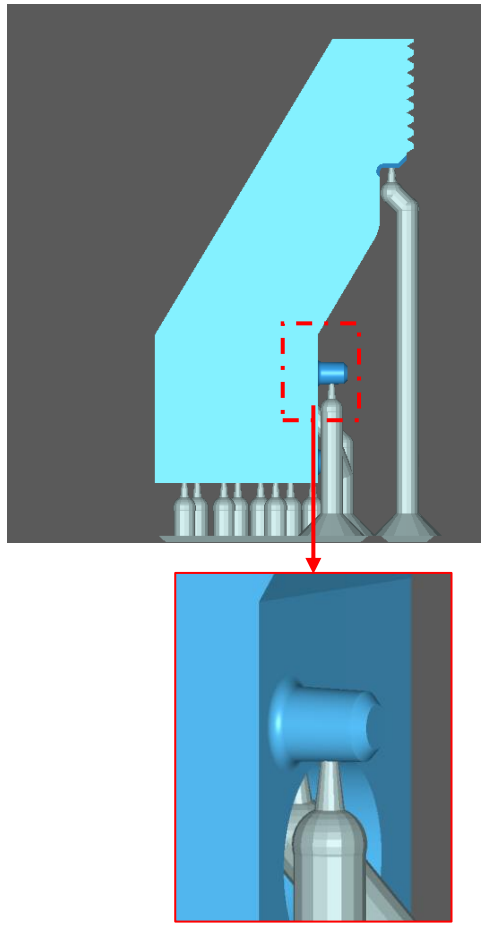
Solution b

MSLA

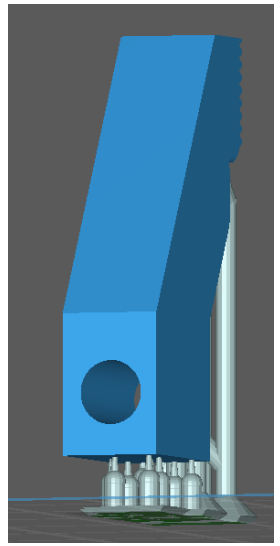
✓ Sticking



Problem 1

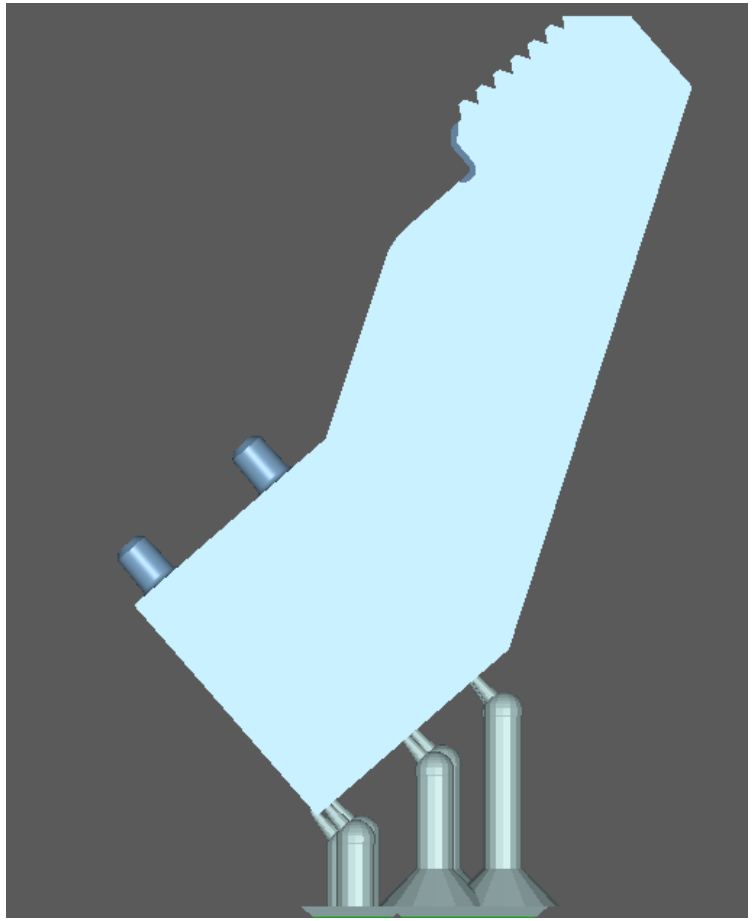


Problem 2



Solution a

MSLA

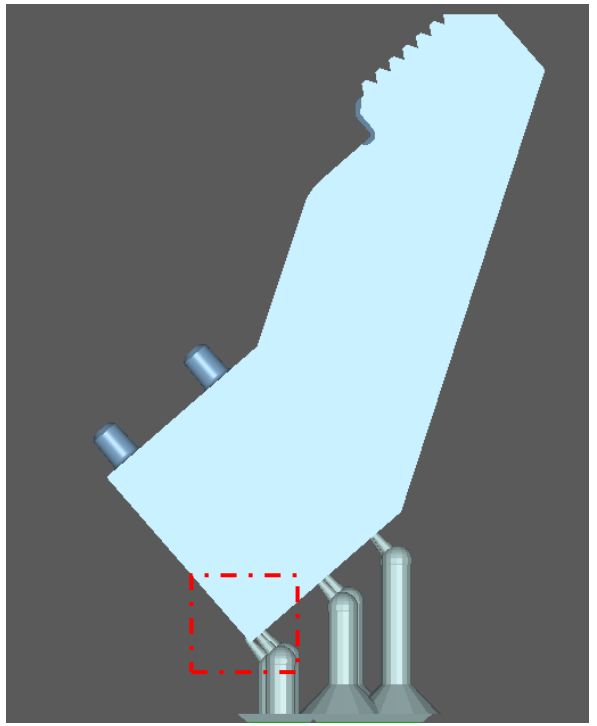


Solution a

MSLA

- ✓ Minimize the cross-sectional adhesion area
- ✓ Minimize the number of supports
- ✓ The hole is self-supporting

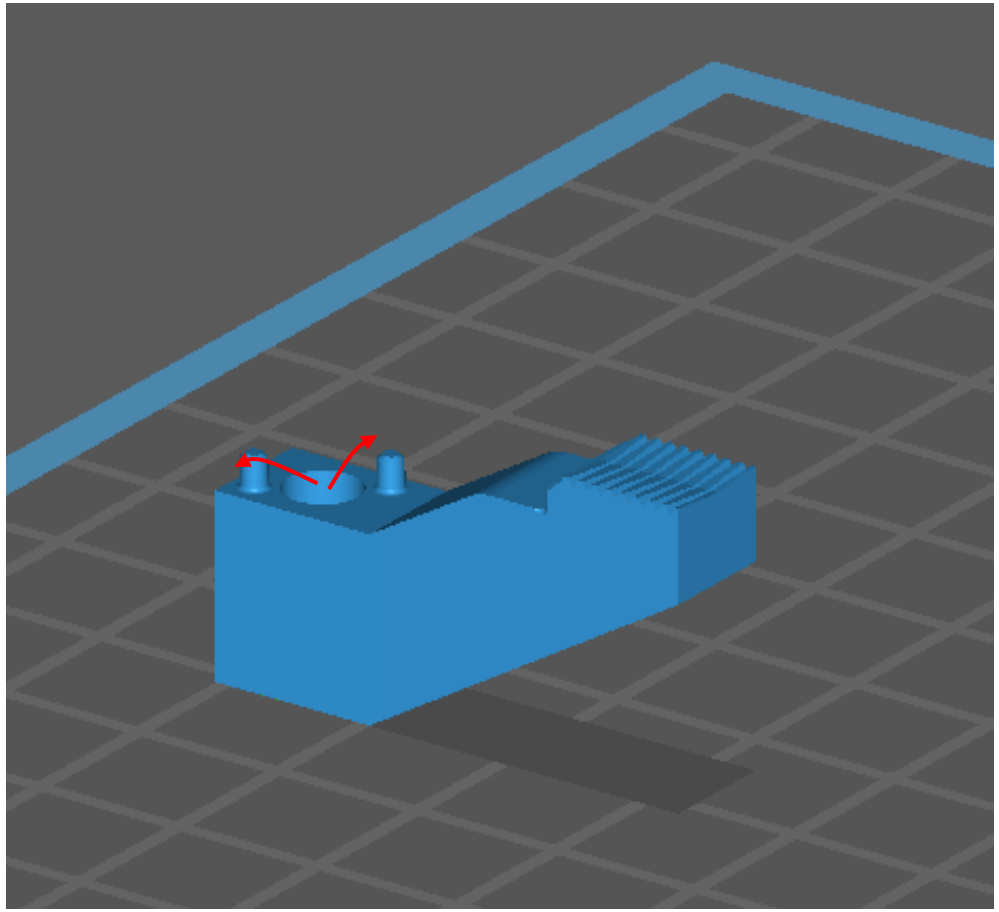
But:Increase the print time



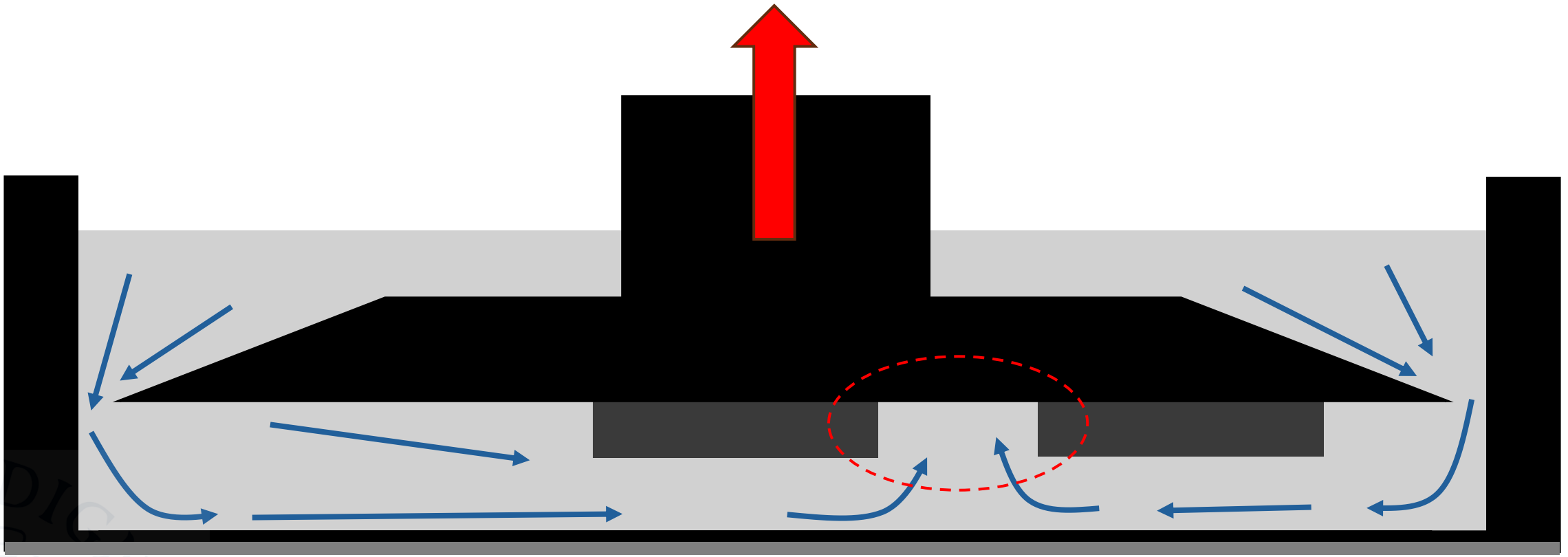
Solution d MSLA?

MSLA

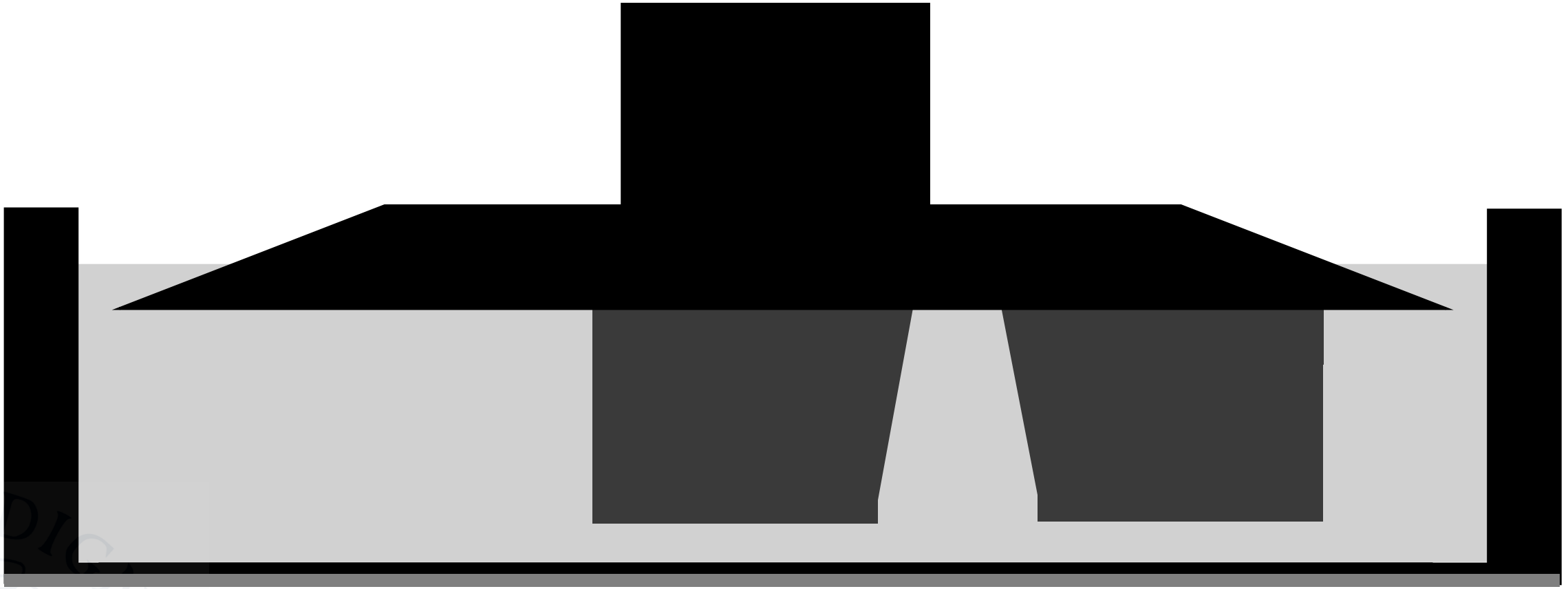
Problem: drainage of the resin inside the hole during printing.
(*cupping*)



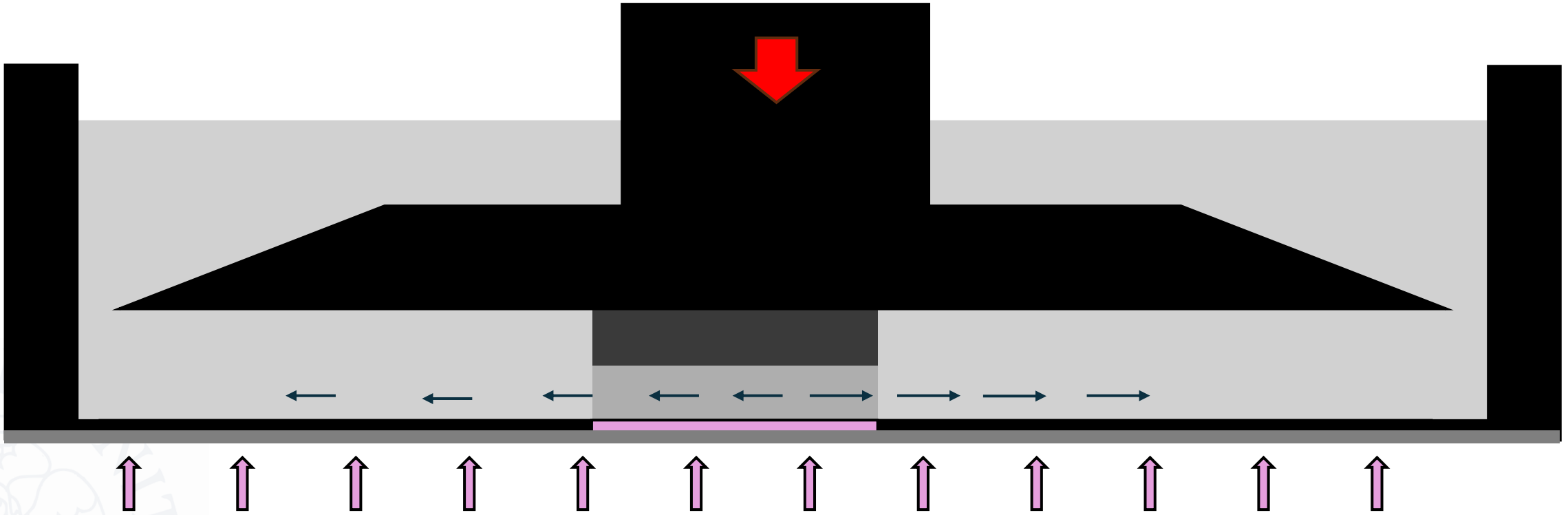
MSLA: cupping



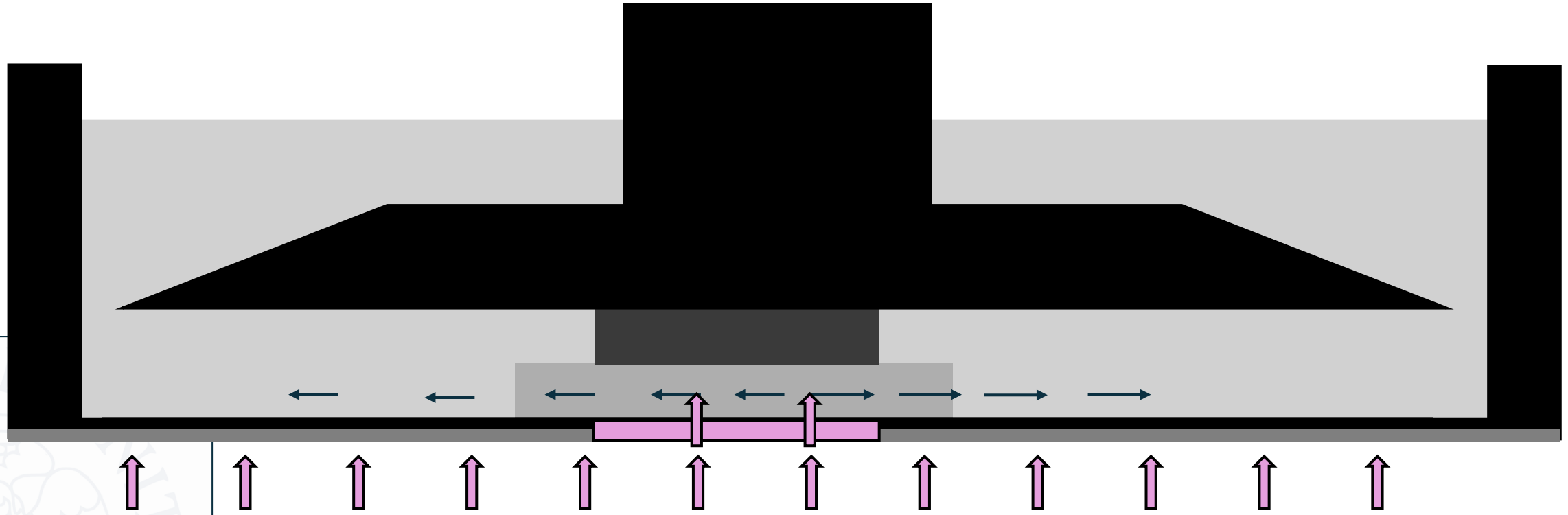
MSLA: cupping



Other issues MSLA



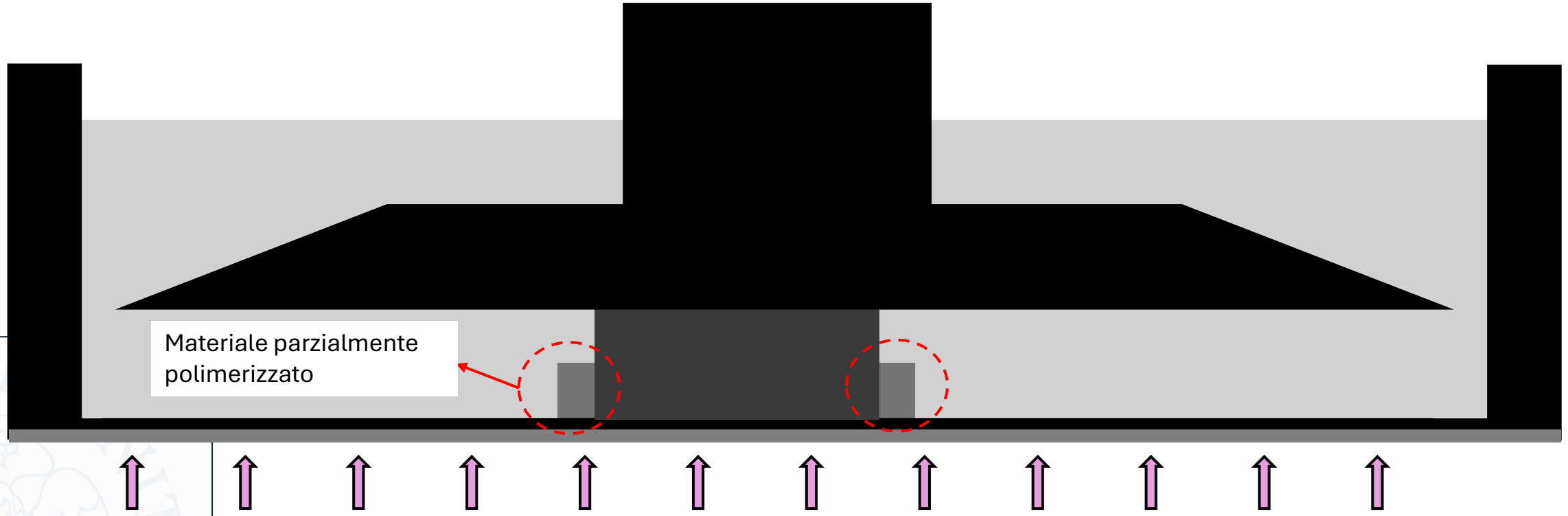
Other issues MSLA



Other issues MSLA

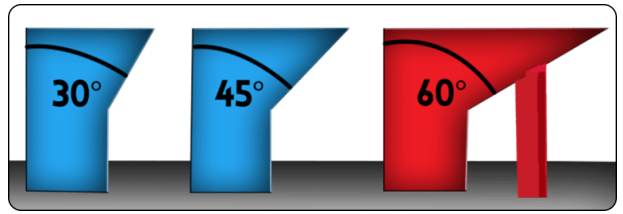
To mitigate the phenomenon, it is possible to:

- Increase the time between the polymerization of two successive layers
- Reduce the retraction speed
- Control the resin temperature

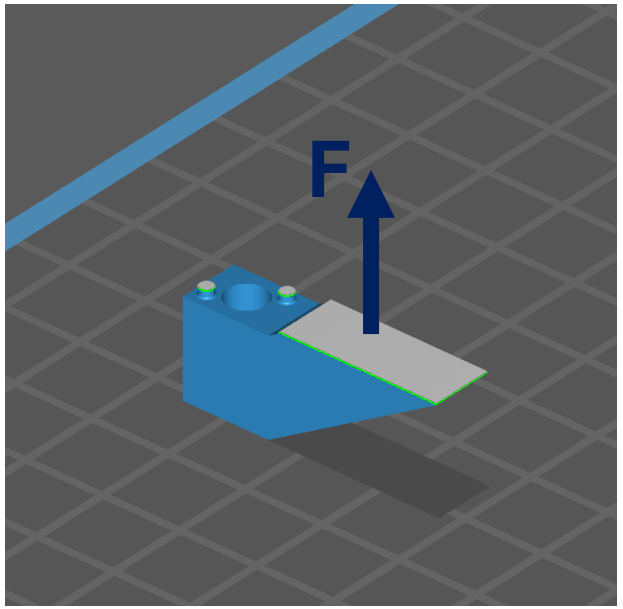


Other considerations for MSLA

MSLA



The supports are made from the same material as the printed part. It is important to correctly choose their position and geometry to facilitate detachment and avoid damaging the model.
Similar considerations apply as in FDM, regarding: load directions (although less influential), number and type of supports (to be minimized), and overhang angles.



Minimize the cross-sectional area in contact with the FEP to reduce the sticking phenomenon and prevent support failure:

- Increase the cross-sectional area and the number of supports
- Increase the number of base layers
- Increase the exposure time of the base layers

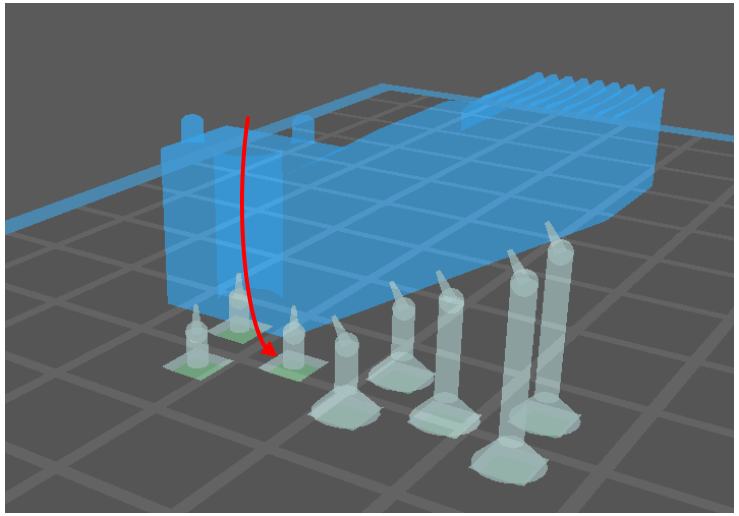
Other considerations for MSLA

MSLA

Position the model in such a way that resin drainage is allowed, even in the case of convex sections relative to the printing plane (cupping). Control the resin temperature.

A viscosity that is too low could cause partial polymerization of the resin and its deposition in incorrect areas.

To mitigate both phenomena, it is possible to:
- Increase the time between the polymerization of two successive layers
- Increase the retraction height
- Reduce the retraction speed



Other considerations for MSLA

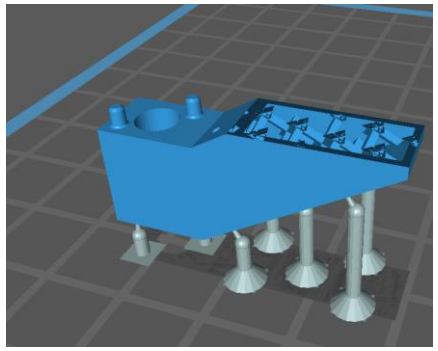
MSLA

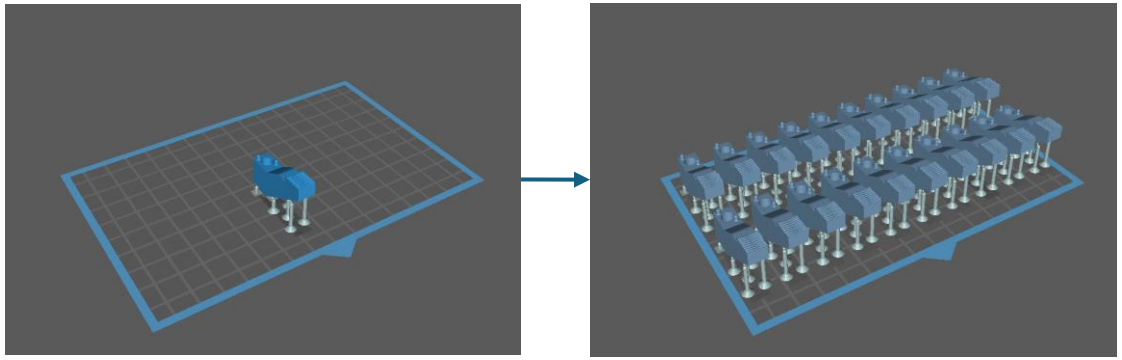
Consider the possibility of creating a hollow model to reduce resin consumption.

In the case of a hollow model, make drainage holes to allow the unpolymerized resin to escape, to avoid subsequent deformations or even delayed breakage of the model.

The **orientation of the part** (its height) directly influences the print time.

The print time does not depend on the number of pieces, but on the height of the tallest piece.





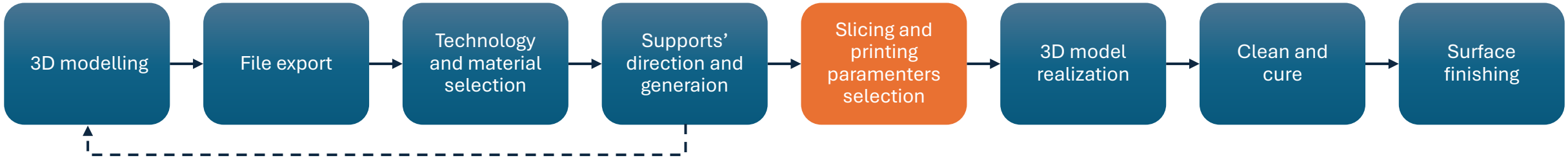
Stesso tempo di stampa!

Other general considerations

FDM MSLA

- **Consider the possibility of creating a hollow model and choose the corresponding infill pattern.**
- Consider the possibility of dividing the model into multiple parts, to be assembled later, in order to minimize print time and simplify the printing process and the generation of supports.
- **Scale the model based on the calibration factor.**

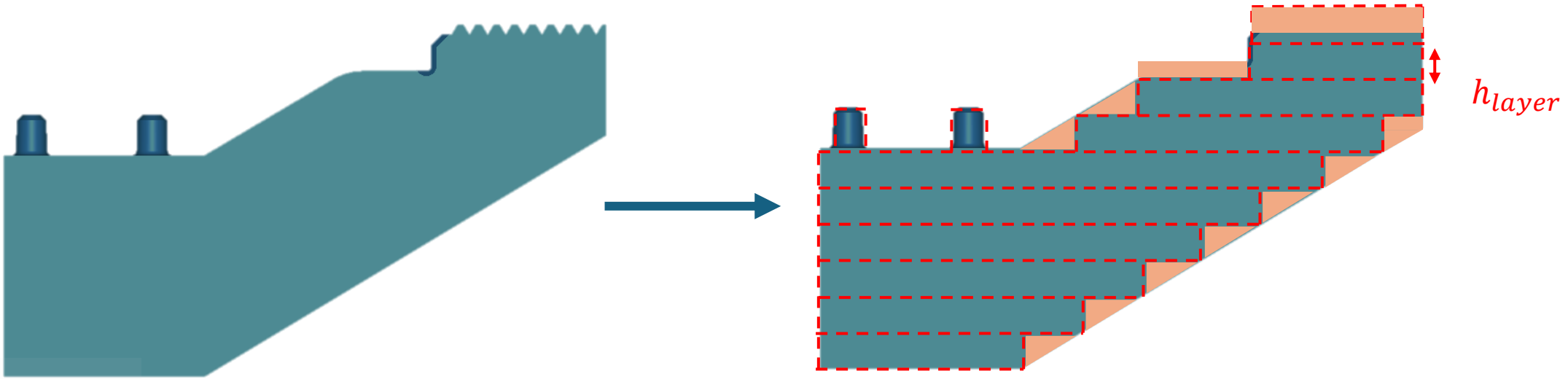
Design of AM parts



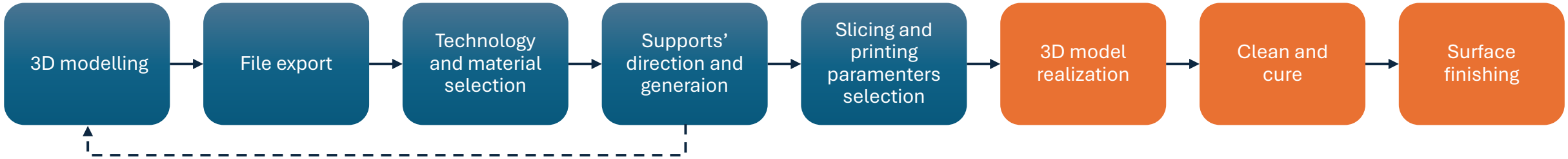
Layer height choice

Layer height influences:

- Print time
- Surface finish
- Level of detail
- Layer adhesion



Design of AM parts



Post processing

FDM

- Detachment from the print bed
- Removal of supports
- Surface finish

MSLA

- Detachment from the print bed
- Removal of unpolymerized resin
- Removal of supports
- Polymerization
- Surface finishing