

Modules of the 2025 course

Topics covered	No	Lecture/Date
VAT Photo polymerization (history) – DLP printer – light engine – part I	5	20.03.2025
DLP printer – chemical components in a photoresin – role of oxygen – CLIP method– part II	6	27.03.2025
Tomographic Volumetric Additive Manufacturing (TVAM): principles and applications	7	03.04.2025
Two photon Polymerization : nanoscale printing	8	10.04.2025
Two photon Polymerization : applications	9	17.04.2025
EASTER BREAK		22.04.2025
Prof. Paul Dalton, University of Oregon: Met Electro Writing (nanoscale)	10	1.05.2025
Gari Arutinov, Holst Center for AM: Mass transfer of microcomponents	11	08.05.2025
Julian Schneider: Scrona	12	15.05.2025
Patrizia Richner: Sonova (hearing aids). // Design Competition	13	22.05.2025

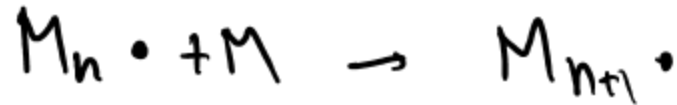
QUIZZ #2

Role of oxygen

Photo-initiation



Propagation
Polymer chain growth

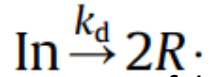


Oxygen radical
scavenging



Reaction kinetics

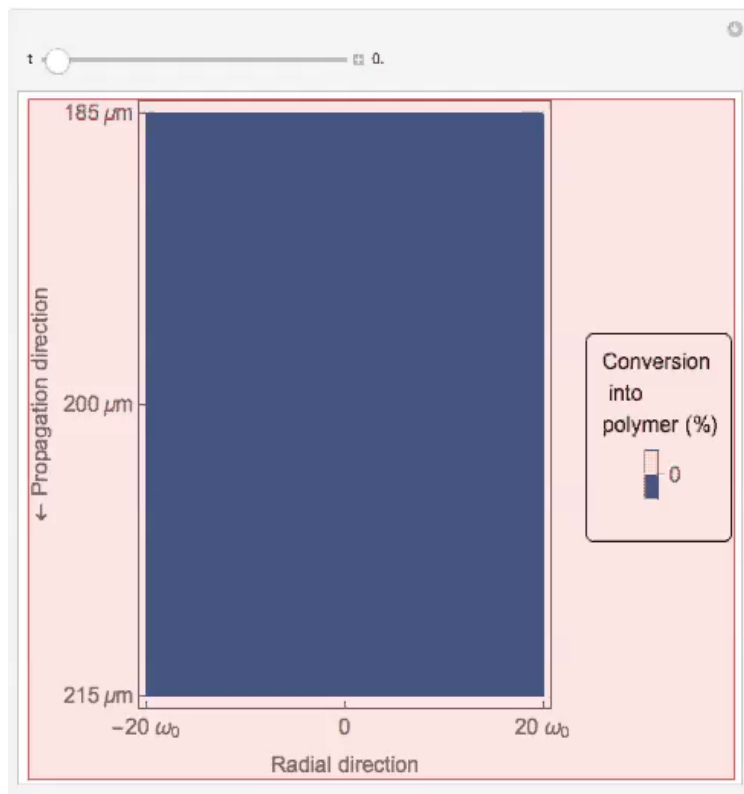
Photoinitiator molecule



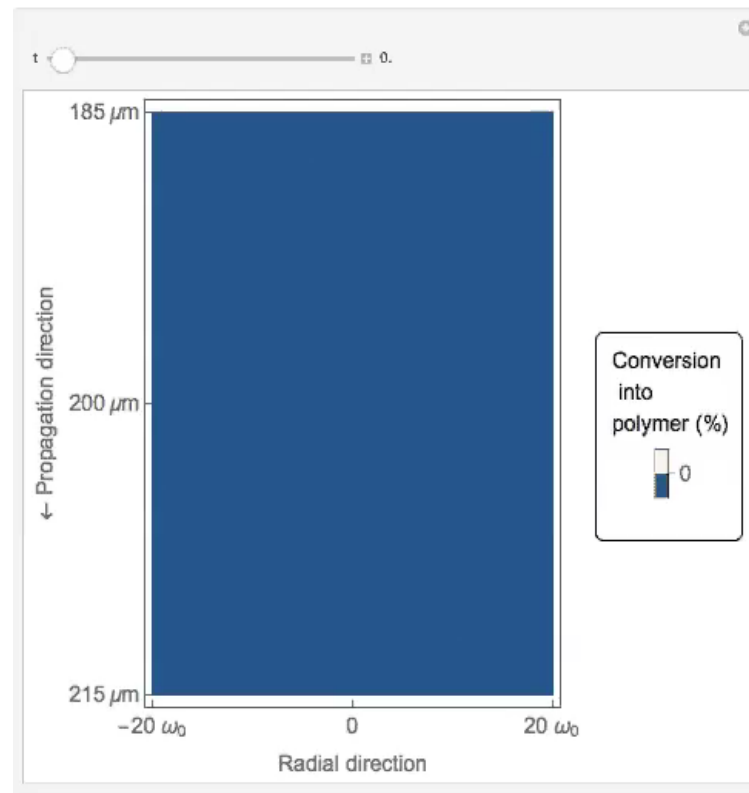
k_d : rate of decomposition

**Photo
initiator**

Simulation without oxygen inhibition



Simulation with oxygen inhibition

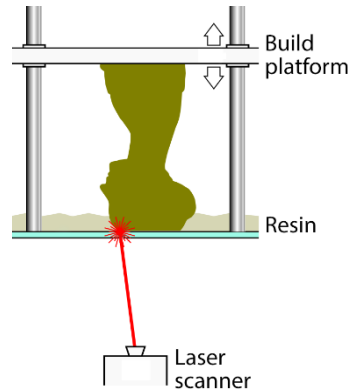


P = 250 nW, polymer: PEG-DA
MICRO-413 week 7

Existing 3D printers are actually 2D printers.

1st generation

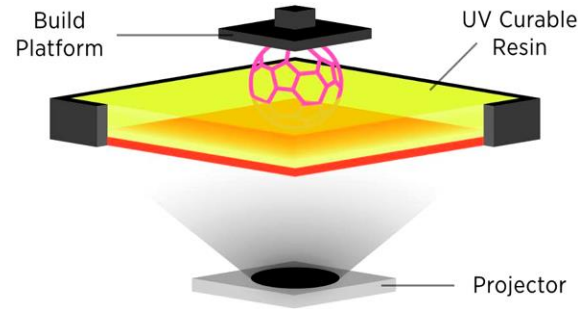
Point-by-point



10 - 50 mm per hour

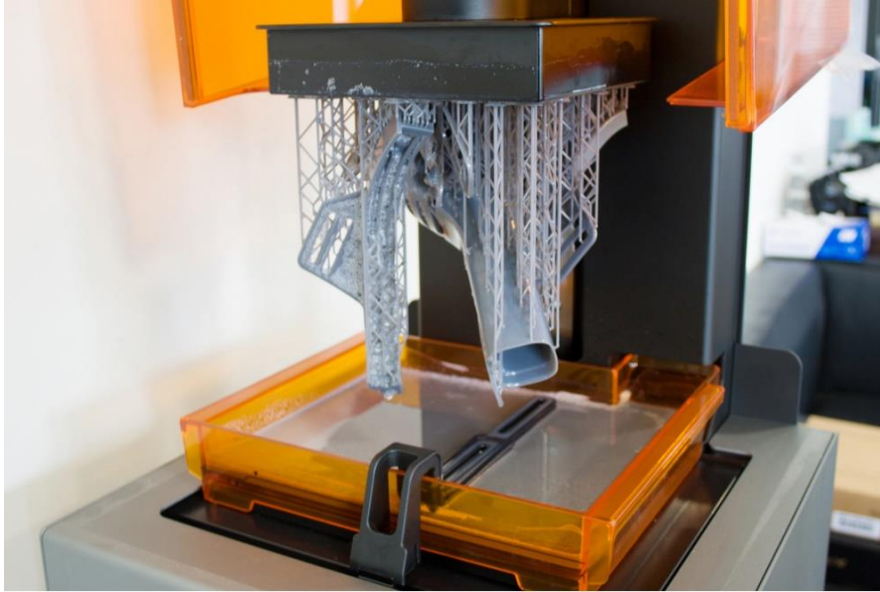
2nd generation

Layer-by-layer



300 - 1200 mm per hour

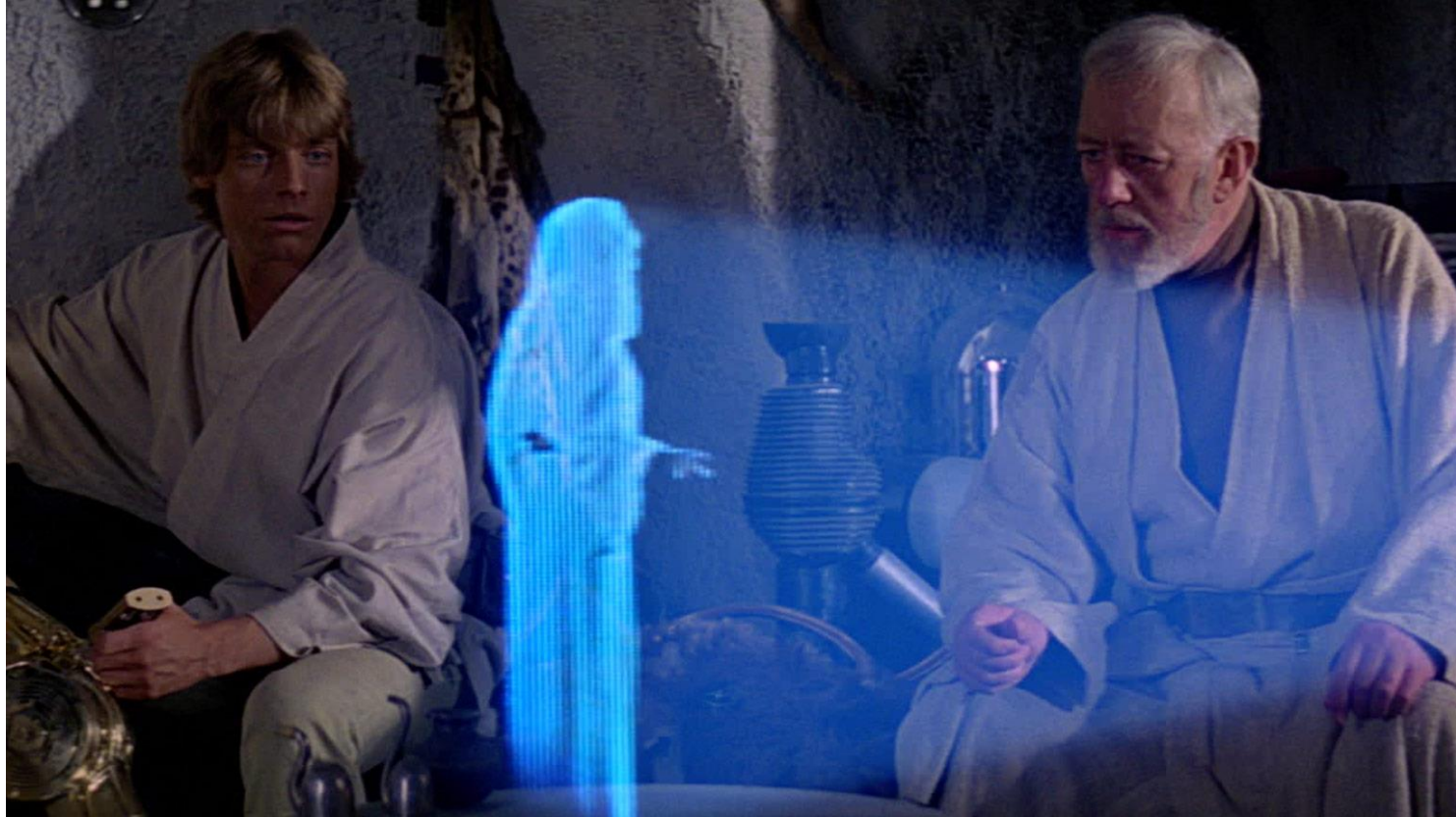
Existing 3D printers are actually 2D printers.



Main limitations

- Layer-by-layer
- Needs support structure
- Still slow
- Does not work for soft materials

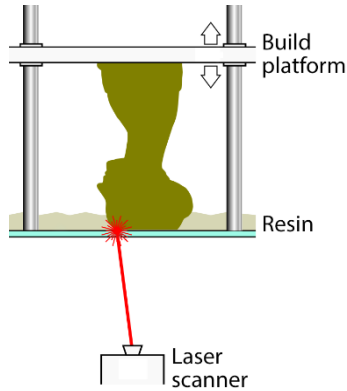
Can we do fully volumetric printing?



Can we do fully volumetric printing?

1st generation

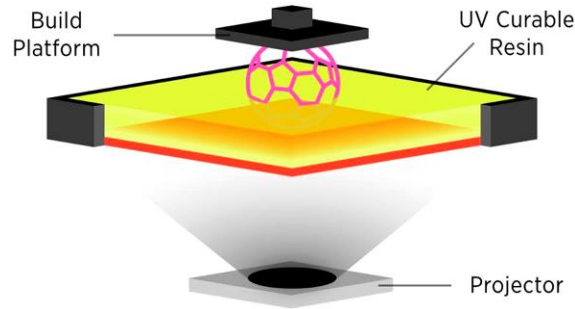
Point-by-point



10 - 50 mm per hour

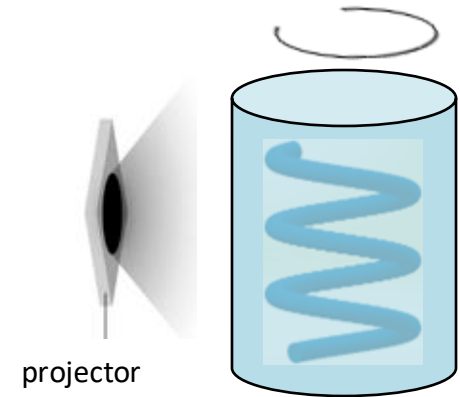
2nd generation

Layer-by-layer



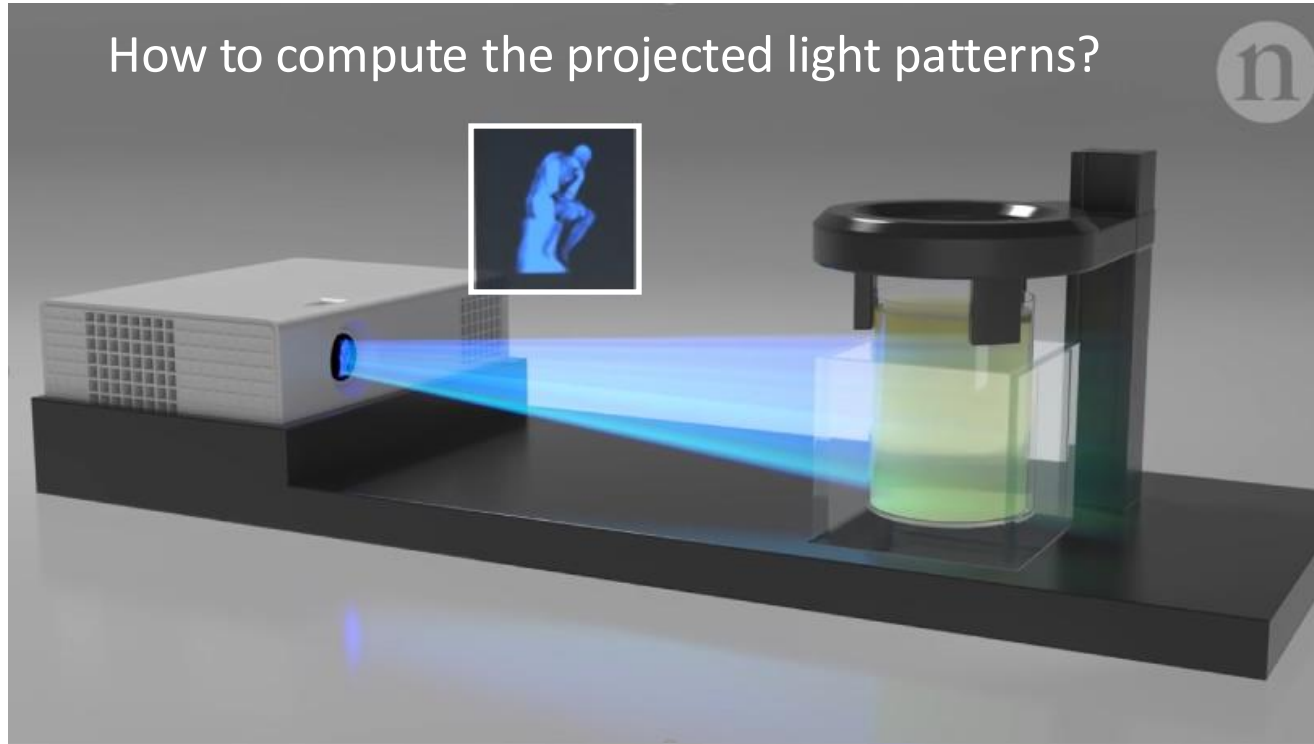
300 - 1200 mm per hour

3rd generation



50 mm³ per seconds

Volumetric 3D printing
By Tomographic projections



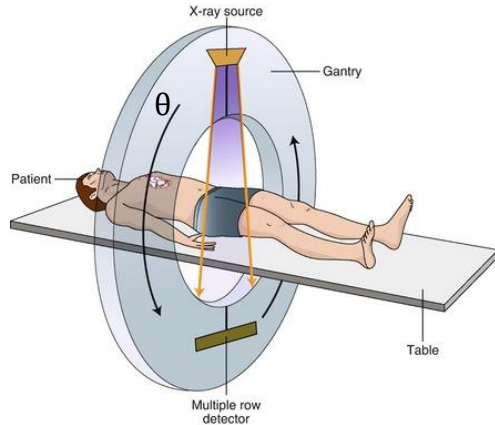
Nature Video | 31 January 2019

3D printing with light <https://www.nature.com/articles/d41586-019-00410-8>

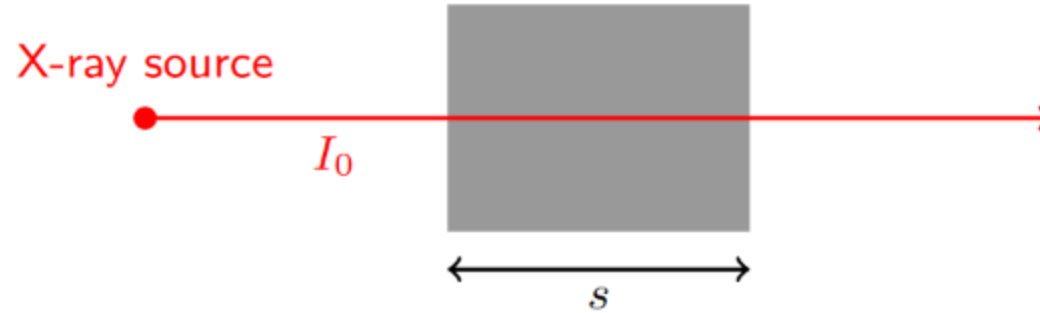
Computed Tomography (CT) imaging

CT is a **non-invasive** device that provides information about the inside of an object by taking measurements from the outside (indirect information)

2D + θ measurements



Simple example: a line in an homogeneous medium

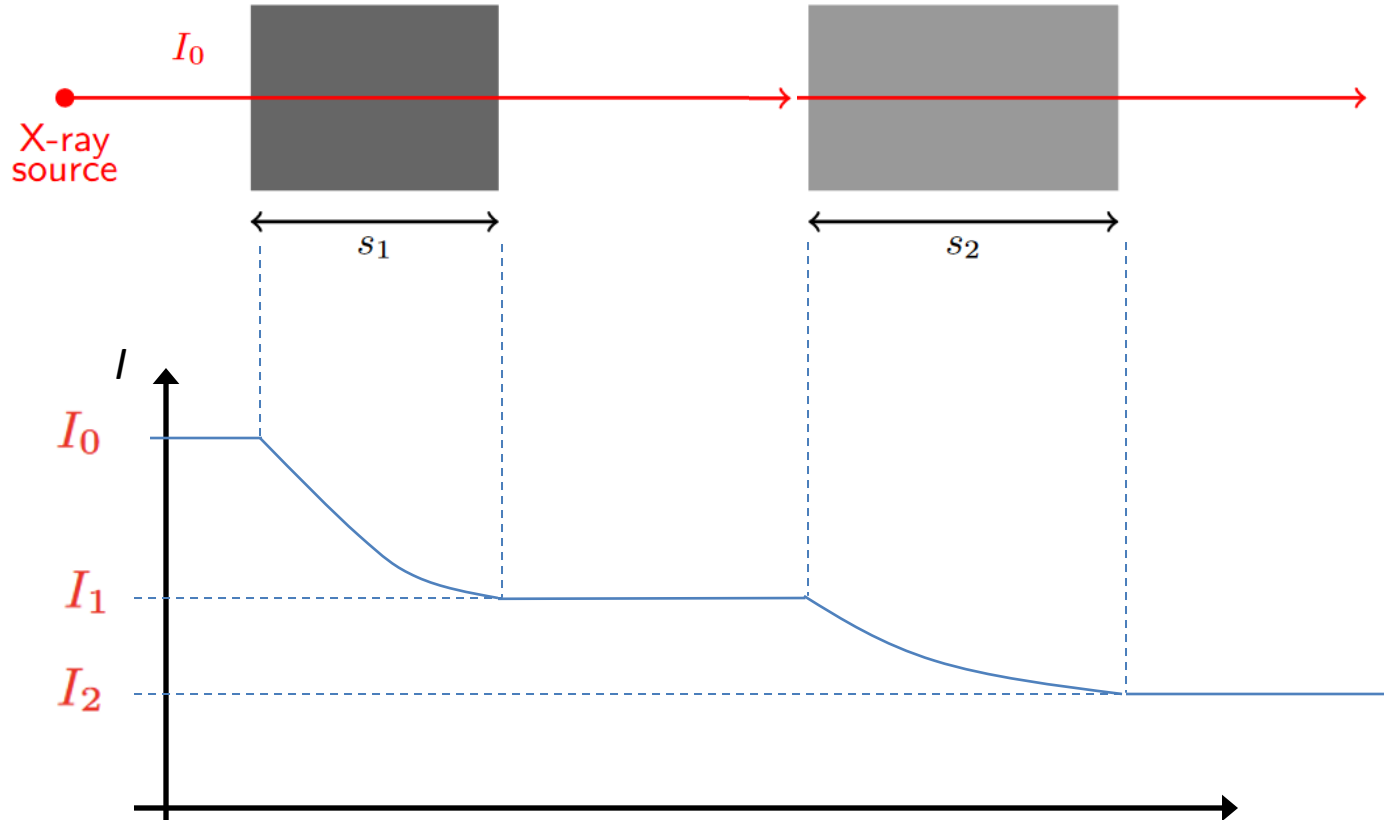


I_0 : initial intensity of the X-ray

s : length of the path of the X-ray inside the body

$\mu > 0$: X-ray attenuation coefficient

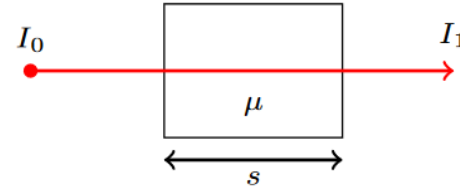
Simple example: two homogeneous blocks



The Beer-Lambert law

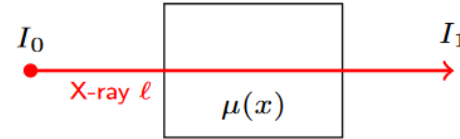
Homogeneous material:

$$I_1 = I_0 e^{-\mu s}$$



Non-homogeneous material:

$$I_1 = I_0 e^{-\int \mu(x) dx}$$



The **Beer-Lambert law** connects the initial and final intensities of an X-ray:

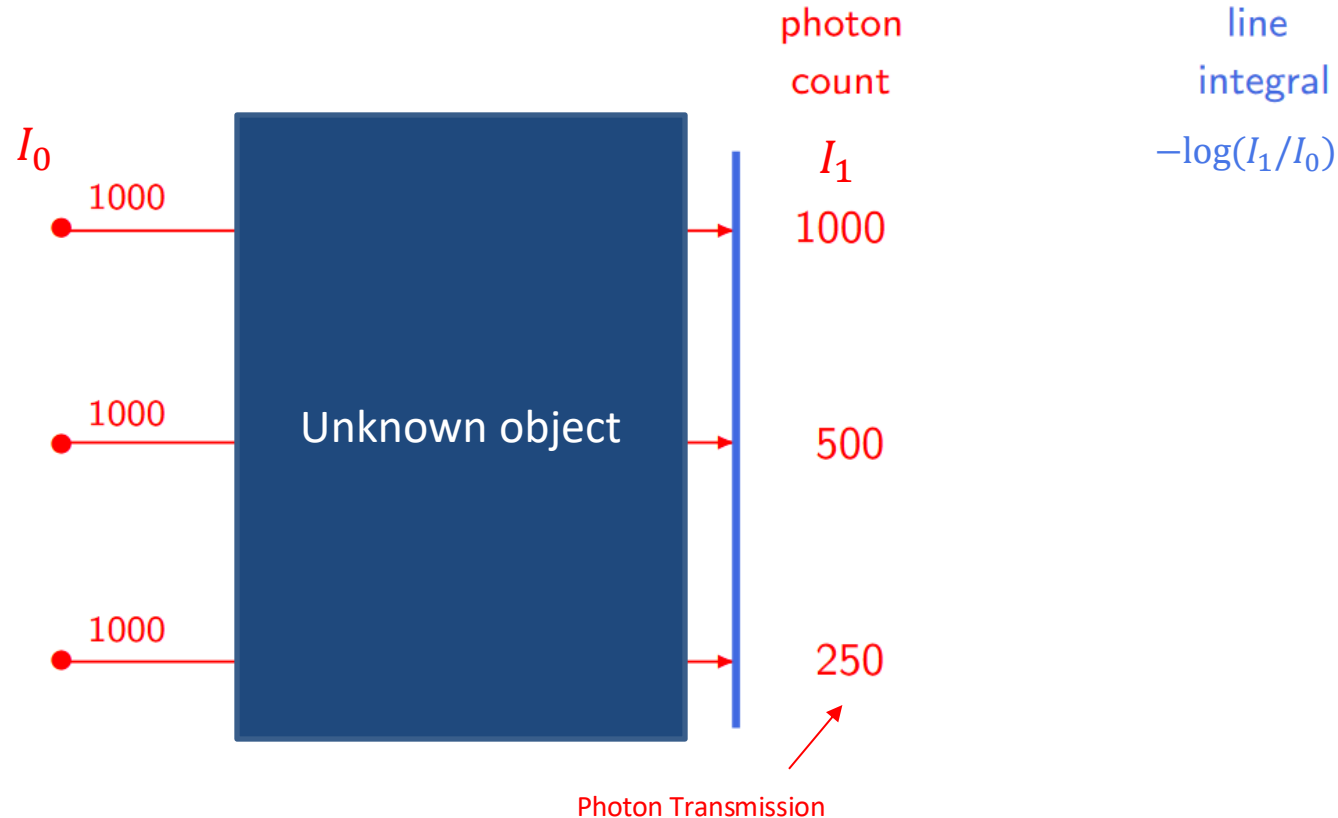
$$I_1 = I_0 e^{-\int_{\ell} \mu(x) dx} \quad \Longleftrightarrow \quad -\log\left(\frac{I_1}{I_0}\right) = \int_{\ell} \mu(x) dx$$

and it is connected to the Radon transform

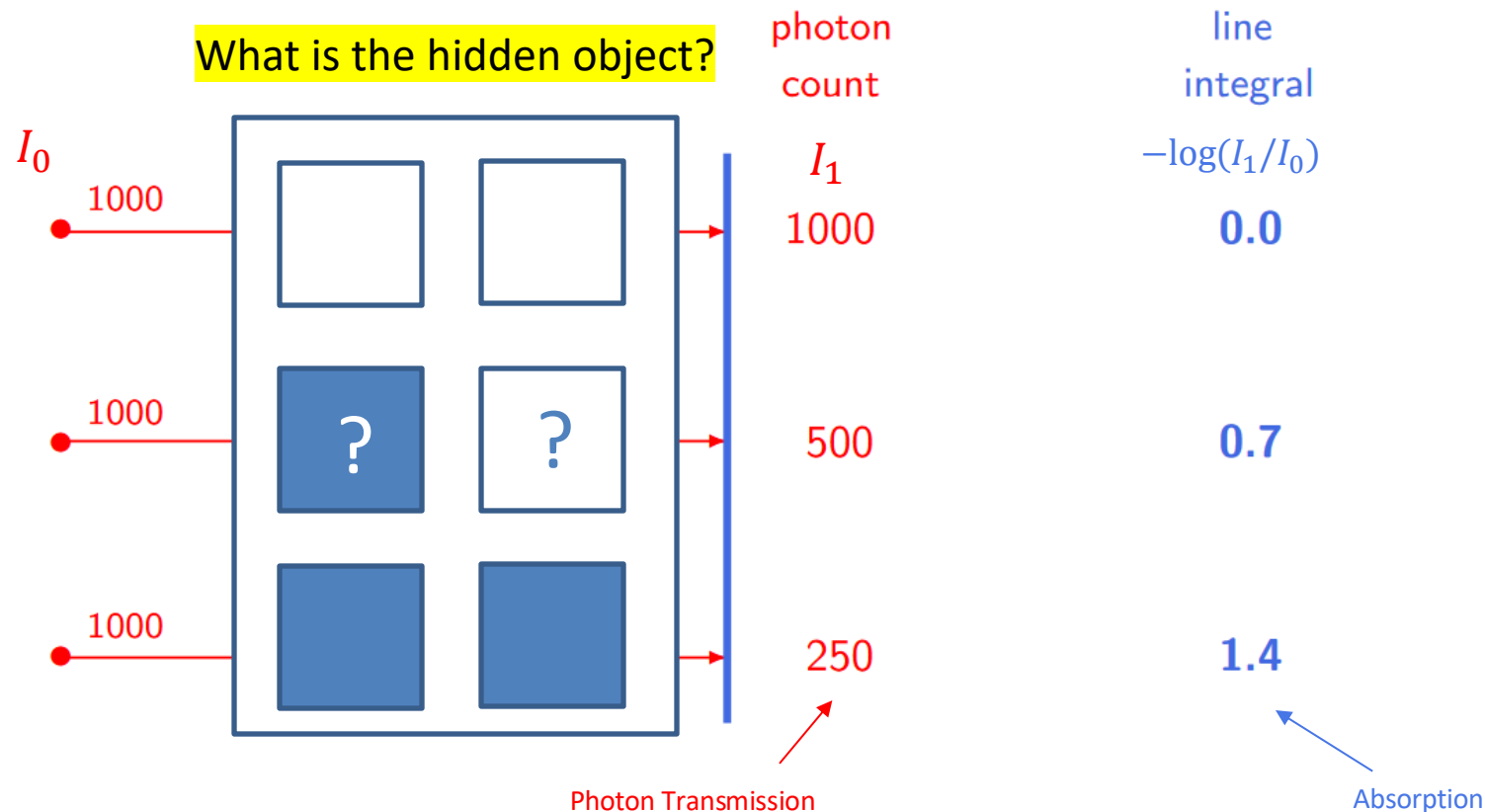
In general, during a tomographic scan:

- I_0 is known from calibration and I_1 from measurement.
- I_1 is measured along many lines $\ell_{(\theta, \tau)}$ to get many line integral values through the object from which to determine $f(x)$.
- The intensity I_1 is called the *transmission*, while the corresponding $-\log(I_1/I_0)$ is called absorption or **projection**. A collection of projections is called **sinogram**.

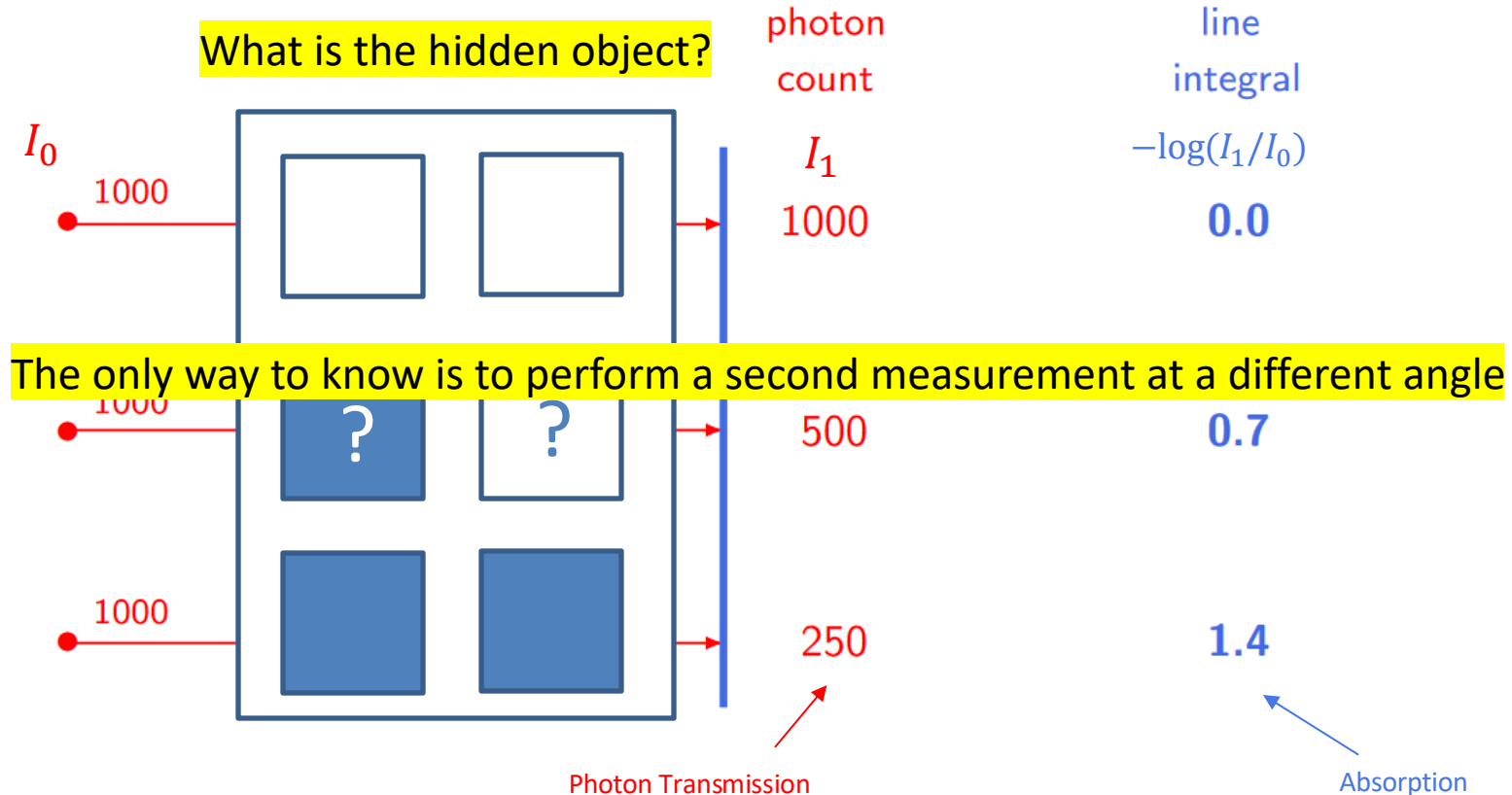
In practice: from transmission to absorption



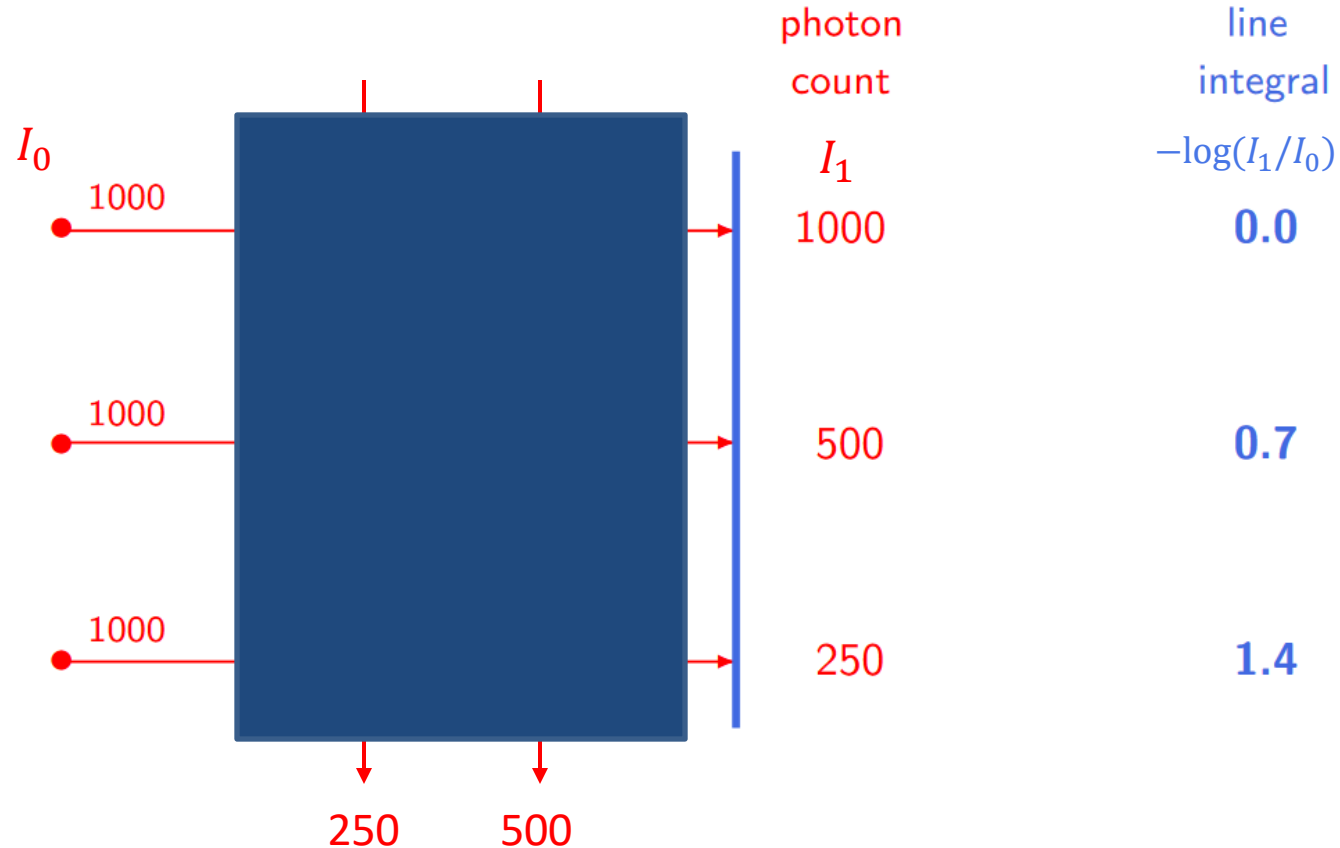
In practice: from transmission to absorption



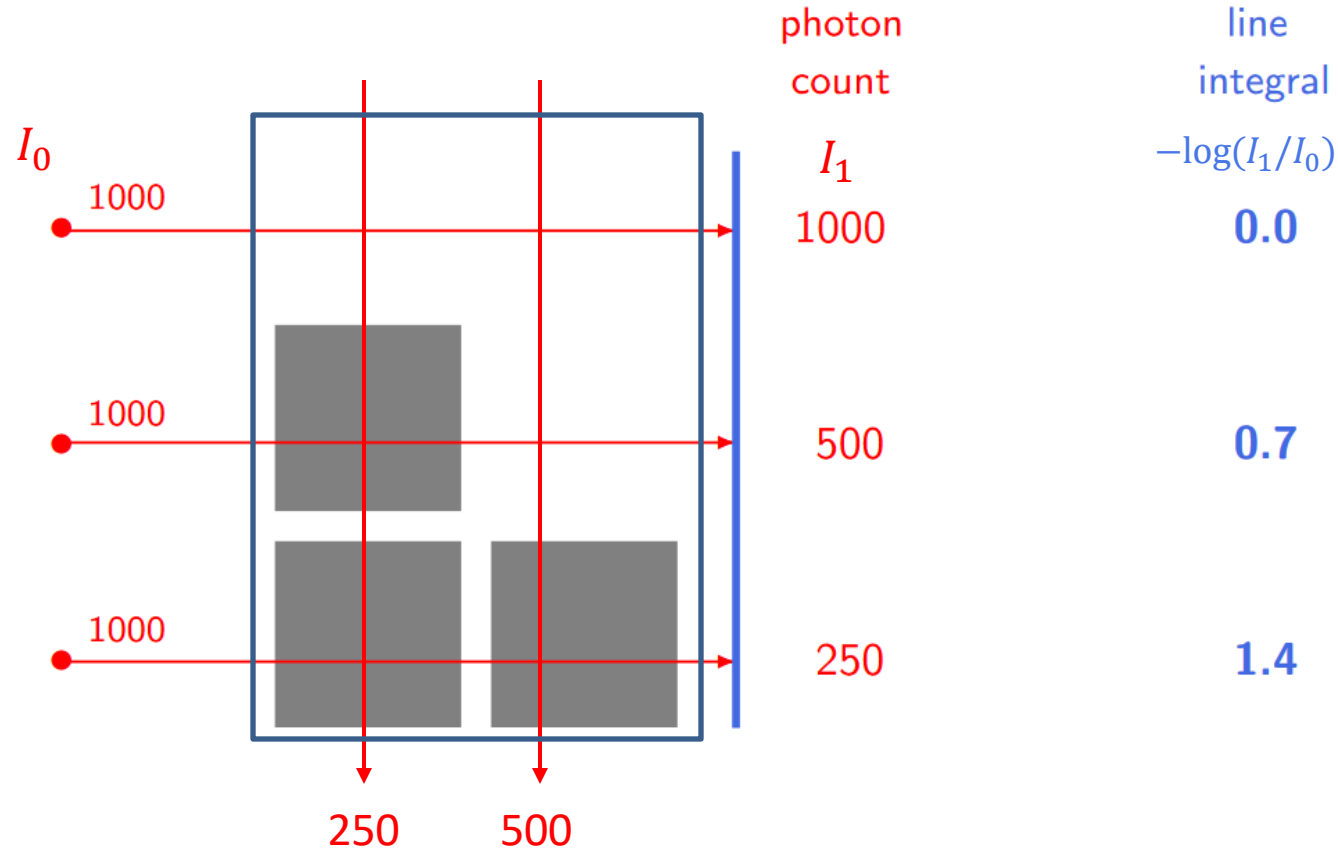
In practice: from transmission to absorption

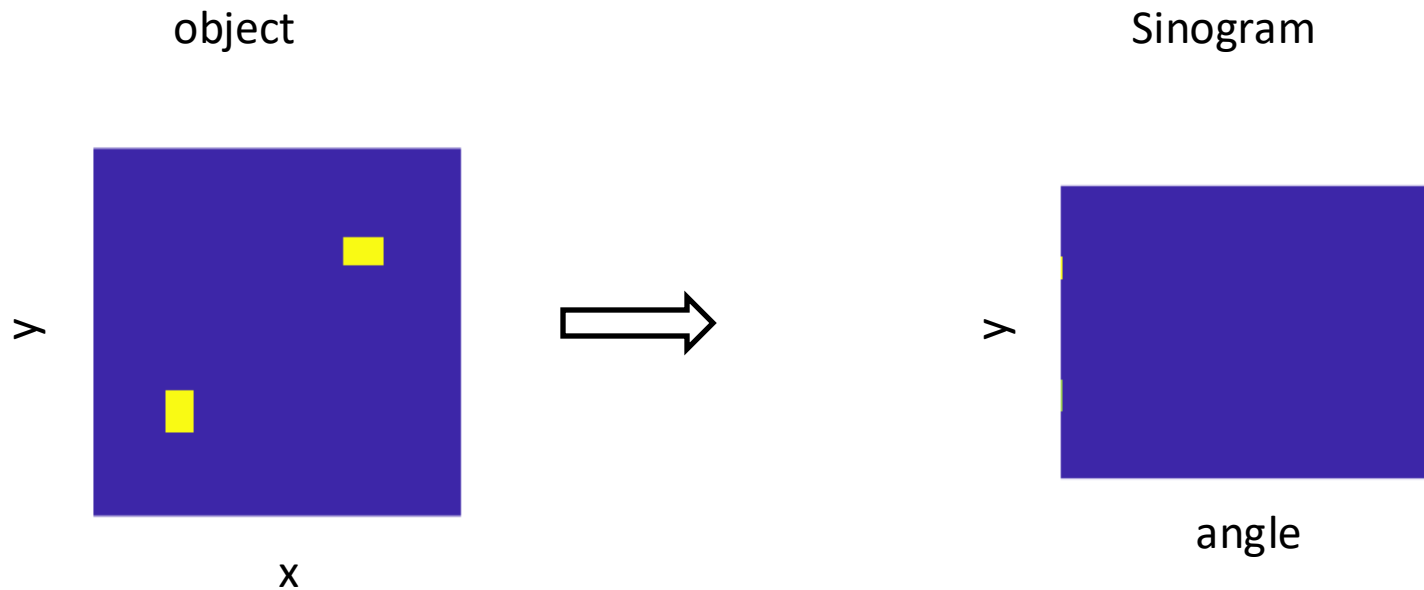


The Beer-Lambert law and Radon transform



The Beer-Lambert law and Radon transform





Tomography: reconstruction principle

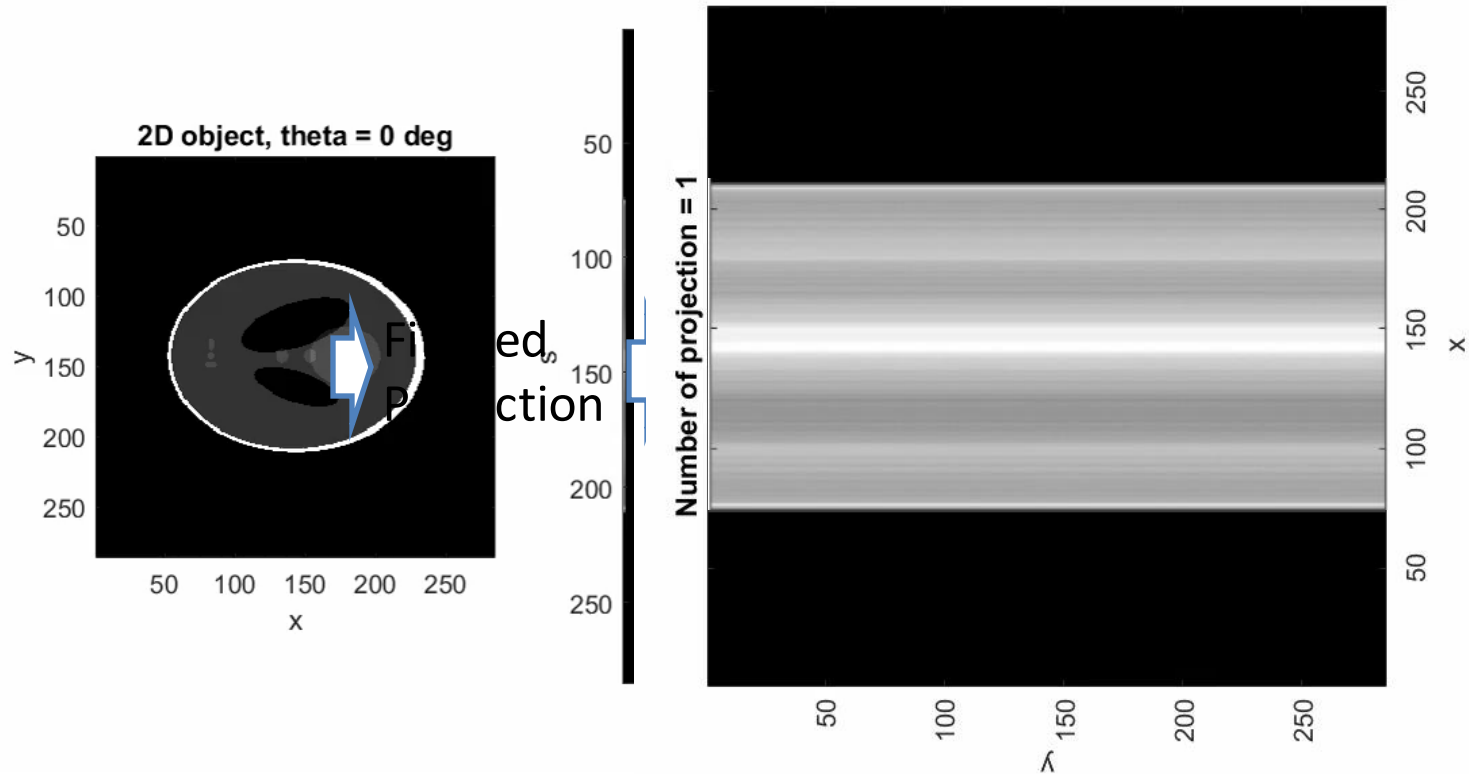
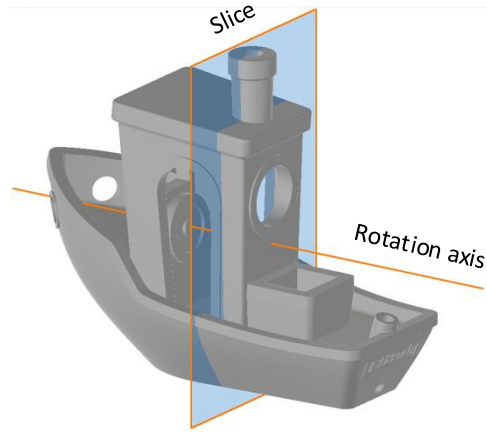
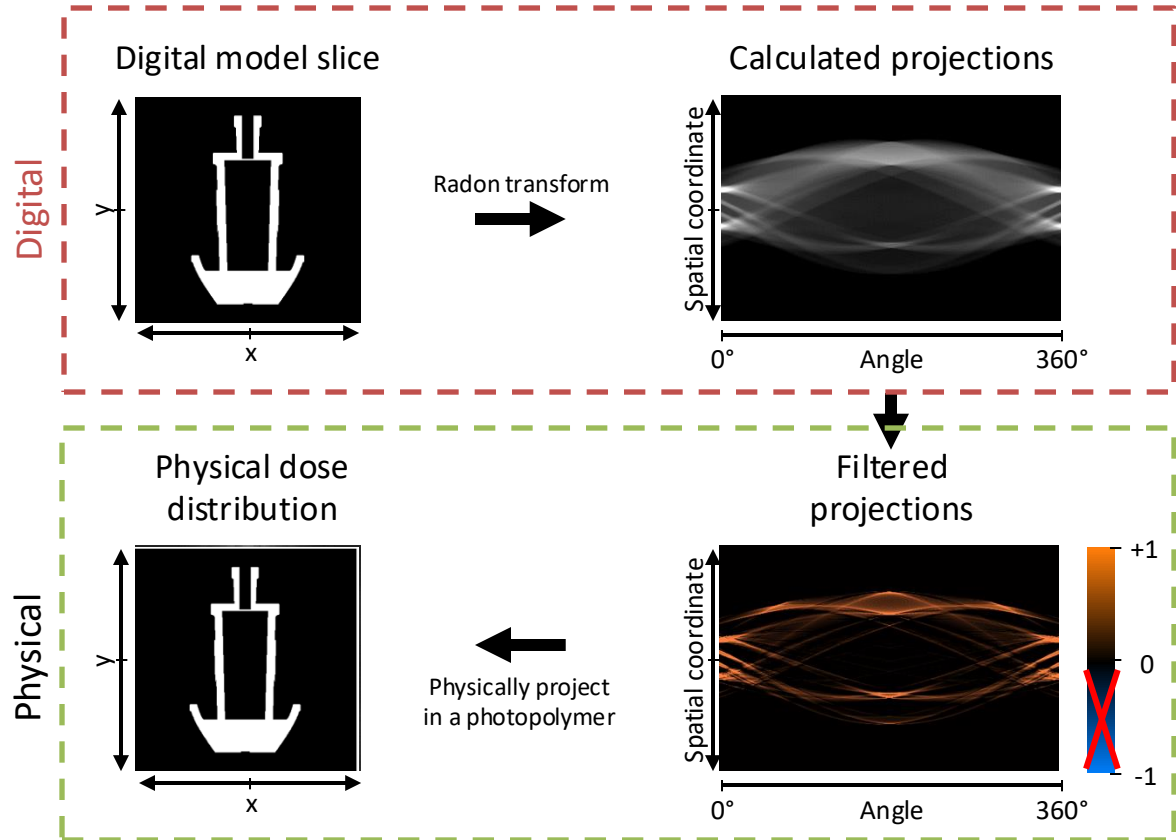


Illustration of the Radon transform in *3D printing* **EPFL**

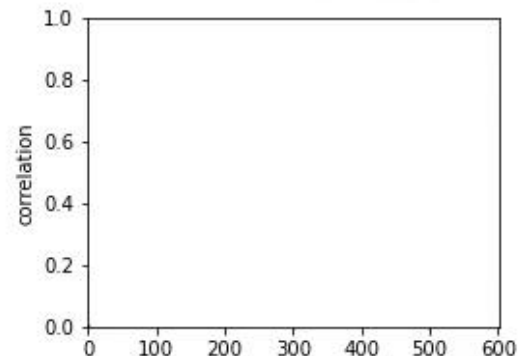
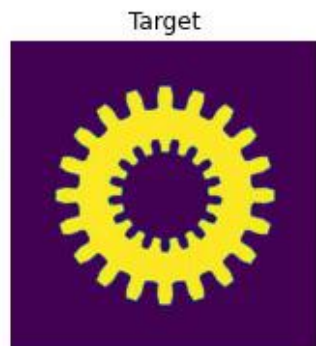
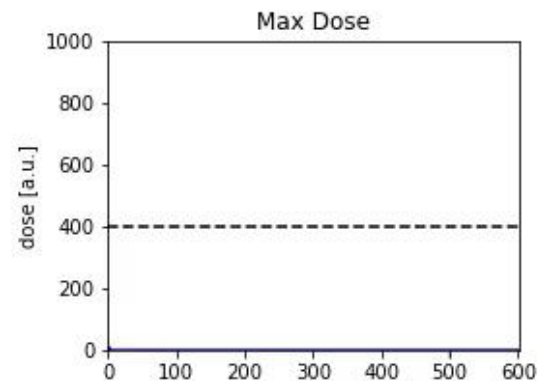
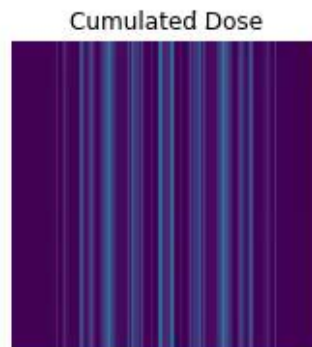
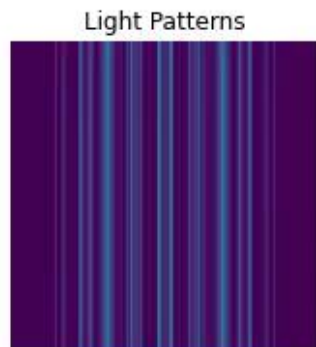


3D object

(3DBenchy by Creative Tools, license CC BY ND 4.0)

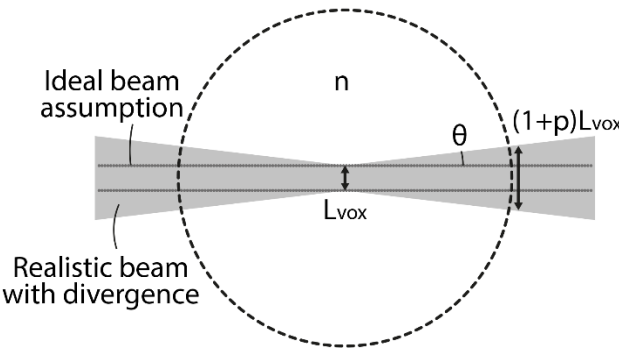


Reverse tomography for 3D printing

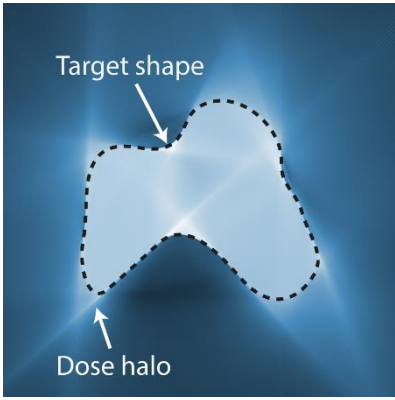




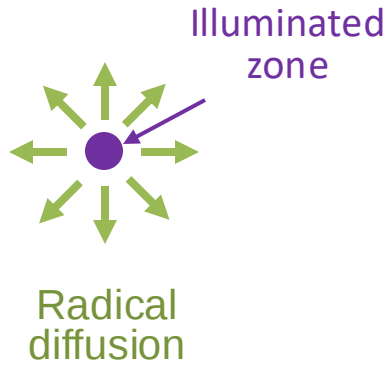
Divergence

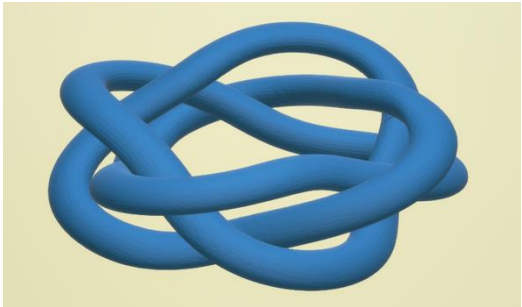


Algorithm

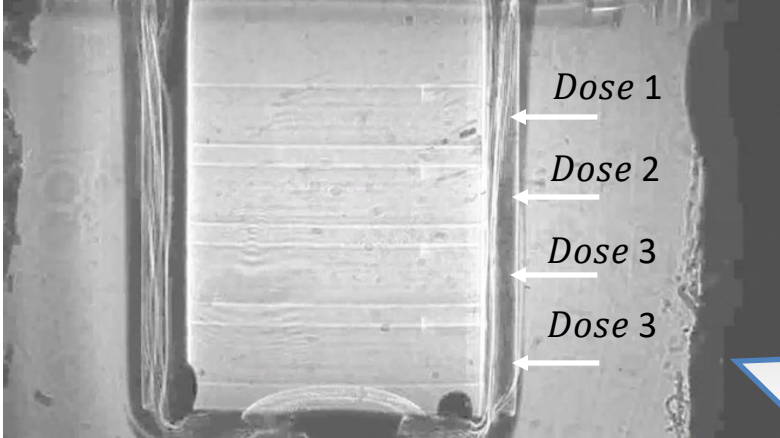


Chemical diffusion



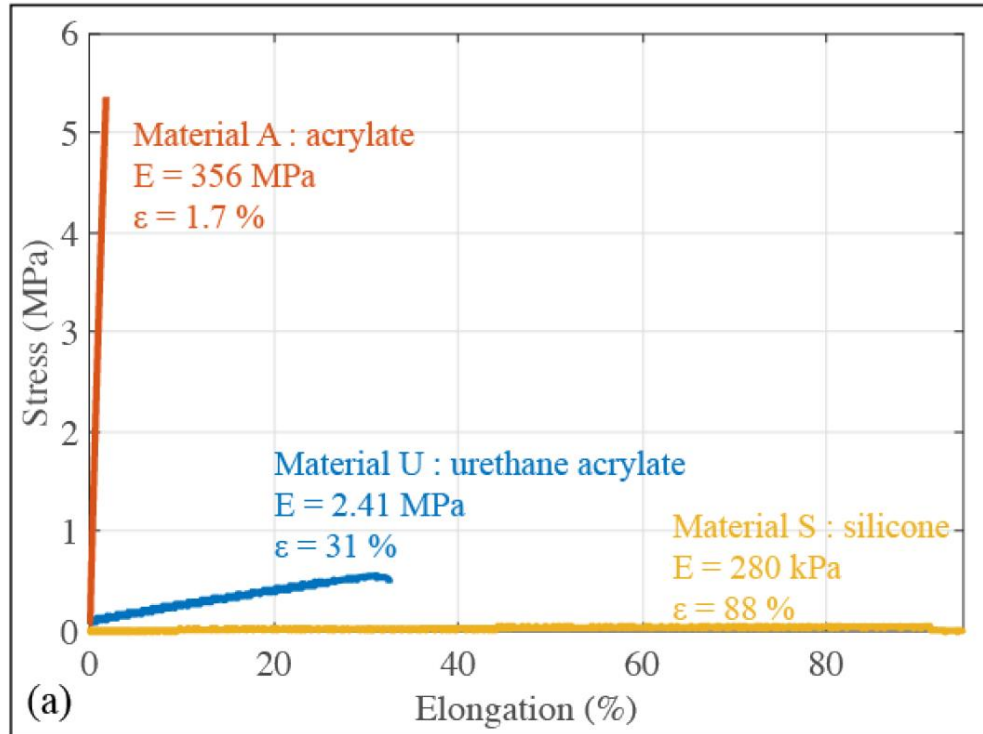


$$Dose[\frac{J}{cm^2}] = I \cdot time$$

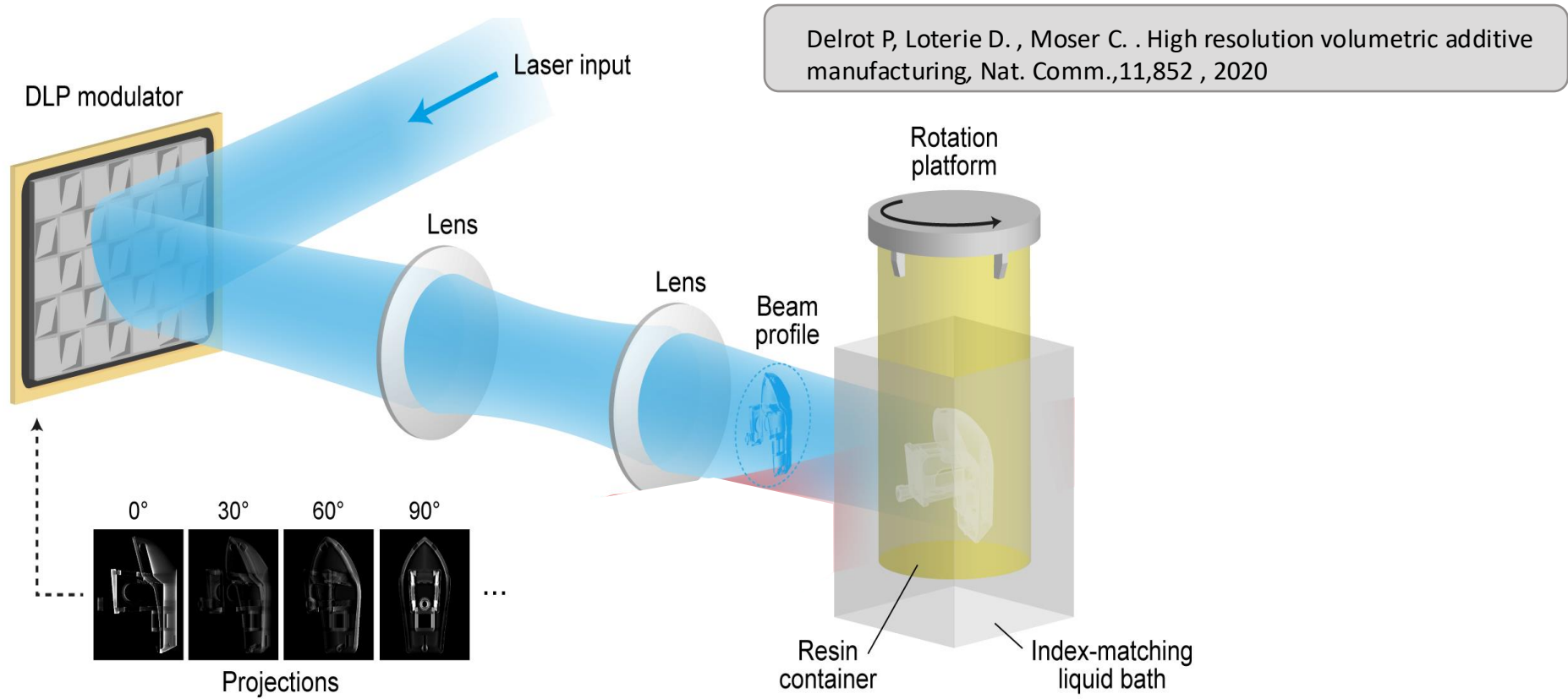


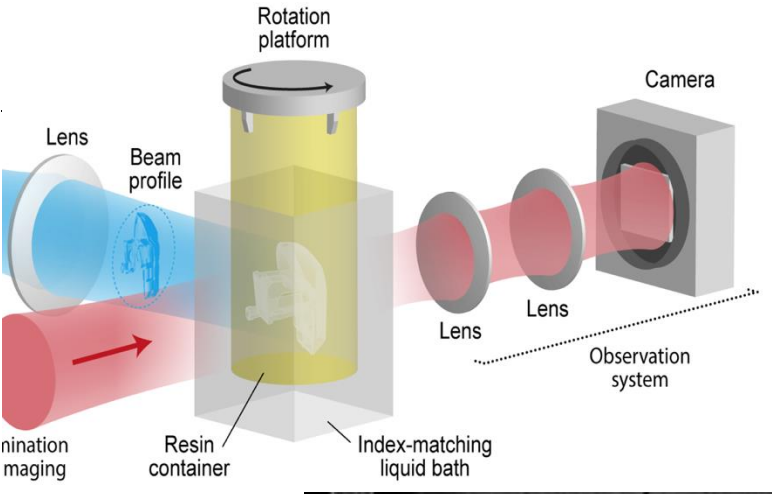
Intensity

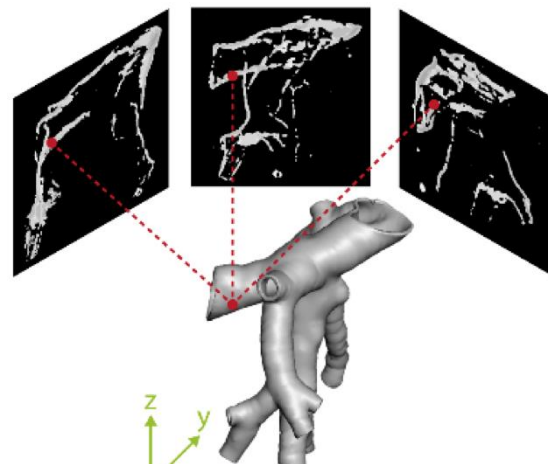
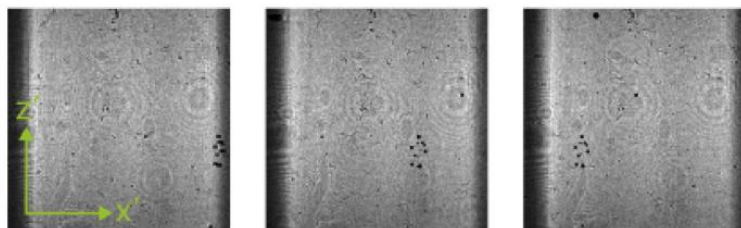




Polymers
Silicones
Hydrogels
Ceramics
Glass



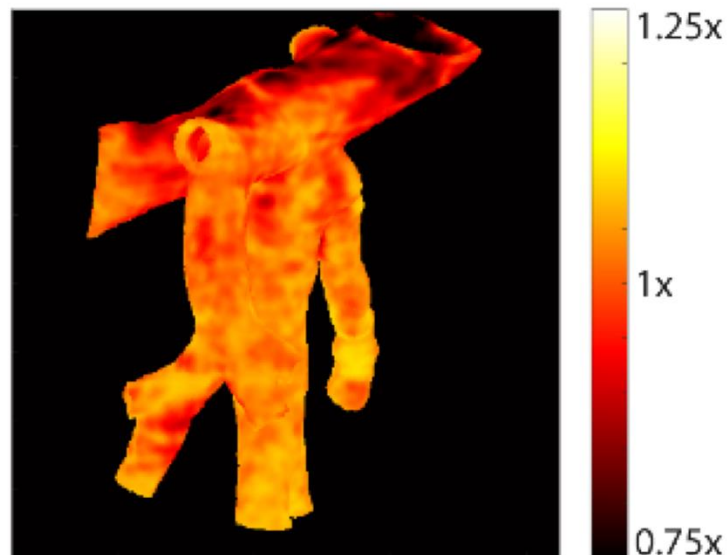


$\theta = 0^\circ$... $\theta = 45^\circ$... $\theta = 90^\circ$


Rot. 8



Rot. 9

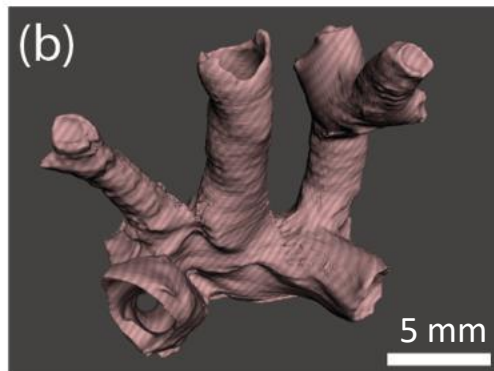


Camera at 22s

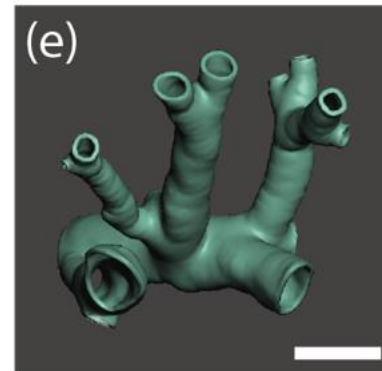


No feedback

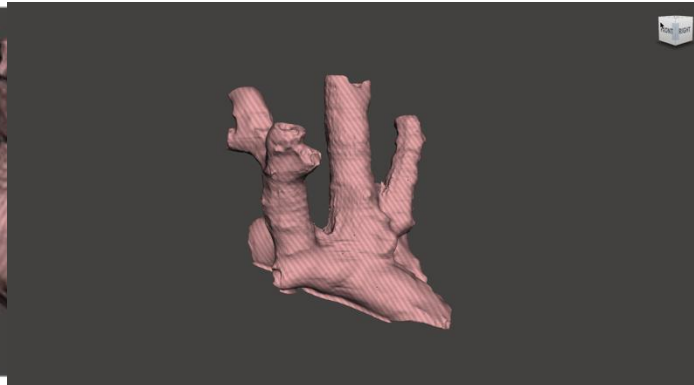
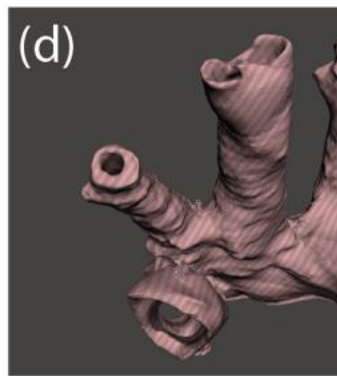
Micro-CT

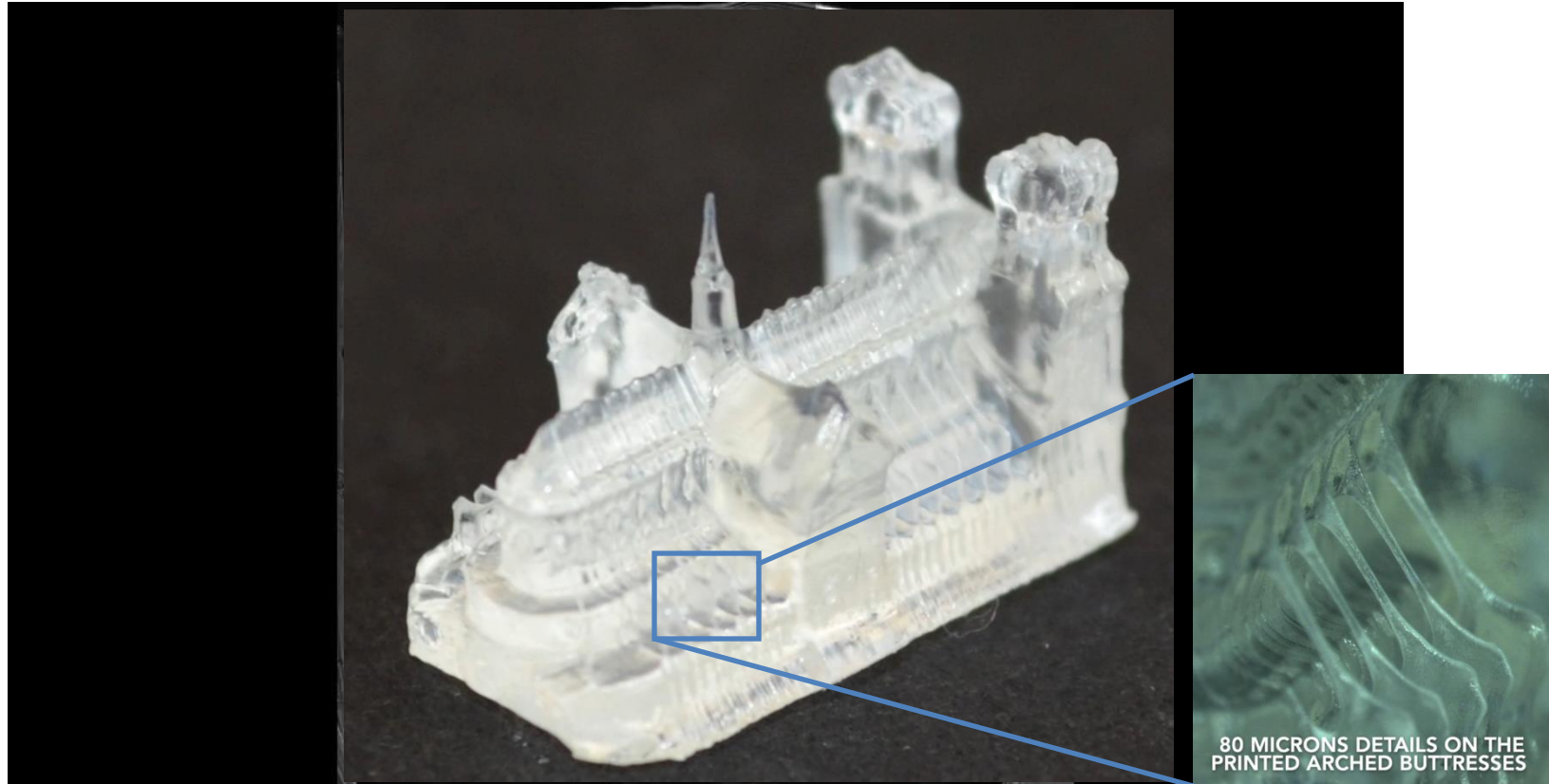


Model



With feedback



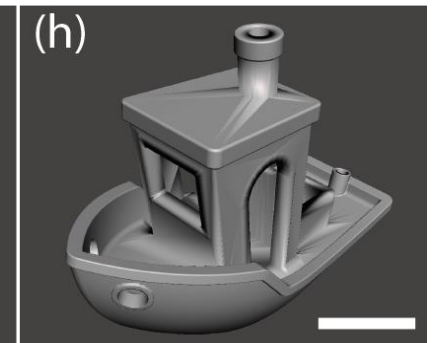
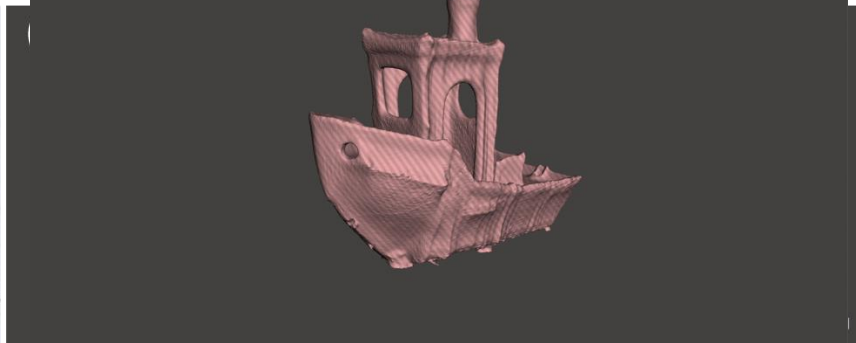
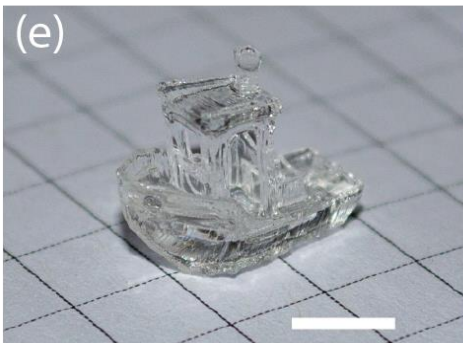
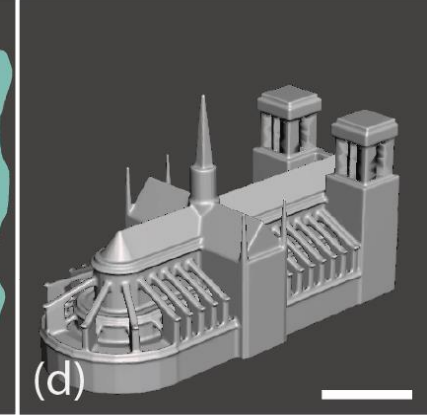
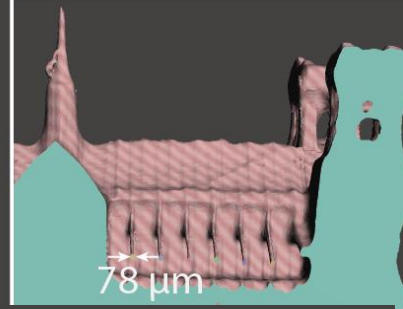
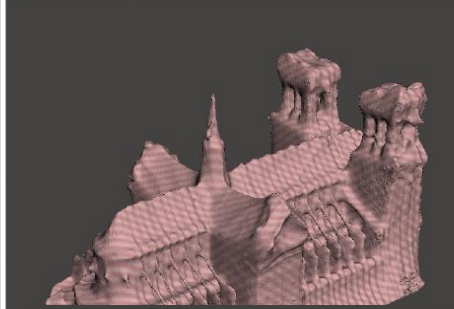
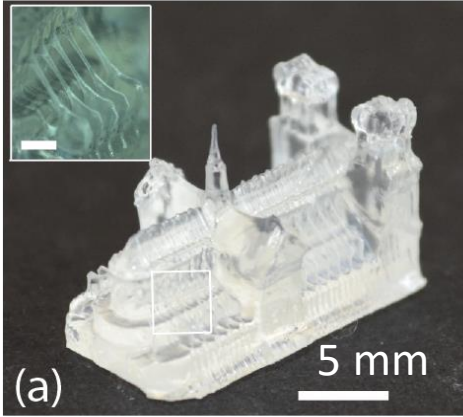


Photograph

Micro-CT

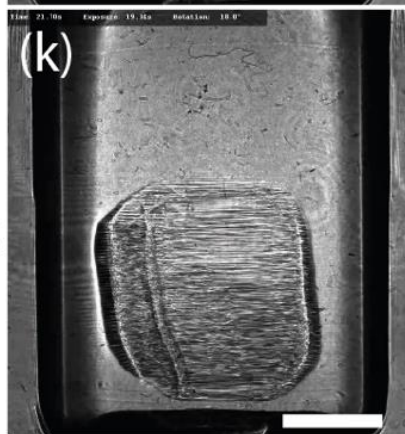
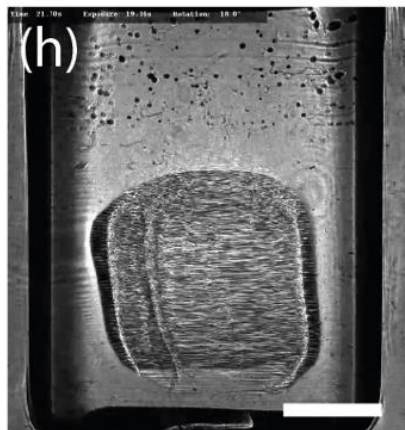
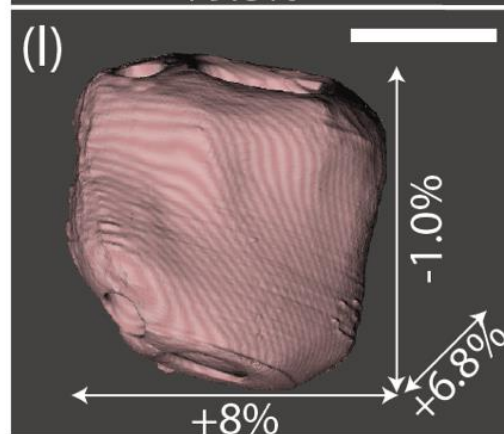
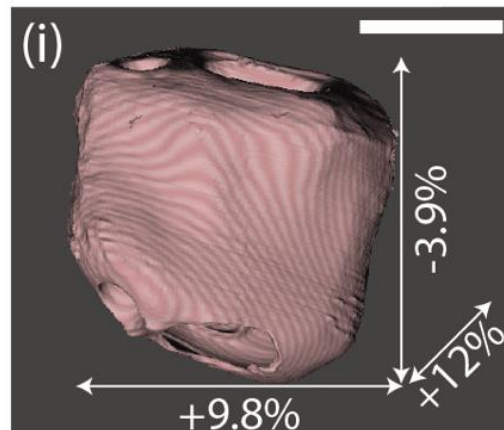
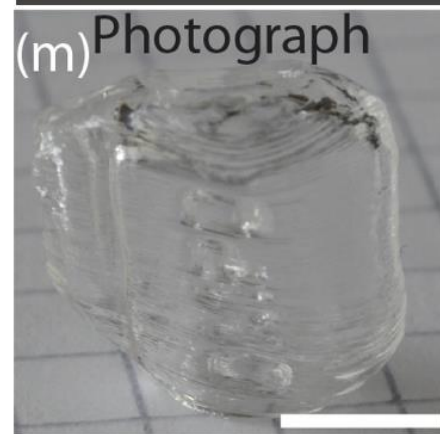
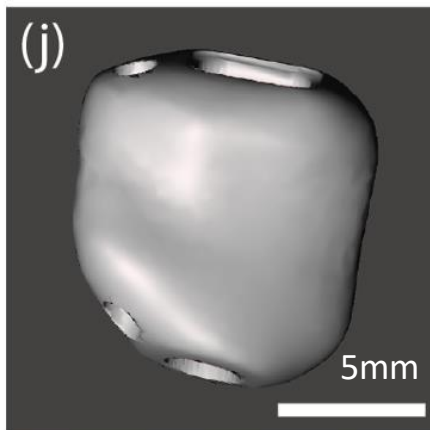
Cross-sections

Model



Camera at 19s

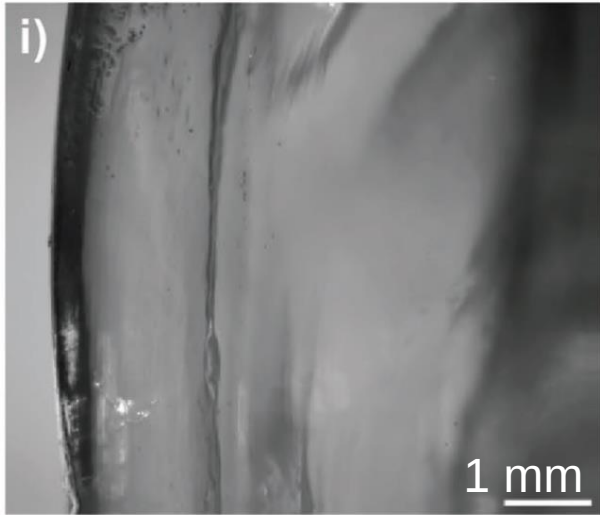
Micro-CT



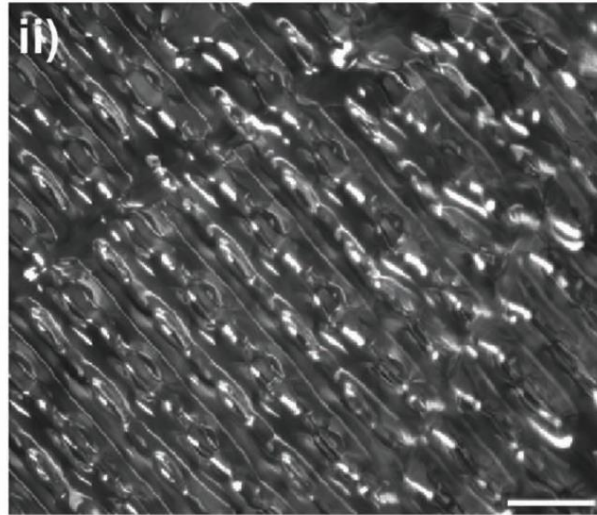
No feedback

With feedback

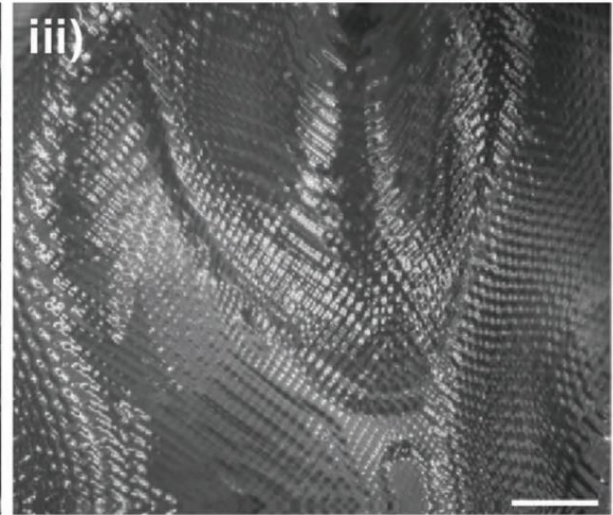
Volumetric Printing



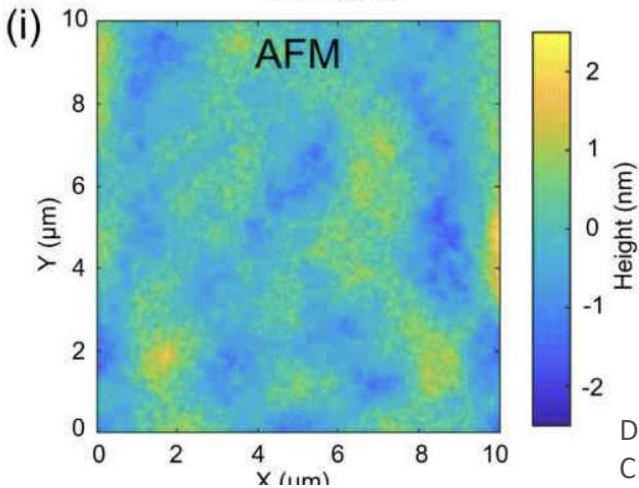
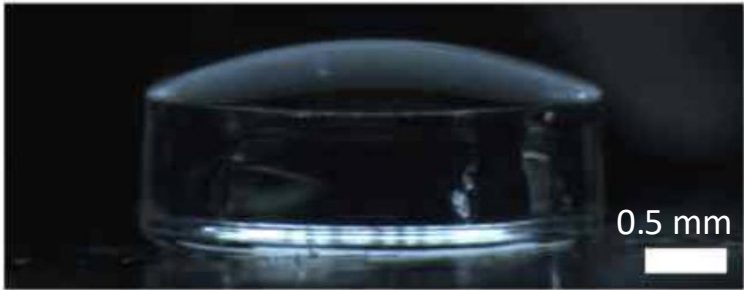
Extrusion-Based Printing



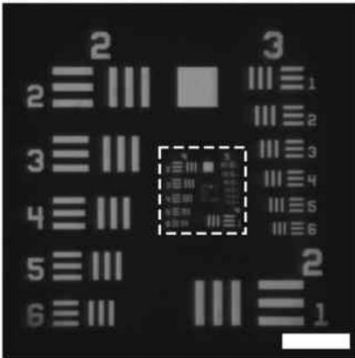
Digital Light Processing



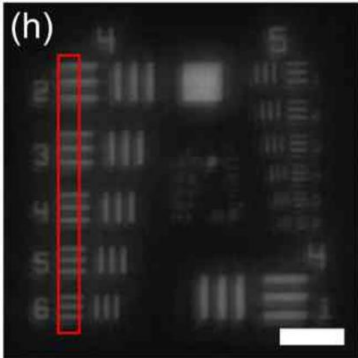
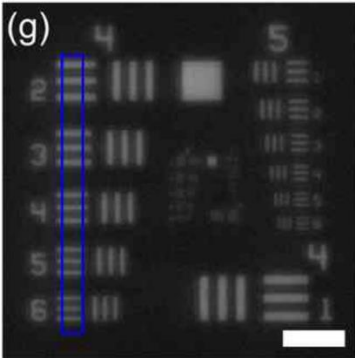
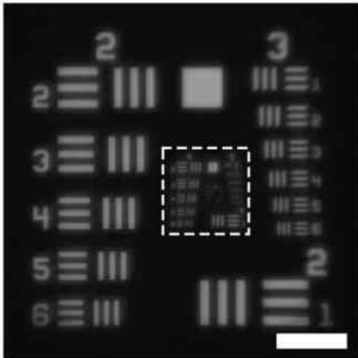
VAM Printed Lens



(c) Glass Lens

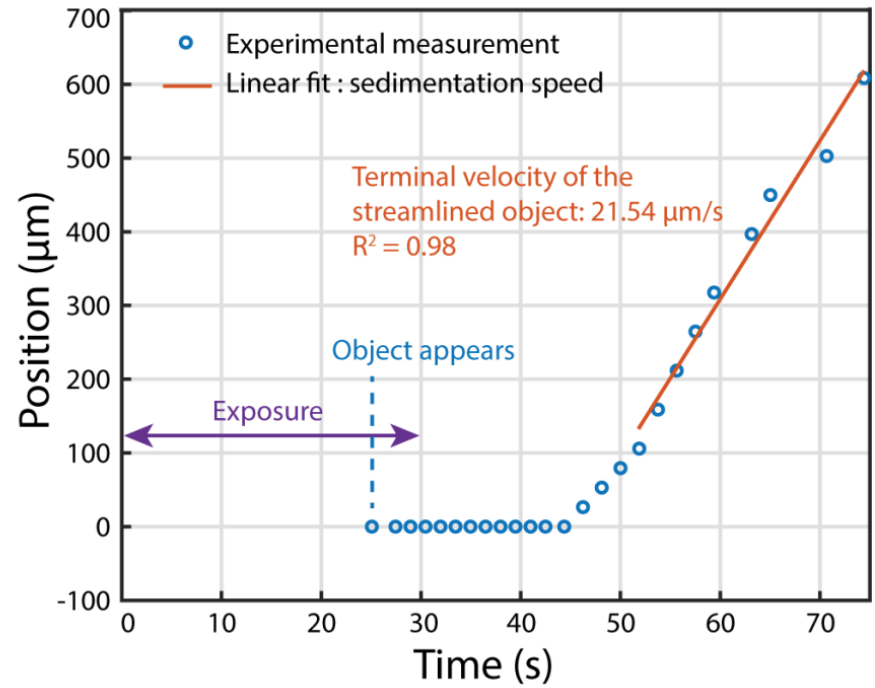
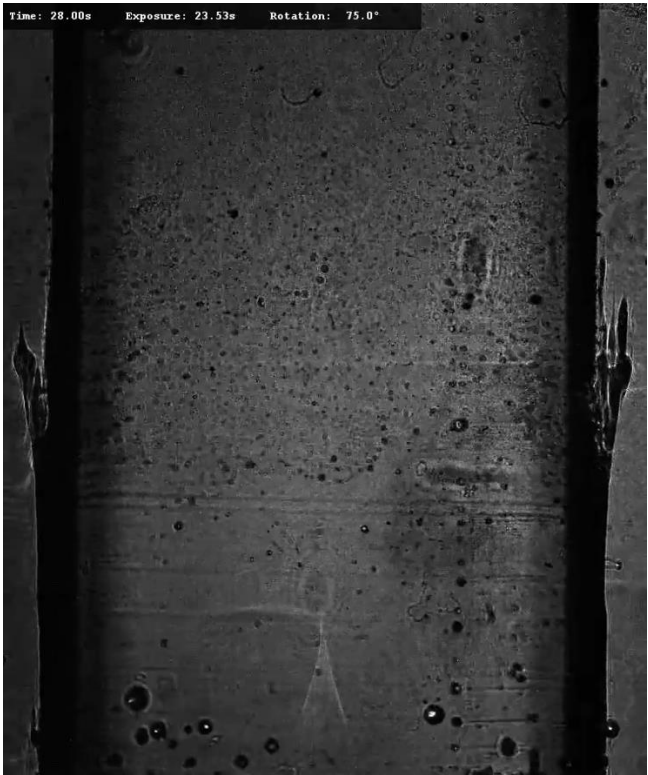


(d) VAM Printed Lens

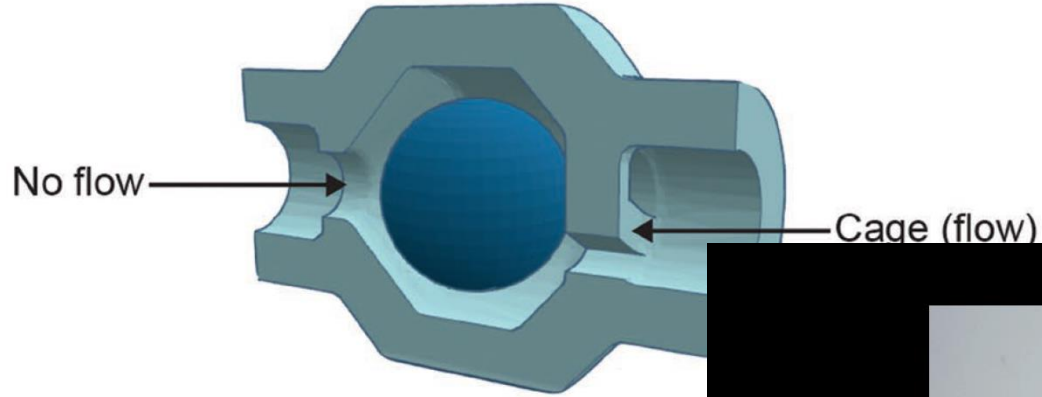


Daniel Webber, Yujie Zhang, Kathleen L. Sampson, Michel Picard, Thomas Lacelle, Chantal Paquet, Jonathan Boisvert, and Antony Orth, "Micro-optics fabrication using blurred micrographs," *Optica* 11, 665-672 (2024)

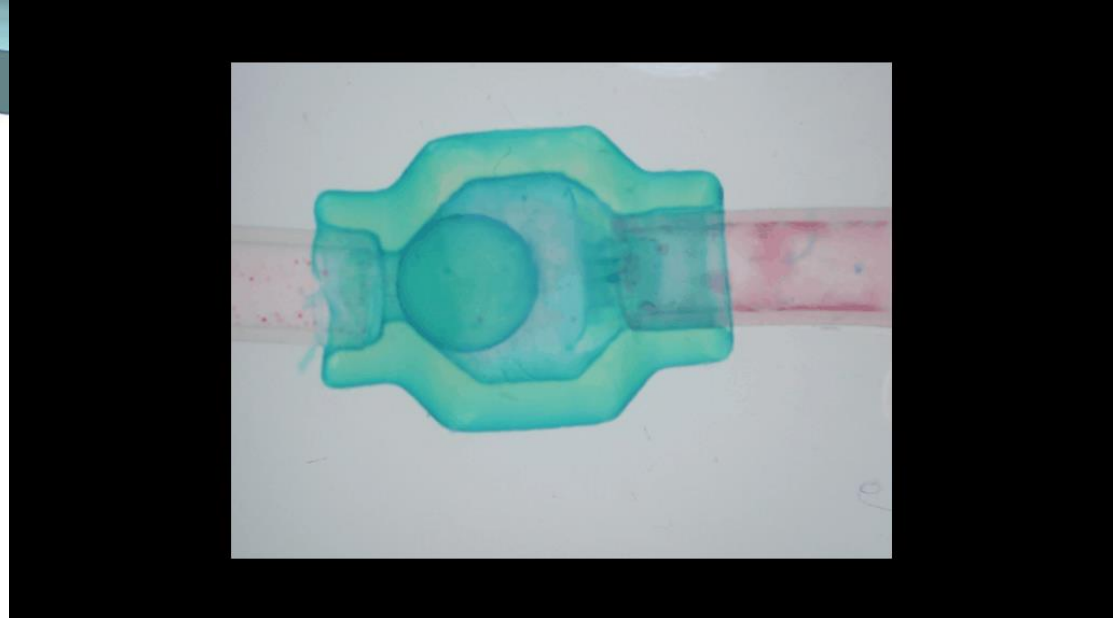
$$v \propto \Delta\rho \cdot r^2 / \mu$$



Unique designs: Ball cage valve



Ball cage cardiac valve



Silicone

Soft hearing aid shell



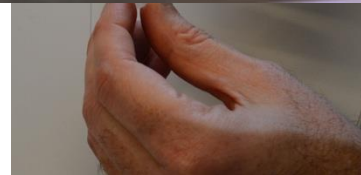
Main cavity

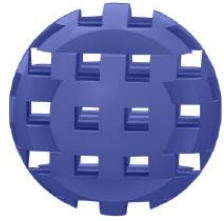


Side vent

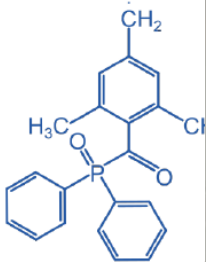


Arterial junction model





3D model



Photoinitiator



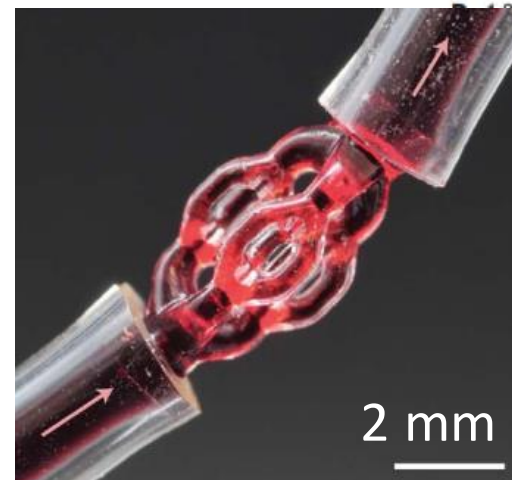
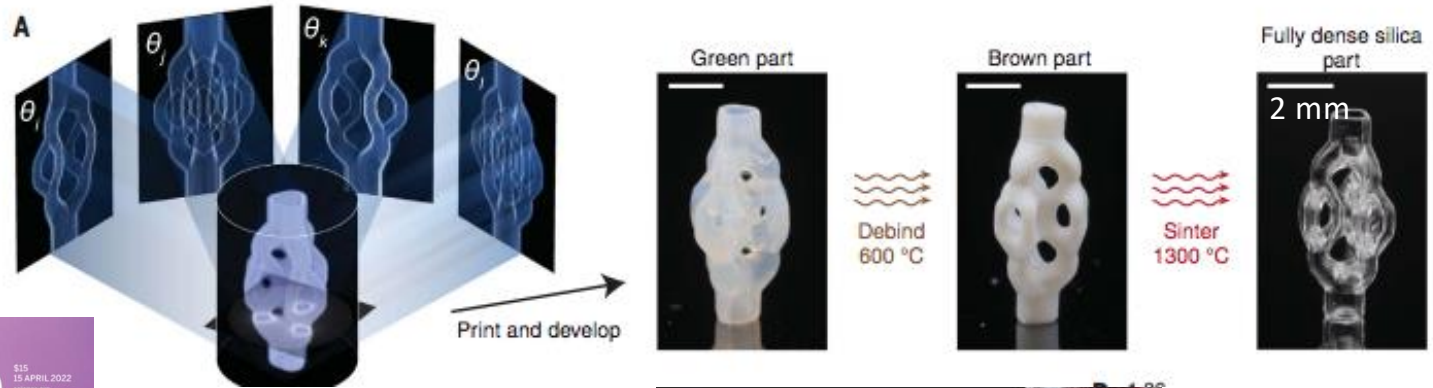
Crosslinker

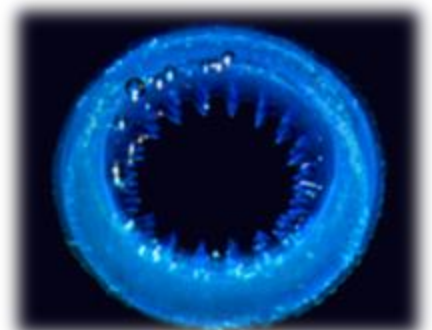
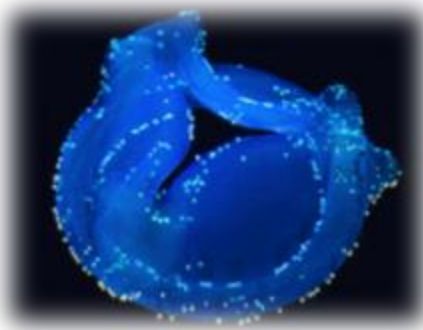
1mm

Silicon oxycarbide

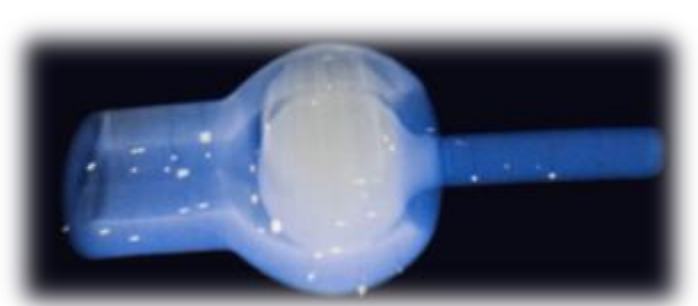
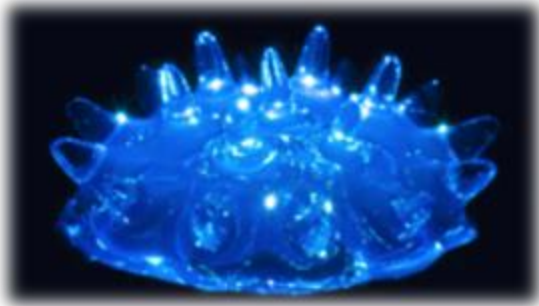


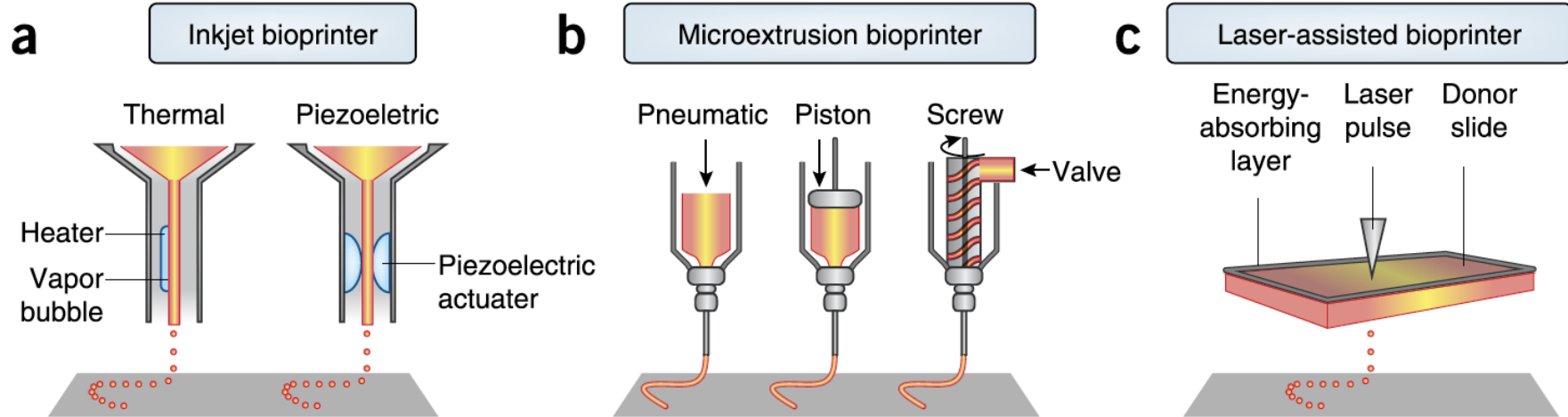
Madrid Wolff J, [...], Moser C. "Tomographic volumetric additive manufacturing of silicon oxycarbide ceramics, Advanced Engineering Materials, 2101345 (2022).

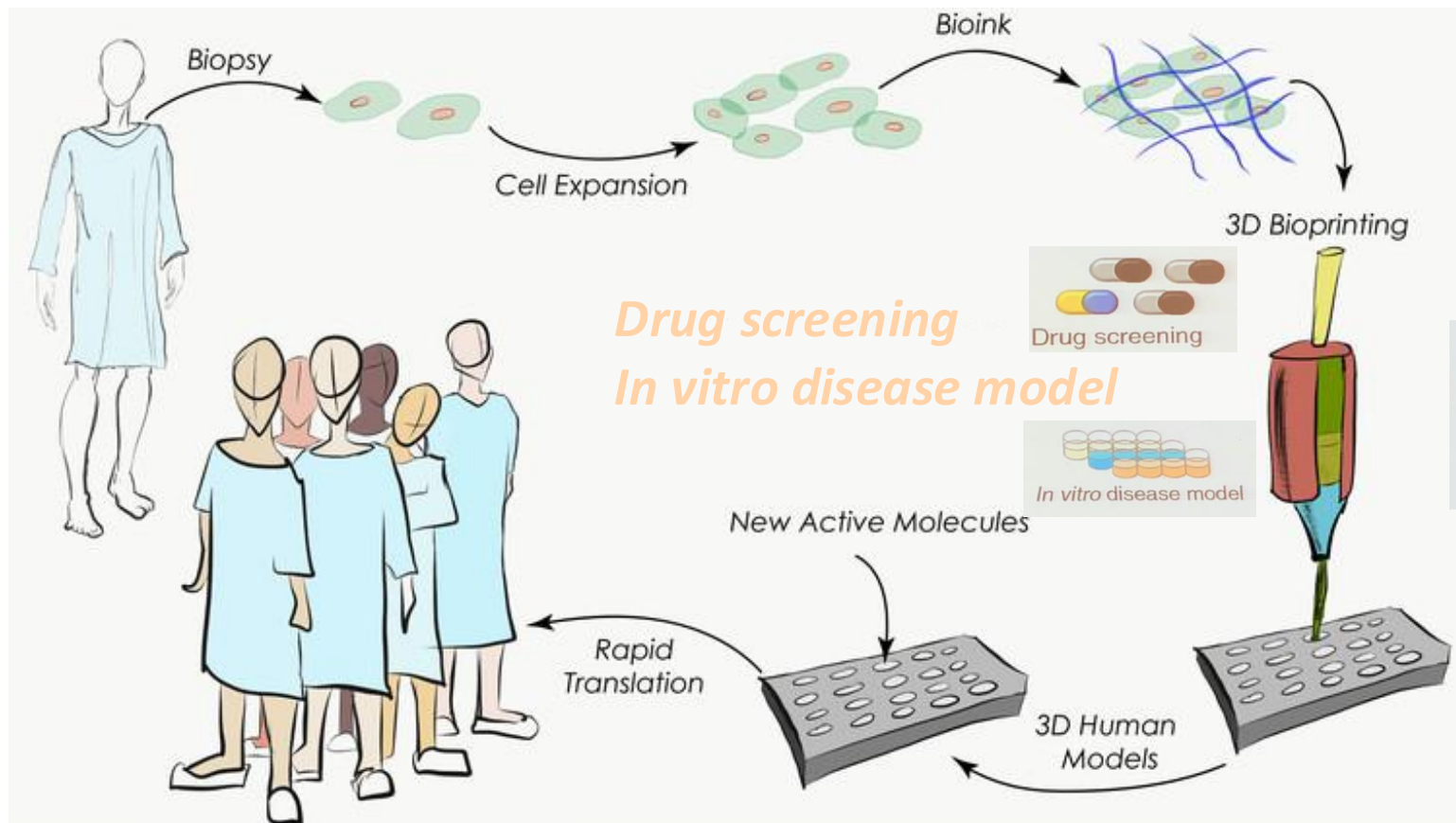




Volumetric Bioprinting with soft hydrogels



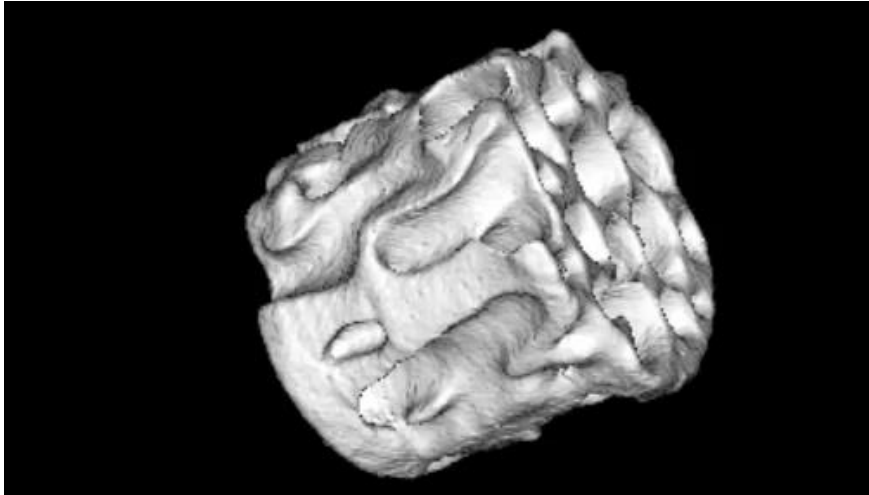




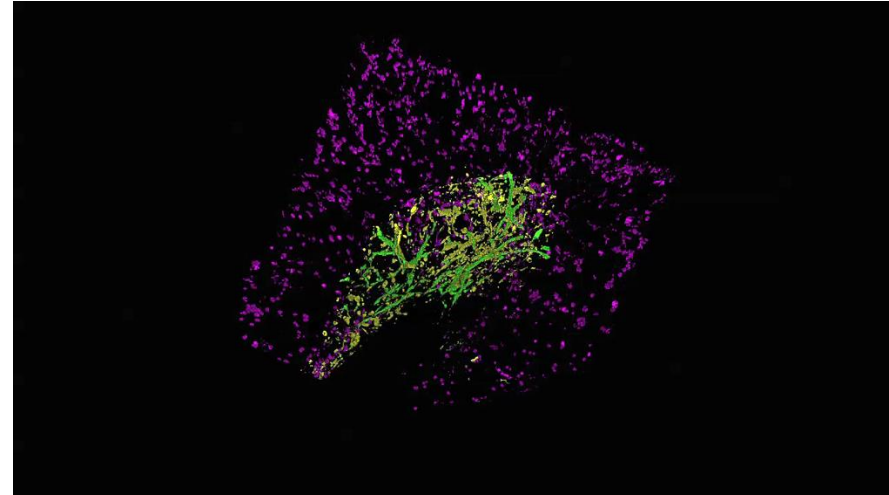


Pour the cell-seeded ink into a sterile vial

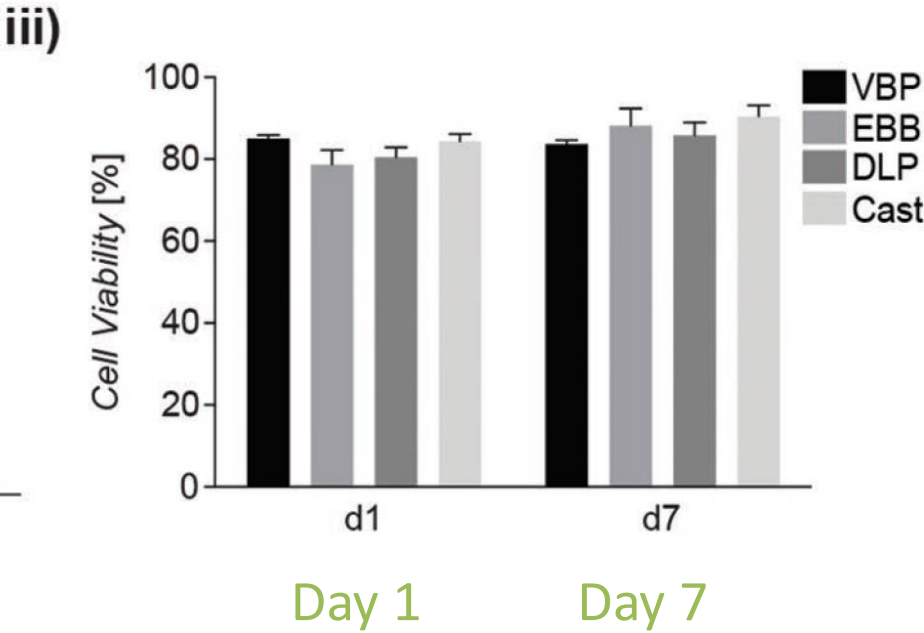
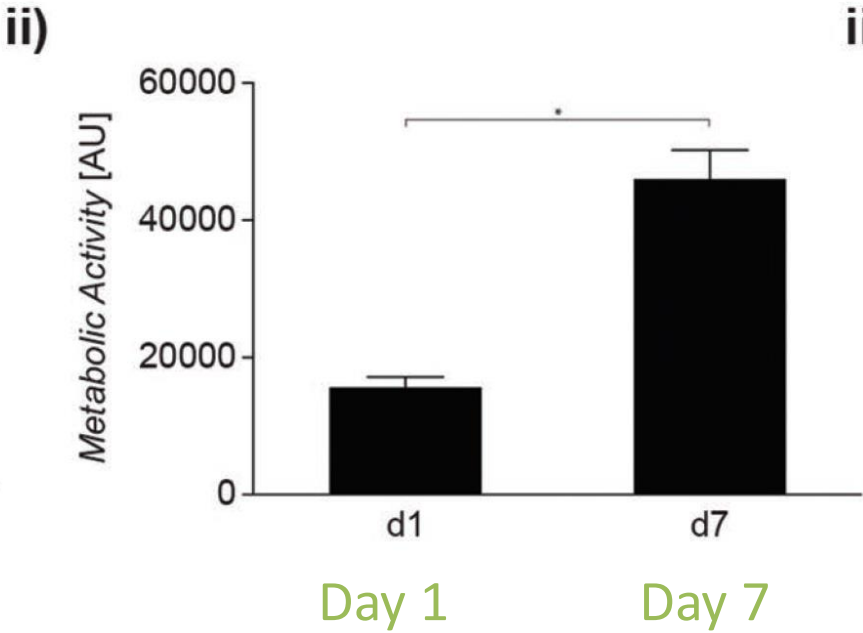
Trabecular Bone construct

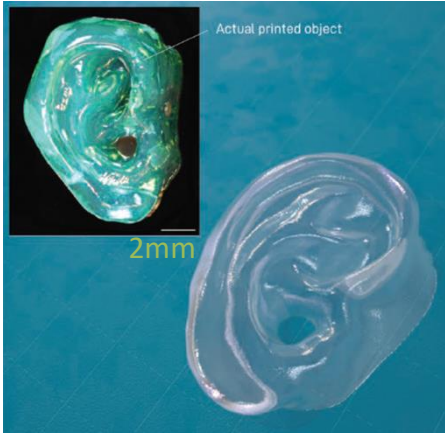
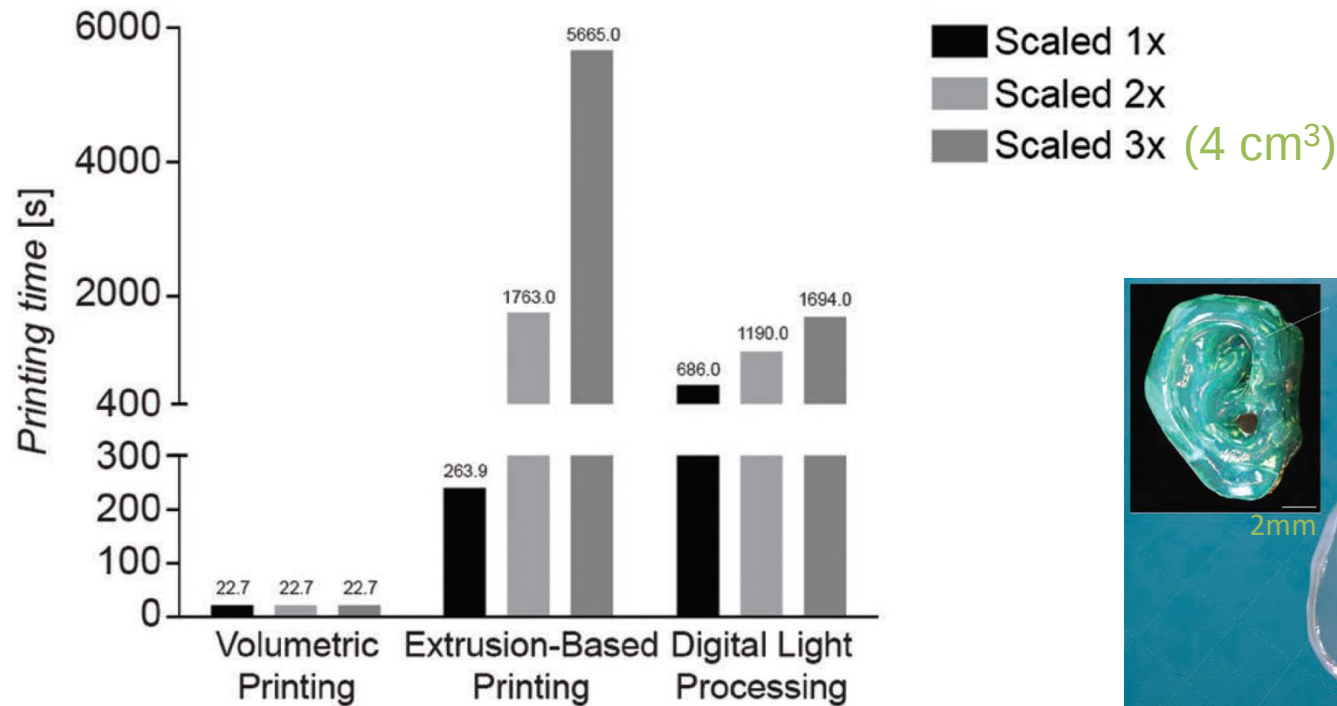


MSC cells in GelMA



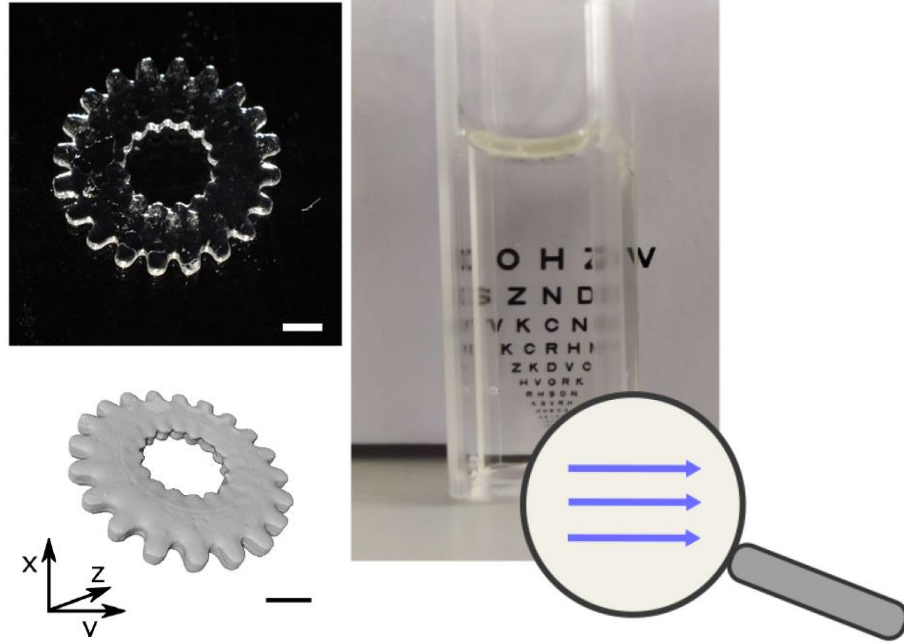
Bernal P.N, [...] Moser C. Levato R.. "Volumetric Bioprinting of Complex Living-Tissue Constructs within Seconds", Adv. Mat., 2019



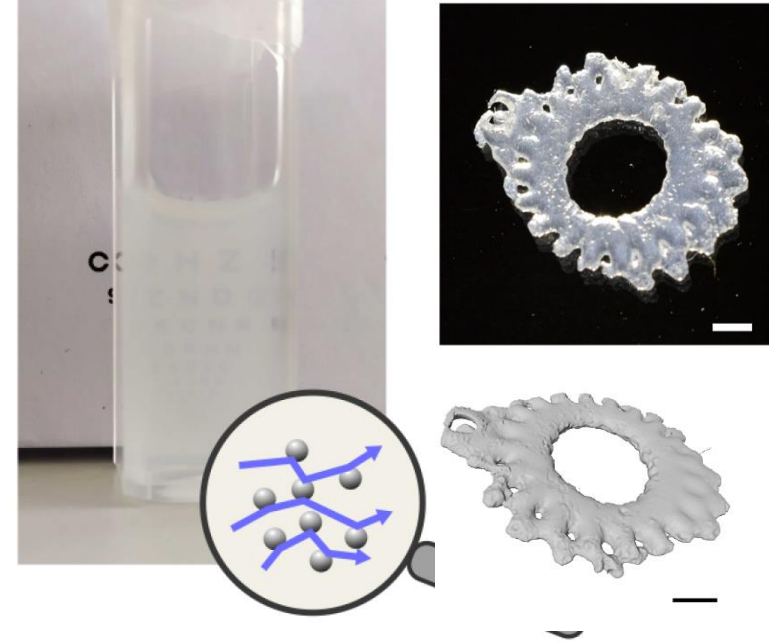


Scattering when cells are added

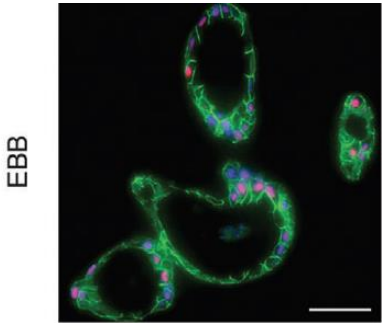
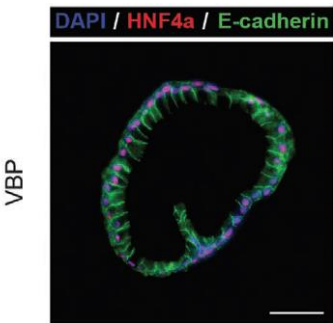
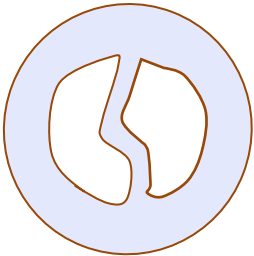
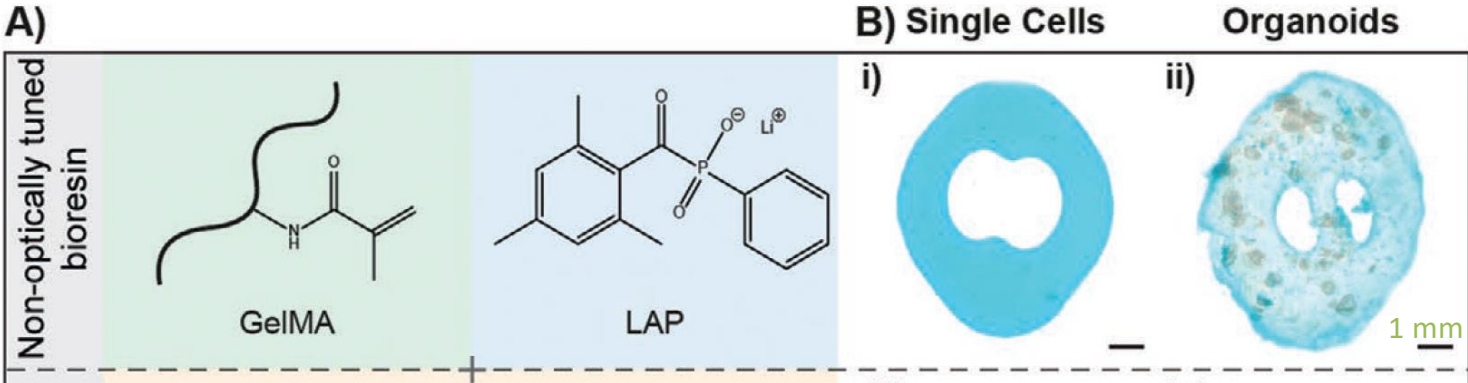
Transparent hydrogel



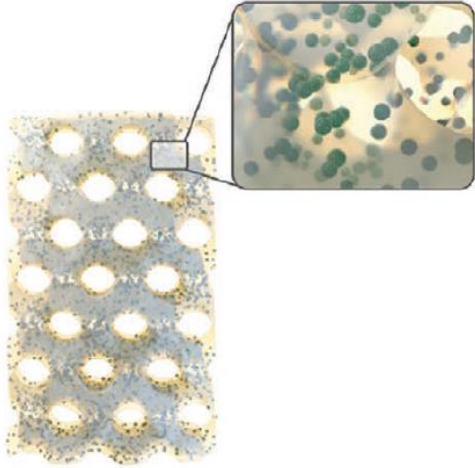
Hydrogel with cells



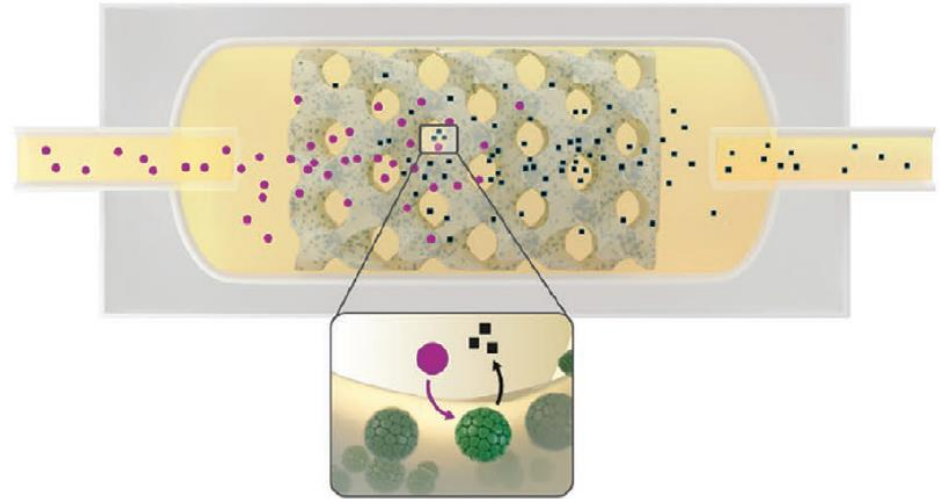




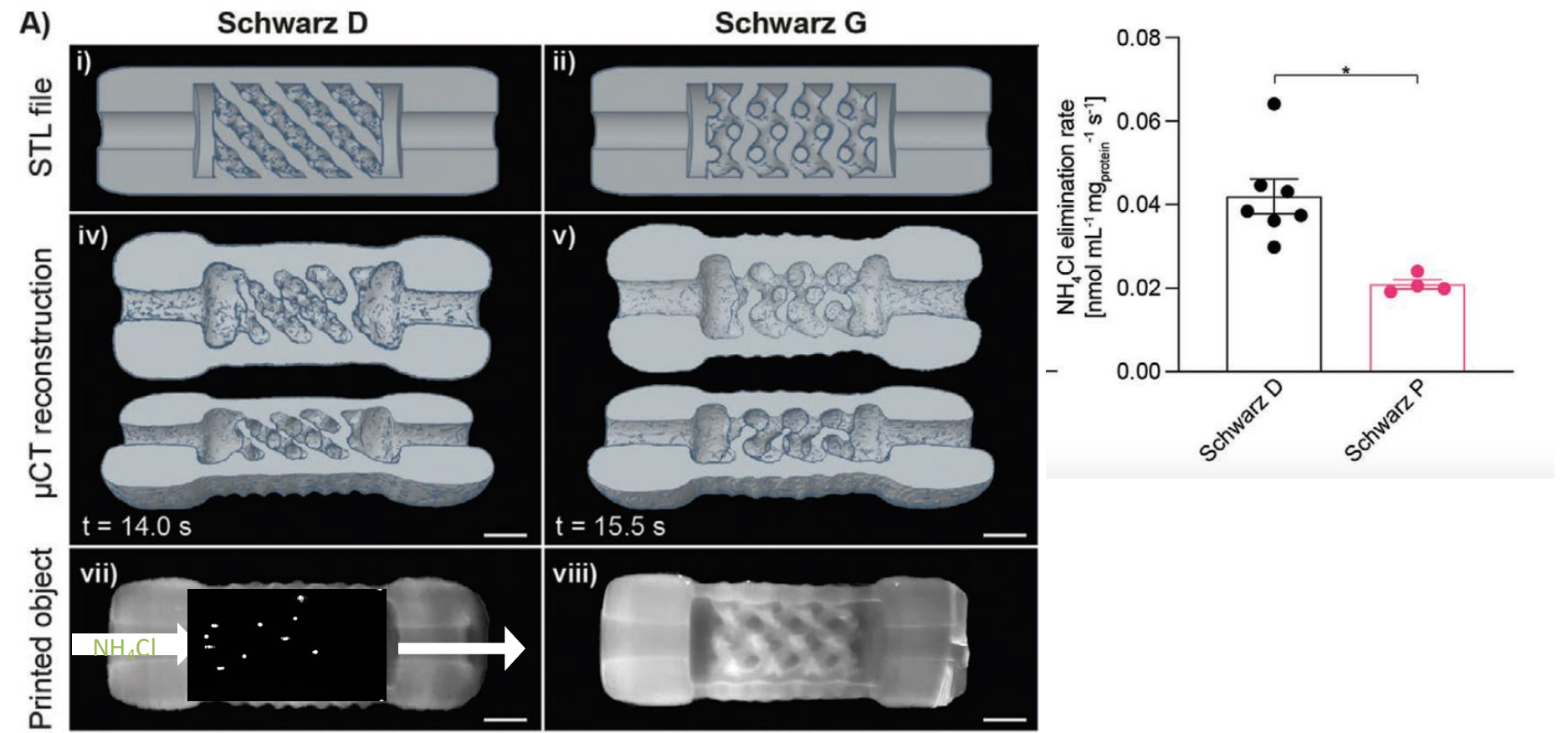
Bernal P., [...] Moser C., Levato R. "Volumetric Bioprinting of Organoids and Optically Tuned Hydrogels to Build Liver-Like Metabolic Biofactories", Adv. Mat, 2022.



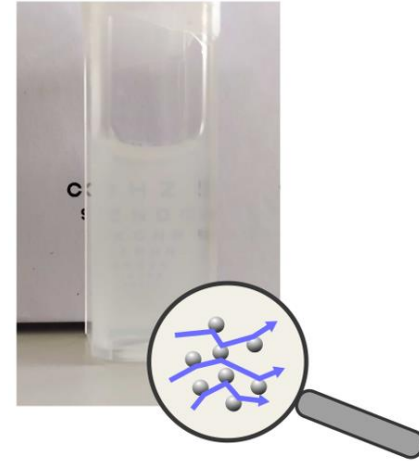
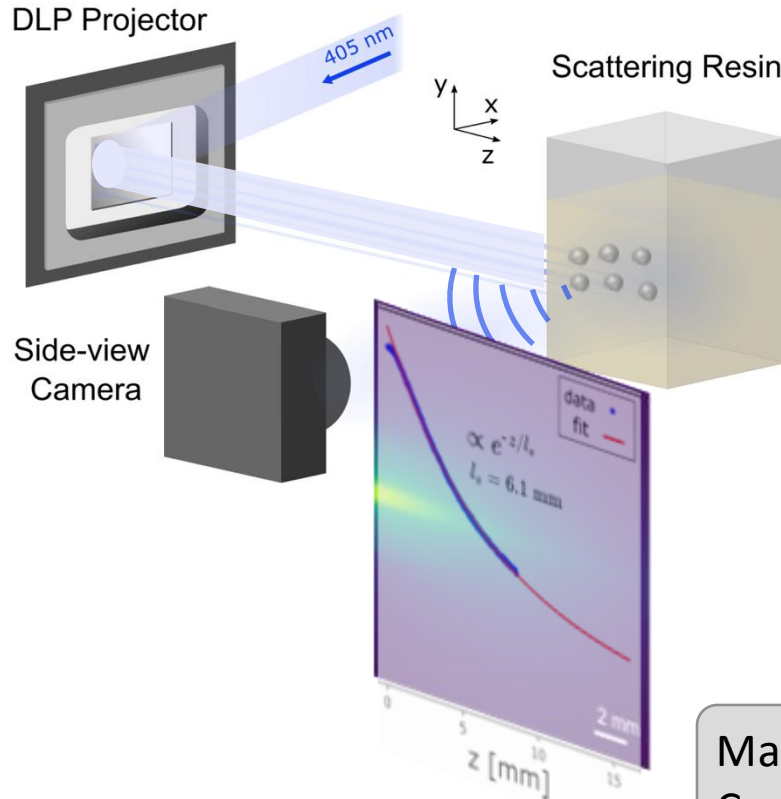
Optimized bioresin
(5% gelMA + 0.1% LAP + 10% iohexanol)
 5×10^6 cells mL⁻¹



Sterile perfusion system for bioprinted constructs



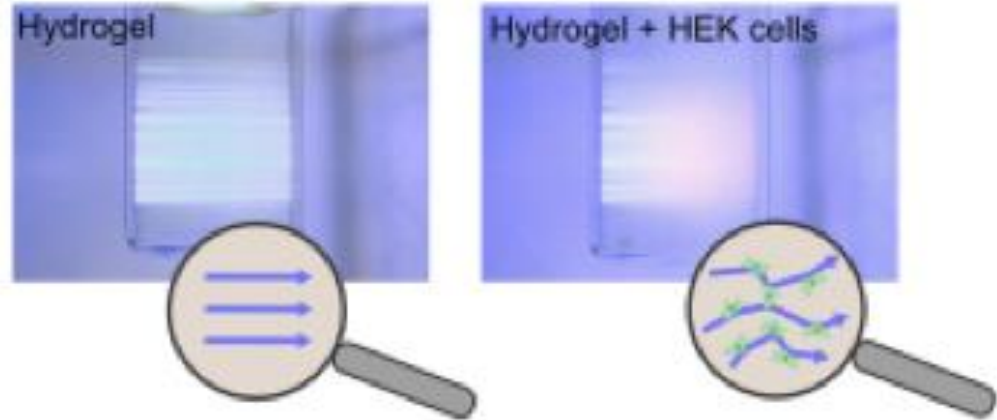
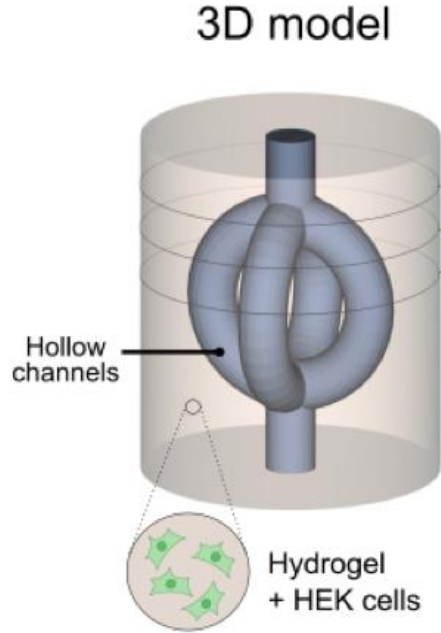
Printing in scattering resins



Acrylate +
100 nm **TiO2** nanoparticles

Madrid-Wolf J, Boniface A., Loterie D., Delrot P.,
Controlling light in scattering materials for volum

Printing in hydrogels with High cell densities



Printing in hydrogels with High cell densities

Conventional Tomographic AM



+ HEK cells

Printing



Obtained Print



Hydrogel
+ HEK cells



Volumetric printing by tomographic back-projections

- Principle of Reverse Tomographic Projection
- Ultra fast printing speed (30 seconds)
- No support structures
- 80 μm resolution

