Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

ENGINEERING
DESIGN
AND
COMPUTING

Introduction to Additive Manufacturing

Prof. Kristina Shea

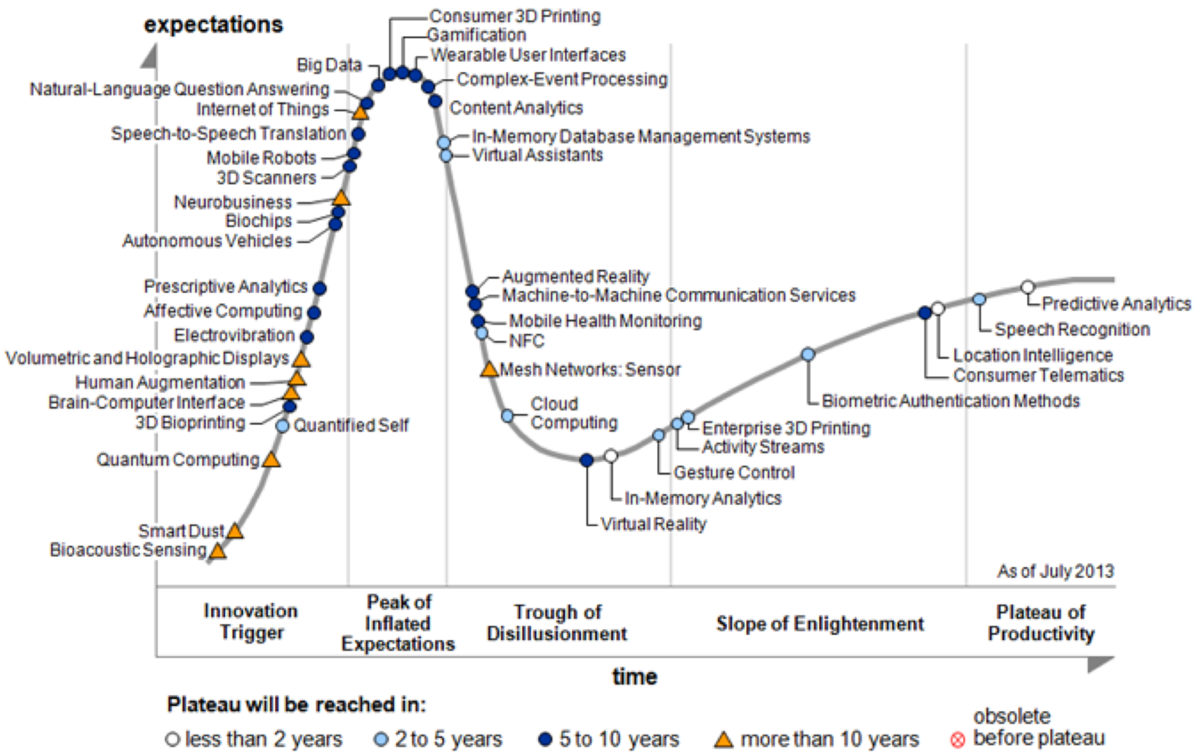
Outline

- Introduction to Additive Manufacturing (AM)
- Overview of AM Processes and Materials
- Design for AM
- Design for AM Framework for Structural Optimization

Rapid Prototyping, Additive Manufacturing and 3D Printing

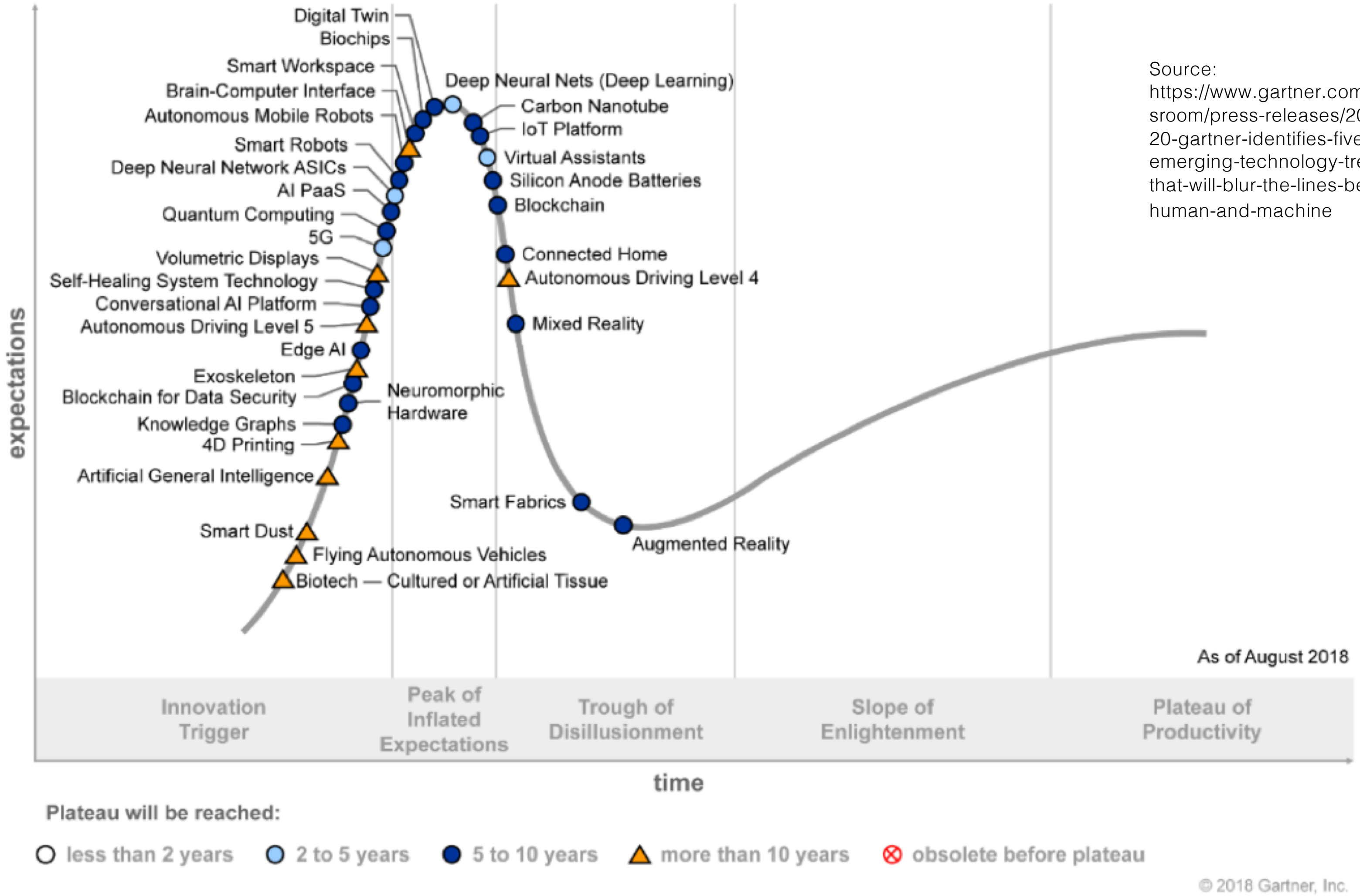
1986	First patent for SLA by Charles Hull
1987	Stereolithography introduced
1988	First SLA machine sold by 3D Systems
1990	First competitors to SLA
1991	Fused Deposition Modeling (FDM) Laminated Object Manufacturing (LOM)
1992	Selective Laser Sintering (SLS)
1996	3D Printing (3DP)
1999	RP industry reaches $1 billion

Key Patents Now Running Out!



"Hype Cycle for Emerging Technologies", Gartner, 2013

Hype Cycle for Emerging Technologies, 2018



Source:
https://www.gartner.com/en/newsroom/press-releases/2018-08-20-gartner-identifies-five-emerging-technology-trends-that-will-blur-the-lines-between-human-and-machine

What is Additive Manufacture?

Digital Design-to-Fabrication

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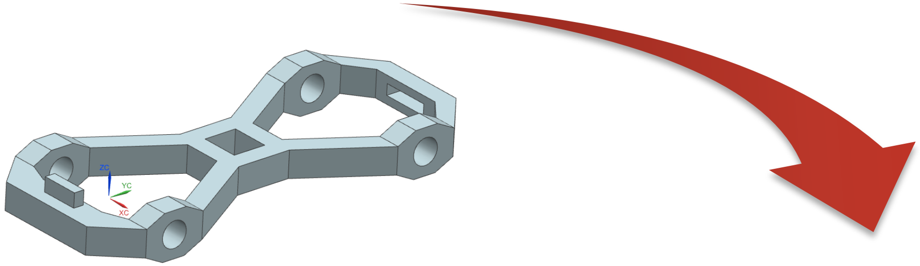
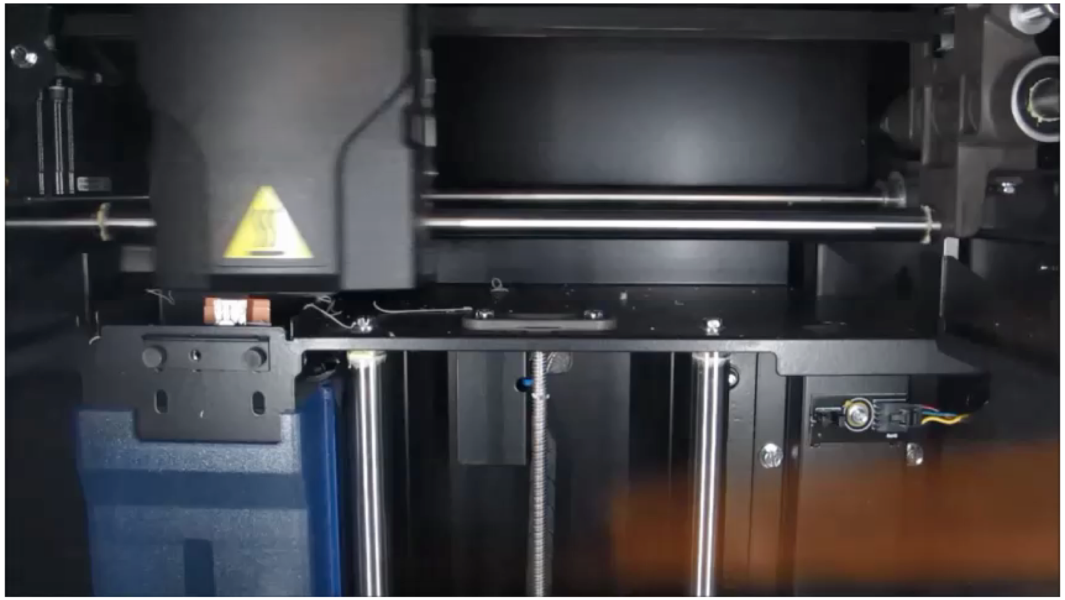


No custom programming! vs. CNC



source://german.injectionmouldtooli
ng.com

No molds! vs. injection molding, stamping, casting, etc.

AM Definitions

- The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies (ASTM F2792).
- Synonyms are additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, freeform fabrication, and 3D-printing.

3D Printing Applications

AM Technologies

AM for Prototyping (41.1%)

Produce physical models and prototypes

AM for Tooling (23.1%)

Produce tools, molds or dies

source: http://www.voxeljet.de

AM for Manufacturing

Produce end-use, single and series parts

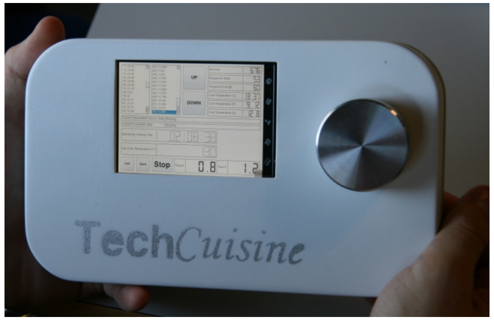
source: http://www.maschinenmarkt.vogel.de/themenkanaele/additive_fertigung/articles/443675/

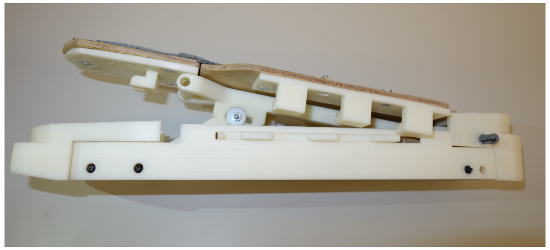
Functional Parts (33.8%)

Distribution source: Wolhers 2018

3D Printing Prototypes

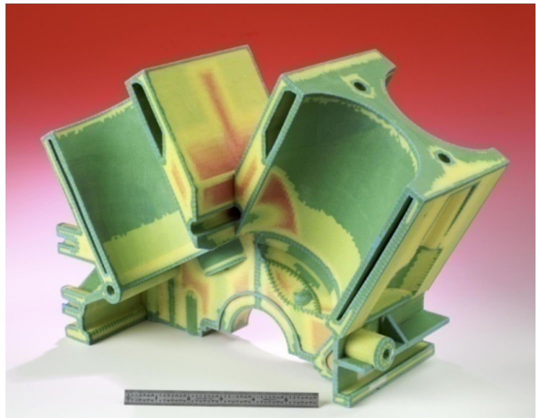
- Concept models
- Form and fit checking
- Ergonomic studies
- Functional testing
- Proposals and presentations
- CAD data verification
- Manufacturing analysis



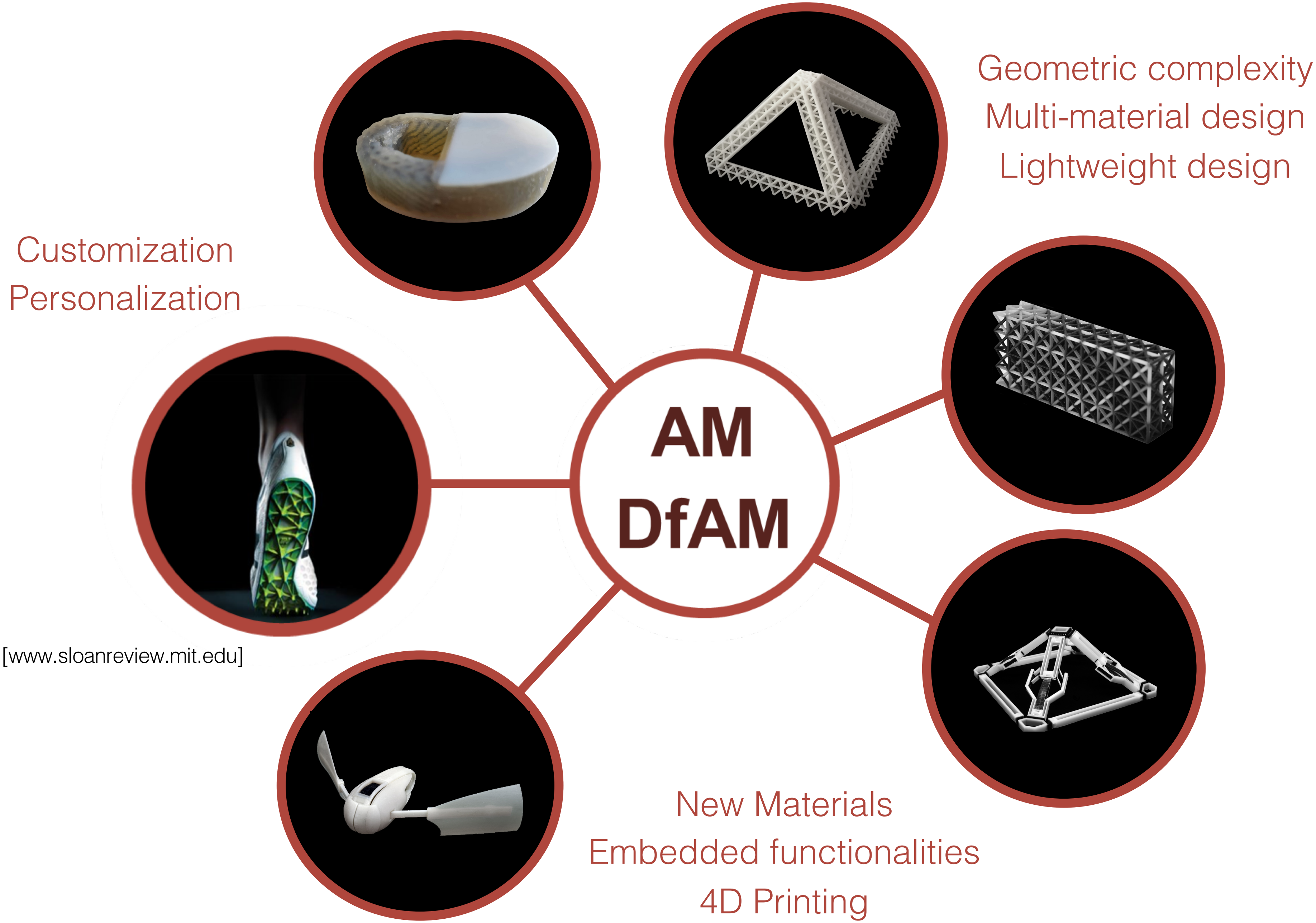


FDM, Stratasys, Inc.

3DP, 3D Systems



3DP, 3D Systems

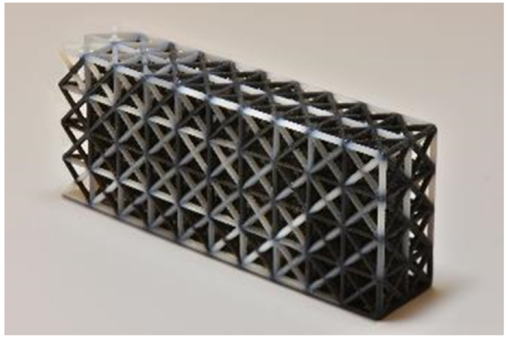


[www.sloanreview.mit.edu]

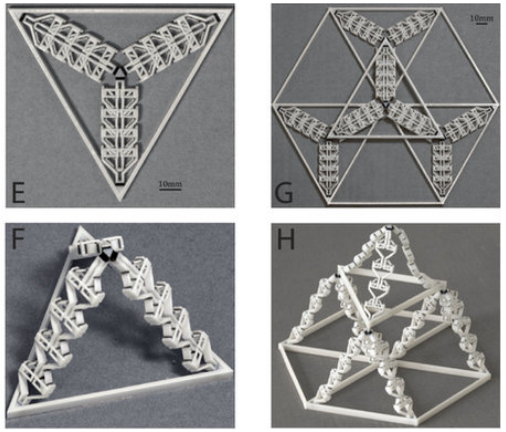
Advantages of AM

- **Shape complexity:** It is possible to build virtually any shape.
- **Material complexity:** Material can be processed one point, or one layer, at a time as a single material or as a combination of materials.
- **Hierarchical complexity:** Features can be designed with shape complexity across multiple size scales.
- **Functional complexity:** Functional devices can be produced in one build.

Applications for personalized medicine



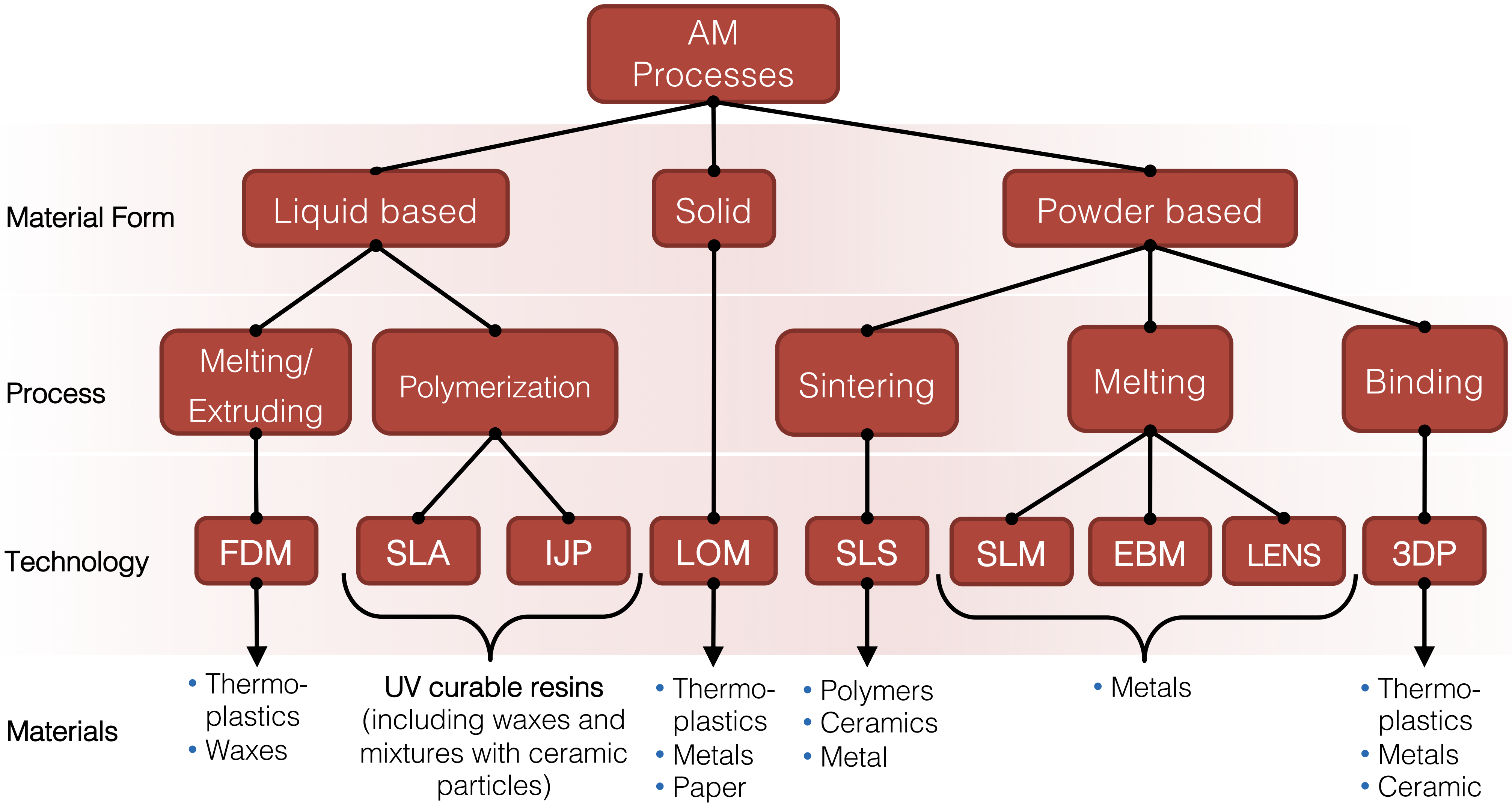
Multi-material cantilever example



Hierarchical 4D lattice structure

Based on: Gibson, Rosen, Stucker, Additve Manufacturing Technologies, Springer, 2010
Image sources:
Thomson et al., Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints, CIRP Annals - Manufacturing Technology, Elsevier, 2016
Tian Chen, Jochen Mueller & Kristina Shea, Integrated Design and Simulation of Tunable, Multi-State Structures Fabricated Monolithically with Multi-Material 3D Printing, Scientific Reports 7, 2017

AM Process Overview



AM Technologies: From DIY to Industrial Printers

- Materials and stability
- Color
- Scale
- Accuracy
- Surface finish
- Post-processing
- Speed
- Cost
- Open vs. closed systems

source: http://3druck.com/3d-drucker-liste/

FDM – Fused Deposition Modeling

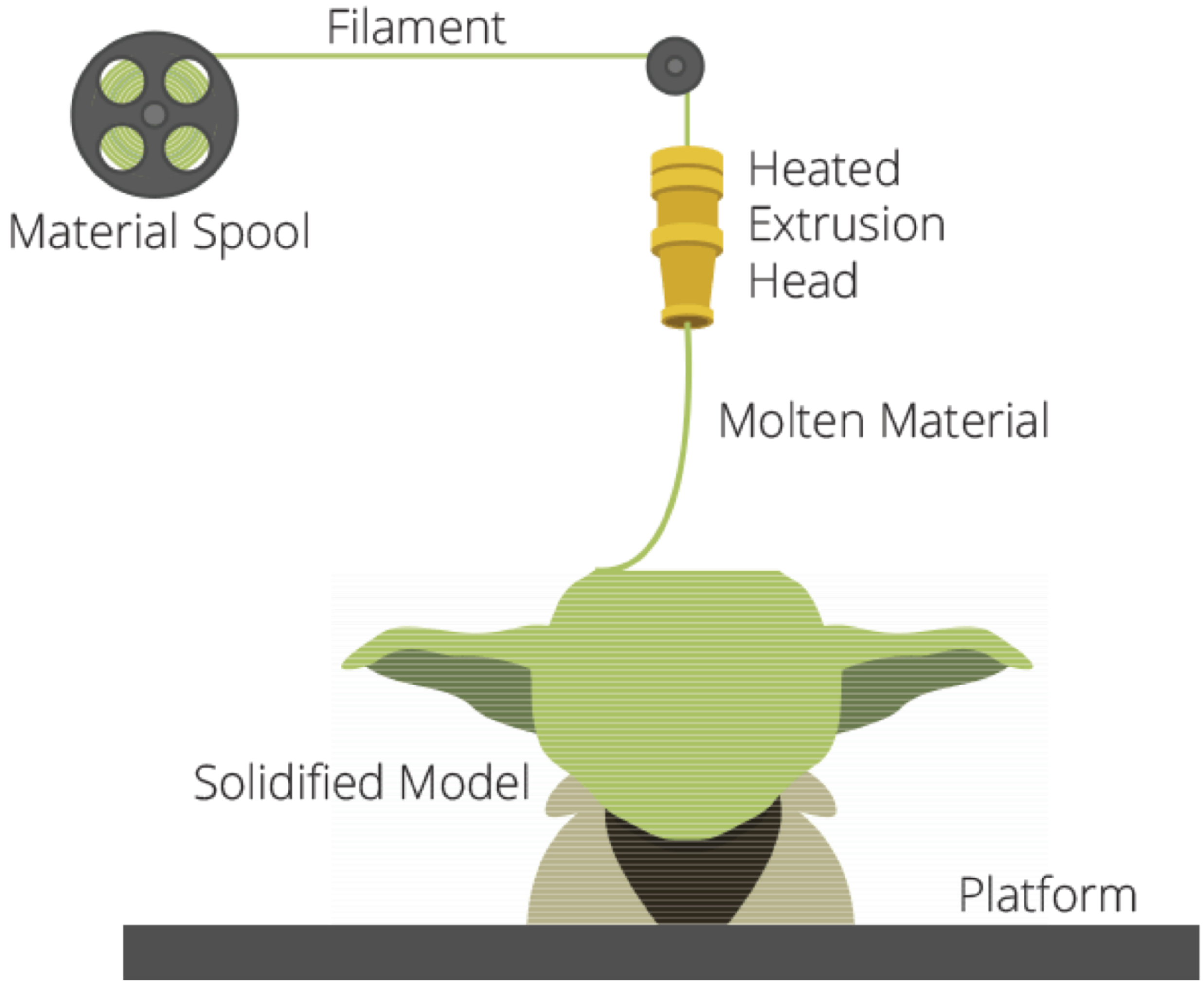


Image: https://3dprintingindustry.com/3d-printing-basics-free-beginners-guide#04-processes

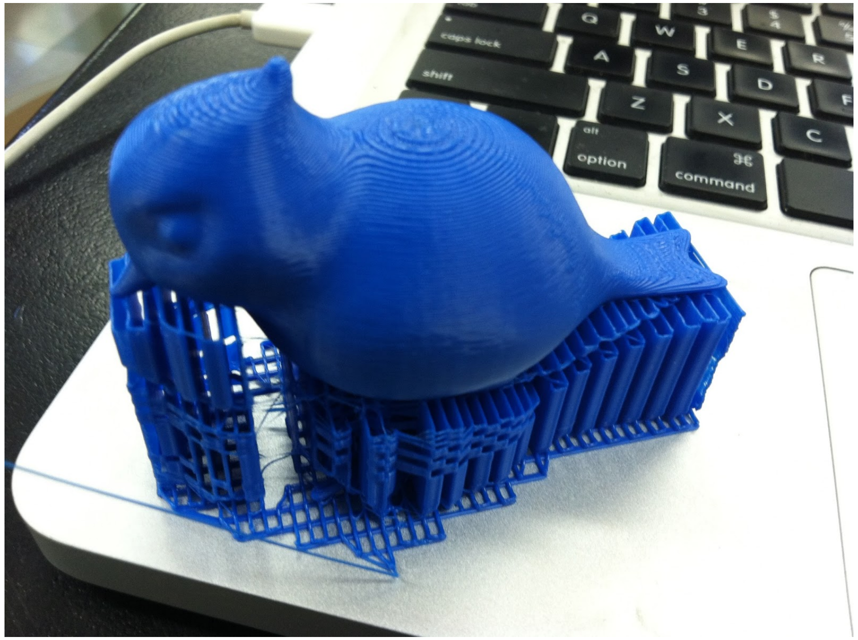
FDM – Fused Deposition Modeling

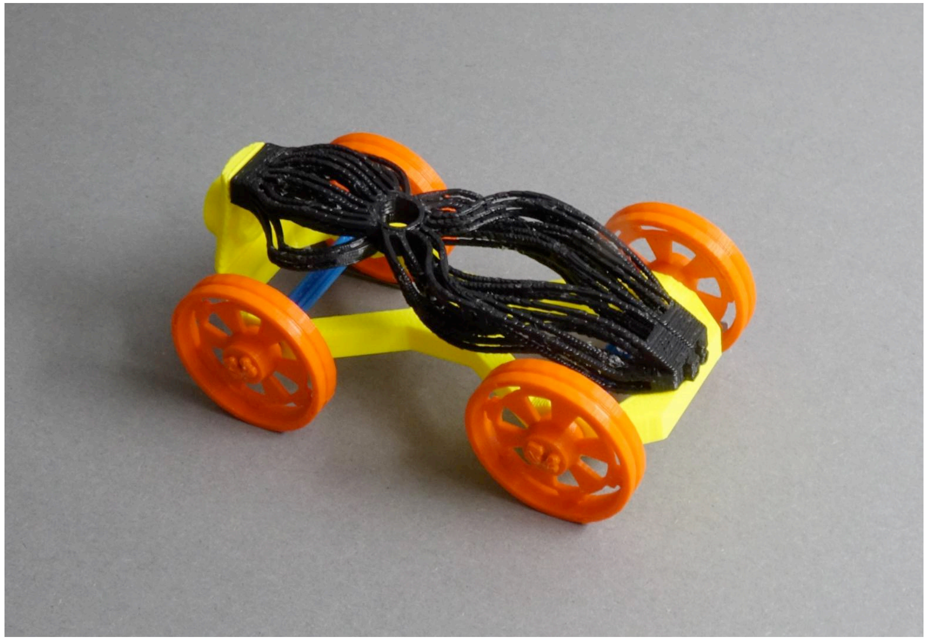
Accuracy	Materials
Layer Thickness: 0.13-0.30 mm (up to 0.076 in some cases)	• Thermoplastics • Investment wax casting • Multi-material possible
Support Structures	**Typical Usage**
• None • Soluble (different material) • Breakaway (different or same material)	• Functional plastic prototypes • Concept models • Form, fit, and function analysis
Disadvantages	• Low part accuracy and density • Highly anisotropic • Short fatigue life

FDM – Fused Deposition Modeling

AM Bird with Support Material

Source: Tales of a 3D Printer - Blogspot





TZ&CAD Student Car

Source: ETH TZ&CAD – Severin Kaderli

SLA/DLP – Stereolithography/Direct Light Processing

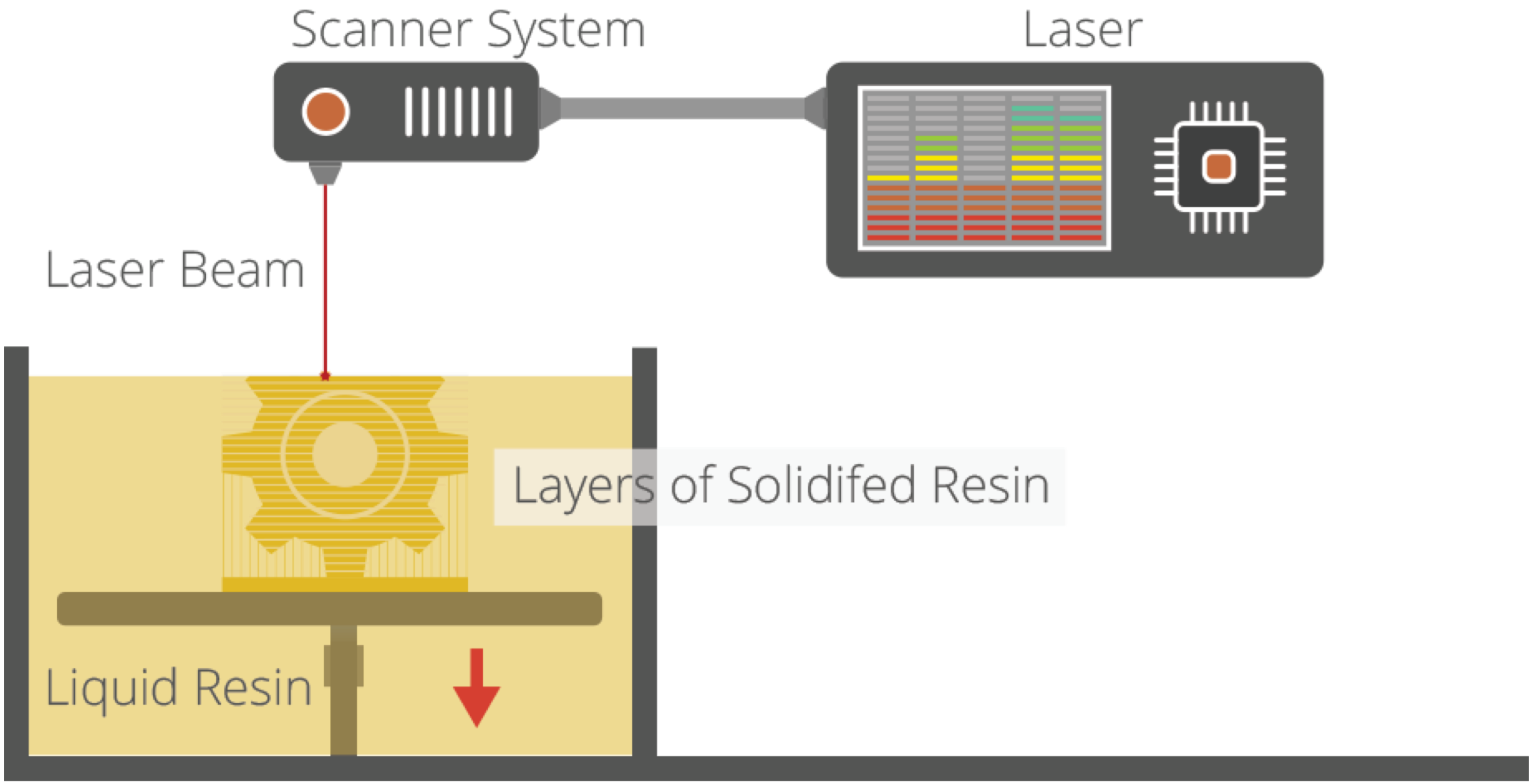


Image: https://3dprintingindustry.com/3d-printing-basics-free-beginners-guide#04-processes

DLP – Direct Light Processing

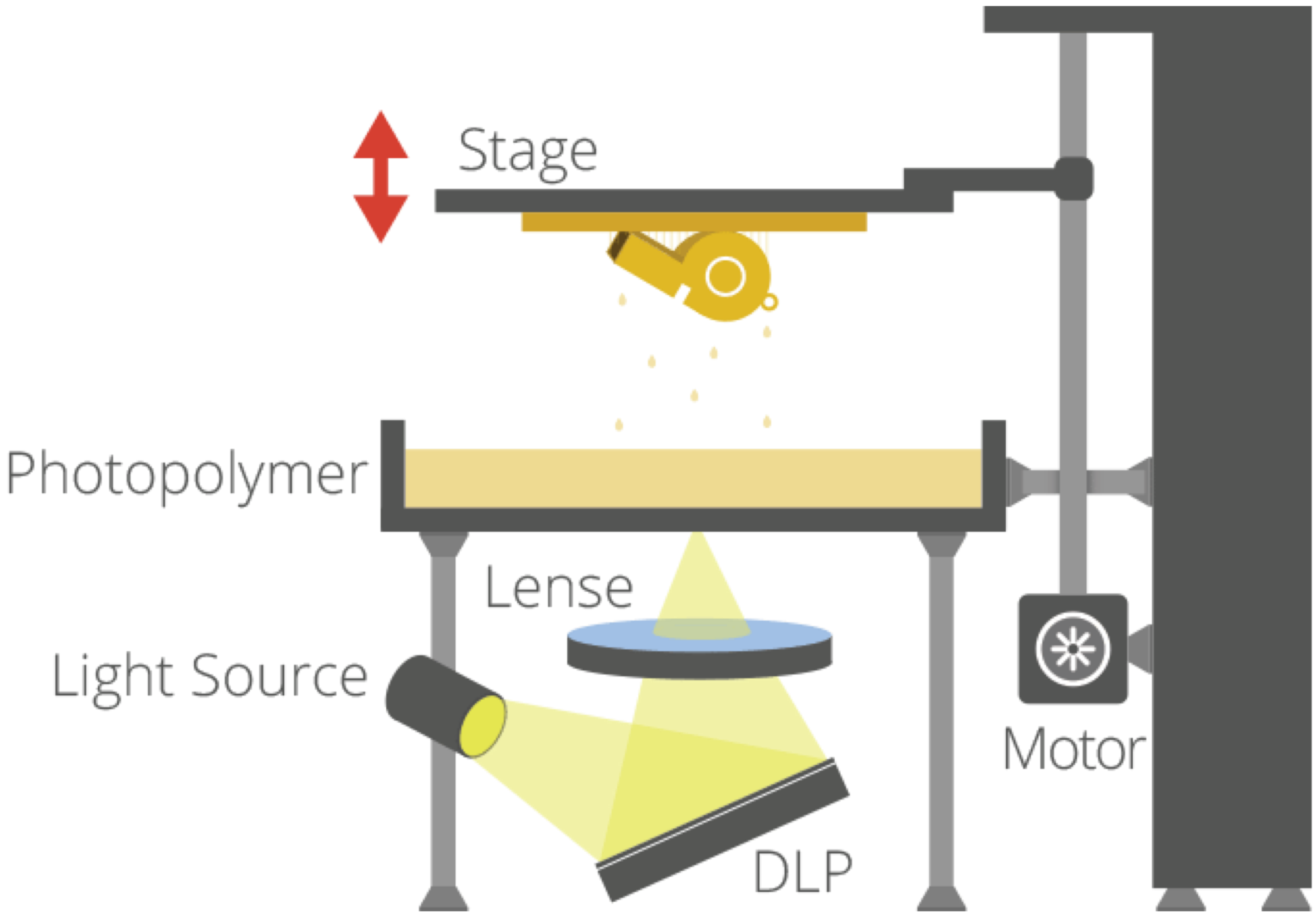
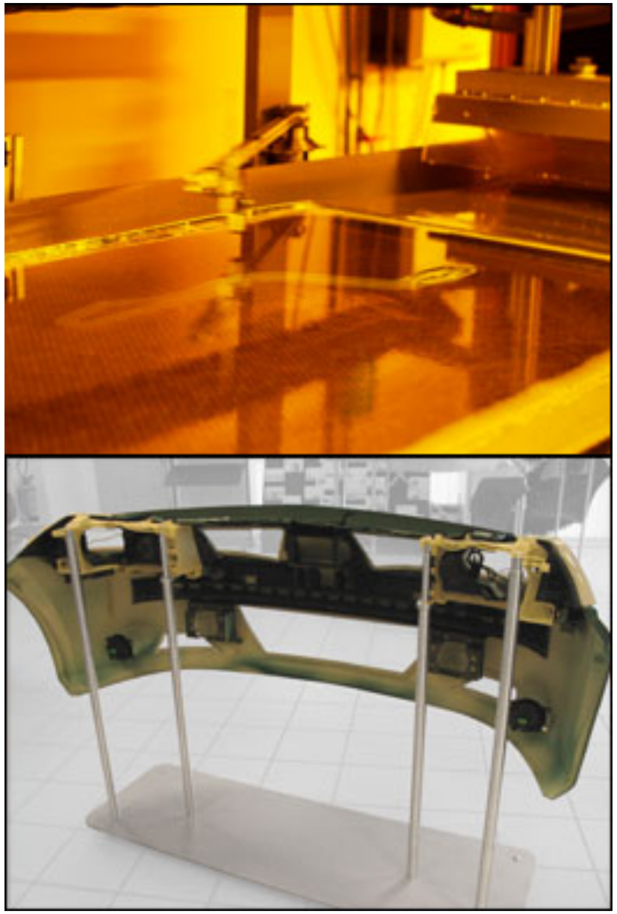


Image: https://3dprintingindustry.com/3d-printing-basics-free-beginners-guide#04-processes

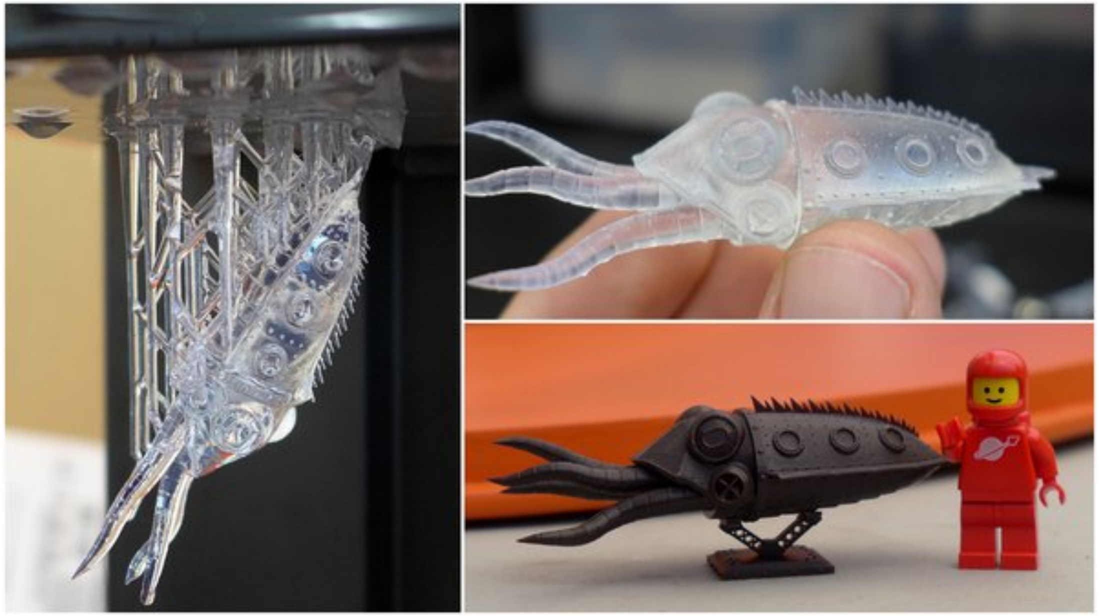
SLA/DLP – Stereolithography/Direct Light Processing

Accuracy	Materials
Layer Thickness: 0.03 – 0.25 mm	• UV Cure Resins • UV Cure Polymers
Support Structures	**Typical Usage**
• None • Breakaway (same material)	• Functional plastic prototypes • Concept models • Form, fit, and function analysis
Disadvantages	• Parts very UV sensitive • Slow if high accuracy desired • Large range of sizes

SLA/DLP – Stereolithography/Direct Light Processing



Car bumper skin built in one single piece within 5 days



Small, detailed figurine

Sources: www.materialise.com, tested.com

Inkjet Polymerization

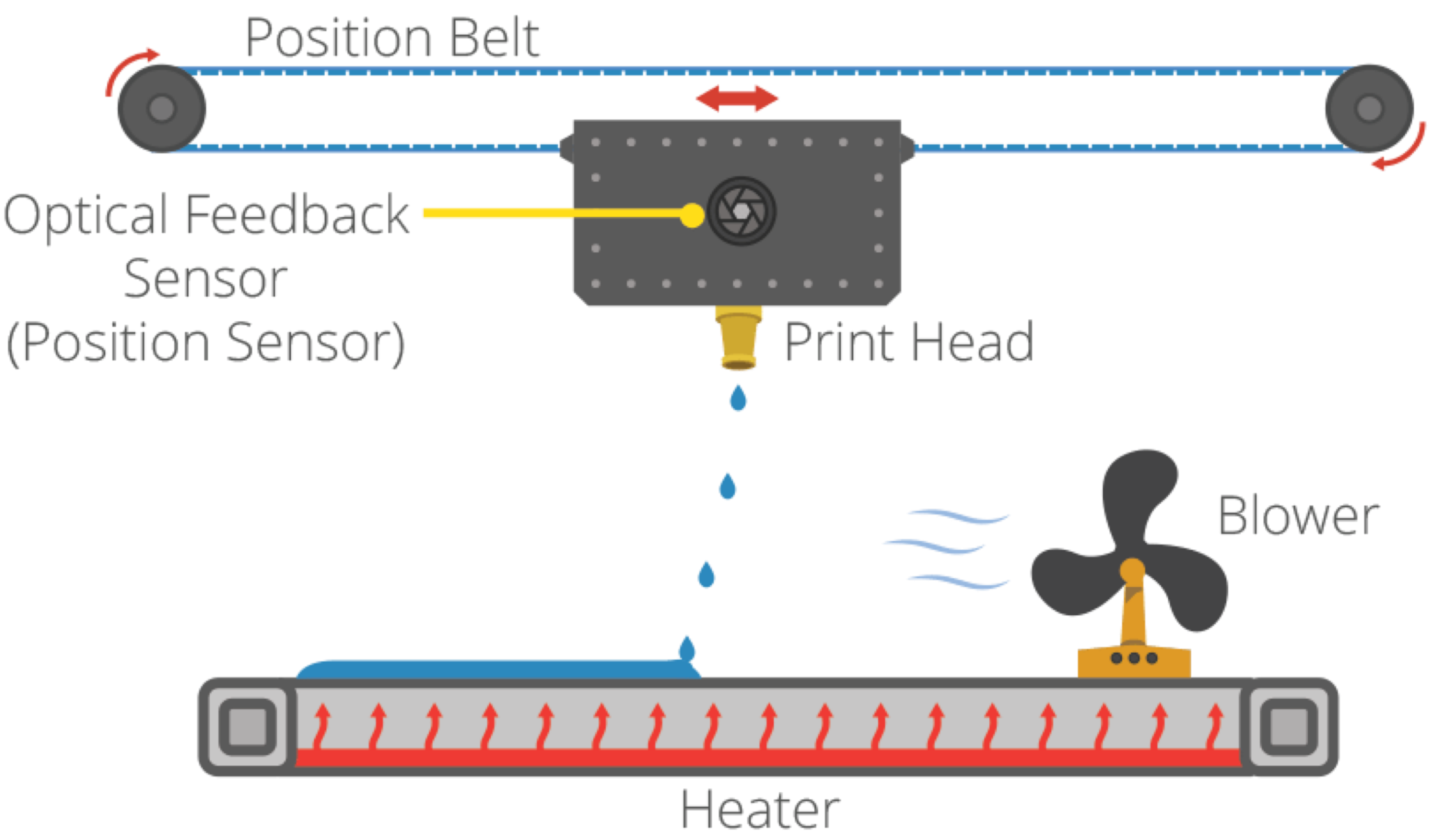
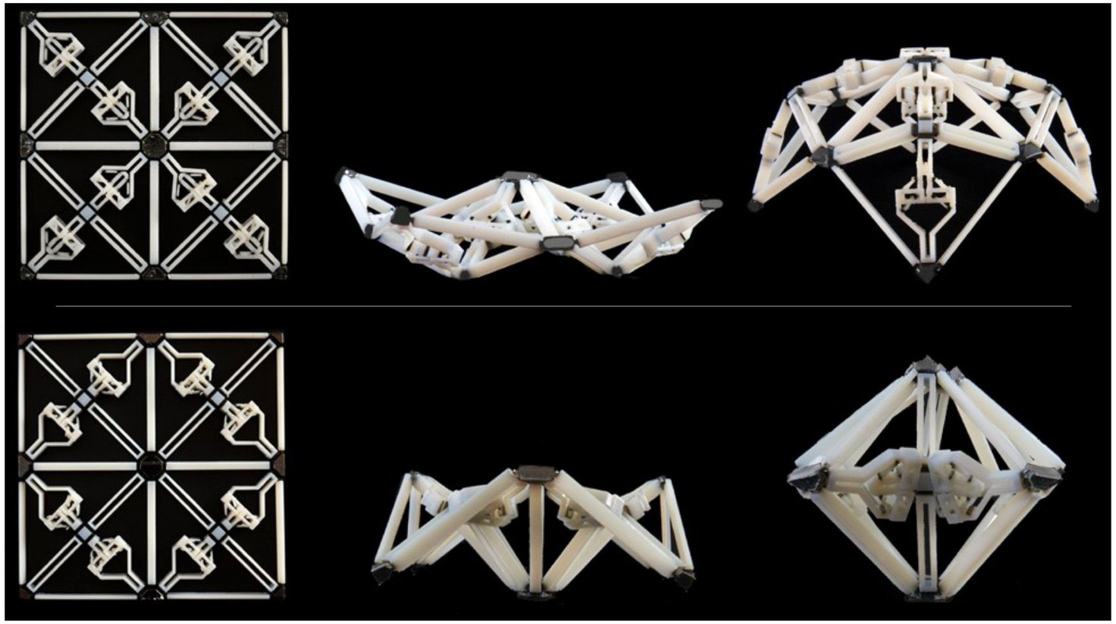


Image: https://3dprintingindustry.com/3d-printing-basics-free-beginners-guide#04-processes

Inkjet Polymerization

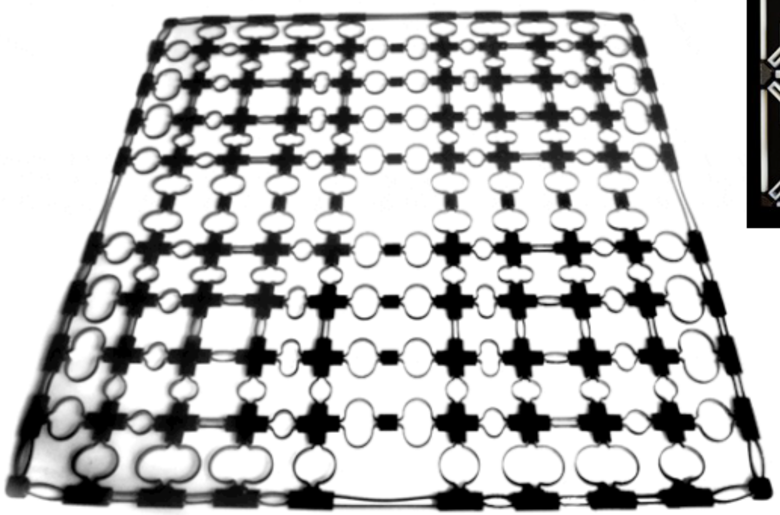
Accuracy	Materials
Layer Thickness: 0.015+ mm	• Air Dry Materials • UV Cure Polymers • Multi-material possible
Support Structures	**Typical Usage**
• Soluble (different material) • Breakaway (different material)	• Prototypes • Science!
Disadvantages	• Slow and expensive • Parts very UV sensitive • Short fatigue life

Inkjet Polymerization



Bistable Transforming Structure

Source: ETH-EDAC – Tim Chen



Active Surface

Source: Self Assembly Lab - MIT

SLS/SLM – Selective Laser Sintering/Melting

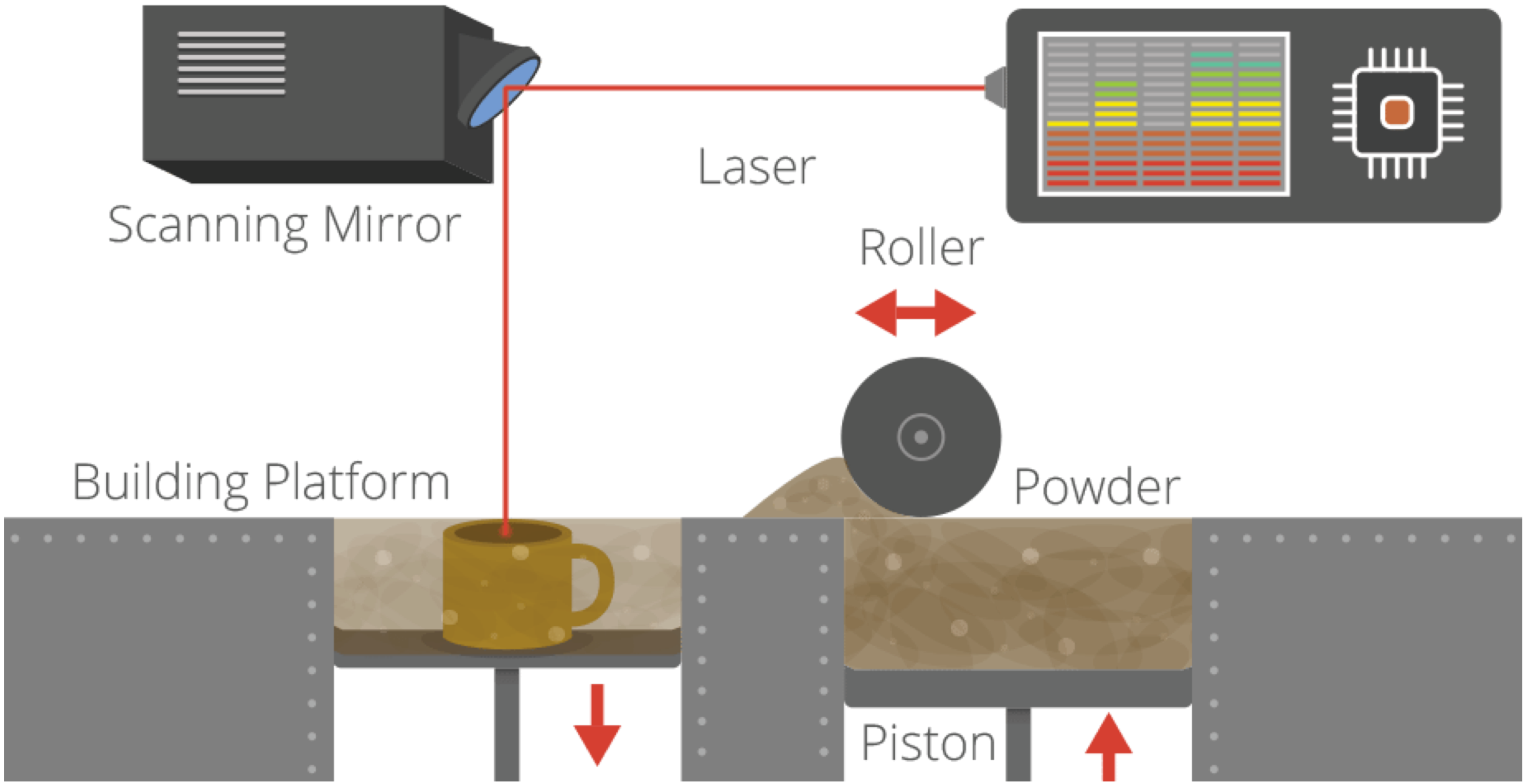


Image: https://3dprintingindustry.com/3d-printing-basics-free-beginners-guide#04-processes

SLS/SLM – Selective Laser Sintering/Melting

Accuracy	Materials
Layer Thickness: 0.10-0.15 mm	• Plastics • Metals • Ceramics
Support Structures	**Typical Usage**
• None (Powder) • Breakaway (same material)	• Prototyping • Production Grade Parts
Disadvantages	• Part porosity • Excess material not always reusable

SLS/SLM – Selective Laser Sintering/Melting

Articulated Joints

Source: Cali et al 2012

Metallic impeller

Source: 3dsystems.com

Binder Jetting

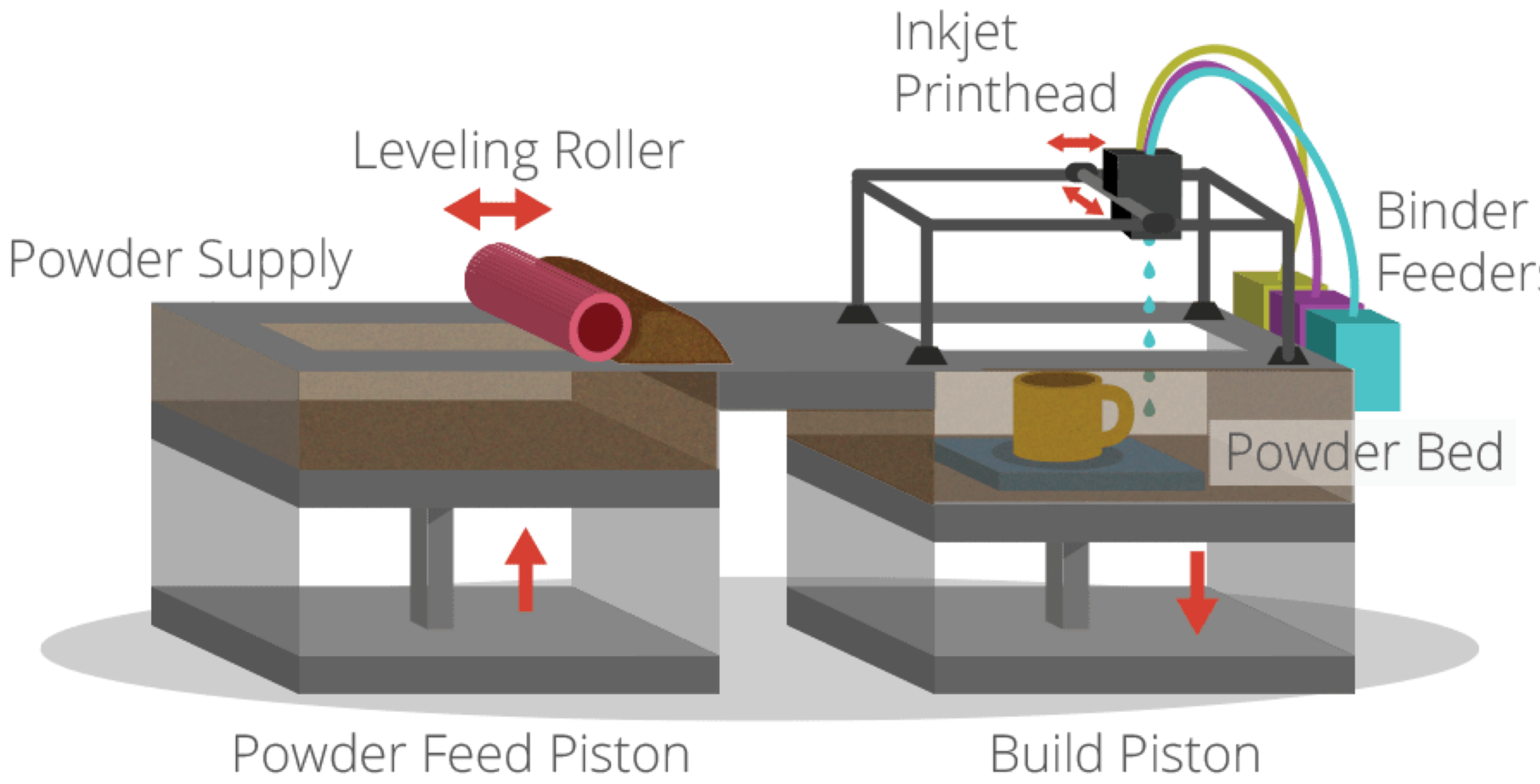


Image: https://3dprintingindustry.com/3d-printing-basics-free-beginners-guide#04-processes

Binder Jetting

Accuracy	Materials
Layer Thickness: 0.1 mm	• Starches & Thermoplastics • Ceramics • Metals
Support Structures	**Typical Usage**
• None (Powder)	• Concept Models • Ceramic and metal green parts
Disadvantages	• Poor accuracy and surface finish • Low durability (when not fired)

Binder Jetting

Figuirines

Source: youtube.com

Plastic armchair

Source: voxeljet.de

EBM - Electron Beam Melting

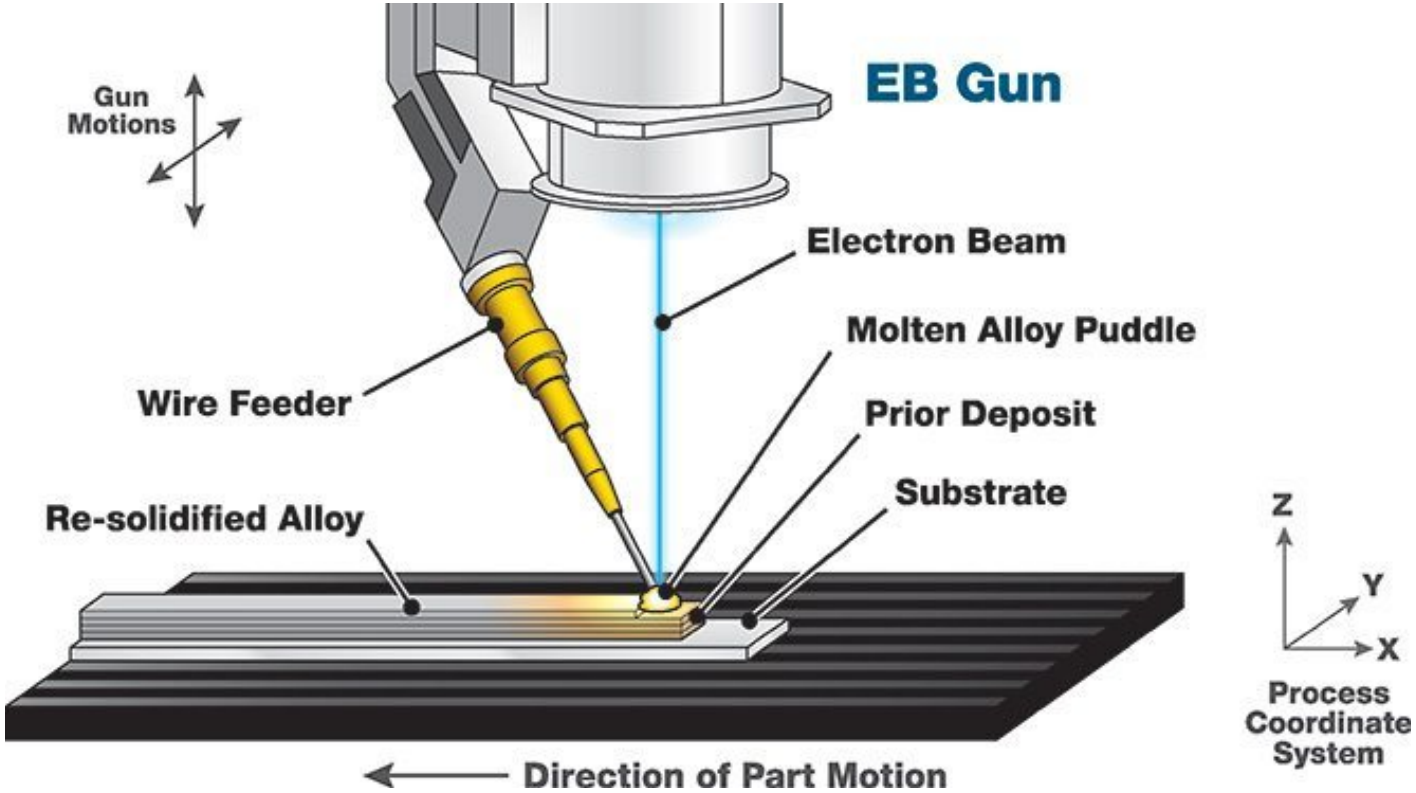


Image: https://3dprintingindustry.com/news/new-facility-selective-electron-beam-melting-84074/

EBM - Electron Beam Melting

Accuracy	Materials
Layer Thickness: 0.05 mm	• Metals
Support Structures	**Typical Usage**
• None • Breakaway (same material)	• Prototyping • Production Grade Parts
Disadvantages	• Expensive and slow • Support remove can be tedious • Part warping

EBM - Electron Beam Melting

Custom Skull Plate

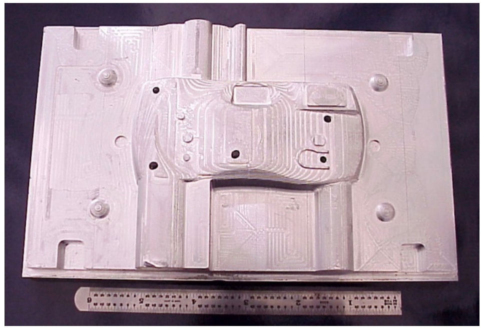
Source: 3ders.org

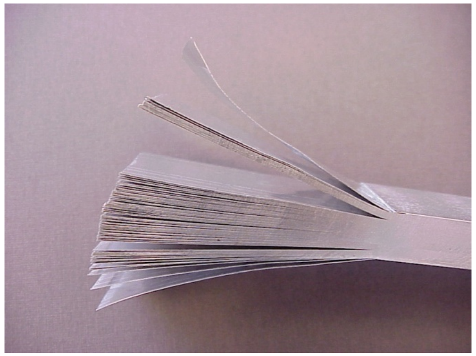
Repaired Turbine Blade

Source: industrial-lasers.com

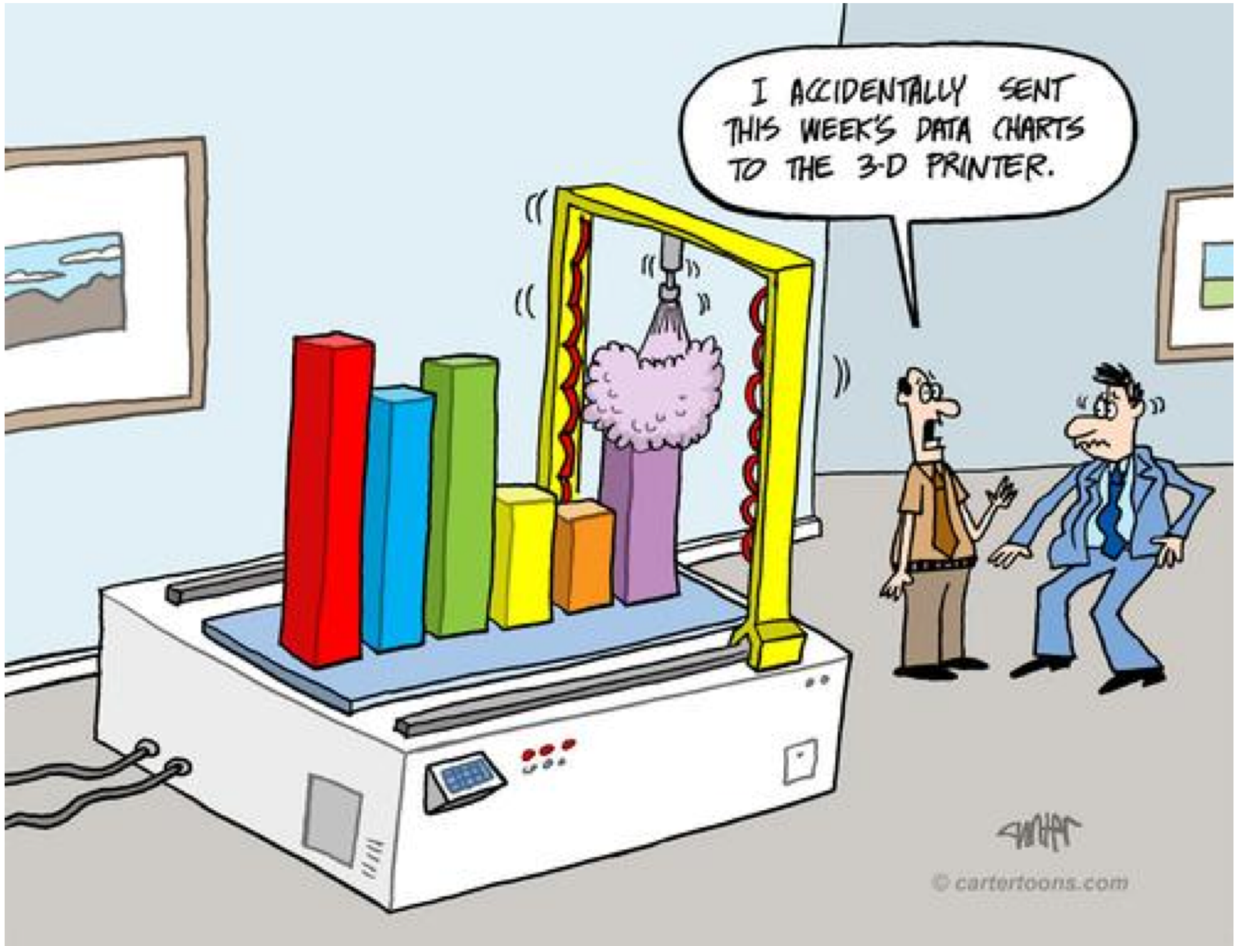
Sheet Metal Lamination (SML)

- **SML:** Combines Ultrasonic Additive Manufacturing (UAM) and Laminated Object Manufacturing (LOM)
  - Ultrasonic welding to consolidate layers of metal foil sheets, e.g. aluminum
  - Sheet cutting using a laser
  - High fabrication speed comparatively
  - Allows for multiple materials and material embedding, e.g. fibers





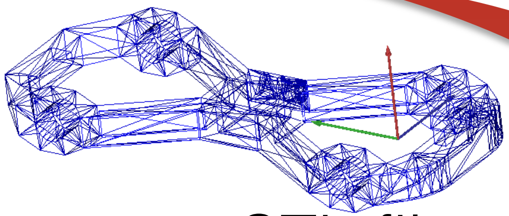
SML, Source: Fadel, 2004



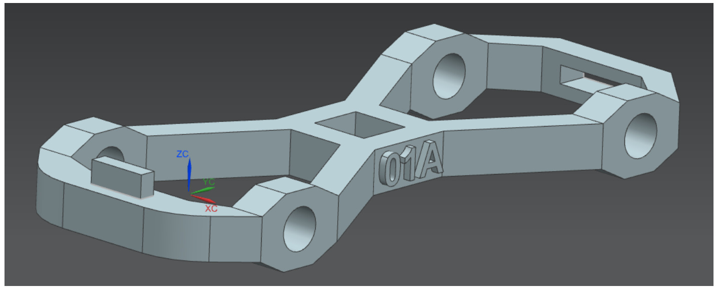
source: http://img.deusm.com/allanalytics/2014/02/271543/AA0024.jpg

Digital Design-to-Fabrication Process

Design process

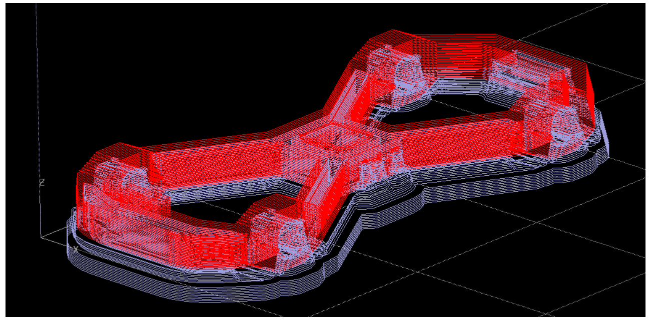


CAD model



STL file generation

Build file creation

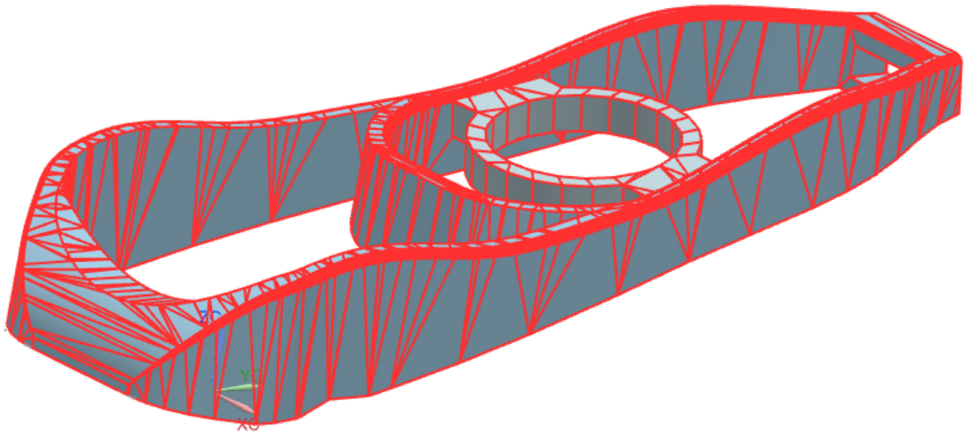


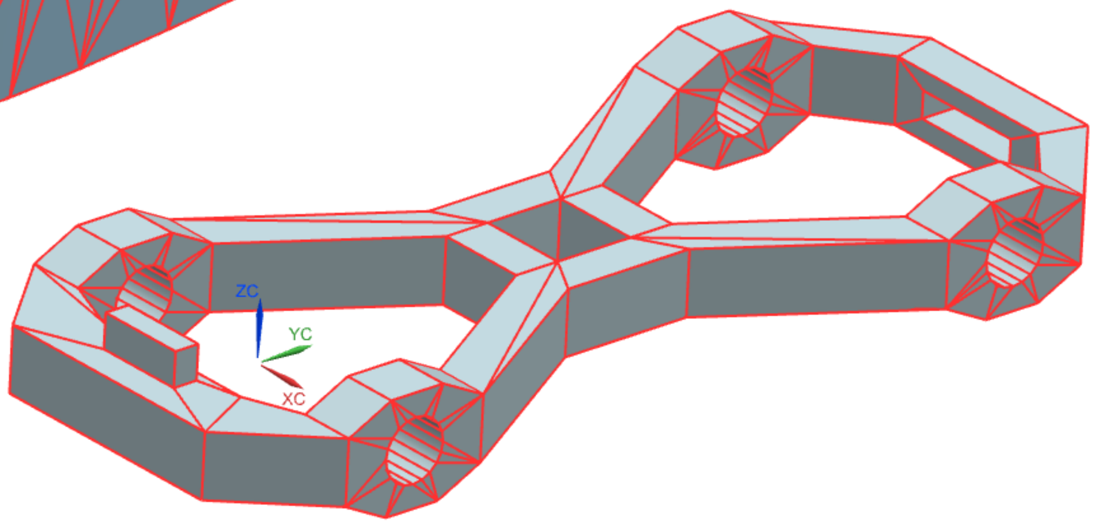
Part construction

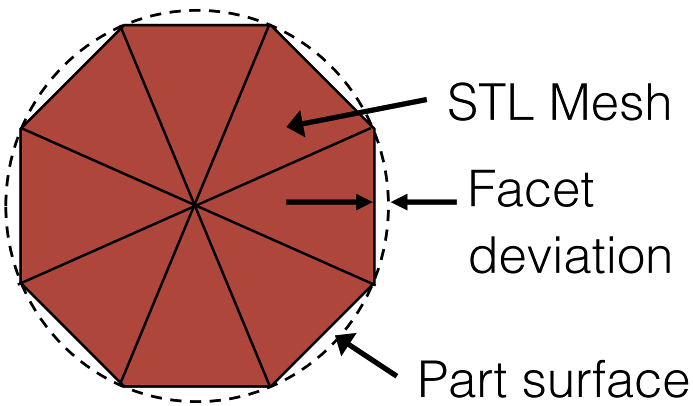
Part cleaning & finishing

Sterolithography File Format (.stl)

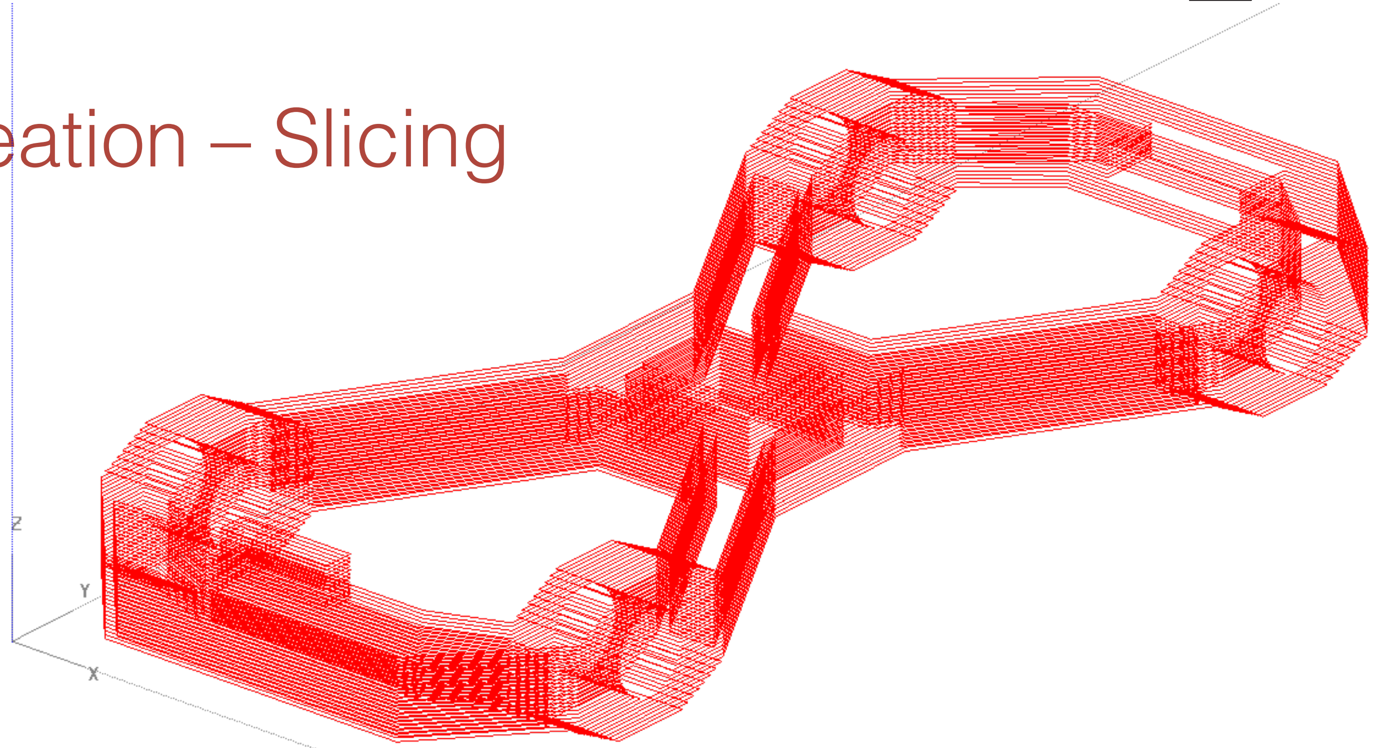
- Triangular mesh approximates boundary surface

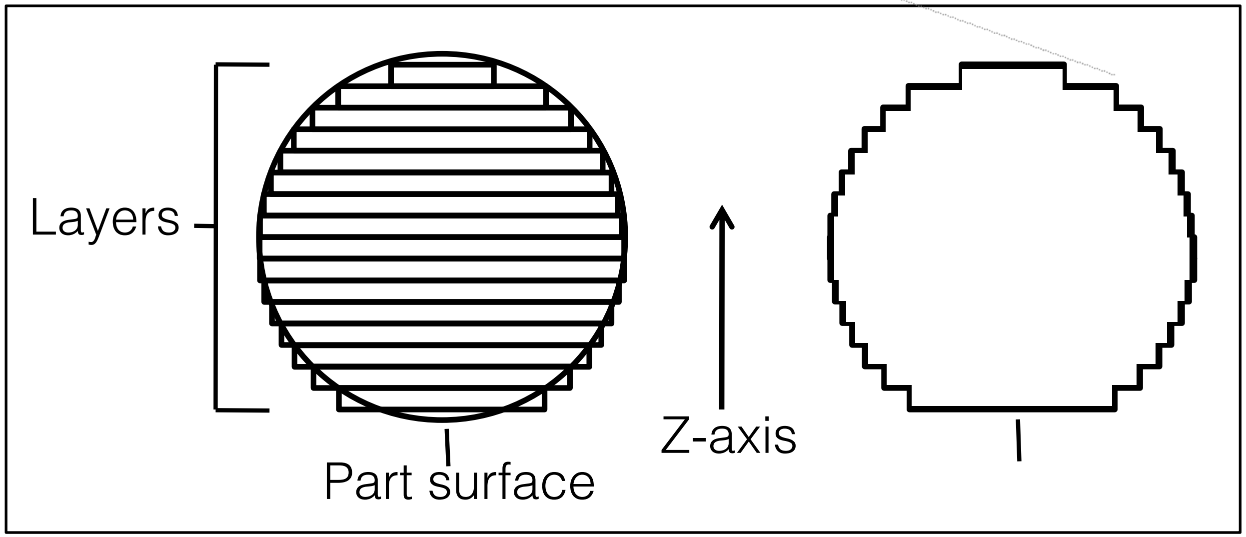




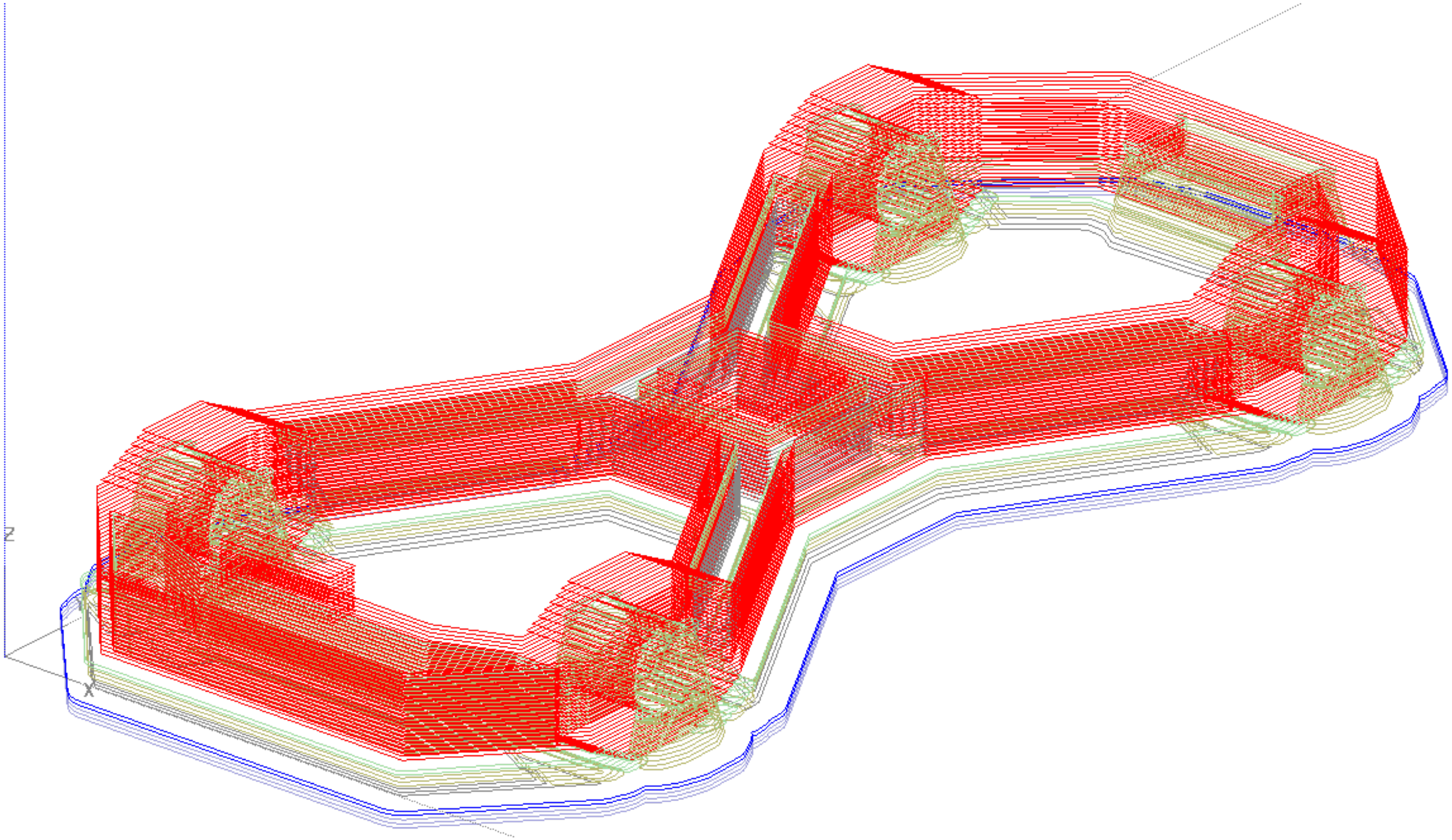


Build File Creation – Slicing





Build File Creation – Support Structure

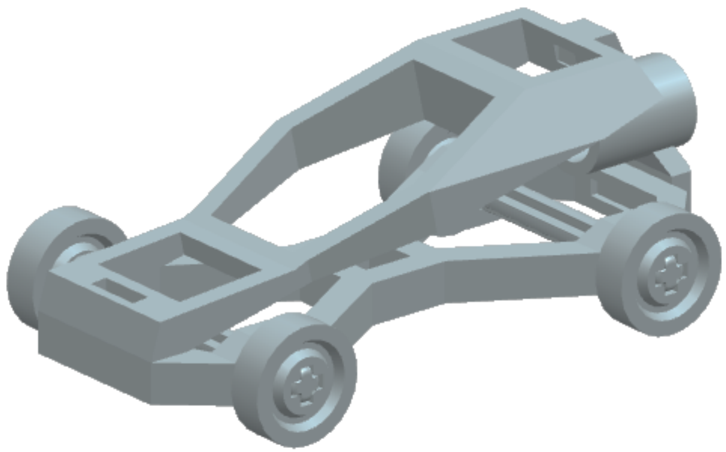


Design for Additive Manufacturing (DfAM)

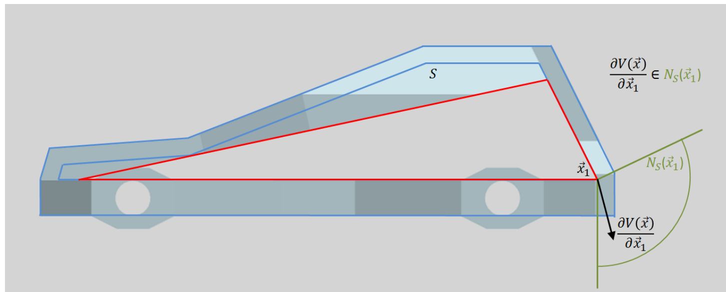
- Synthesis of shapes, sizes, geometric meso-structures, and material compositions and microstructures to best utilize manufacturing process capabilities to achieve desired performance and other life-cycle objectives

Based on: Gibson, Rosen, Stucker, Additive Manufacturing Technologies, Springer, 2010

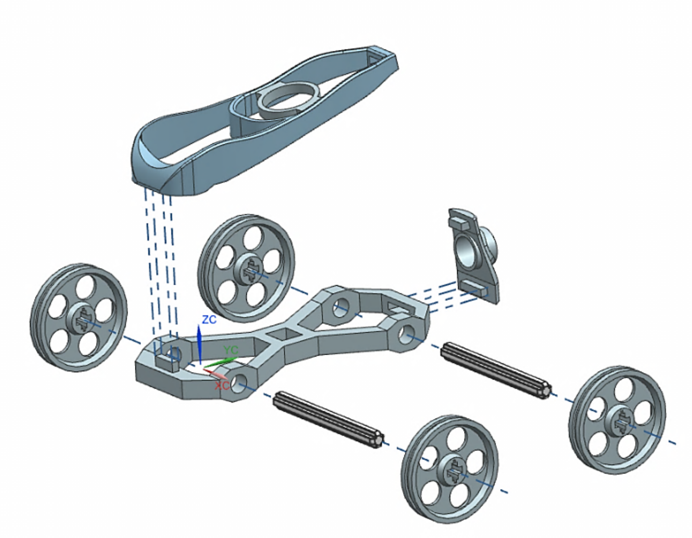
Design for AM – Small Series Production

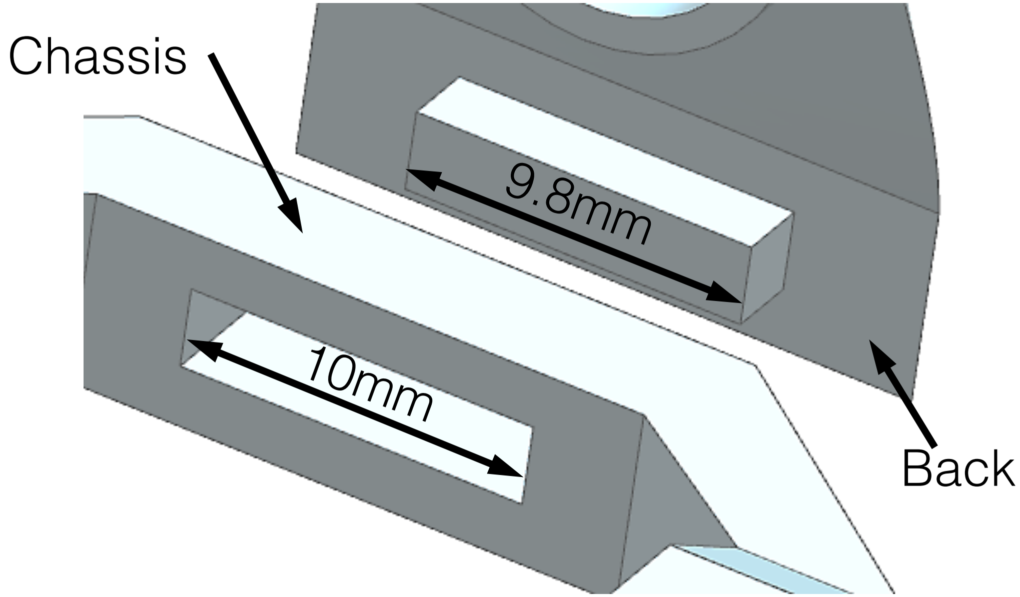


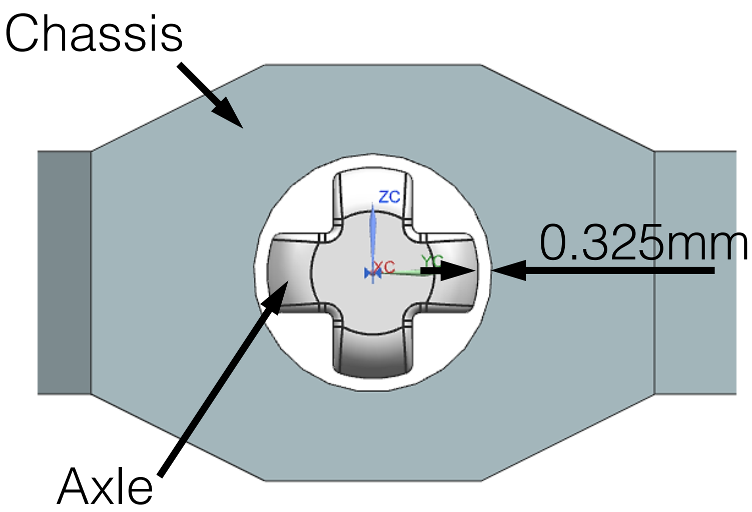
460 cars printed
10 FDM machines (Uprint Plus)
6 cars printed in 6:40 h
6.5 days total

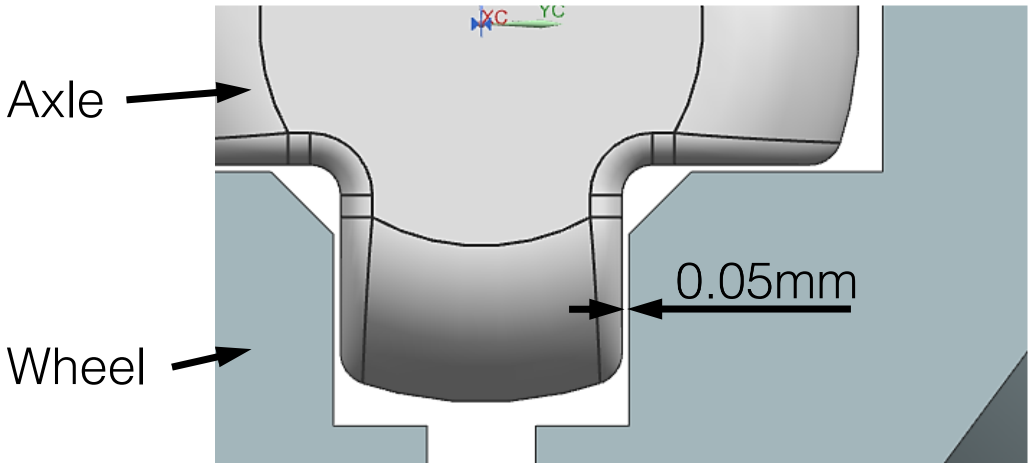


Defining the Car Fits



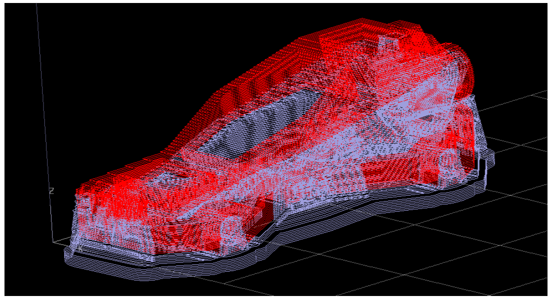




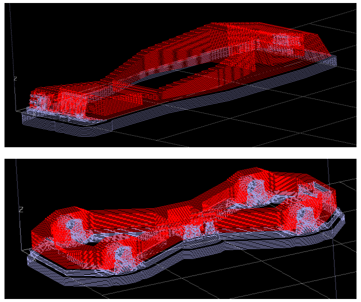


Some Design Issues for 3D Printing (with FDM)

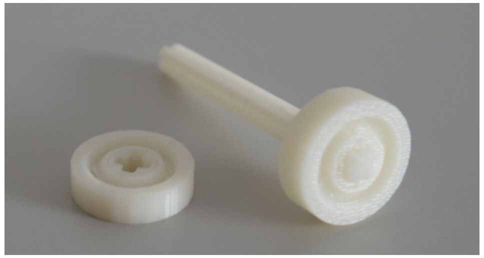
Monolithic vs. Assemblies and Tolerances



Support: 11.4 cm^3
Build time: 2:11 h

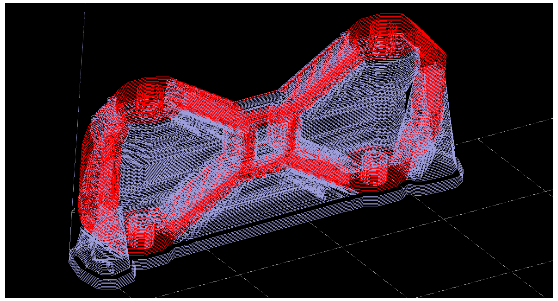


Support: 8.1 cm^3
Build time: 1:47h

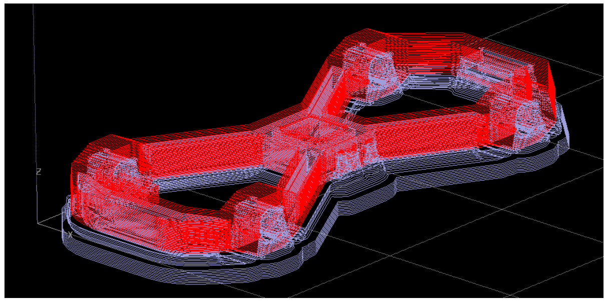


Tolerances between parts

Part Orientation and Packing



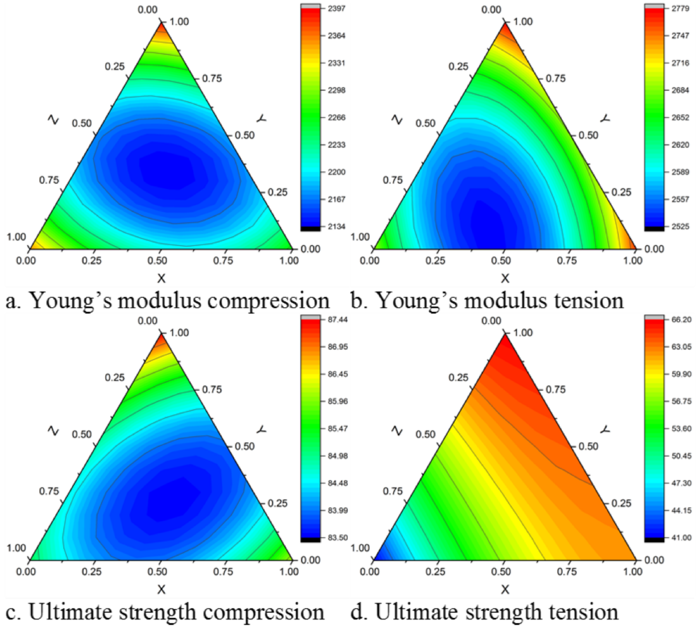
Support Material: 7.2 cm^3
Build time: 1:43 h

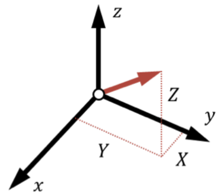


Support Material: 5.6 cm^3
Build time: 0:48 h

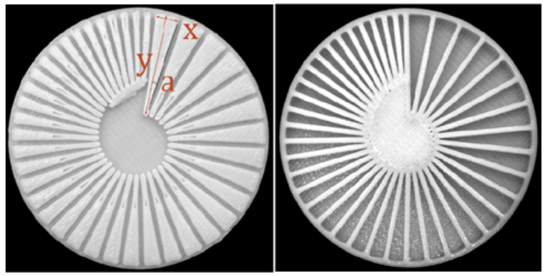
Constraints of AM

1. **Constraints associated with discretization and directionality:**
   - Material properties
   - Surface roughness
   - Support structures
2. **Design guidelines:** Process- and machine-specific constraints and considerations
3. **CAD and digitalization constraints:**
   - Appropriate CAD support
   - New file format to support DfAM
4. **Other constraints:**
   - Life-cycle: maintenance, repair, and recycling
   - External and regulatory constraints

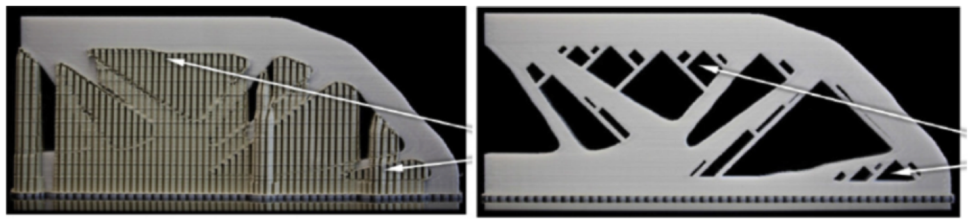




Anisotropy of material property example (IJ)



Geometric constrains example (FDM)



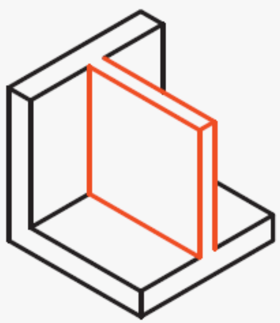
Topology optimized cantilever beam successfully built with support (left) and redesigned to be self-supporting (right).

Image sources: J. Mueller, K. Shea, and C. Daraio, "Mechanical properties of parts fabricated with inkjet 3D printing through efficient experimental design," Materials & Design, 86, pp. 902-912, 2015. Chen, T. and Shea, K. (2015), "Computational Design-to-Fabrication Using Spatial Grammars: Automatically Generating Printable Car Wheel Design Variants", Proceedings of the 20th ICED, vol.2, pp.35 Leary M, Merli L, Torti F, Mazur M, Brandt M (2014) Optimal Topology for Additive Manufacture: A Method for Enabling Additive Manufacture of Support-Free Optimal Structures. Mater Des 63:678–690.

Examples Design Guidelines

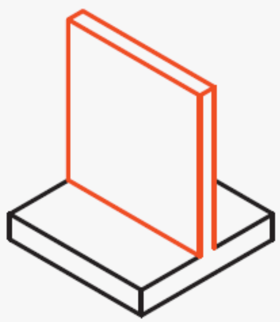
Supported Walls

Walls that are connected to the rest of the print on at least two sides.



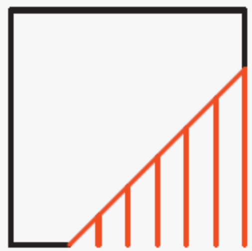
Unsupported Walls

Unsupported walls are connected to the rest of the print on less than two sides.



Support & Overhangs

The maximum angle a wall can be printed at without requiring support.



Horizontal Bridges

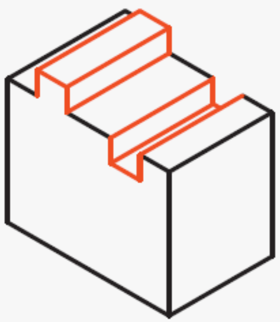
The span a technology can print without the need for support.

Images: 3D Hubs

Examples Design Guidelines

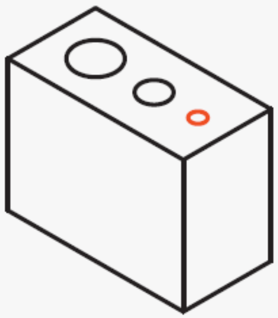
Embossed & Engraved Details

Features on the model that are raised or recessed below the model surface.



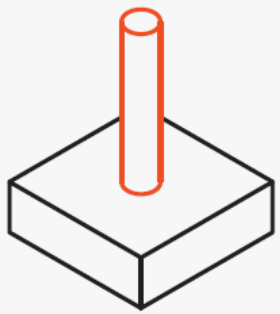
Holes

The minimum diameter a technology can successfully print a hole.



Pin Diameter

The minimum diameter a pin can be printed at.



Minimum Features

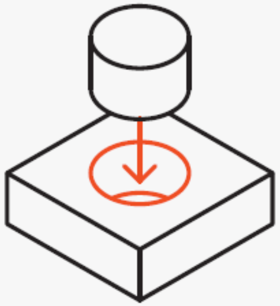
The recommended minimum size of a feature to ensure it will not fail to print.

Images: 3D Hubs

Examples Design Guidelines

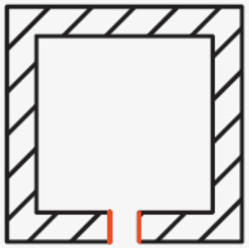
Connecting /Moving Parts

The recommended clearance between two moving or connecting parts.



Escape Holes

The minimum diameter of escape holes to allow for the removal of build material.



Tolerance

The expected tolerance (dimensional accuracy) of a specific technology.

Images: 3D Hubs

Test Your Machine and Material

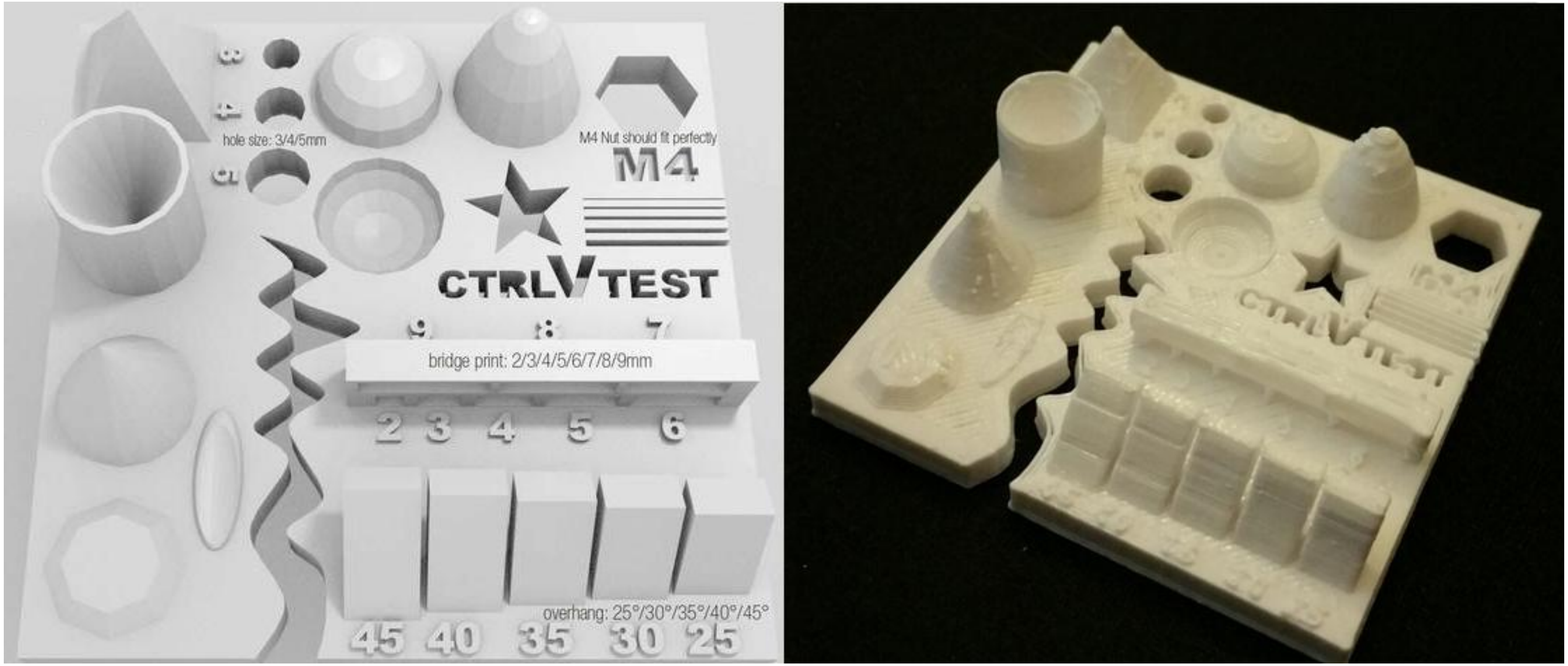
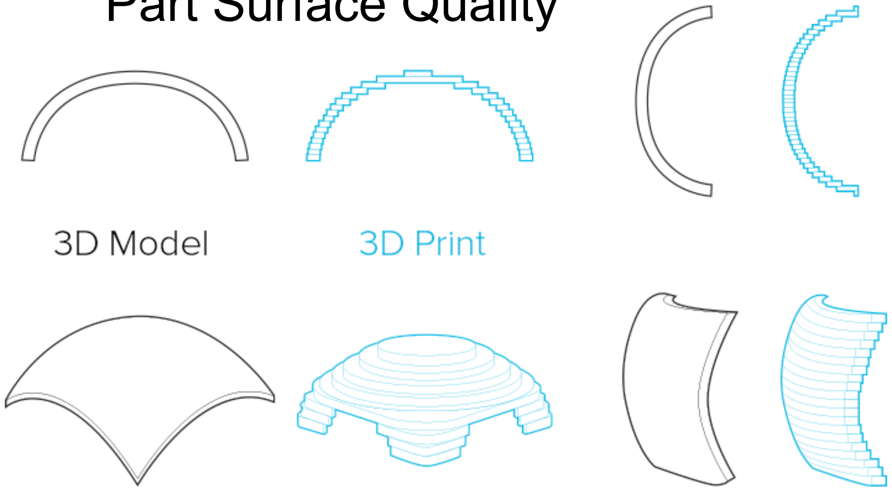


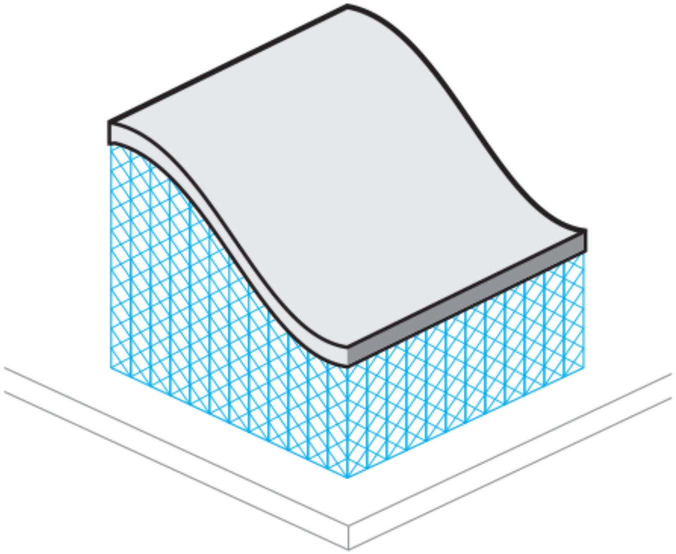
Image: 3DPrint.com

Other Things to Consider

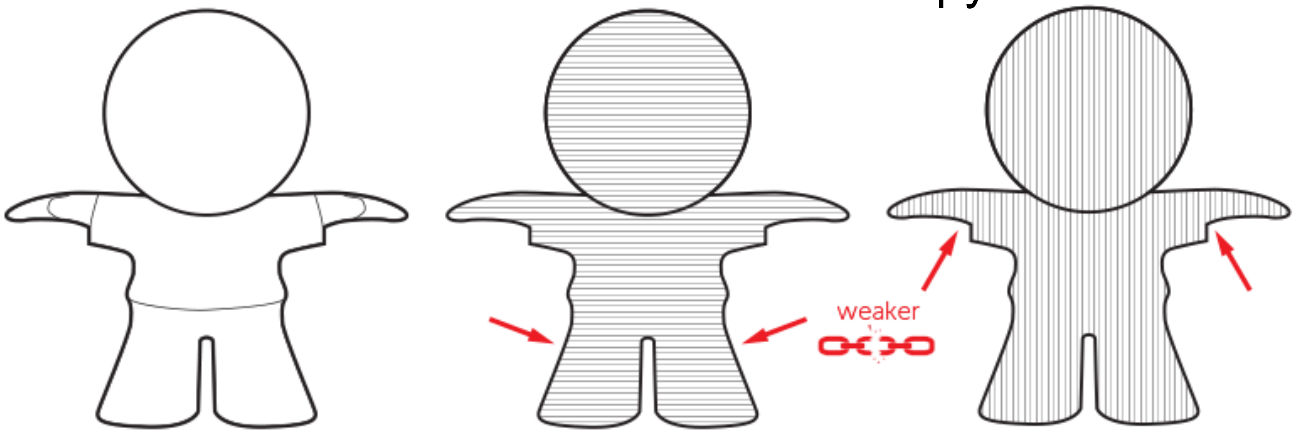
Part Surface Quality



Support Material



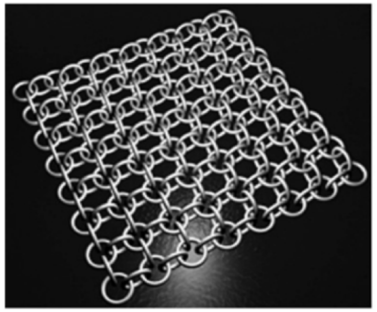
Anisotropy

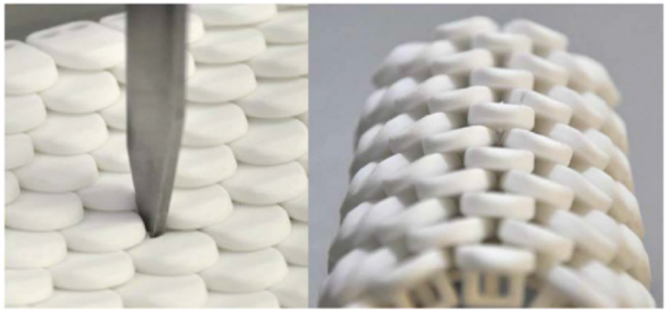


Images: Materialise

Part Integration and Direct Production of Assemblies

Articulated joints produced using selective laser sintering (SLS)





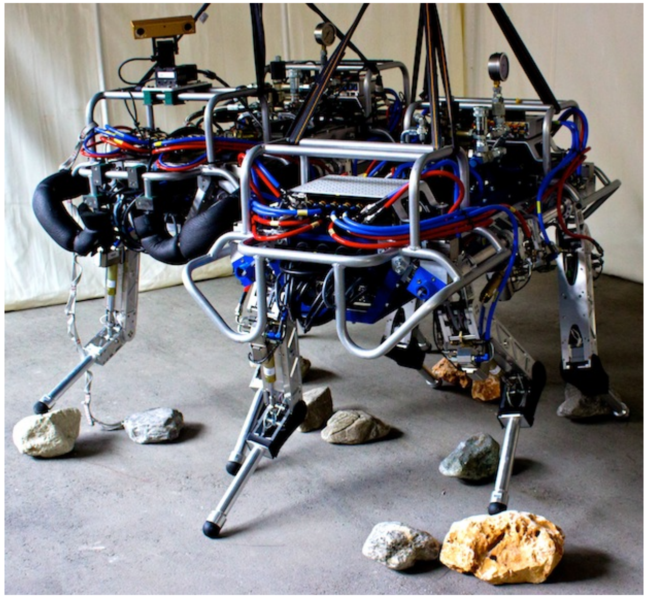
Additively manufactured chain mail (left) and laser sintered articulated stab-resistant armor (right)

Images from: Thomson et al., Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints, CIRP Annals - Manufacturing Technology, Elsevier, 2016

Robotic Systems

Active Robotic Systems

- Actuators and feedback control
- High task flexibility possible
- Responsive to environment
- High robustness



http://www.adrl.ethz.ch/doku.php/adrl:robots

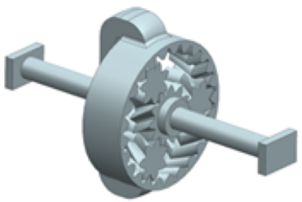
Passive Robotic Systems

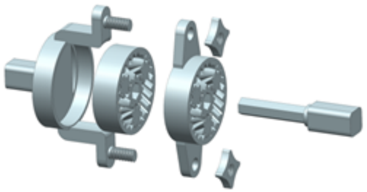
- No actuators and control
- No energy source necessary
- Potential to save energy

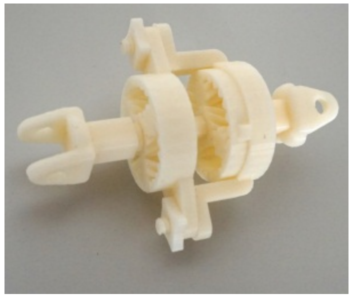
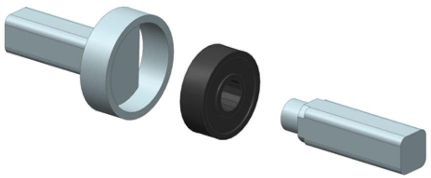
Passive dynamic walking, Mcgeer, T., 1990, International Journal of Robotics Research

Prototyping of Passive Walking Robots using FDM (1)

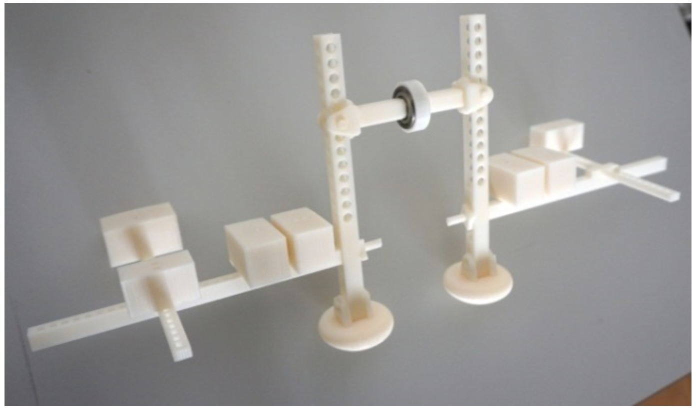
Design of different bearings



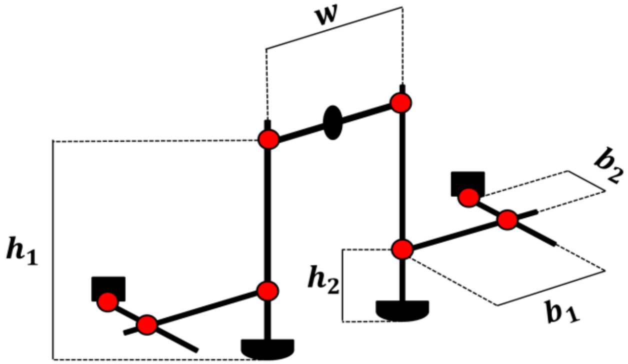


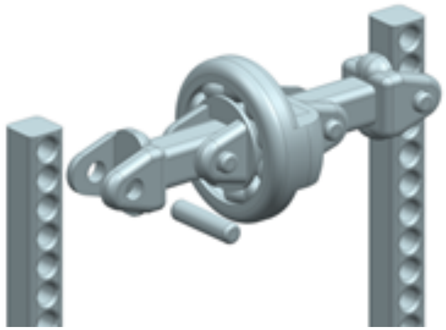




A modular design

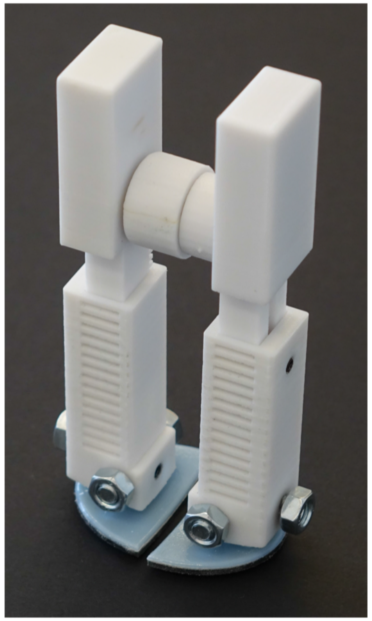


Design variables can be adjusted after printing

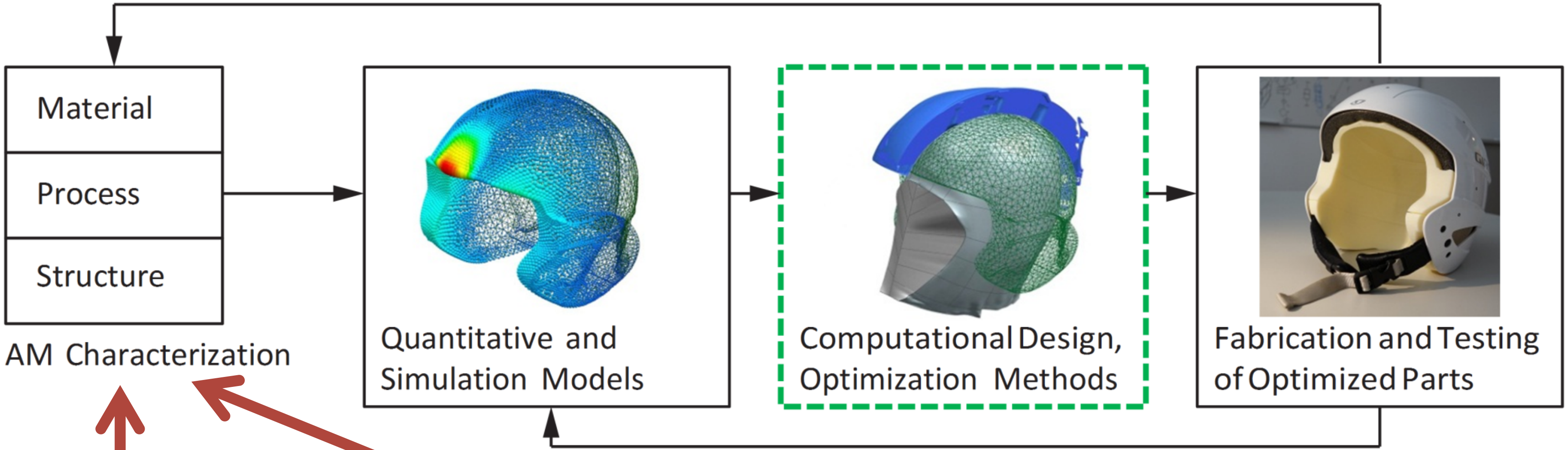


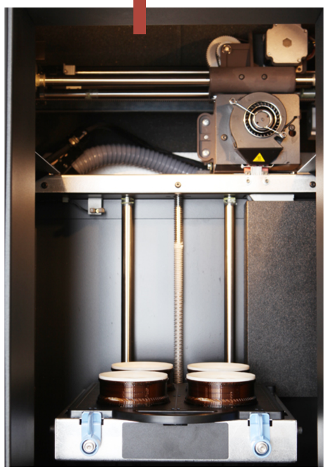


Prototyping of Passive Walking Robots using FDM (2)

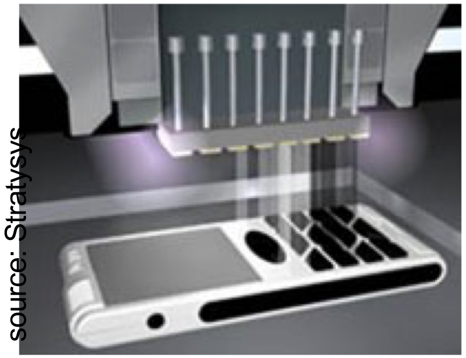


Design for Additive Manufacturing Framework





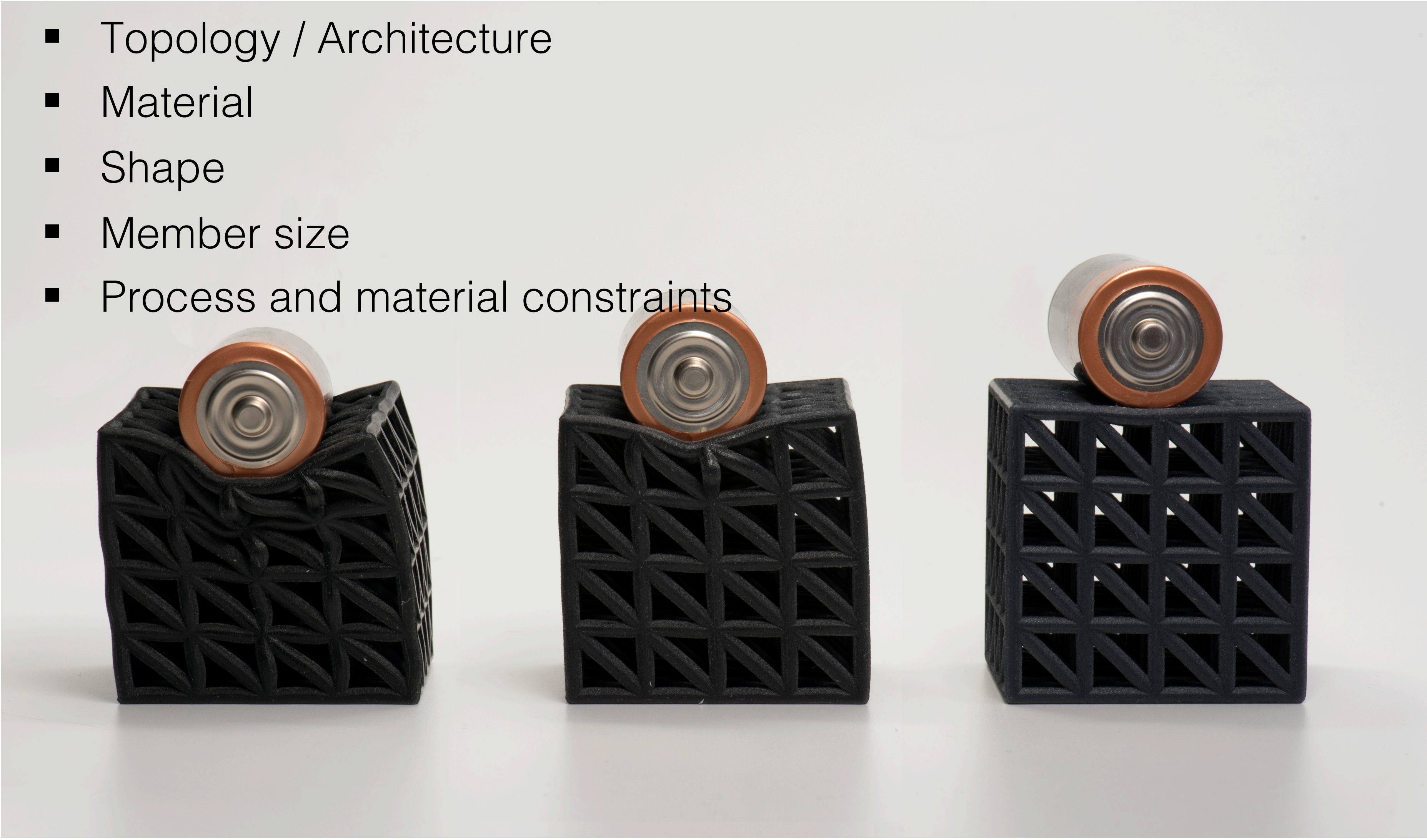
e.g., Fused Deposition Modeling



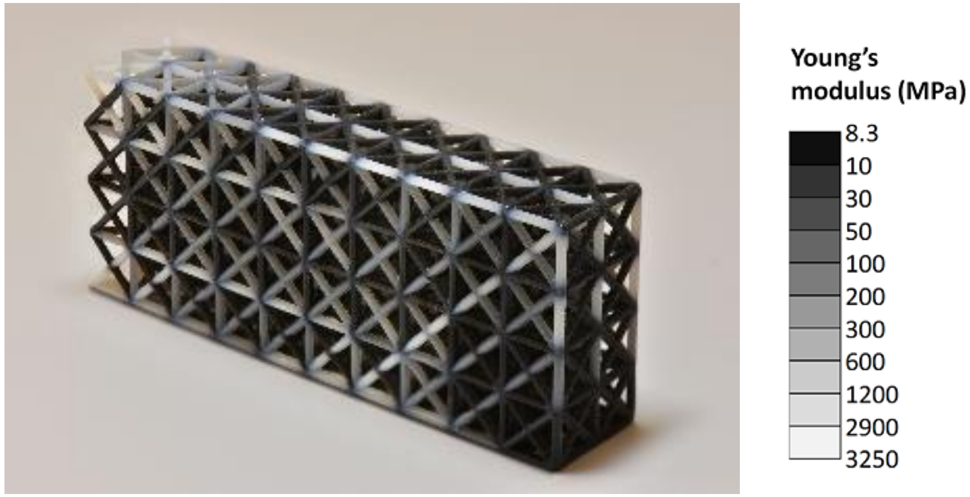
e.g., Polyjet Multi-Material 3D Printing

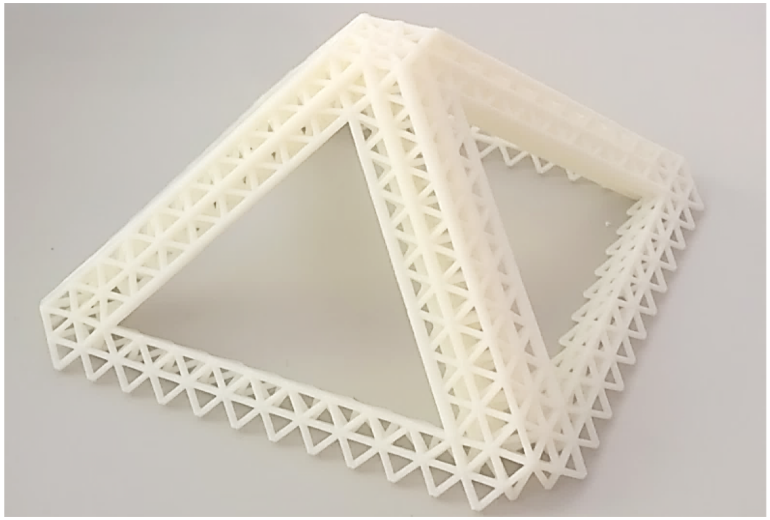
Challenges for Designing AM Multimaterial Lattices

- Topology / Architecture
- Material
- Shape
- Member size
- Process and material constraints



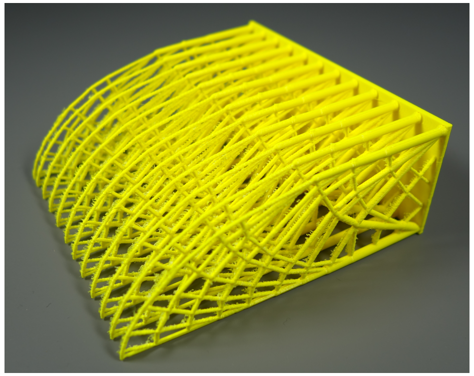
Optimization of Lattice Structures for AM





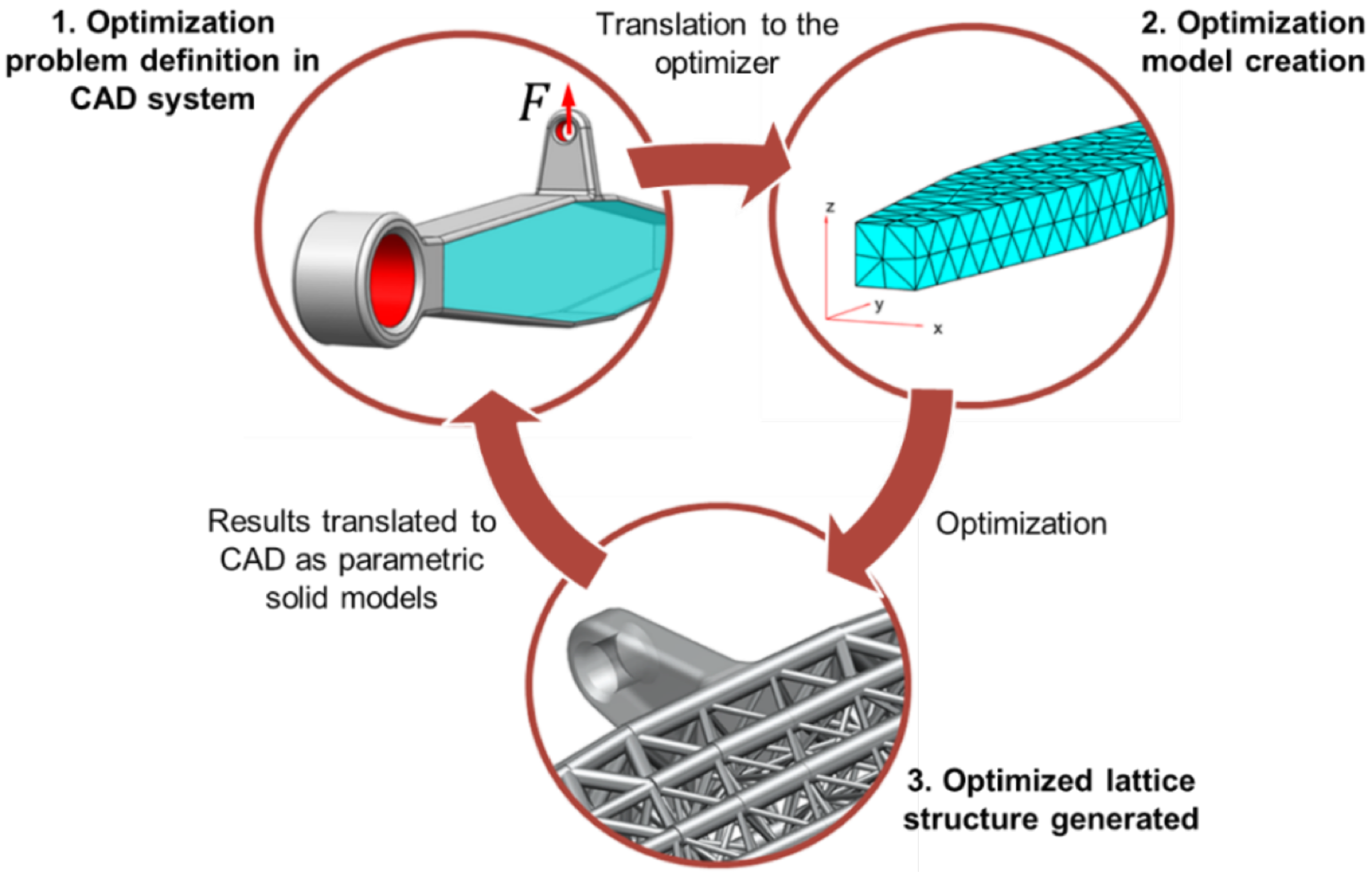
Optimization for Multiple Materials

Optimization for Anisotropy



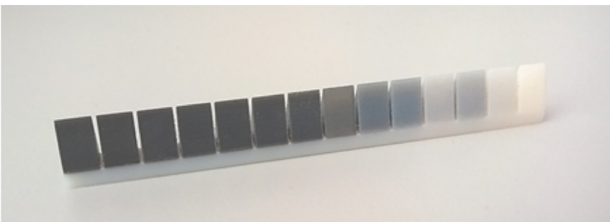
An integrated Linear Programming approach for shape and size optimization

Design Optimization Framework for AM Lattice Structures

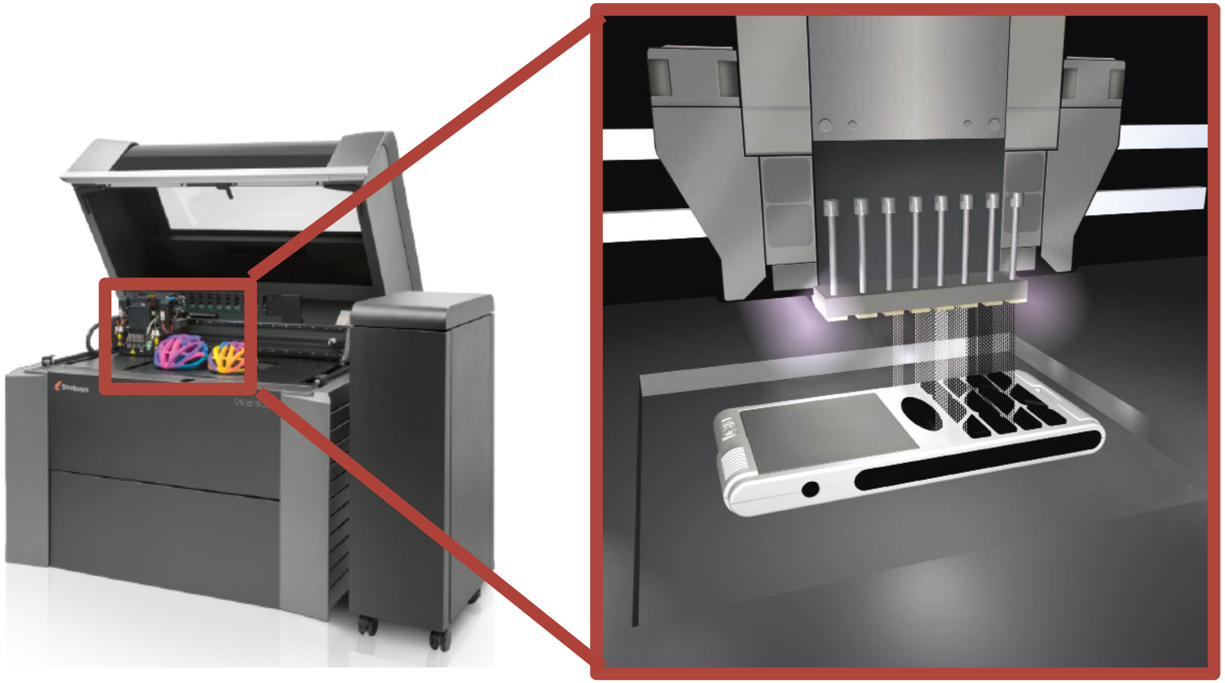


Material Jetting
Stratasys Objet500 Connex3

- Up to three model materials plus support material – 40 digital materials
- Eight print heads jetting material (two per material)
- Instantly cured layers of a liquid photopolymer
- Removable, gel-like support material
- No post-curing needed
- Accuracy: 0.2 mm

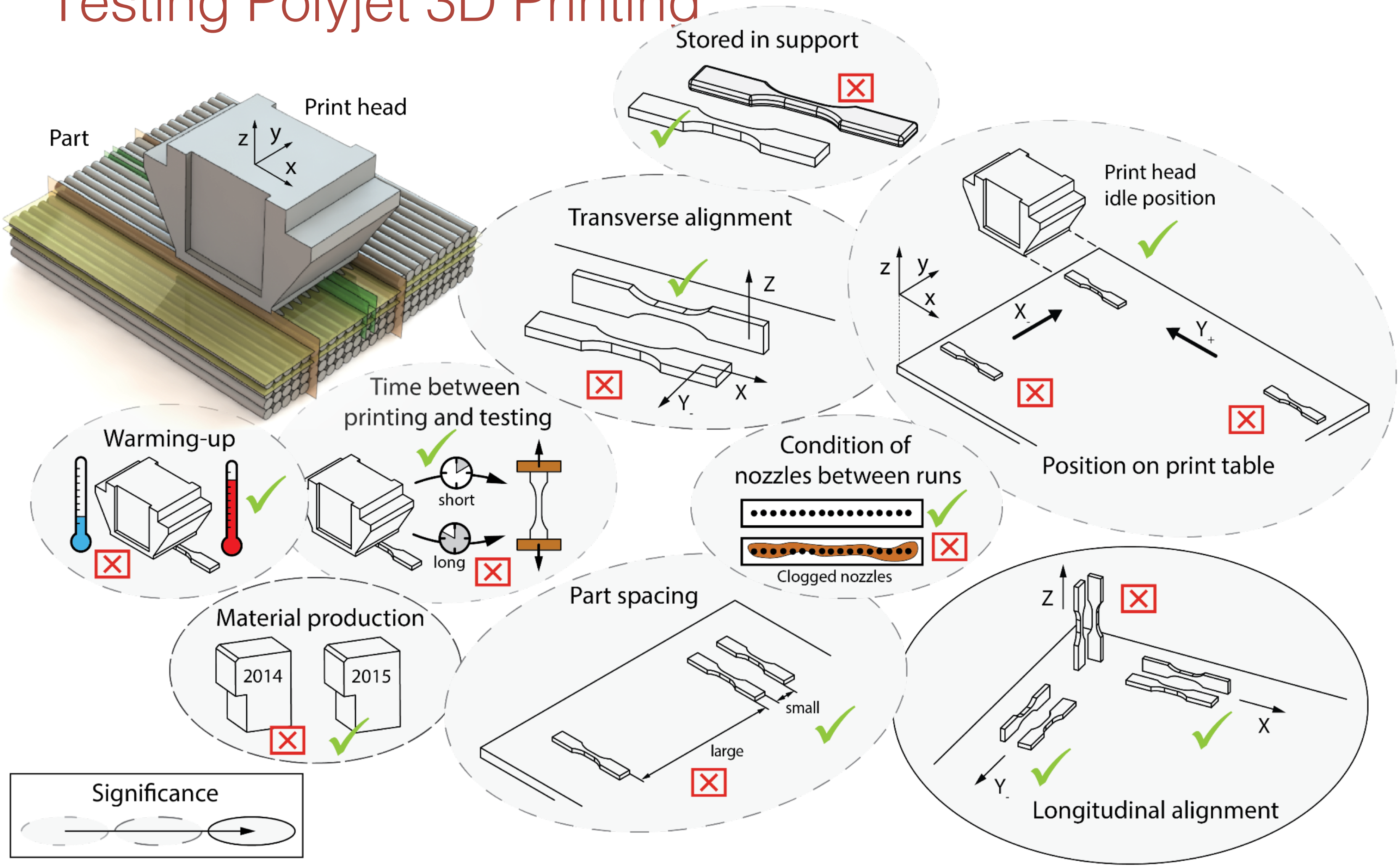


14 materials



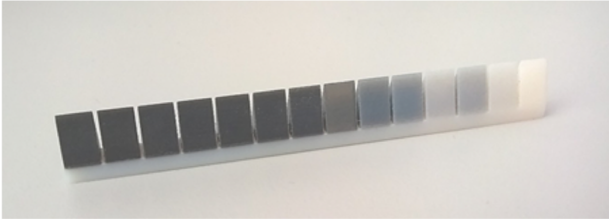
http://www.stratasys.com, accessed 02.12.2014

Testing Polyjet 3D Printing



Material Characterization

Establishing Young's Modulus as a Function of Density



Stratasys Objet500 Connex3

Two base materials

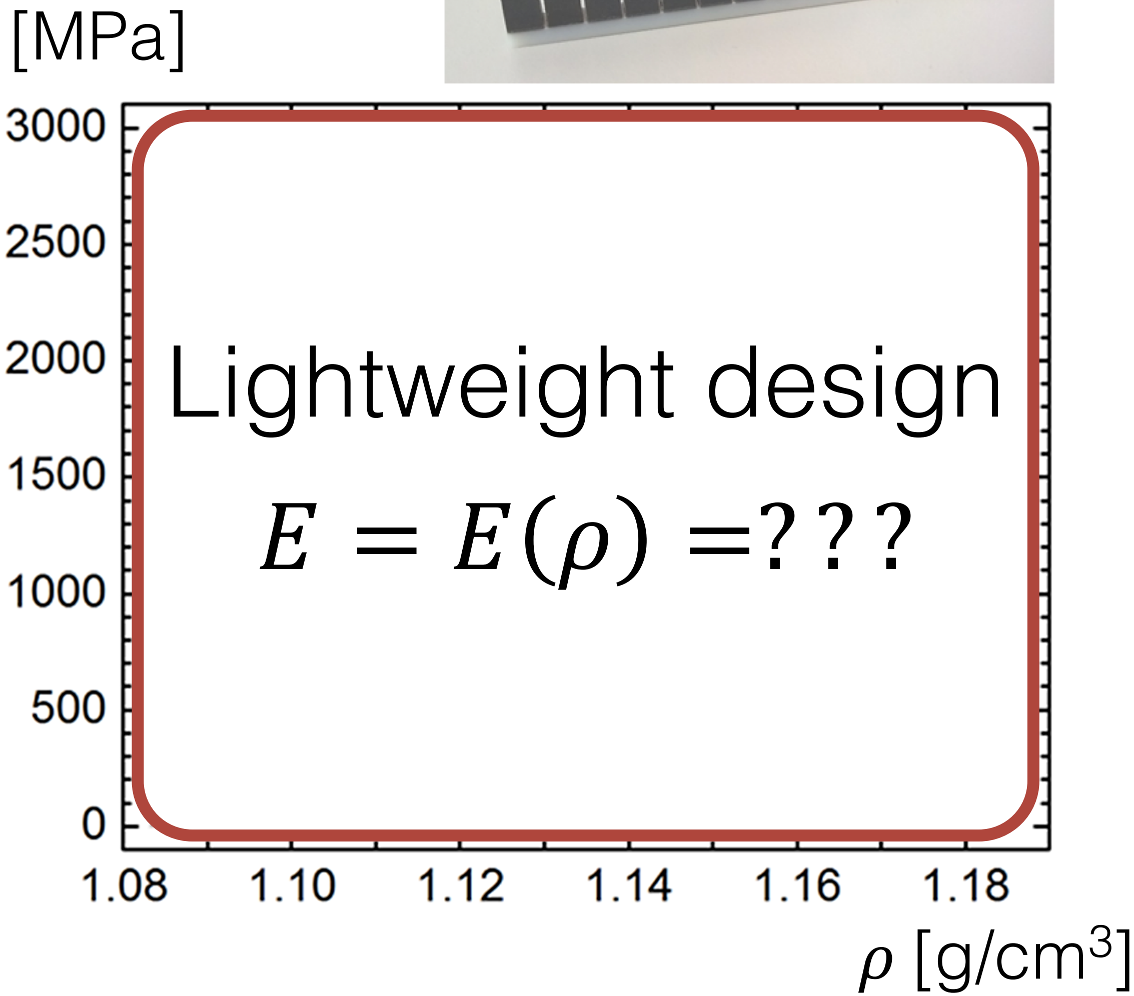
VeroWhitePlus

TangoBlackPlus

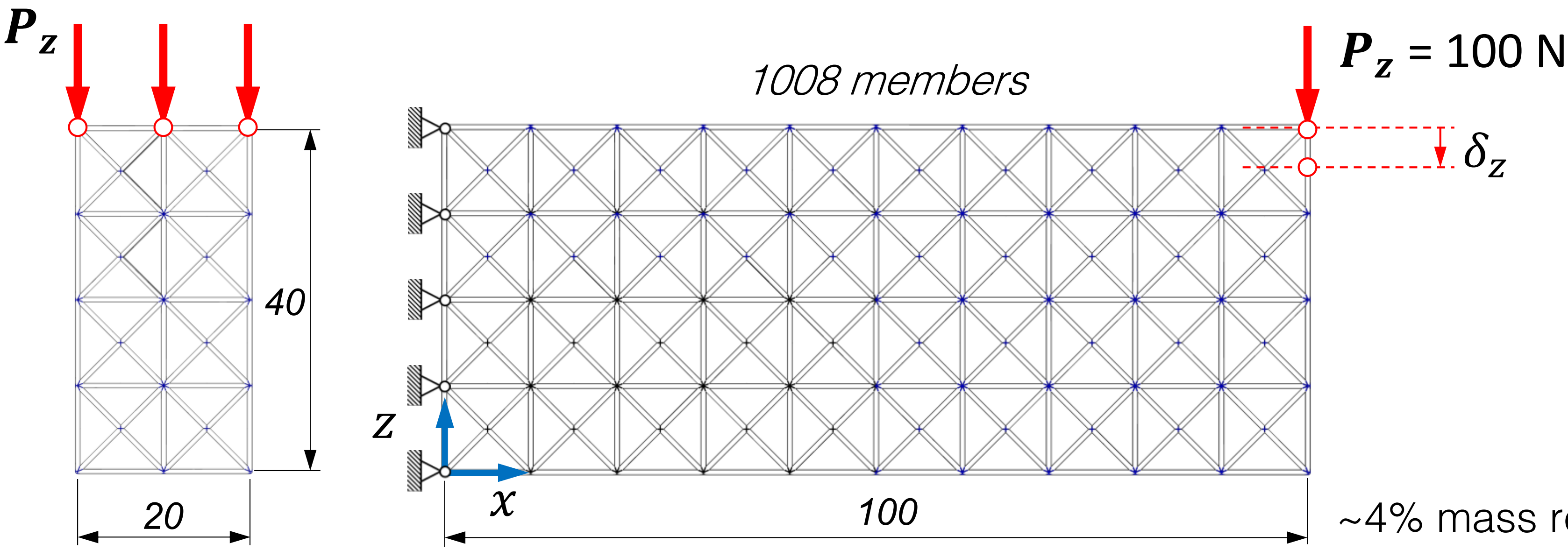
Testing:

- 14 material gradings
- ASTM D638-10
- *Instron ElectroPuls E3000* testing machine

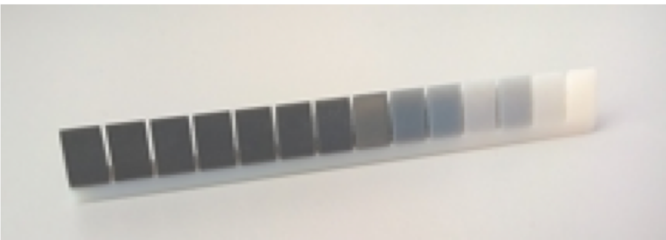
$$\rho(E) = \log x_0 - \frac{\log\left(\frac{A_2 - A_1}{E - A_1} - 1\right)}{p}$$

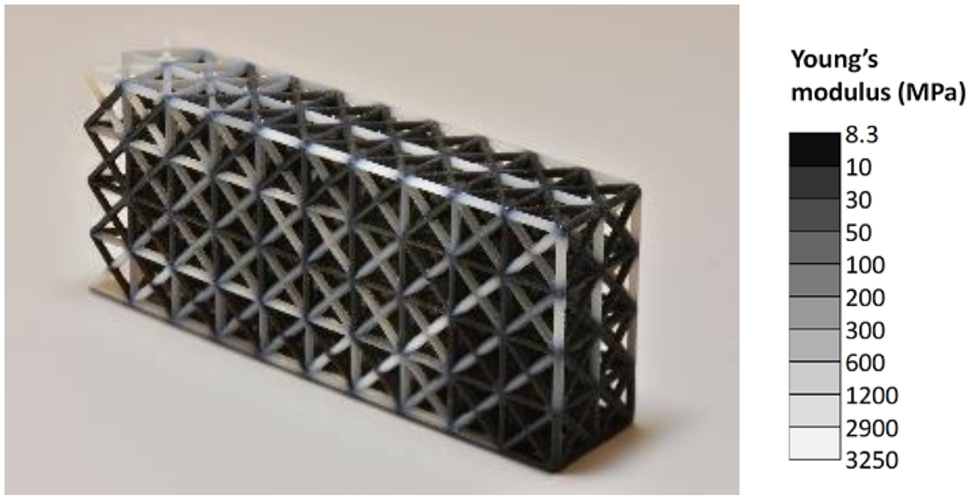


Multi-Material Cantilever Design Optimization



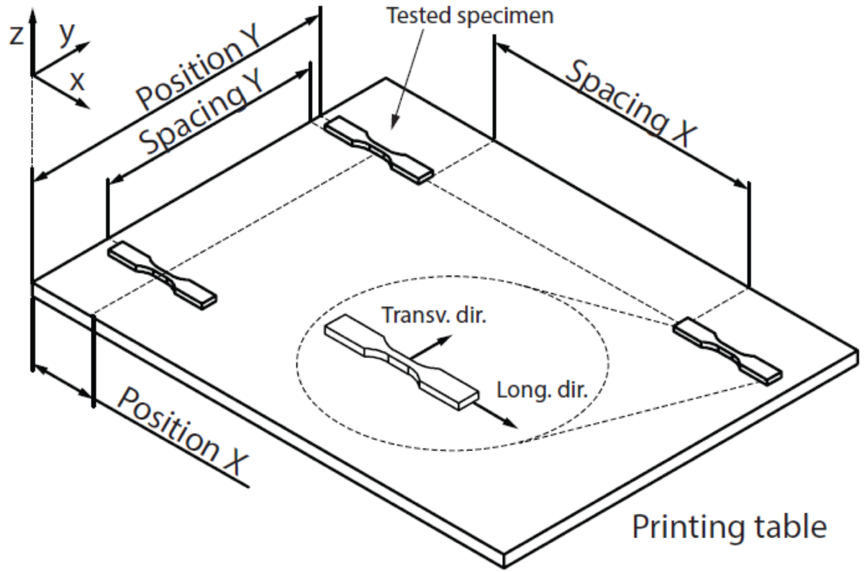
~4% mass reduction



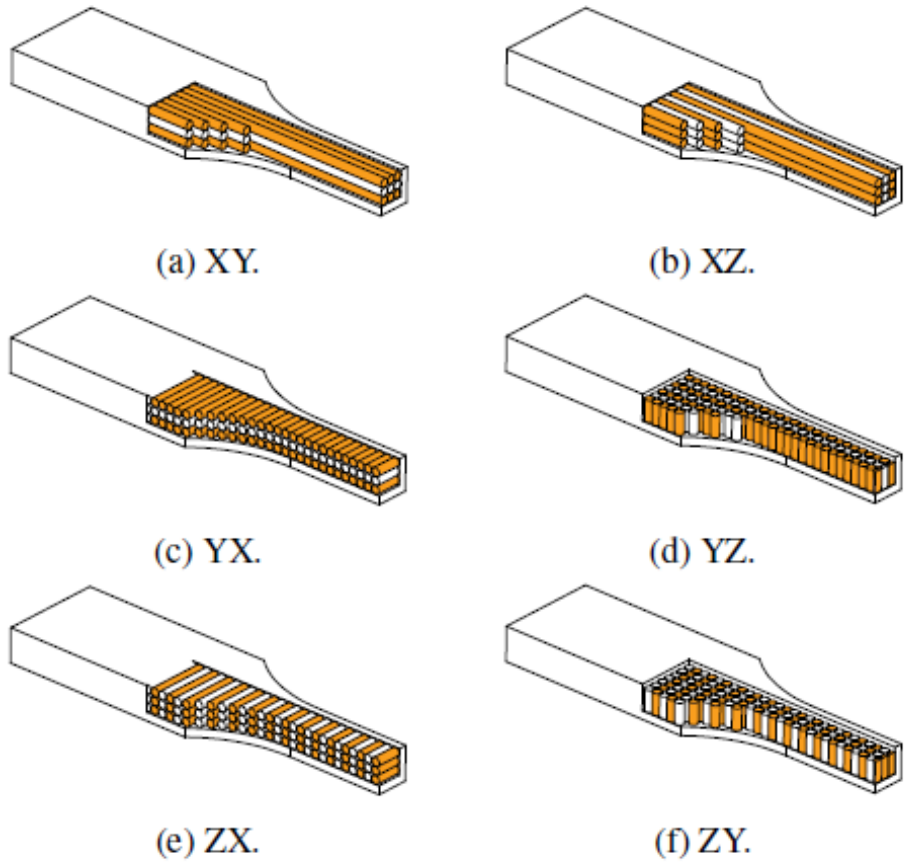


Partially based on: Stanković, T., Mueller, J., Egan, P. and Shea, K.: A Generalized Optimality Criteria Method for Optimization of Additively Manufactured Multi-Material Lattice Structures, *Journal of Mechanical Design*, 2015, doi:10.1115/1.4030995

Characterizing Anisotropy

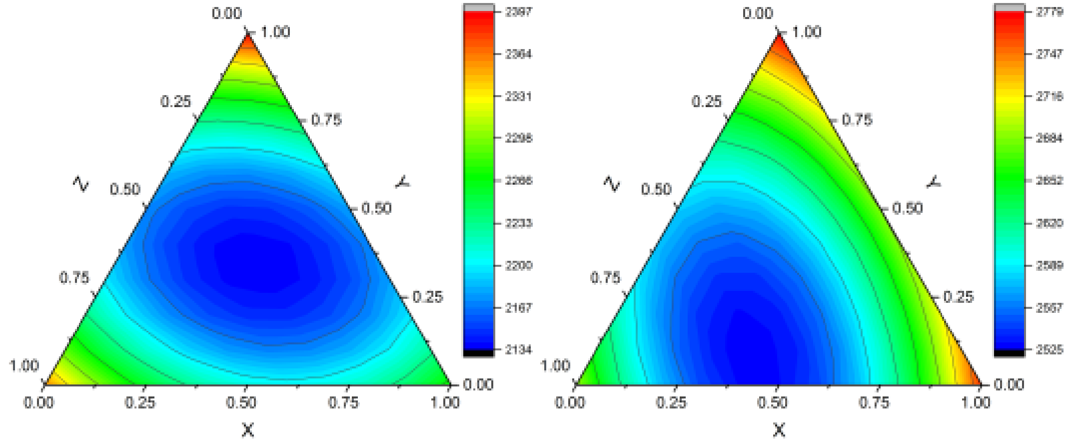


Alignment on printing table

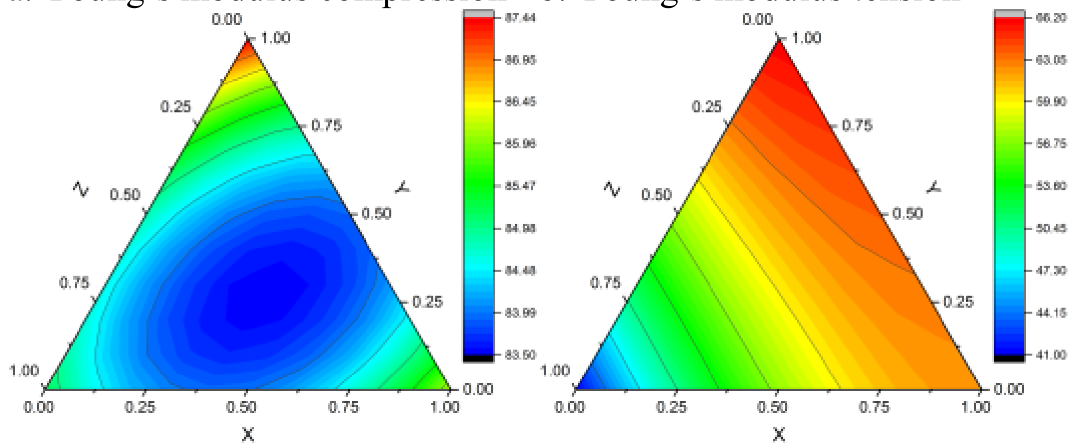


Anisotropy: Investigating layers and intersections in layers

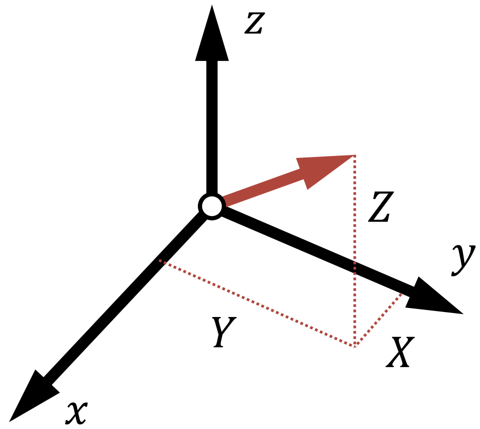
Anisotropy in Material Jetted Lattice Structures

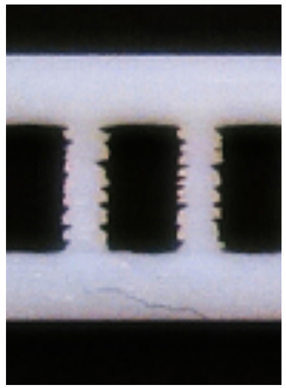


a. Young's modulus compression b. Young's modulus tension



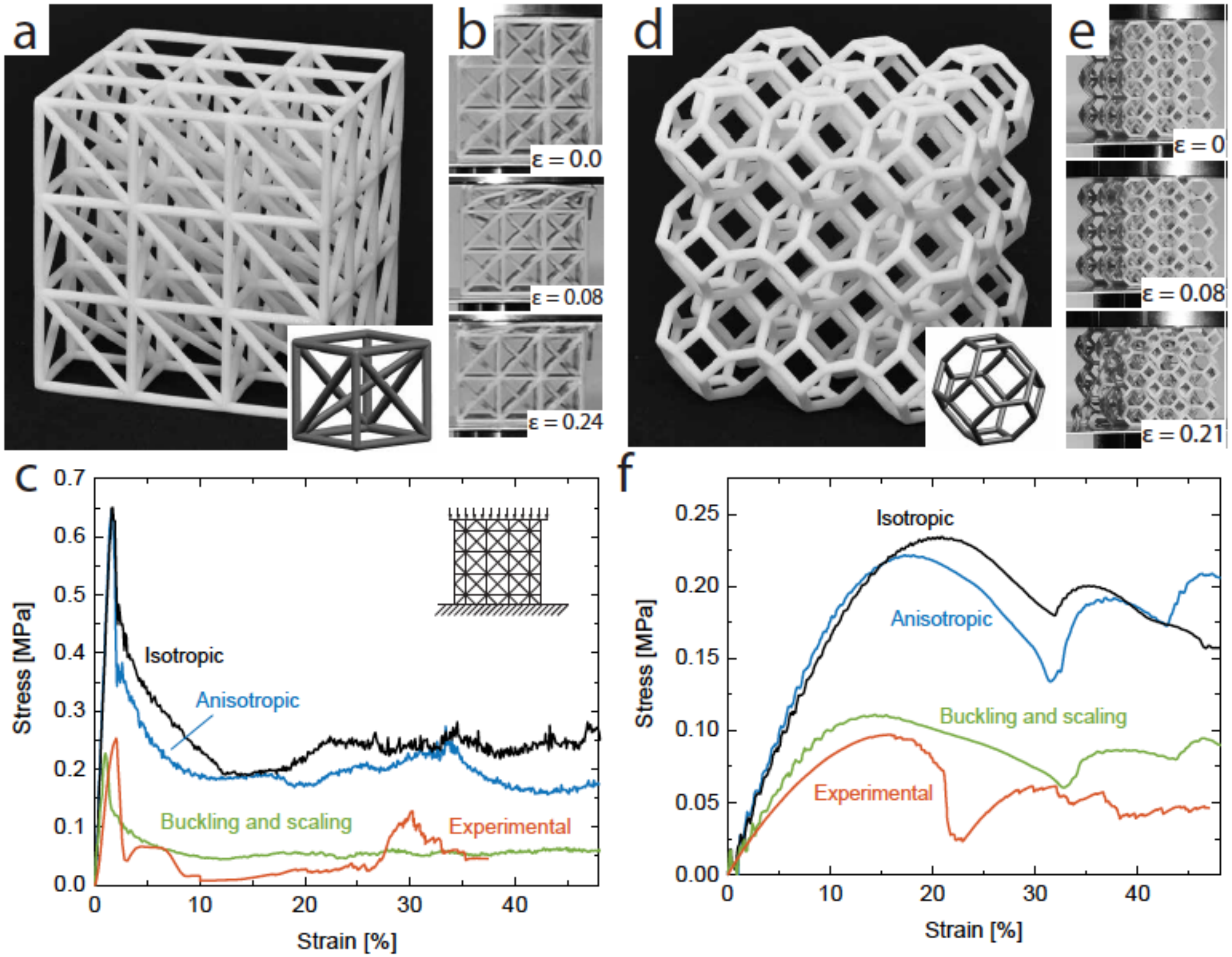
c. Ultimate strength compression d. Ultimate strength tension





J. Mueller and K. Shea, "The effect of build orientation on the mechanical properties in inkjet 3D-printing," International Solid Freeform Fabrication Symposium, Austin, TX, United States, 2015.

Scale Effects in Material Jetted Lattice Structures

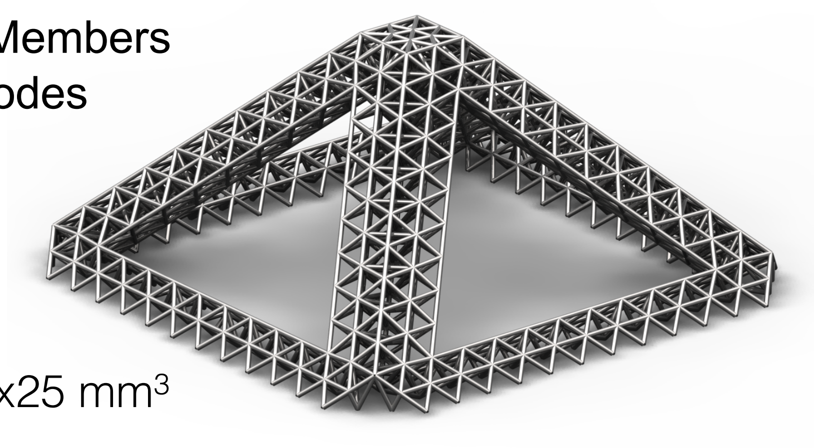


Mueller, J. and K. Shea (2018), "Buckling, Build Orientation, and Scaling Effects in 3D Printed Lattices", *Materials Today Communications*, vol. 17, pp. 69-75.

Stanković, T., Mueller, J. and Shea, K. (2017) "The Effect of Anisotropy on the Optimization of Additively Manufactured Lattice Structures", *Additive Manufacturing*, 17:67-76

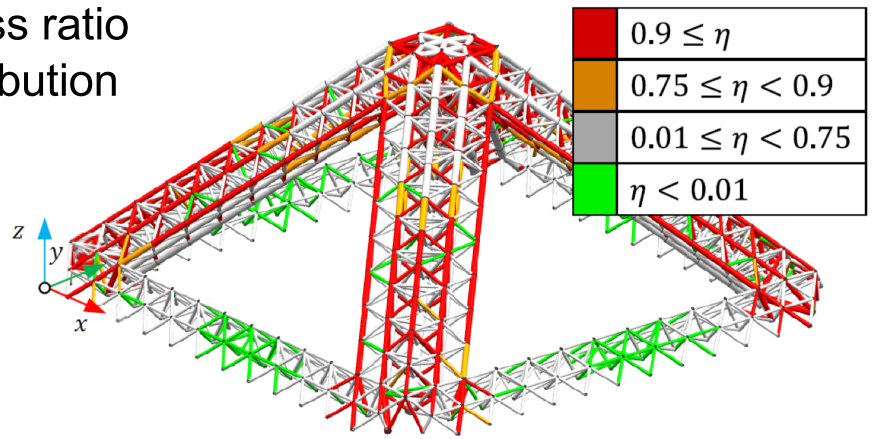
Hierarchical Lattice Optimization for Anisotropy

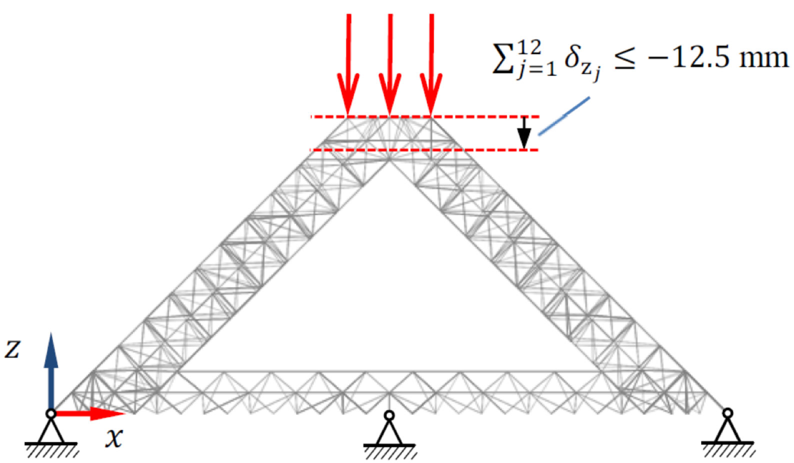
2165 Members
577 Nodes



50x50x25 mm³

Stress ratio distribution





	Properties based on:	Mass [g]
1	Compression test	1.19
2	Tensile test	1.12
3	1 and 2 together	1.19
4	Full anisotropy	1.25

On average 58 steps for the optimization

Comparison 2-4: 414 members would fail