Welcome to CSC2521
Computational Design and Fabrication

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A Third Industrial Revolution

The Economist (Cover)

What you will learn in **CSC2521**

- Focused on Computational Side of Fabrication
- Advanced computer graphics methods
  - Geometry processing
  - Solid modeling
  - Simulation (FEM)
  - Optimization
- Latest research in computer graphics and fabrication

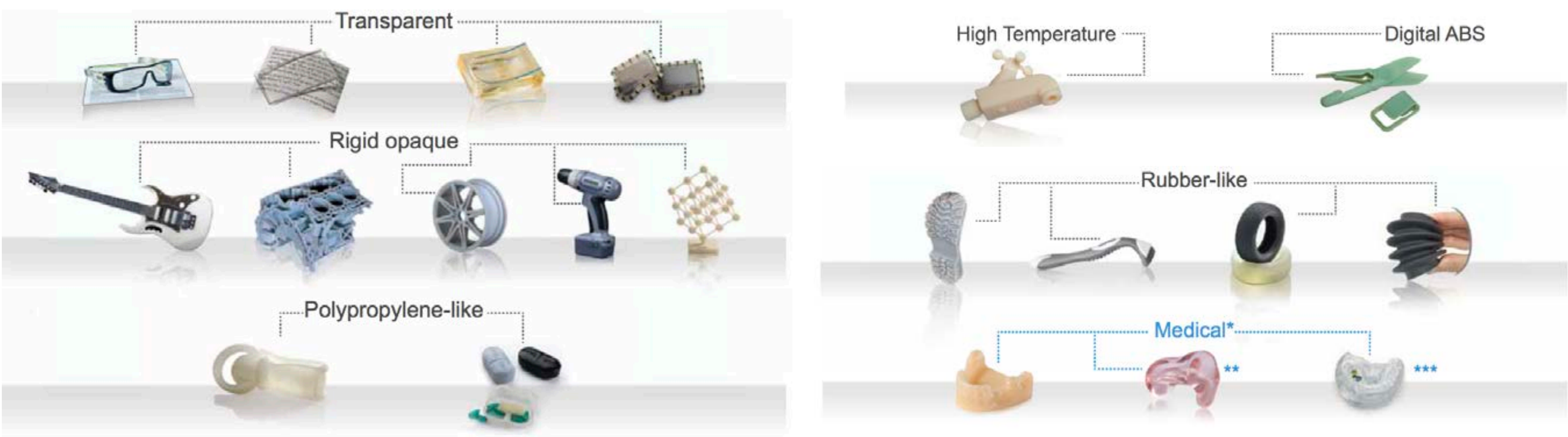
What are the challenges?

Challenges: Hardware

- Slow
  - Printing 5’’ x 5’’ x 5’’ object takes 10+ hours
- Expensive
  - $100 / lb
- Size

Challenges: Materials

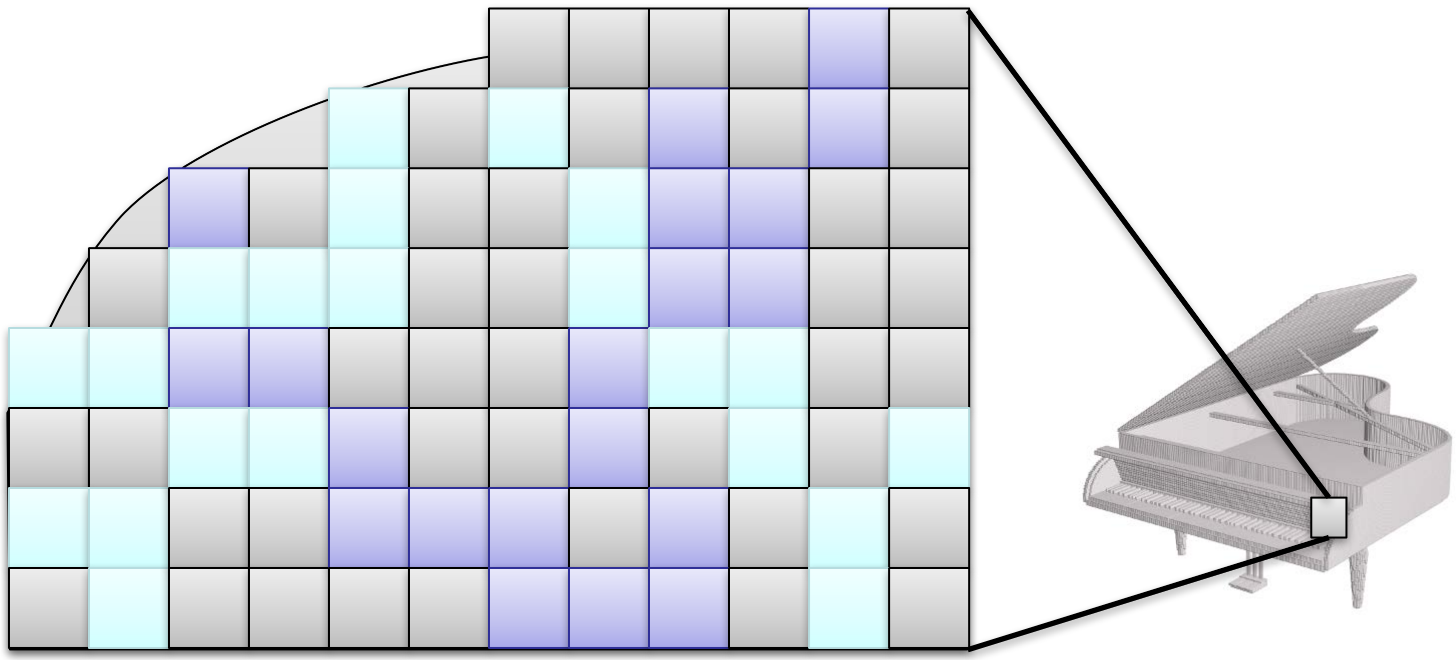
- Functional Materials
- Large Material Library for AM



Courtesy of Stratasys

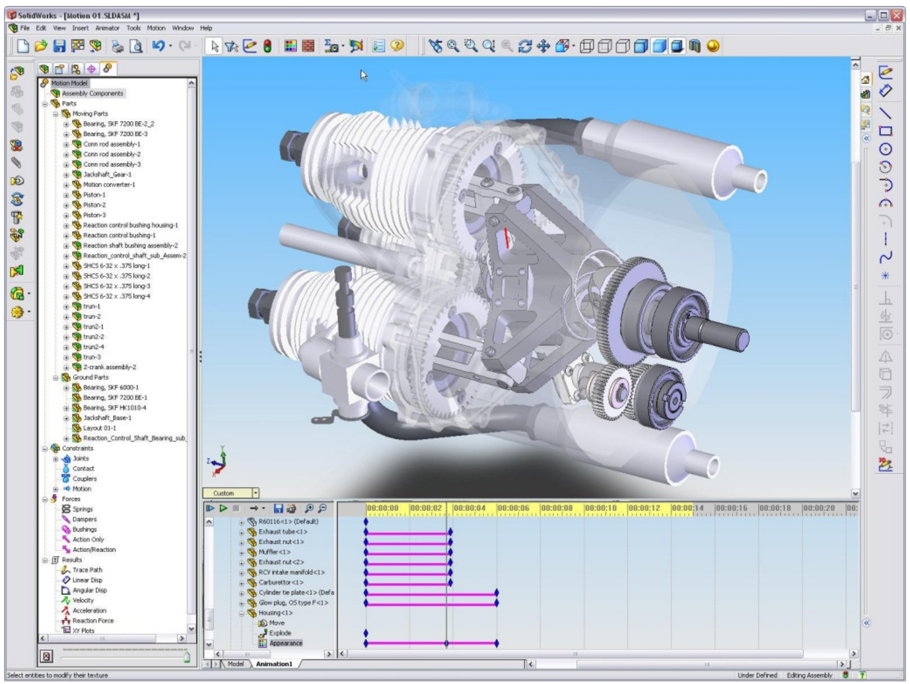
Software Challenges: Data Requirements

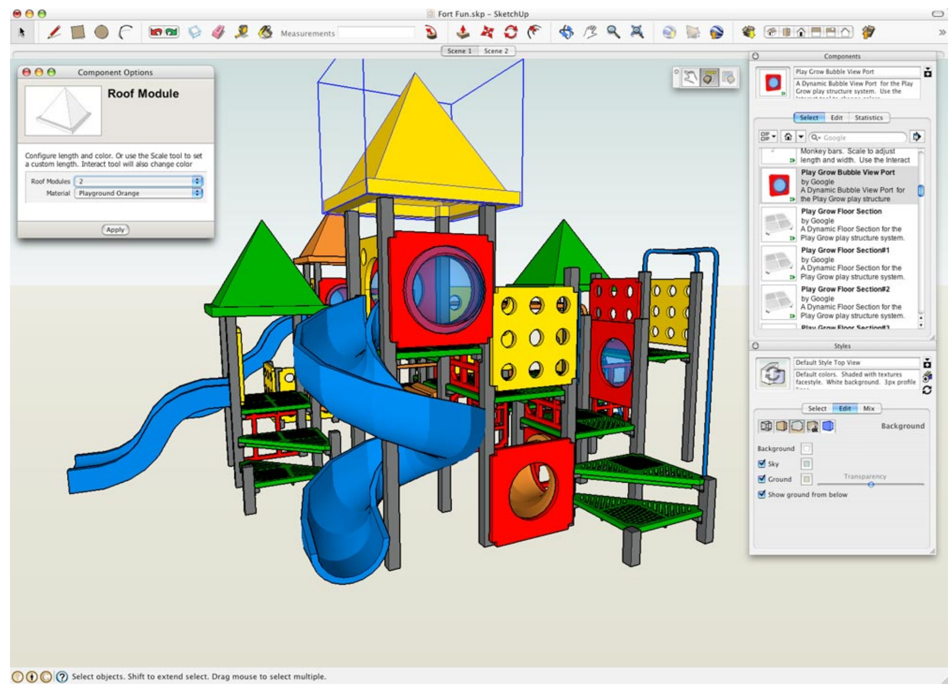
- Giga voxels/inch^3, Tera voxels/foot^3



Challenges: Modeling Interfaces

- 3D modeling is difficult

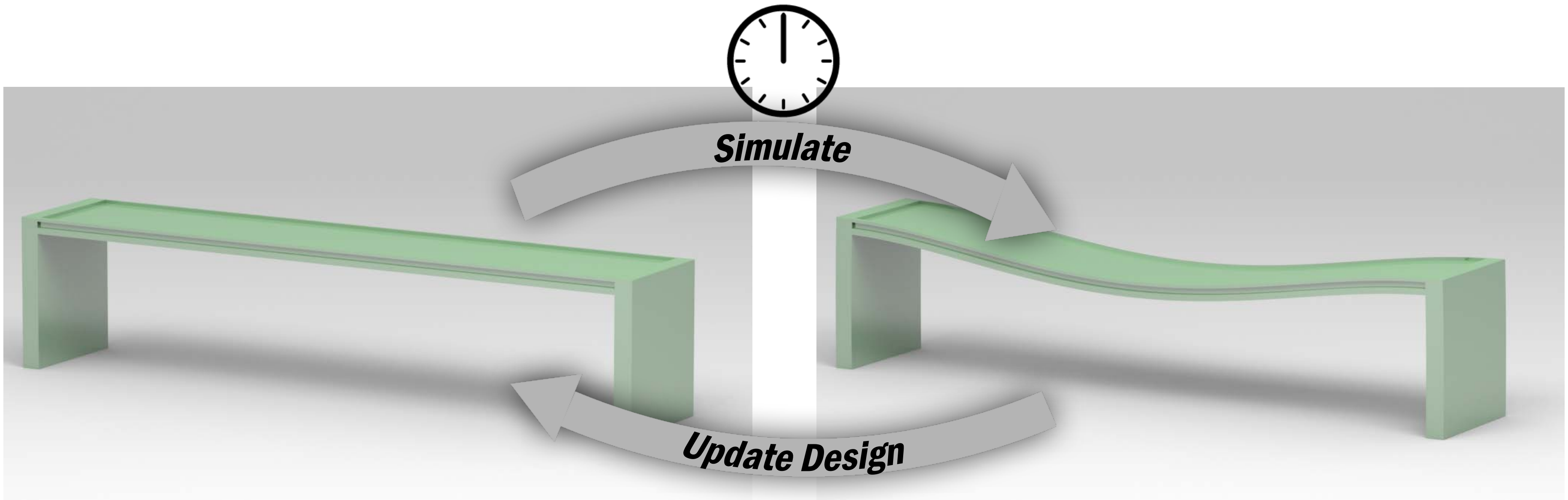




Challenges: Modeling Materials

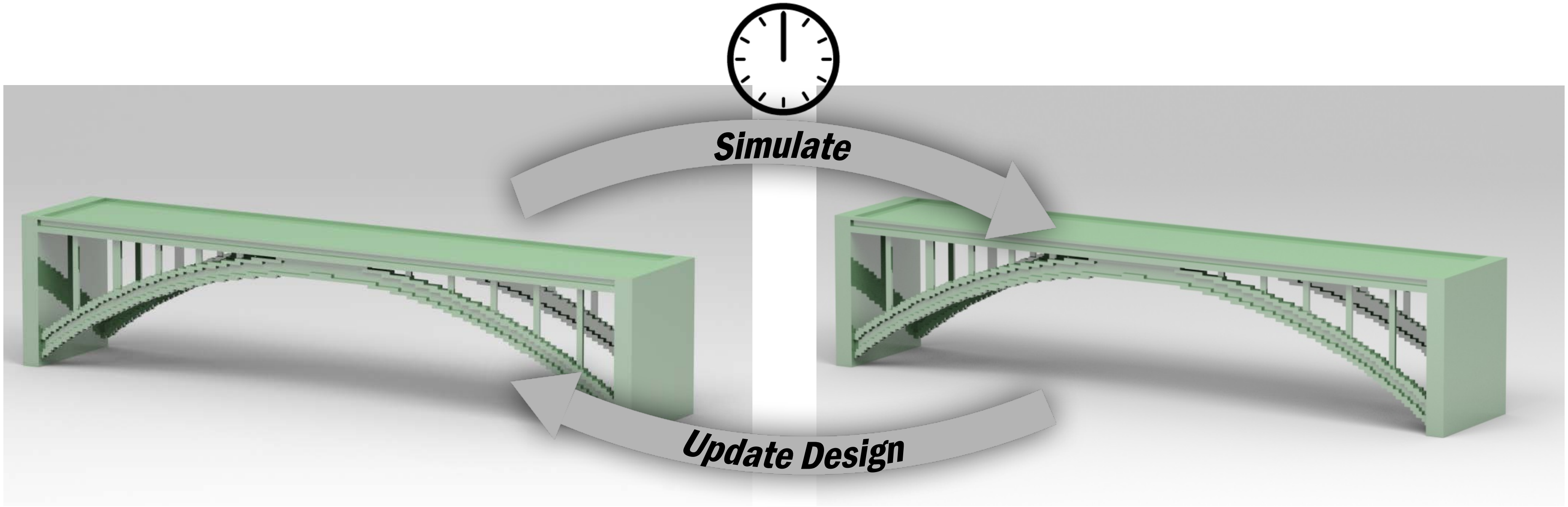
- Focus on 3D geometry
- Currently one material per part
- How to model parts composed of many materials?

Challenges: Fast and Accurate Simulation



Digital Design **Simulation**

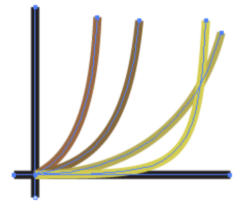
Challenges: Fast and Accurate Simulation



Digital Design **Simulation**

Challenges: Fast and Accurate Simulation

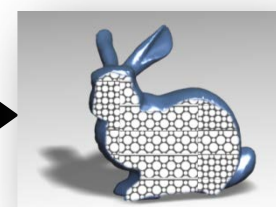
Measurement



Base Materials

Material Library

External Conditions
(e.g. forces, lighting)



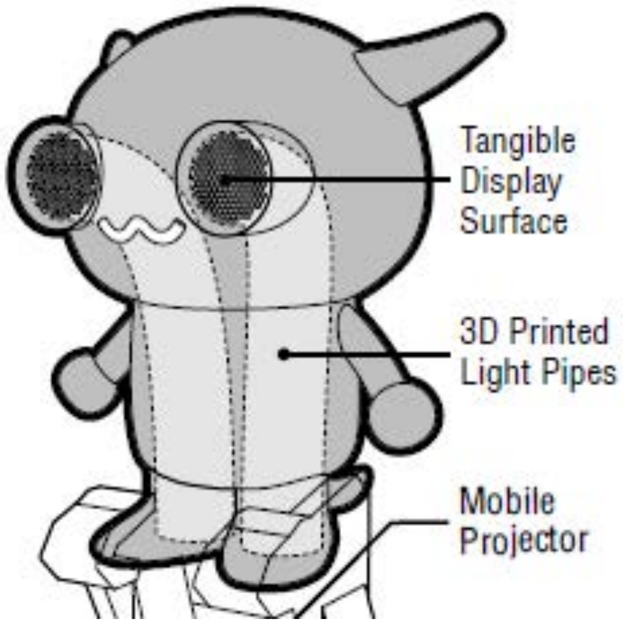
Simulation

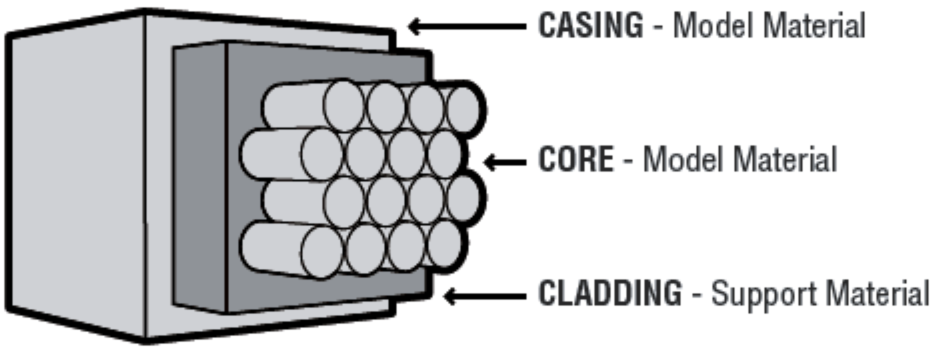
Geometry

What are the applications?

Applications: Fabricating Refractive Materials

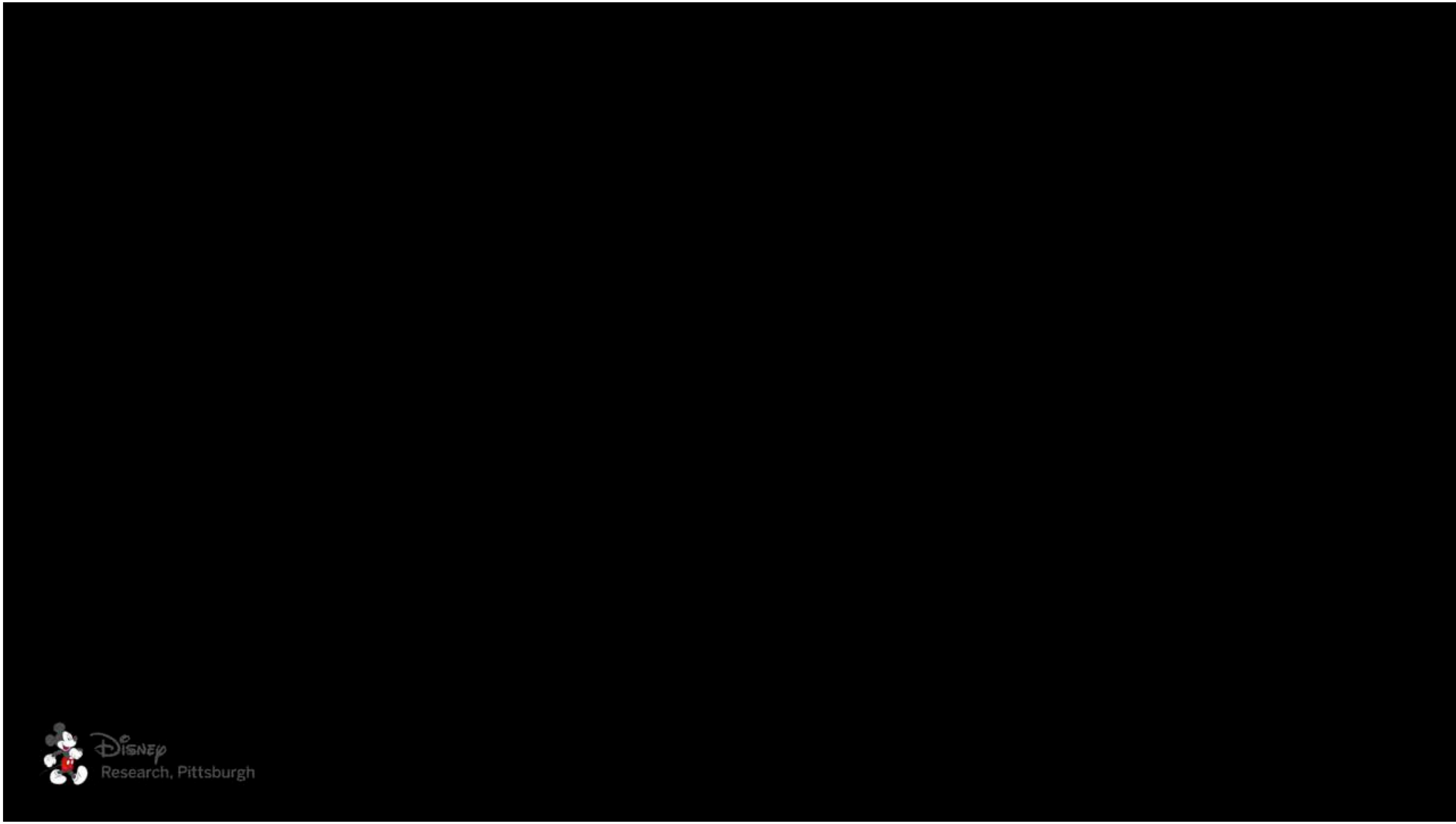
Willis et al. 2012





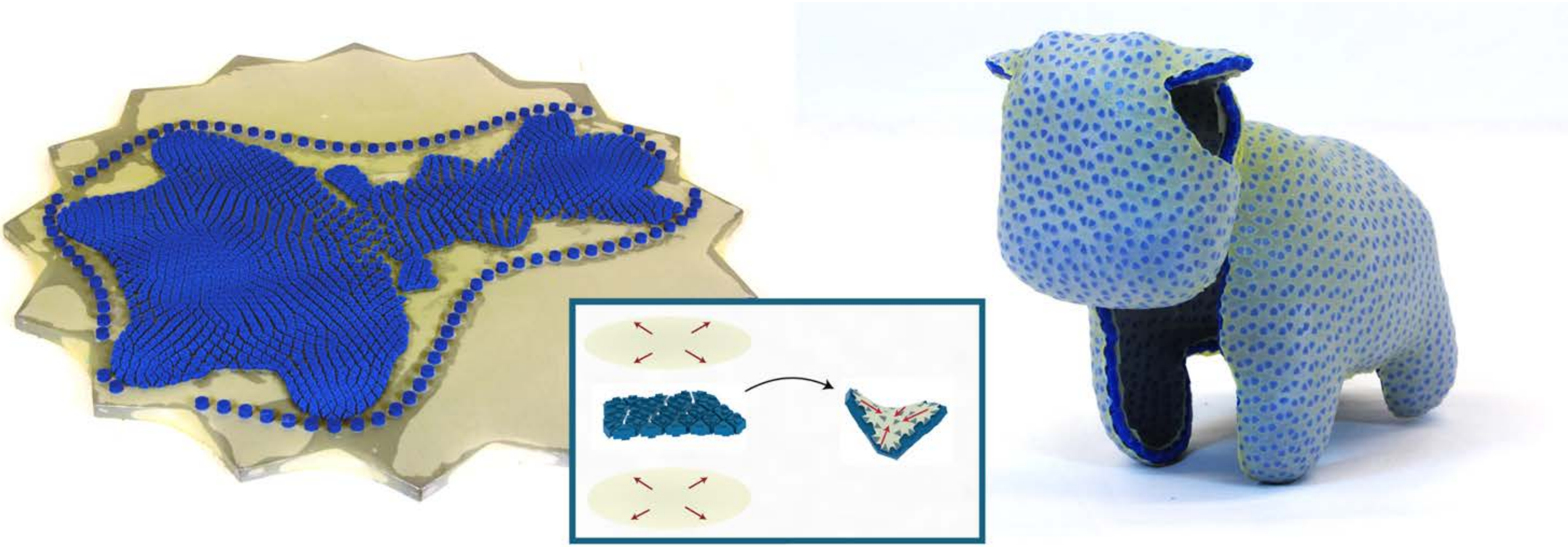
Applications: Fabricating Refractive Materials

Willis et al. 2012

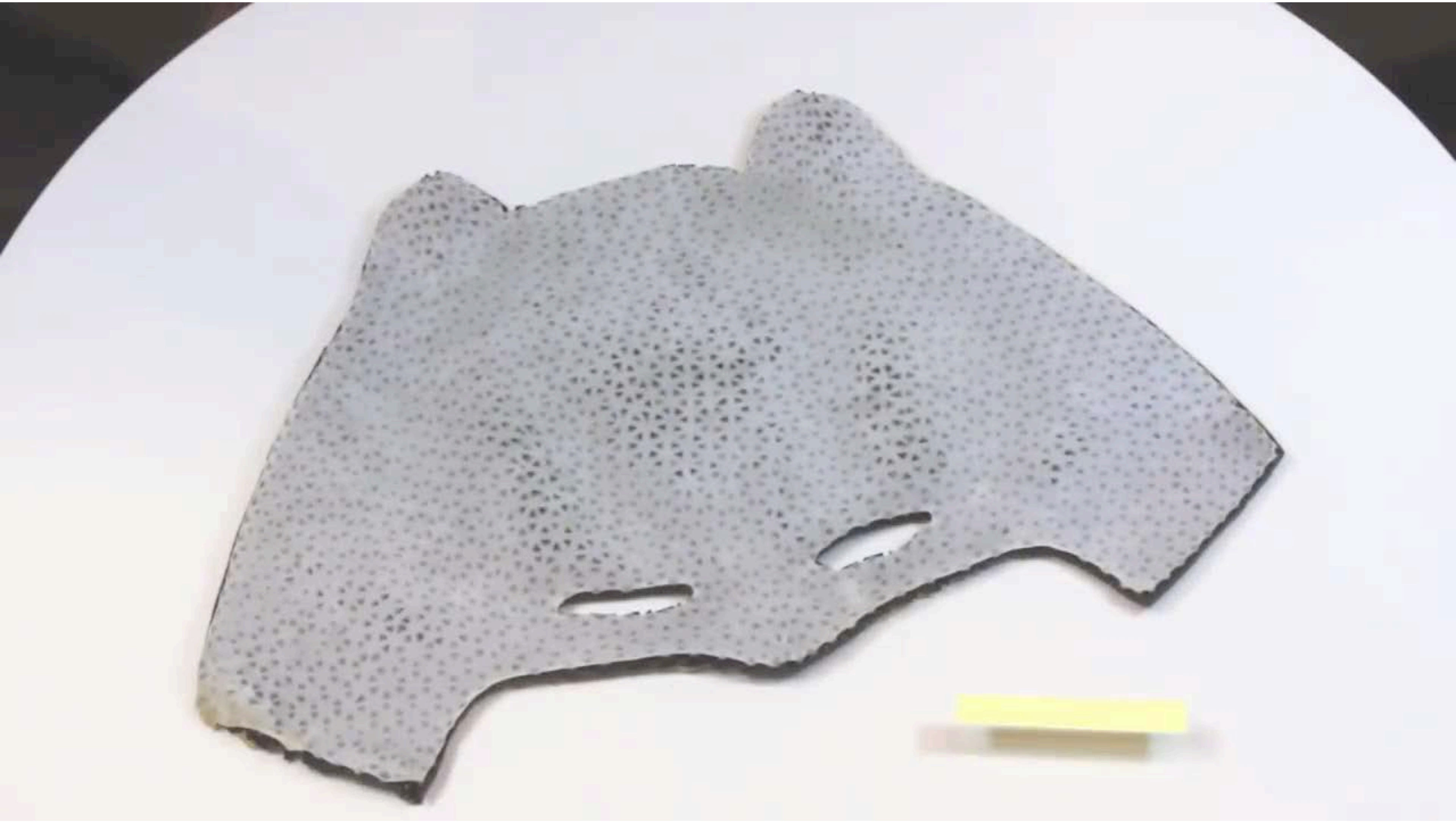


Applications: Self Assembly

Guseinov et al. 2017



Applications: Self Assembly



Plan

- Overview of computational fabrication
- **Administration**
- Overview of the semester
- Overview of the assignments
- 3D Printing Hardware

Prerequisites

- No strict prerequisites
- All assignments require some programming
  - C++, Matlab
- Calculus, linear algebra
  - solving equations, derivatives, integrals
  - vectors, matrices, basis, systems of equations
  - if these things seem scary come and talk to me

Communication

- Website:
  - Syllabus etc on Quercus
  - https://github.com/dilevin/DGPCompFab
- Contact: diwlevin@cs.toronto.edu
- Office Hours:
  - BA5268
  - What’s a good time ?

Grading Policy

- Assignments: 50%
  - 5 assignments (10% each, completed individually)
- Project: 40%
  - Final presentation: 20%
  - Final report: 20%
- Participation: 10%
  - Talk in Class
- No midterm/final

Assignments

- Turn in a report
- Turn in code and executable (if appropriate)
- Collaboration policy
  - The assignments should be done **individually**
- Late policy
  - 10% per day
  - 3 late days to use without questions
  - Other extensions, come and see me
- Academic Honesty Policy on the Quercus website

Assignments

1. Shape Modelling (C++)
2. Optimization (C++)
3. Intro to Simulation (C++)
4. Finite Element Methods (C++)
5. Mechanical Linkages (MATLAB)
6. Topology Optimization (maybe)

Projects

- Final project presentations (20%)
  - due December 5th
- Project report (20%)
  - due December 19th
  - Use the ACM SIGGRAPH format
  - https://www.siggraph.org/learn/instructions-authors

Projects

- We’ll discuss next lecture
  - Done in groups
  - I’ll pitch some ideas to choose from
  - Pitch your own idea, make a slide, present!

Questions?

Plan

- Overview of computational fabrication
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- **Overview of the semester**
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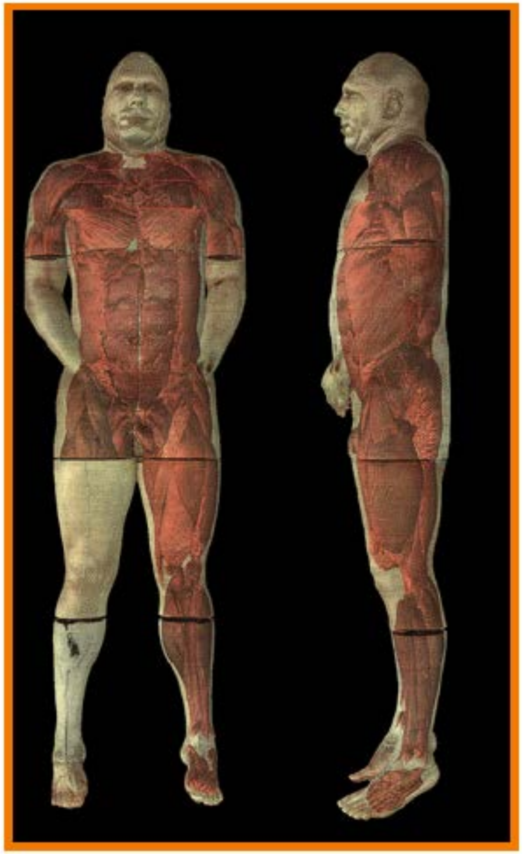
Overview of the Semester

- Solid and Procedural Modelling
- Continuous Optimization
- Physics Simulation
- Materials
- Mechanisms
- Topology Optimization

Solid Modeling

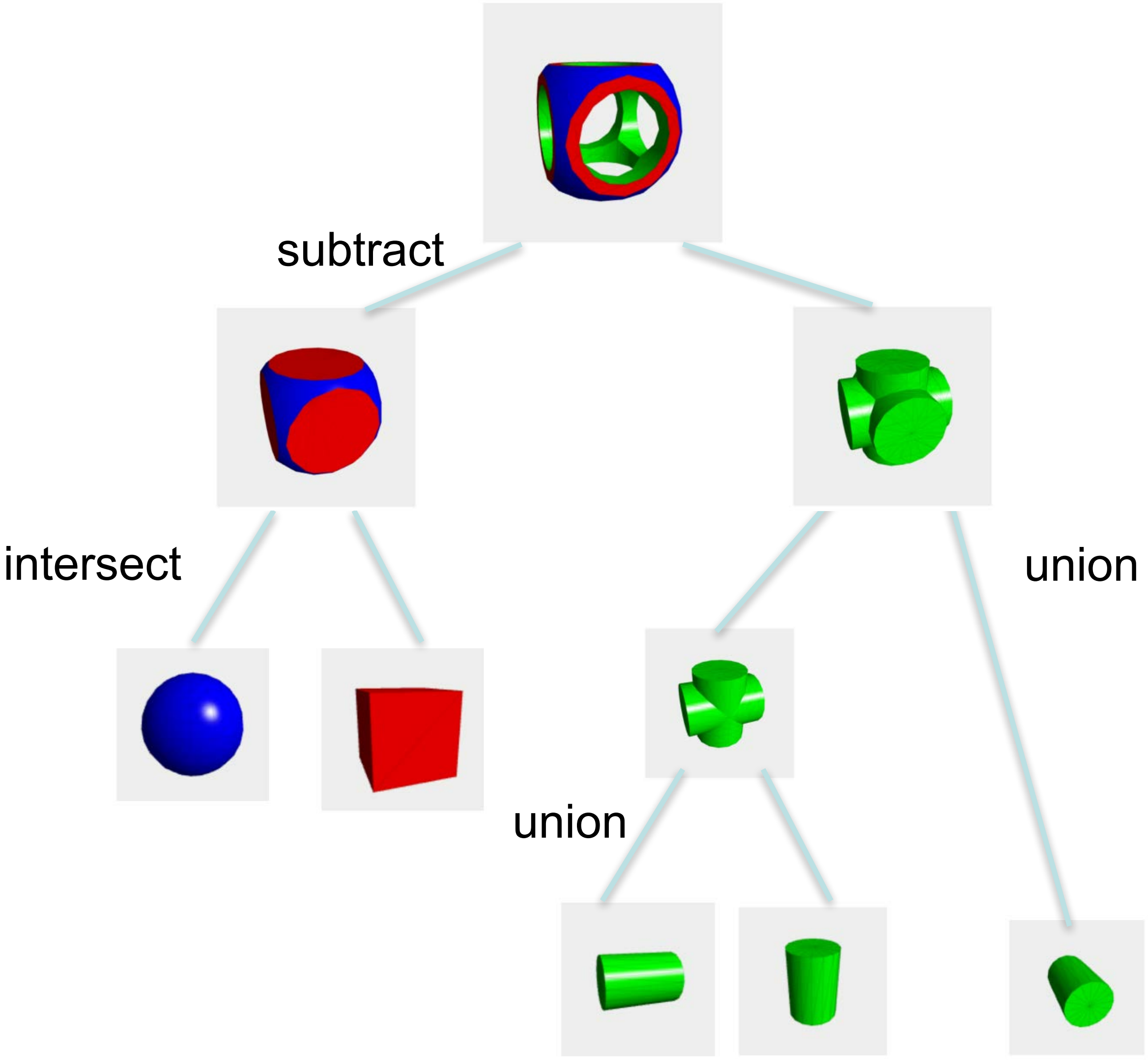
- Represent solid interiors of objects



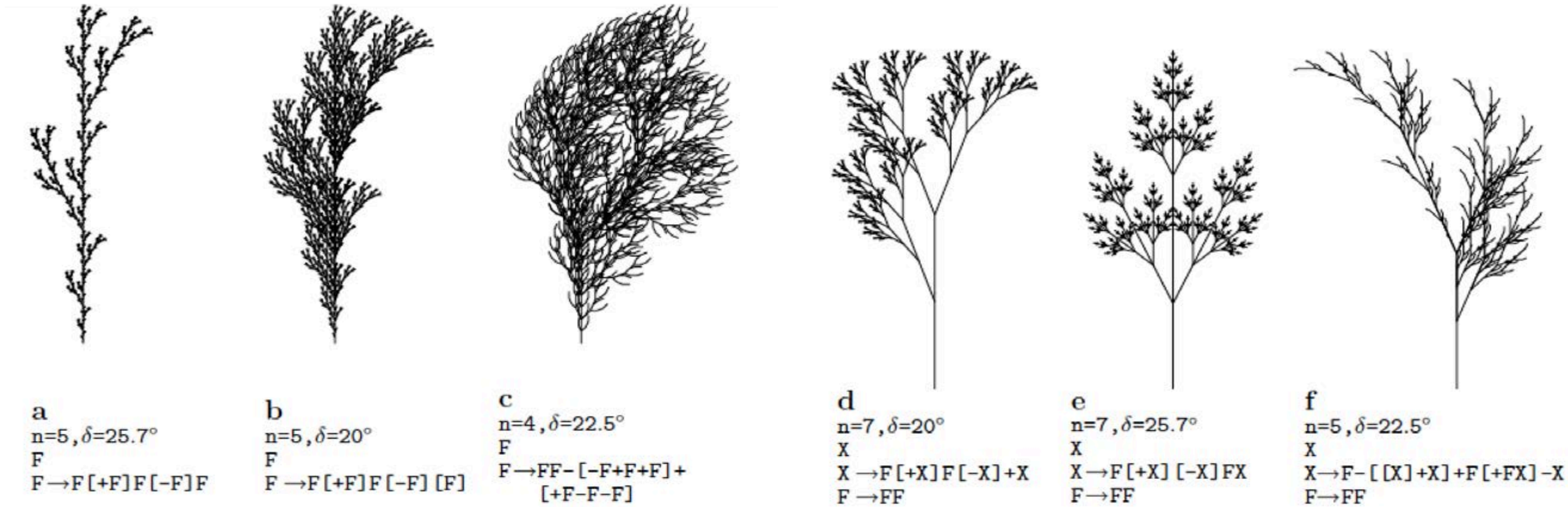
Visible Human
(National Library of Medicine)

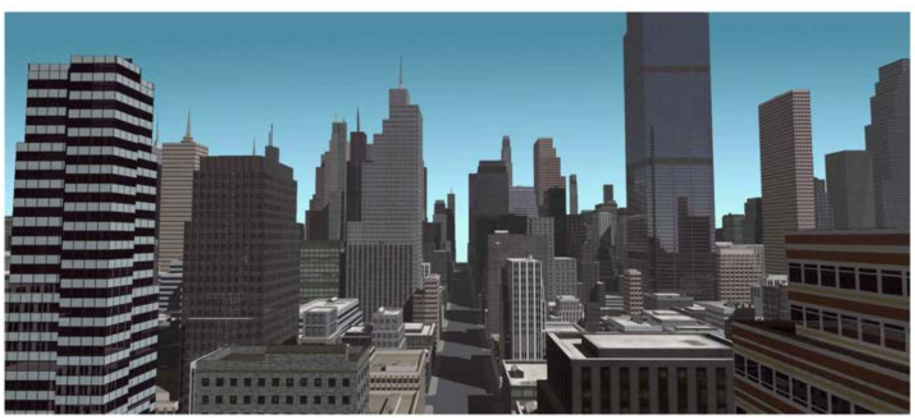
SUNY Stony Brook

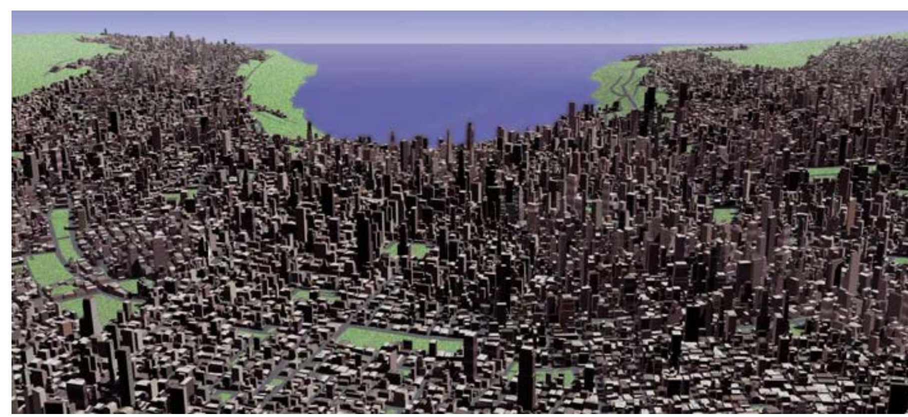
Constructive Solid Geometry (CSG)



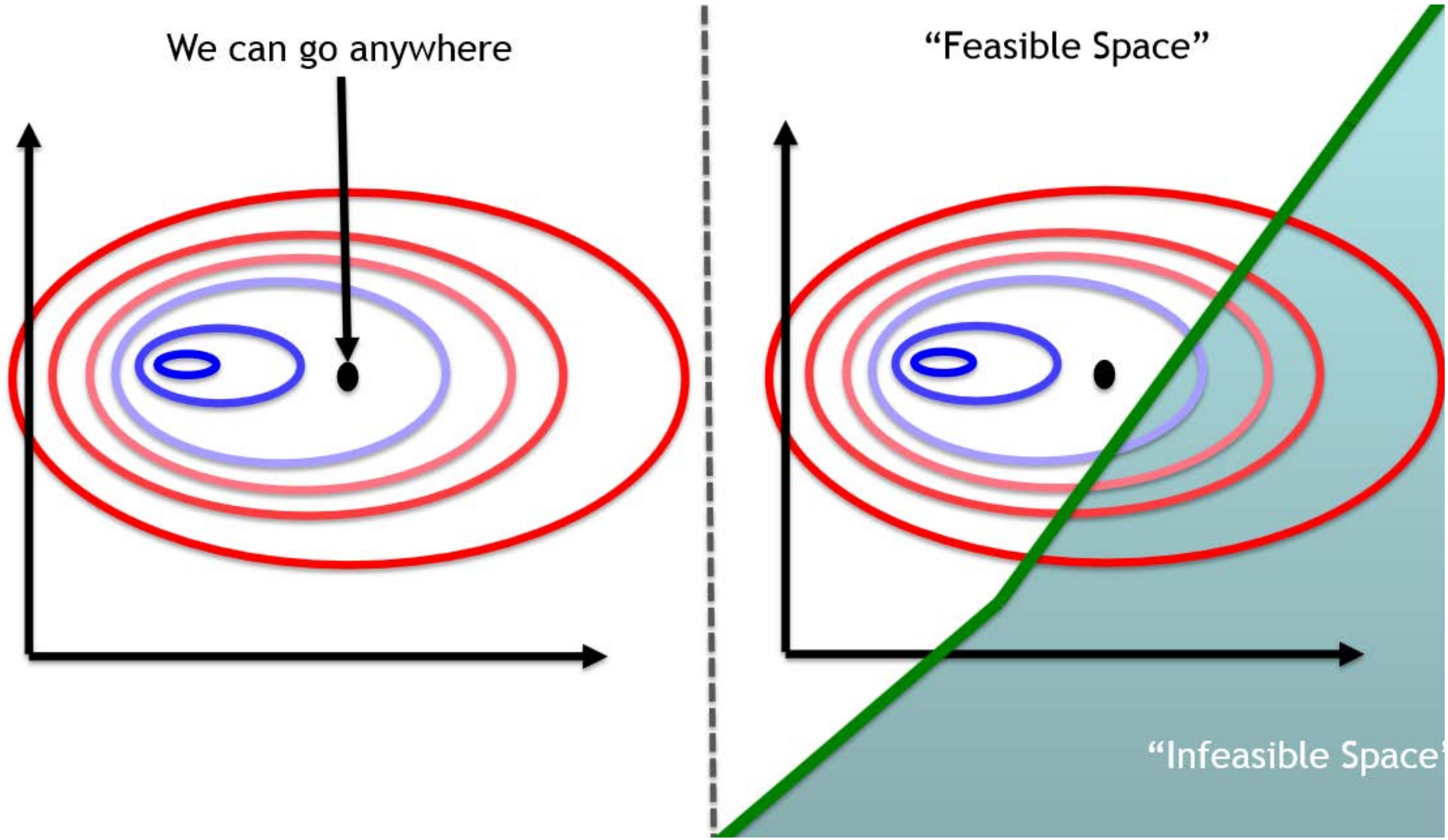
Procedural Geometry





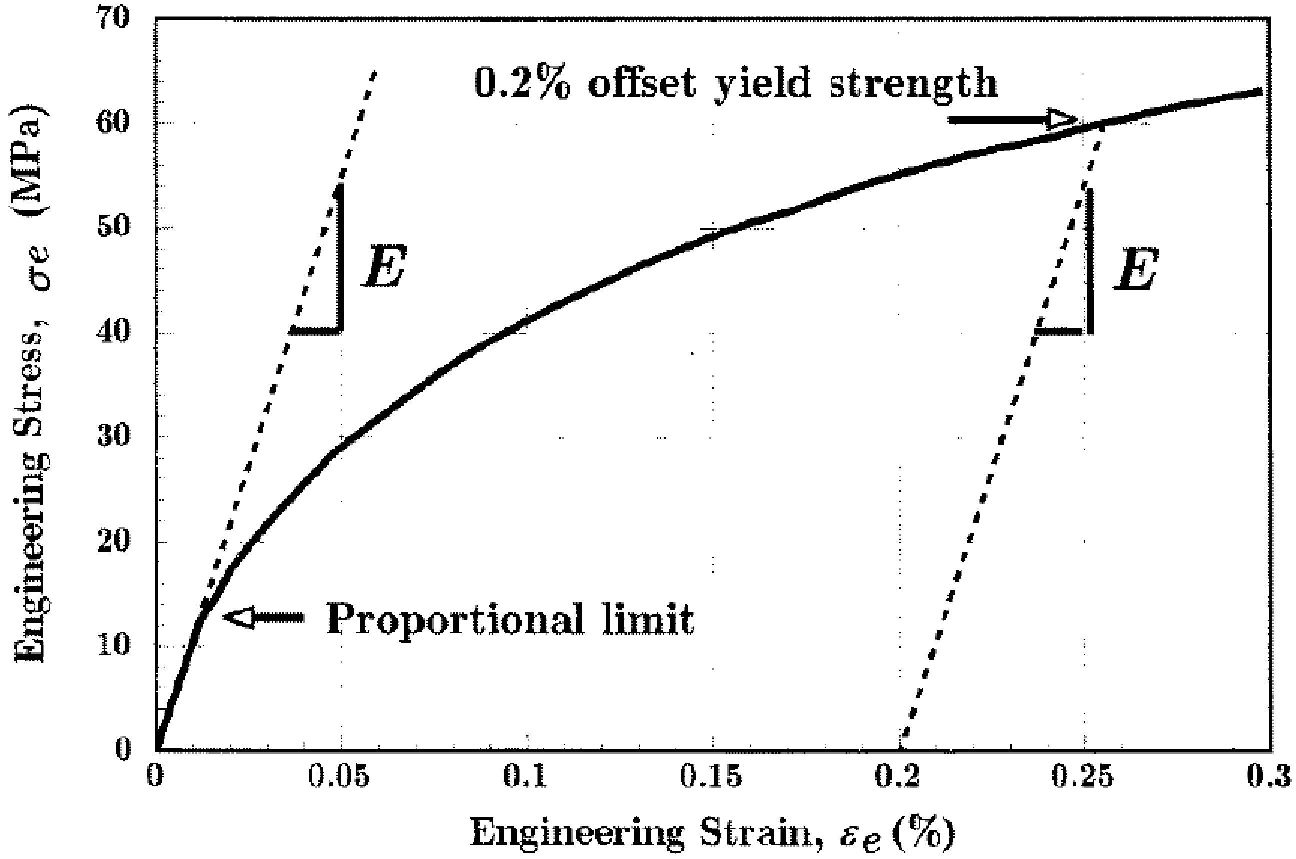


Optimization

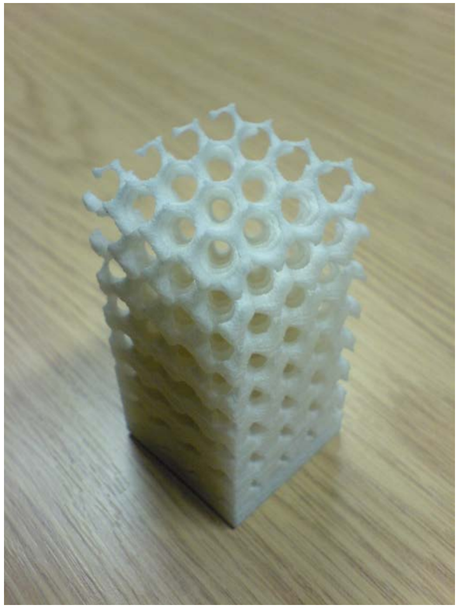


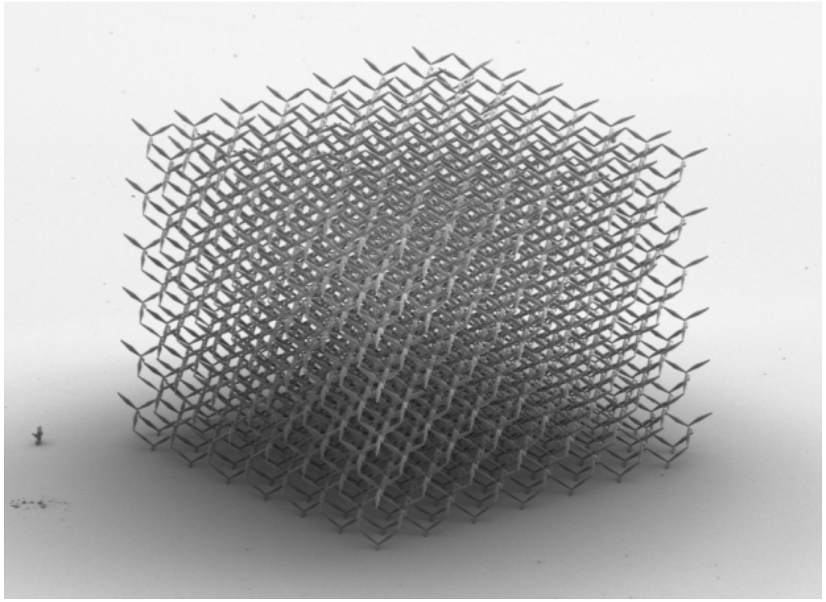
The Finite Element Method

Material Models

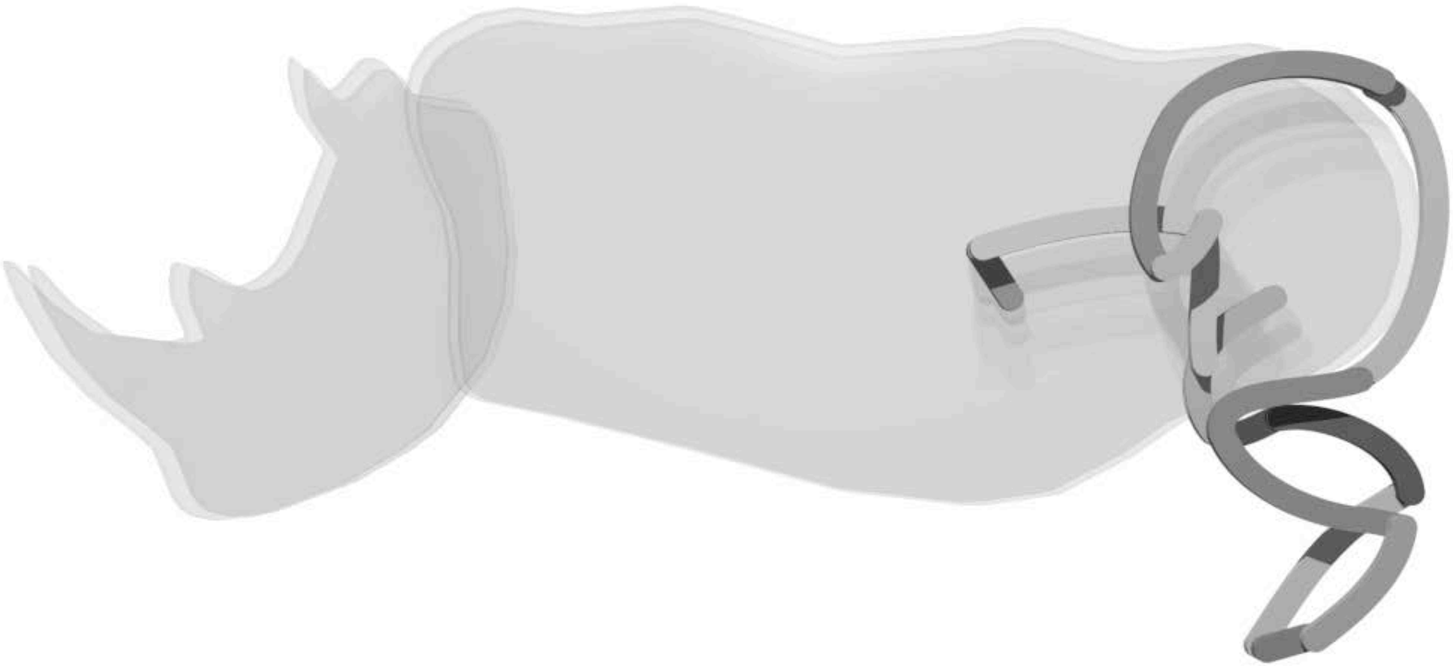


Advanced Materials

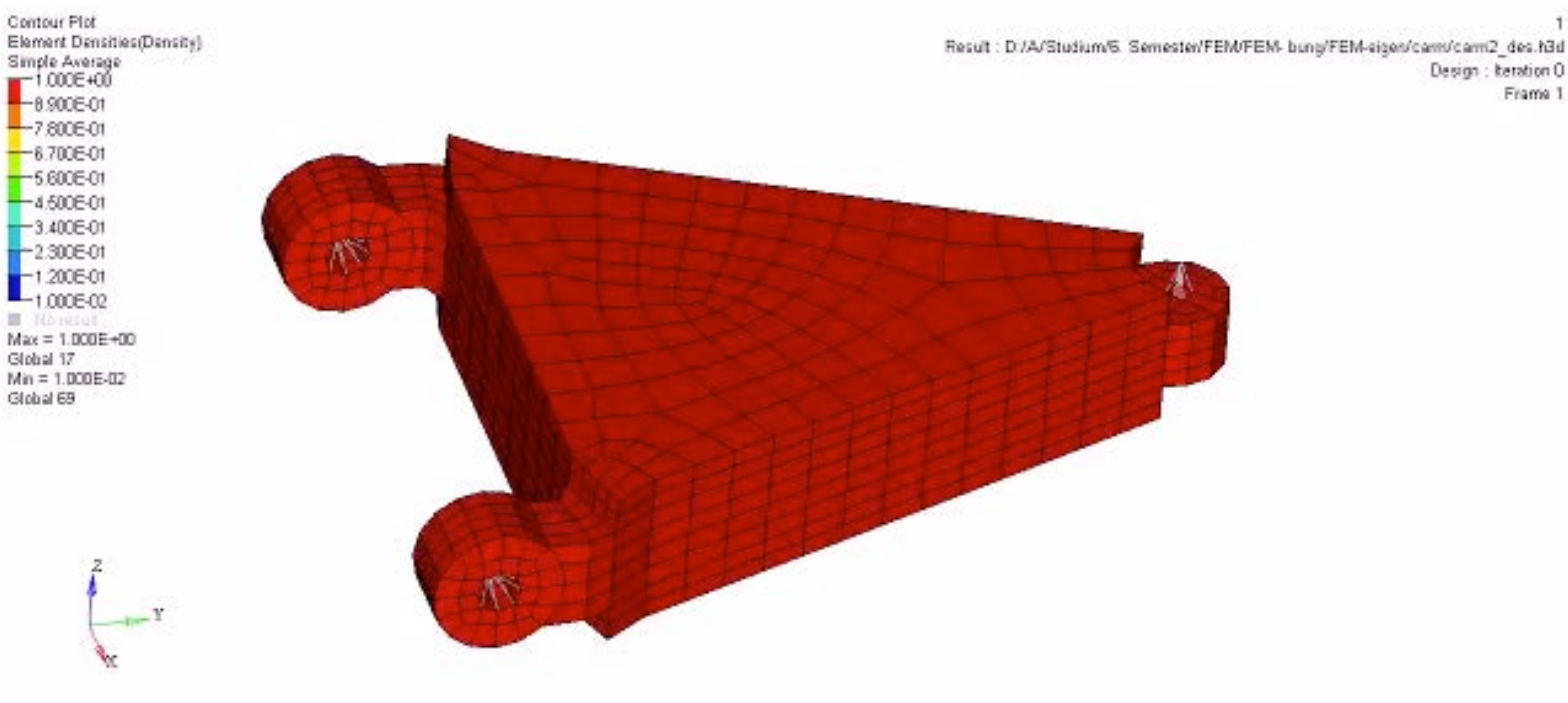




Mechanisms



Topology Optimization



Questions?

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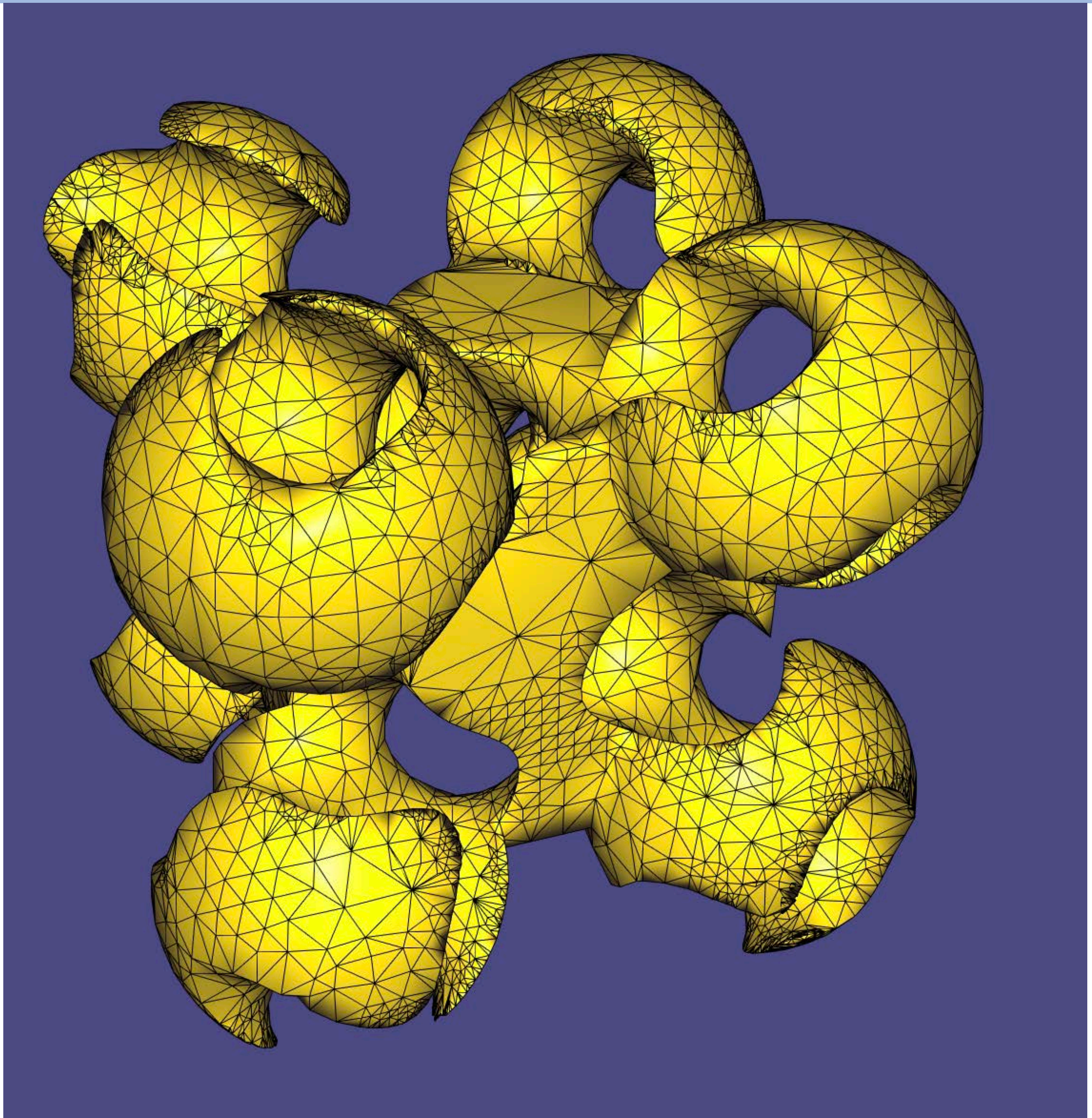
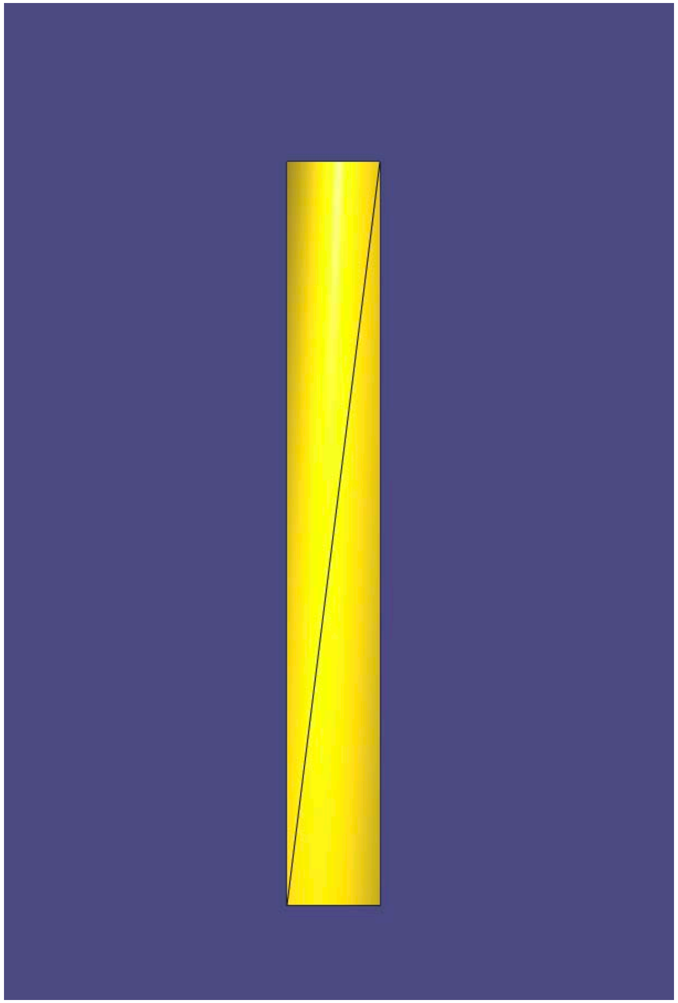
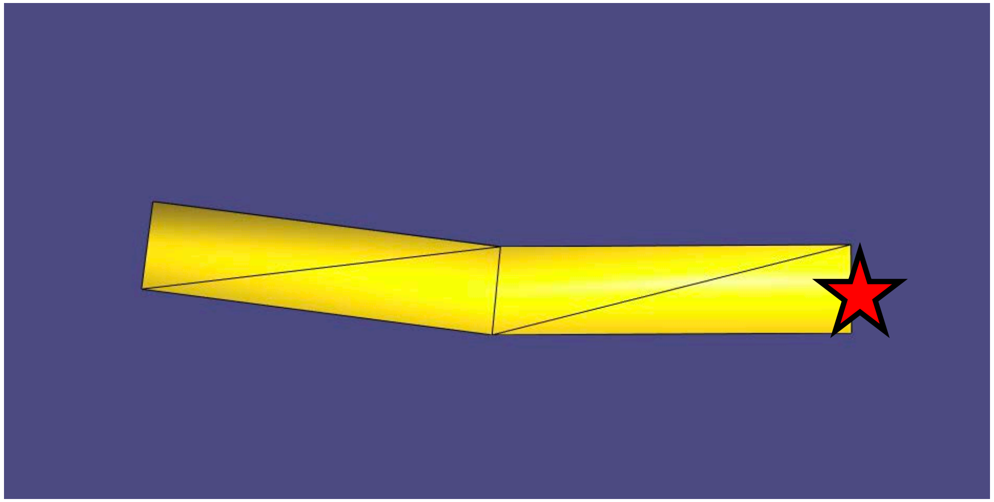
Assignment 1: Modelling



Assignment 2: Optimization

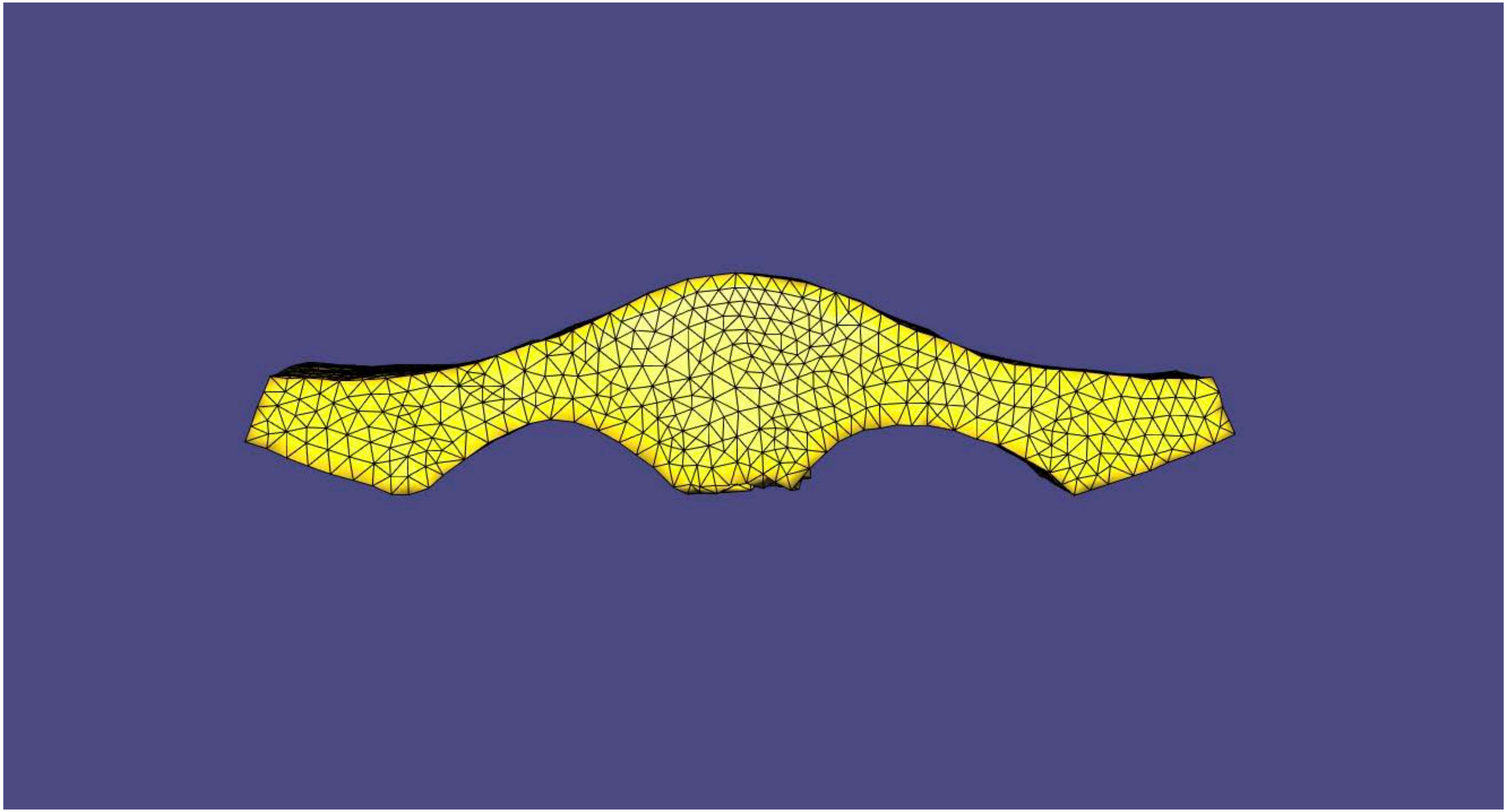


Initial State



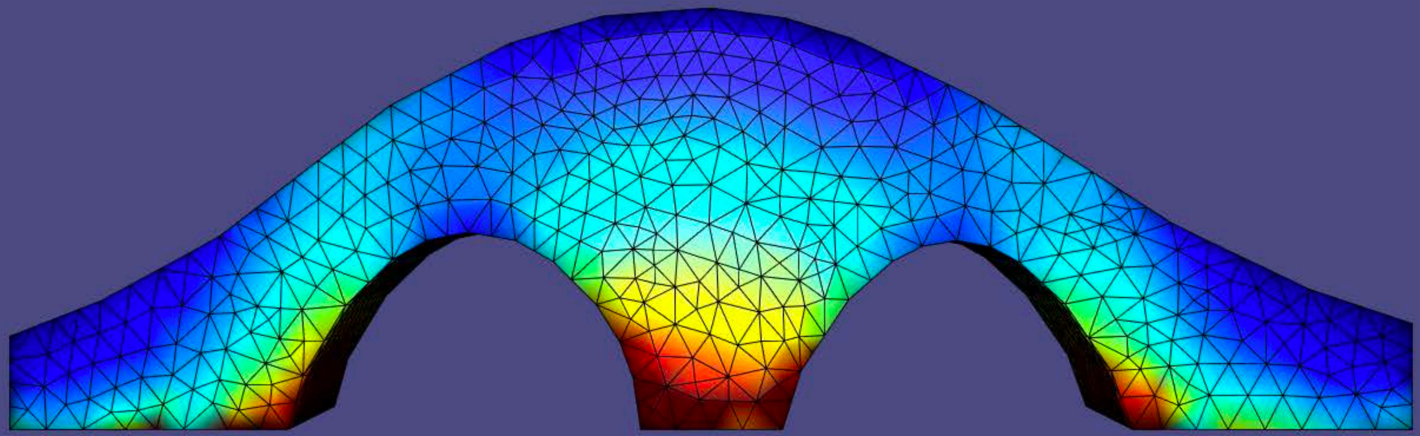
Final State

Assignment 3: Intro to Simulation



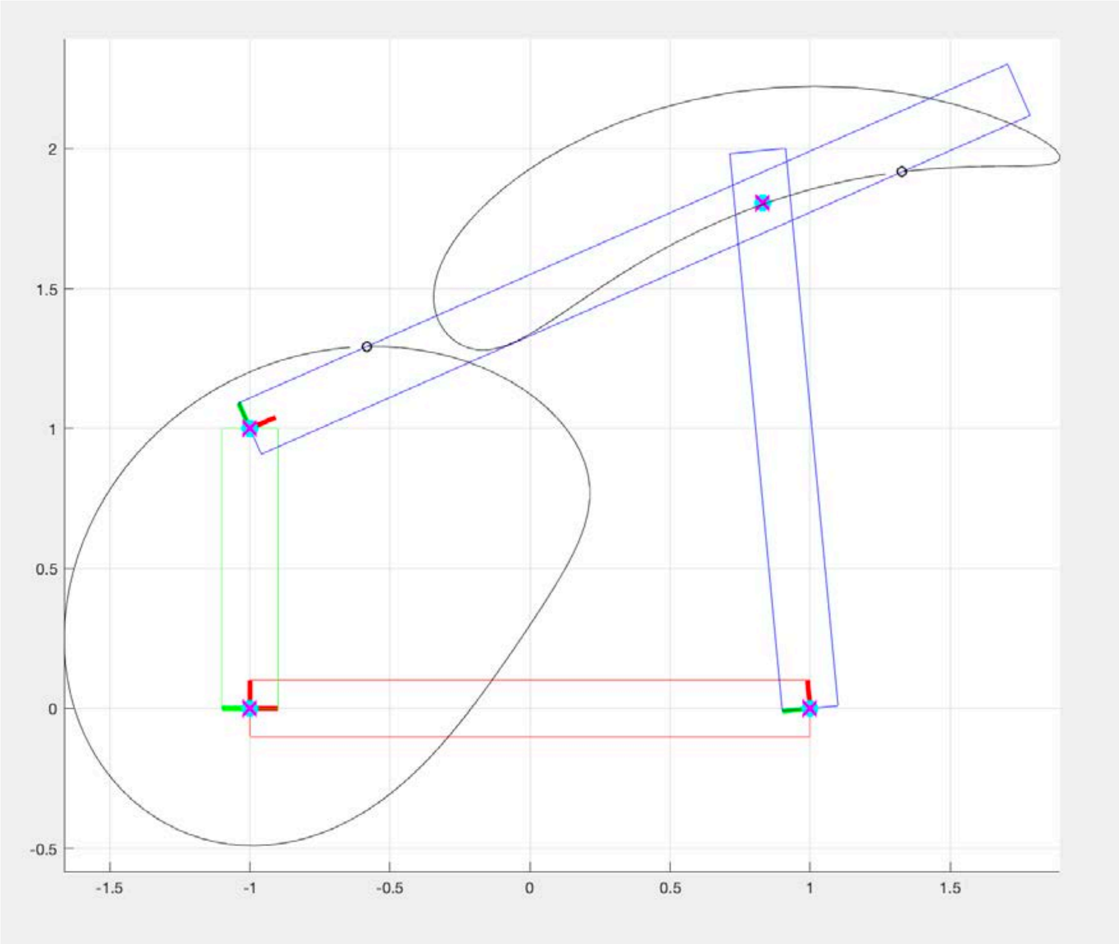
Bouncy Bridge

Assignment 4: Finite Element Method



Mechanical Stresses in Bridge

Assignment 5: Mechanism Design



Four-Bar Linkage

Plan

- Overview of computational fabrication
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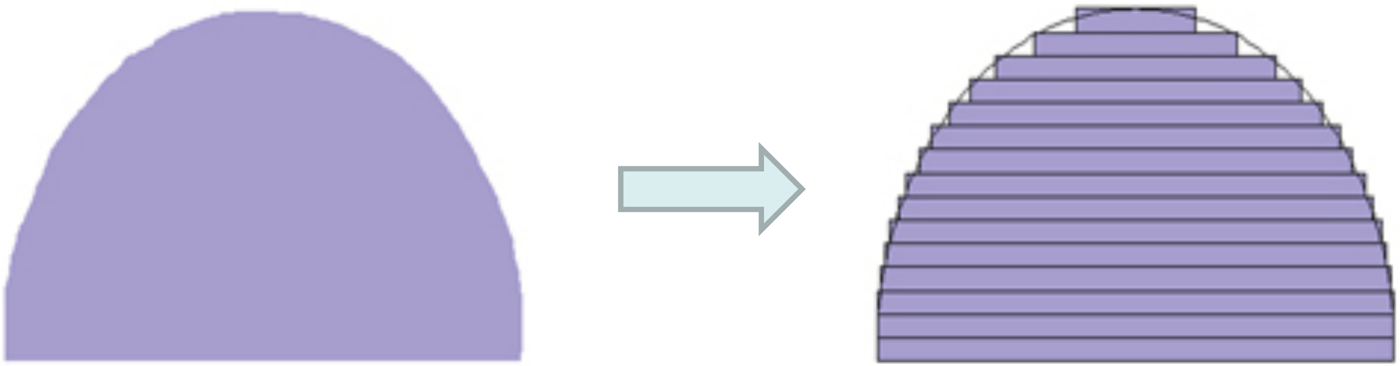
- **3D Printing Hardware**

3D Printing = Additive Manufacturing

https://commons.wikimedia.org/wiki/File:3D_printing_on_replicator_2.webm

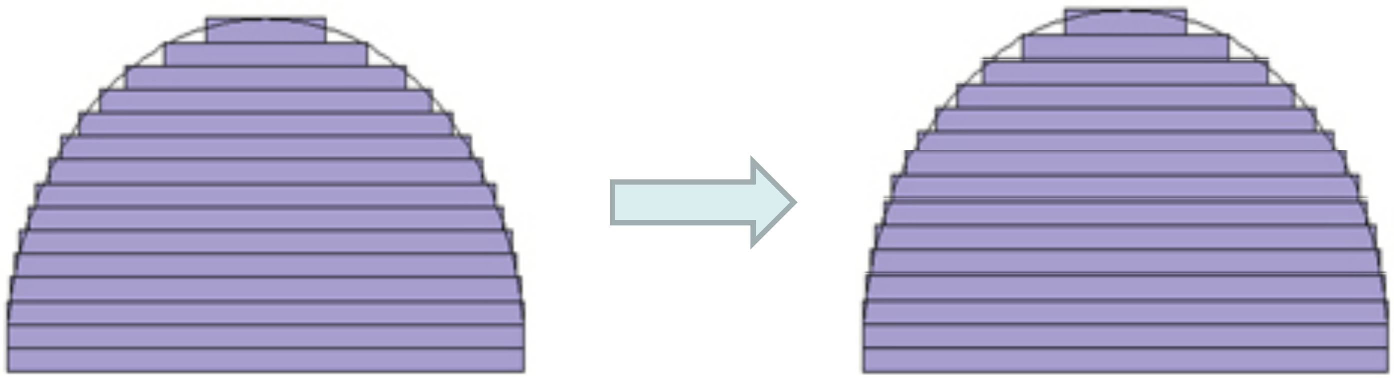
3D Printing Process

- Slice 3D model into layers



3D Printing Process

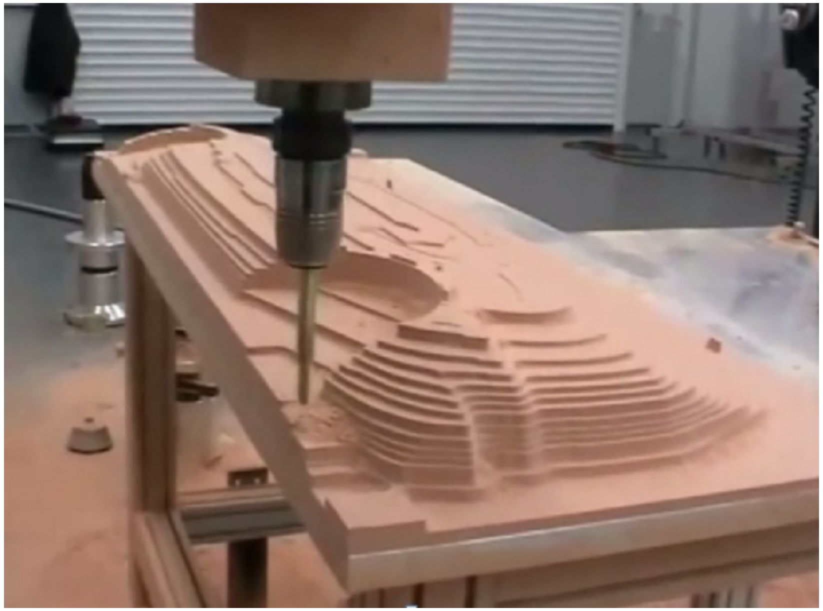
- Slice 3D model into layers
- Manufacture layers one by one (e.g., bottom-up)



Source:
https://commons.wikimedia.org

Subtractive Manufacturing

- Start with a block of material
- Remove material to obtain a given 3D shape



Source:
https://commons.wikimedia.org

Additive Manufacturing Technologies

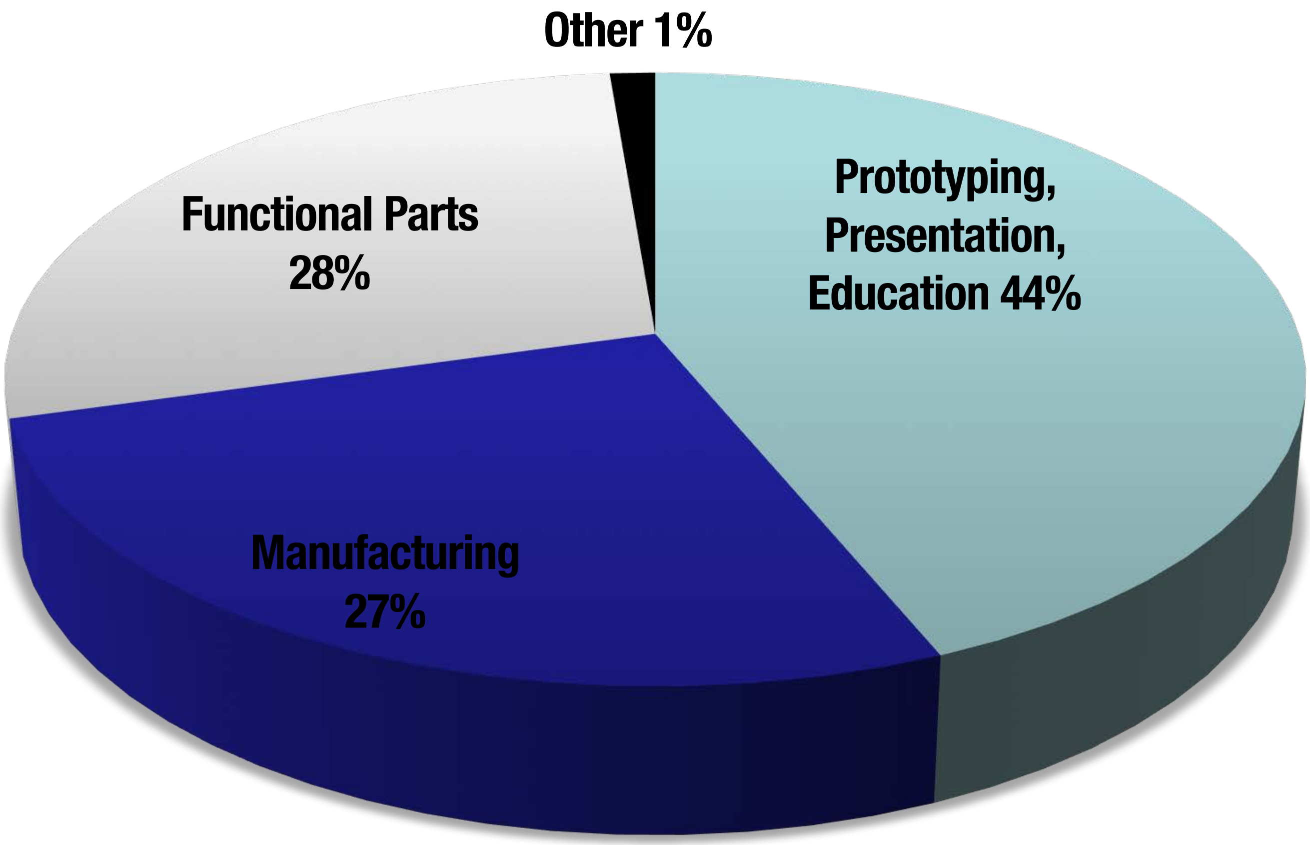
- Fused deposition modeling (FDM)
- Stereolithography (SLA)
- DLP 3D printing
- Selective laser sintering (SLS)
- Direct metal laser sintering (DMLS)
- Plaster-based 3D printing (PP)
- Photopolymer Phase Change Inkjets
- Thermal Phase Change Inkjets
- Laminated object manufacturing (LOM)

Applications of 3D Printing

Why Additive Manufacturing?

- Good for custom parts or short production runs
- Can build objects with complex geometry
- No (or little) waste material

What Is 3D Printing Used For?



Applications: Dental and Medical Industries

Crowns, copings, bridges

Custom Hearing Aids

Implants

Prosthetics

Source: Envisiontec,
on3dprinting.com

Applications: Architecture & Design

Source: aecbytes.com, Z Corp, object.com

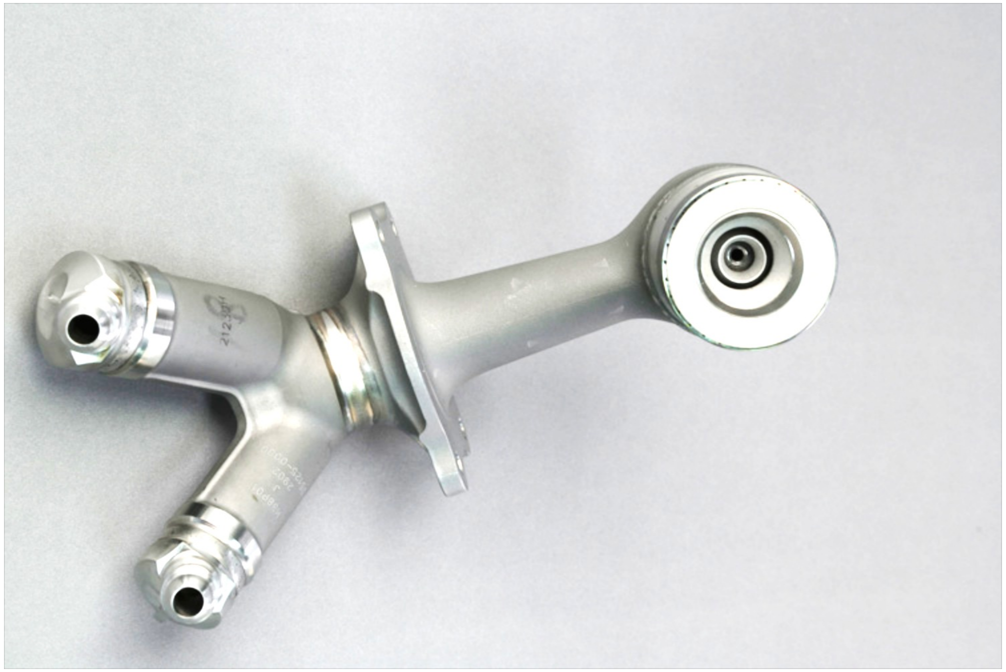
Applications: Automotive

Honeycomb
Tires

3D Printed Ventilation Prototype
(High Temperature 3D Printing
Material)

Source: www.uprint3dprinting.com, gizmodo.com

Applications: Aerospace



3D printed fuel injection nozzle for a jet engine

Airbus wing brackets

Source: GE, 3dprintingindustry.com

Applications: Jewelry

- Direct metal printing and casting patterns



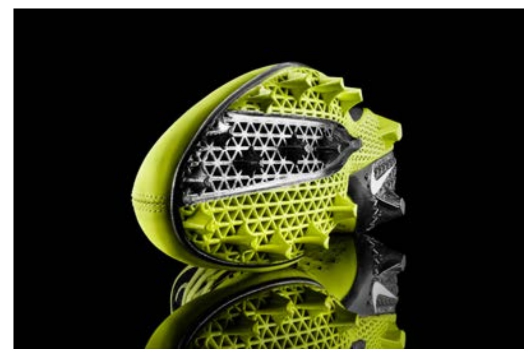


Source: Shapeways, replicatorinc.com

Applications: Footwear





Source: 3dprintingindustry.com,
.rapid3d.co.za

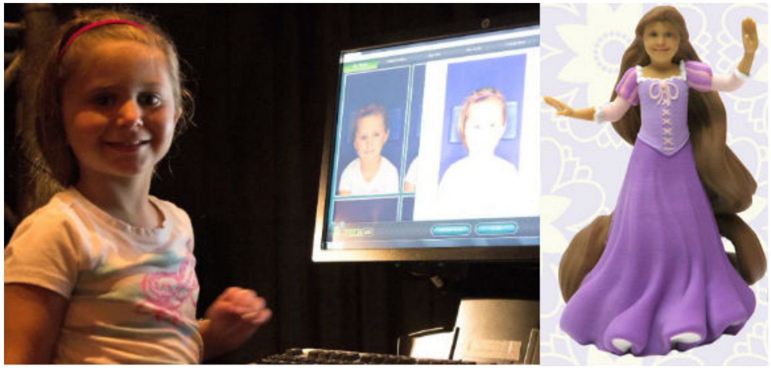
Applications: Consumer Home Products





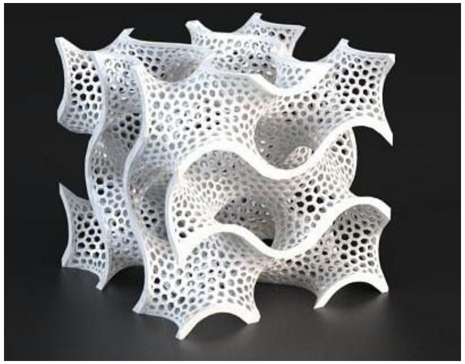
Source: Shapeways

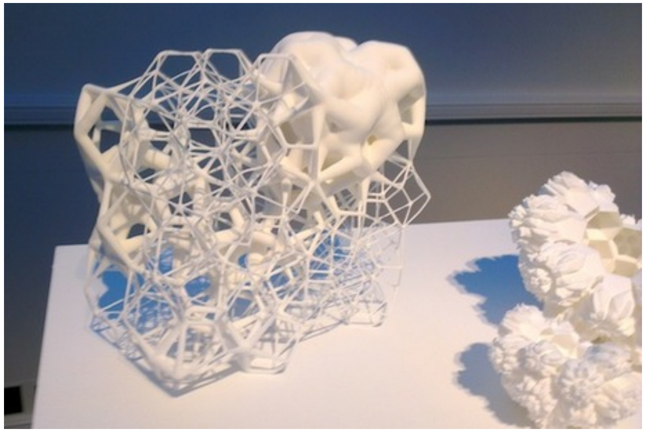
Applications: Toys & Gadgets



Source: Shapeways, singularityhub.com, MyRobotNation.com

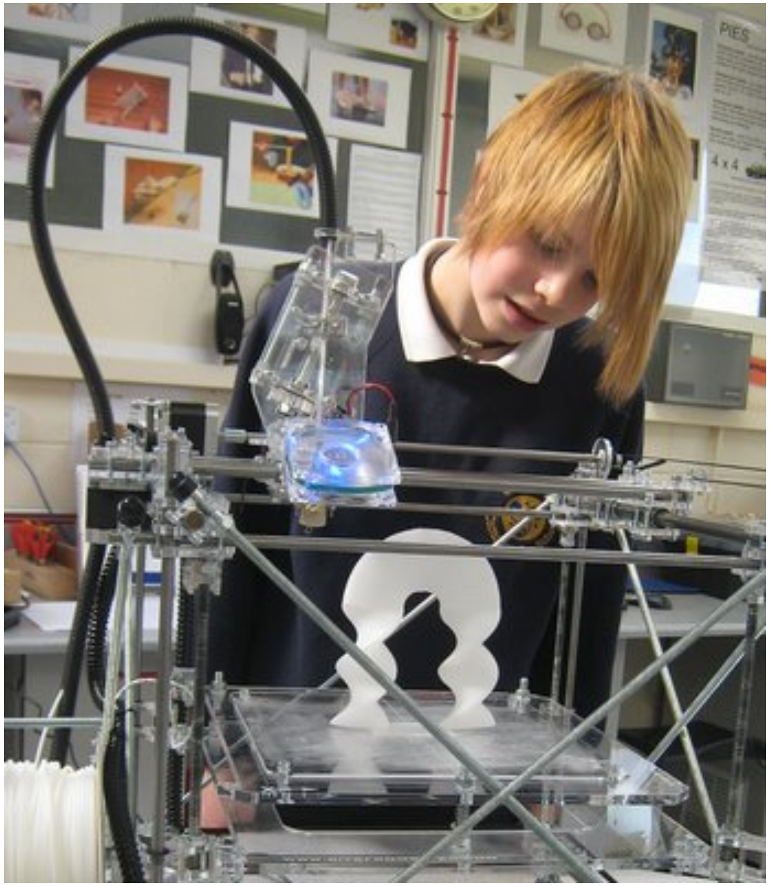
Applications: Art

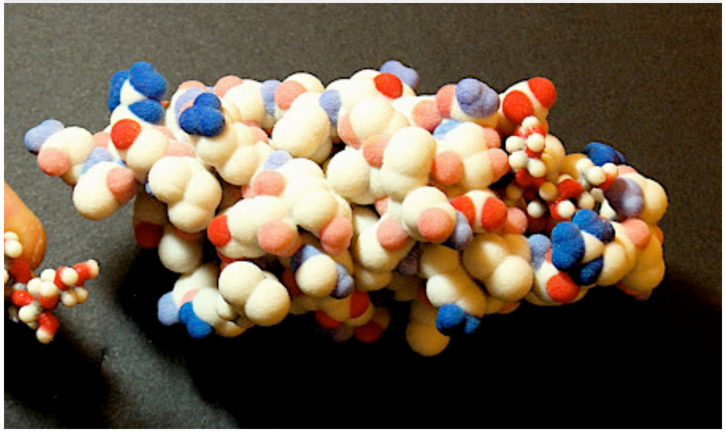




Source: Shapeways, Carlo Sequin,
techdigest.tv

Applications: Education





Source: printcountry.com, designfax.net

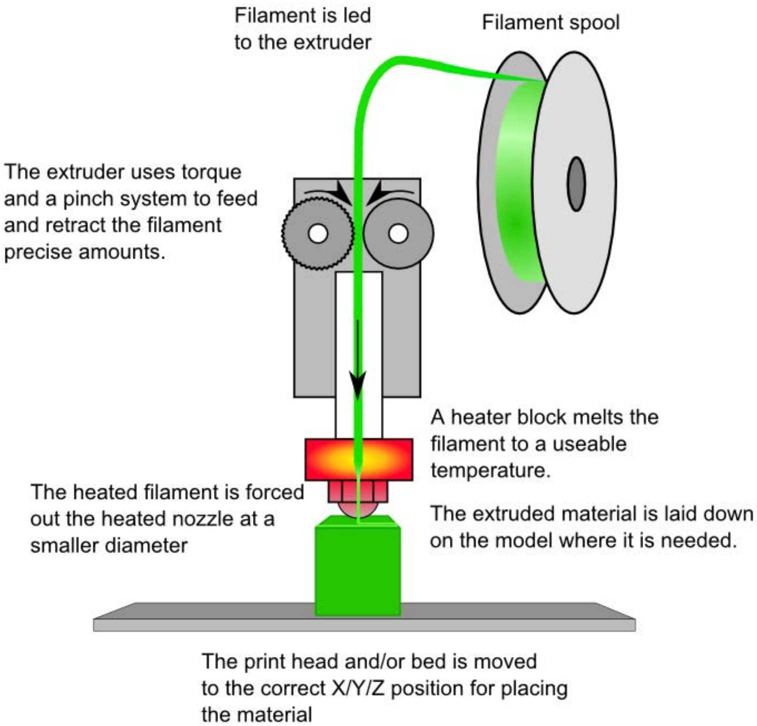
3D Printing Hardware and Materials

3D Printing Technologies

- Fused deposition modeling (FDM)
- Stereolithography (SLA)
- DLP 3D printing
- Selective laser sintering (SLS)
- Direct metal laser sintering (DMLS)
- Plaster-based 3D printing (PP)
  - Powder bed and inkjet head 3D printing
- Photopolymer Phase Change Inkjets
- Thermal Phase Change Inkjets
- Laminated object manufacturing (LOM)

Fused Deposition Modeling (FDM)

- Fused Filament Fabrication (FFF)
- Filament is made of thermoplastic materials
  - e..g., ABS, polycarbonate, PLA
- Temporary support structure can be made from water-soluble material such as PVA
  - removed using heated sodium hydroxide solution



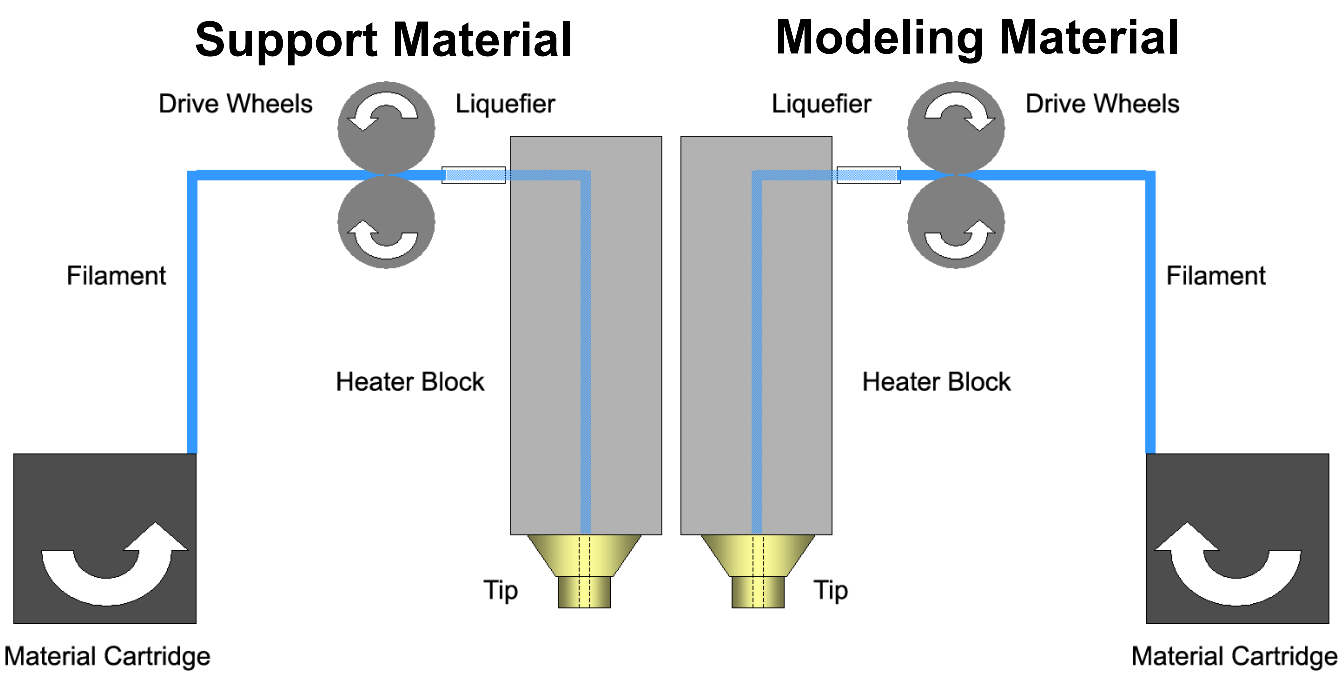
Source: http://reprap.org

FDM Process Timelapse

https://commons.wikimedia.org/wiki/File:3D_printing_on_replicator_2.webm

Fused Deposition Modeling - History

- Developed by Scott and Lisa Crump in the late 80s
  - Founded Stratasys
  - FDM is trademarked by Stratasys
    - Fused Filament Fabrication (FFF) should be used instead



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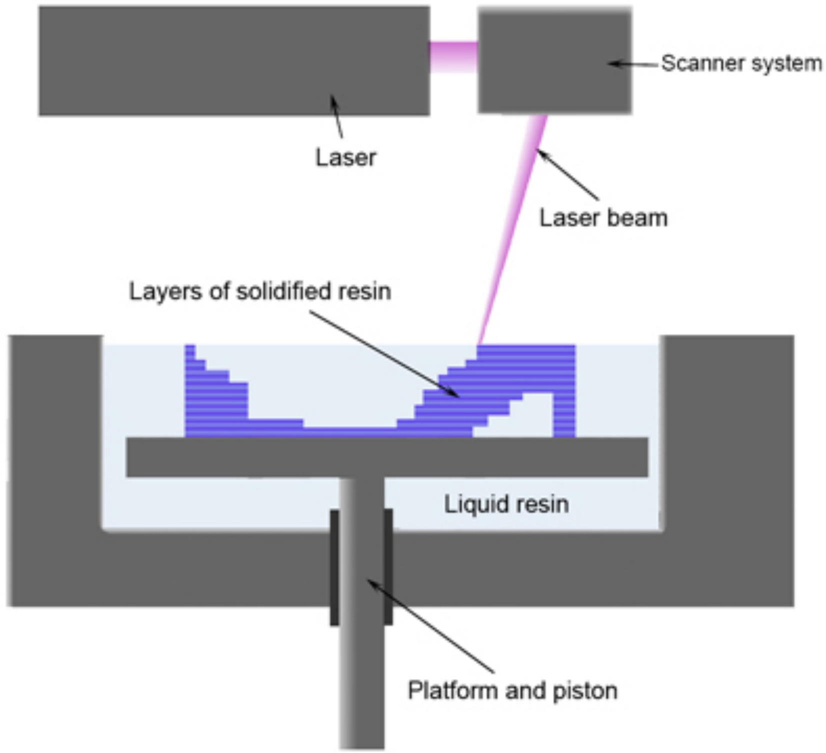
Stereolithography (SLA)

- SLA uses liquid ultraviolet curable photopolymer resin
- Laser beam traces one layer on the surface of the resin
- Laser light cures and solidifies the layer
- The platform descends by one layer



Source: http://en.wikipedia.org/

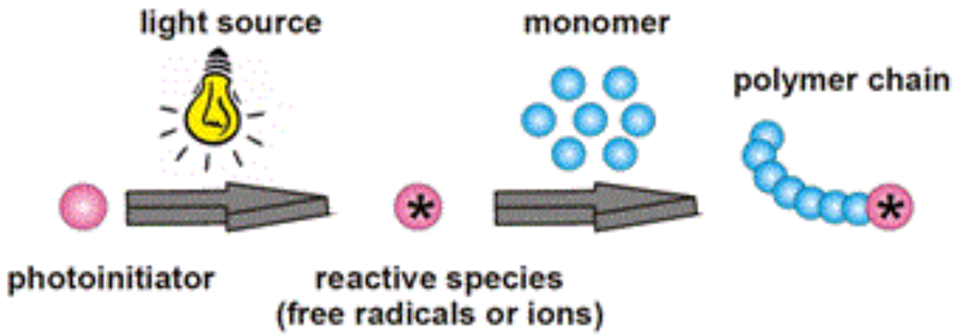
Photopolymers

- Change from a liquid state to solid state when exposed with light of a certain wavelength

- Typical ingredients:
  - **Monomers:** small molecules, lower viscosity
  - **Oligomers:** relatively high molecular weight, e.g., acrylates, epoxies, etc.
  - **Photoinitiators:** generate reactive species (free radicals) under light exposure to initiate the polymerization
  - **Additives:** binders, surfactants, stabilizers, etc.

How Photopolymers Work

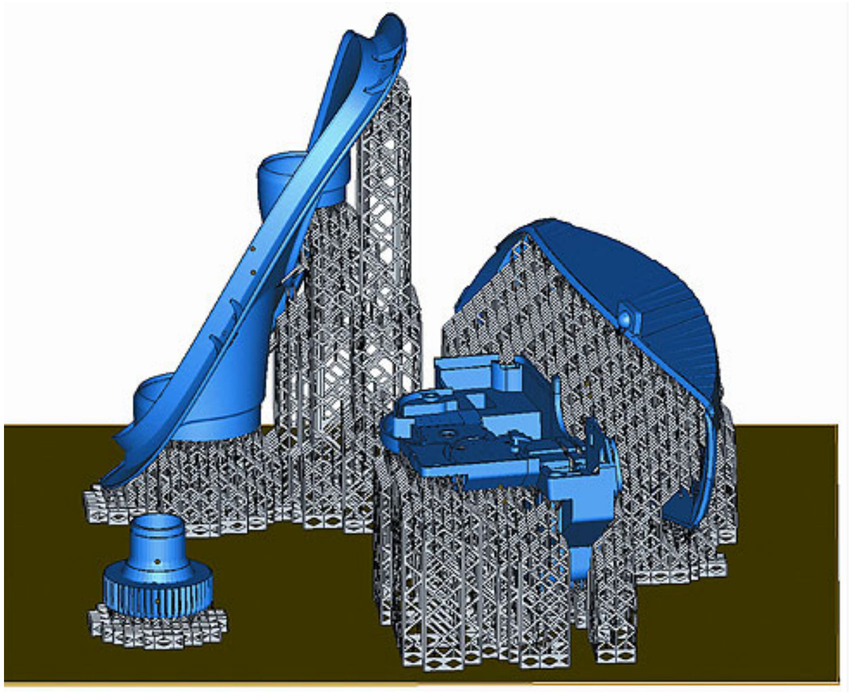
- Free Radical Polymerization
  - **Initiation:** Free radicals are generated through the initiator when exposed to light
  - **Propagation:** Free radicals react with monomer molecules to generate new reactive center, monomers react with reactive center repetitively to grow into a long chain
  - **Termination:** Chain termination occurs when two reactive centers come close and react with each other to yield complete macromolecules

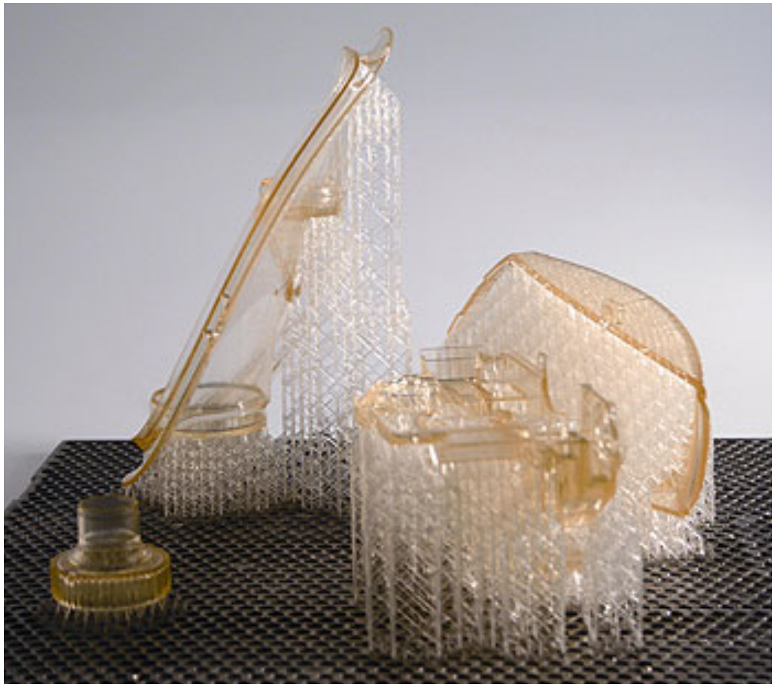


Source: http://www.additive3d.com/photo.htm

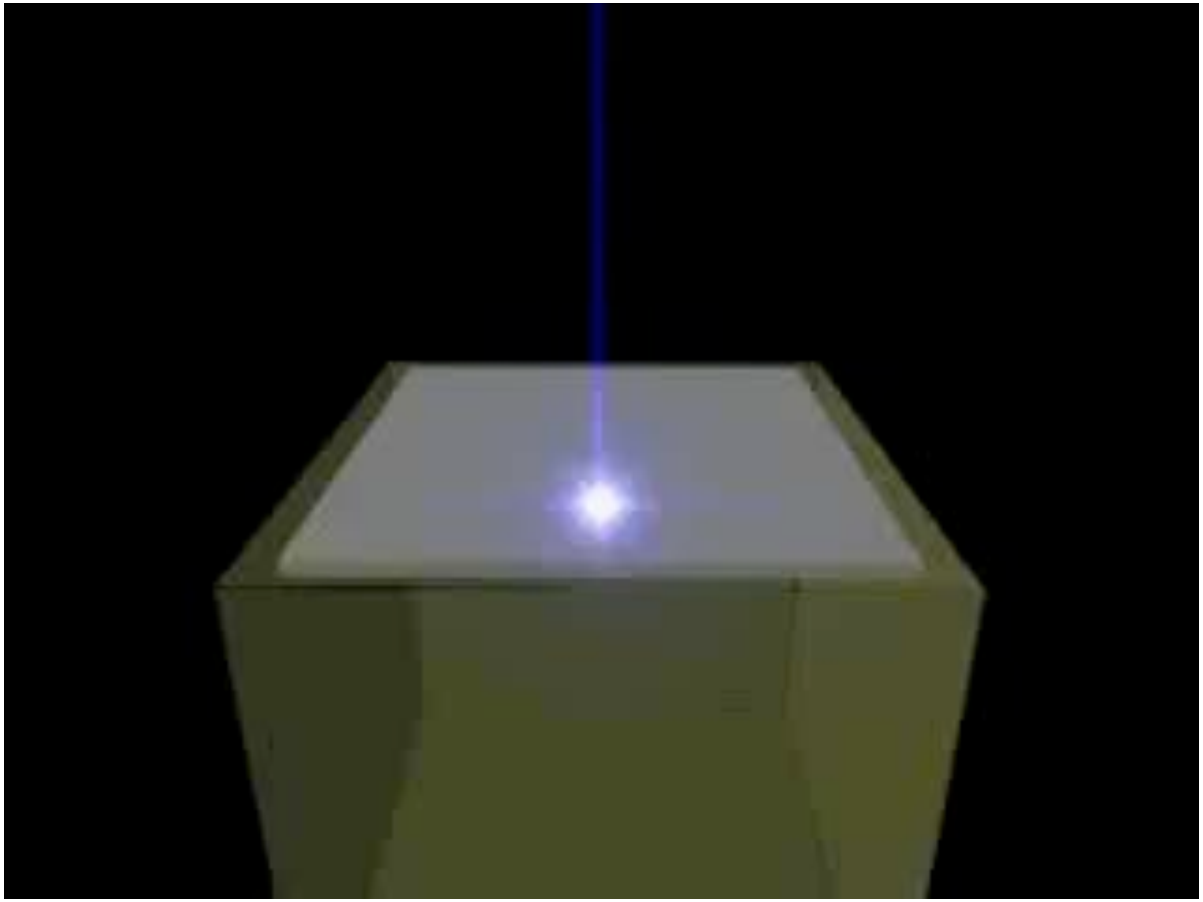
Stereolithography (SLA)

- Support structure
  - thin support lattice can be broken off



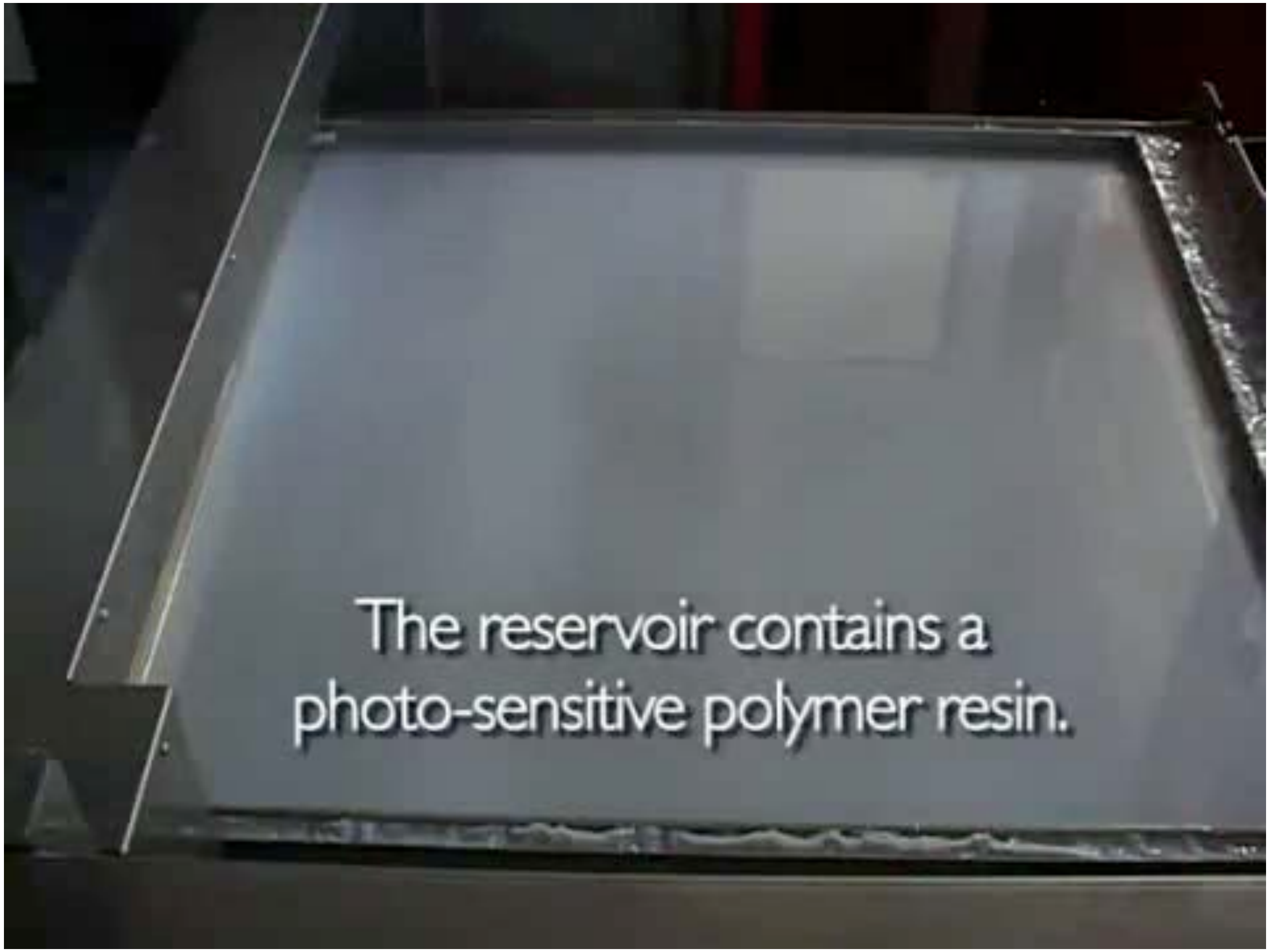


Stereolithography Process



http://www.youtube.com/watch?feature=player_embedded&v=5L5vdpklrtU

Stereolithography Process



http://www.youtube.com/watch?feature=player_embedded&v=5L5vdpklrtU

Stereolithography - History

- Developed by Charles Hull in the 80s
  - Coined term stereolithography
  - Founded 3D Systems in 1986

Charles Hull next to one of his latest 3D printers, the SLA7000

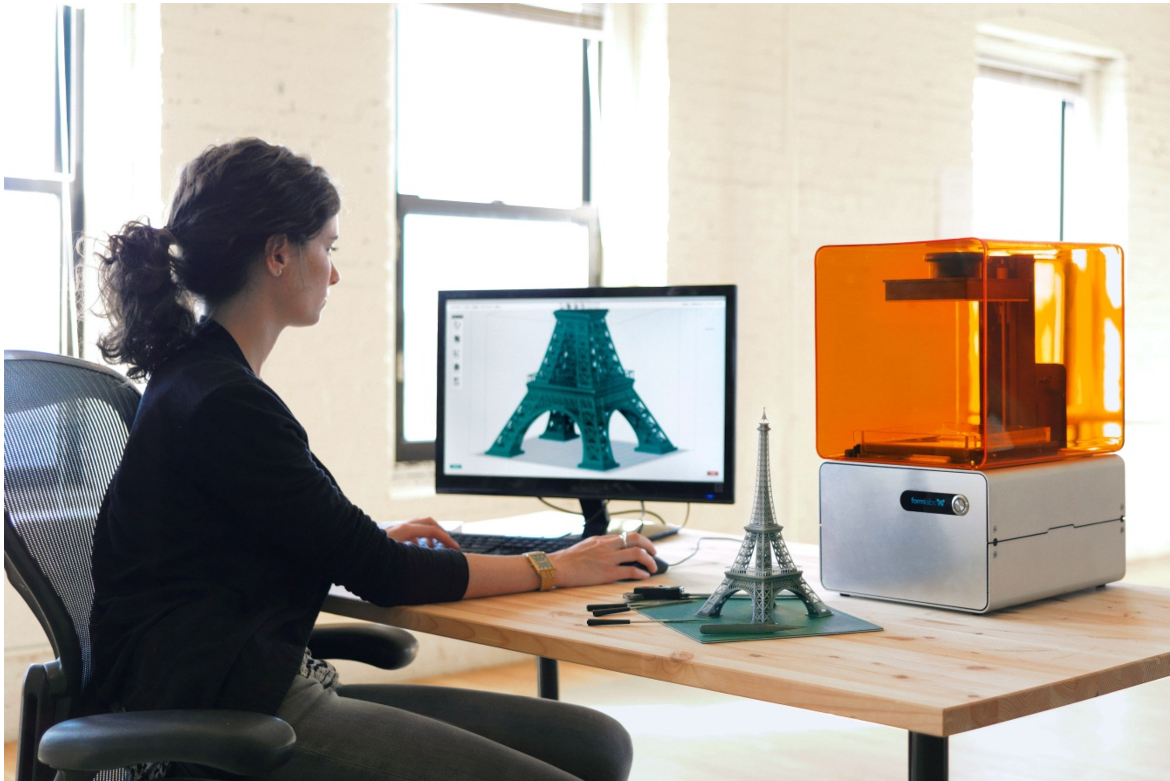
Stereolithography - 3D Systems

- Two main families
  - ProJet
  - iPro
- Build volume: varies (e.g., 10 x 10 x 10 in)
- Resolution up to 0.05mm
- Materials (only one can be used):
  - photopolymers
  - clear, opaque, temperature resistant, ceramic-like, abs-like
- Typical laser power: 200mW

ProJet® MP 7000

Stereolithography - Clones

- Formlabs
  - Smaller build volume
  - Similar resolution
  - Less expensive



3D Printing Technologies

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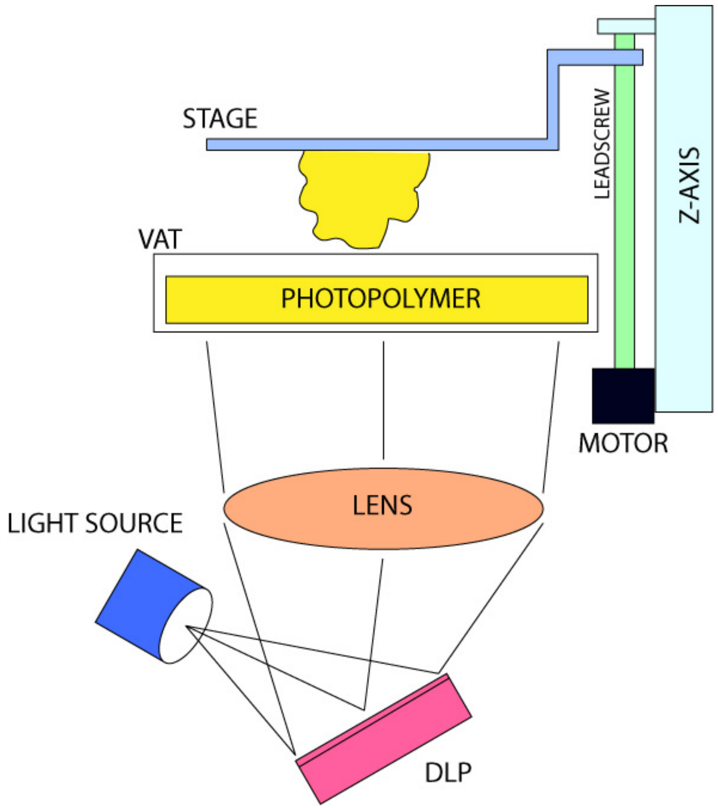
- Thermal Phase Change Inkjets
- Laminated object manufacturing (LOM)

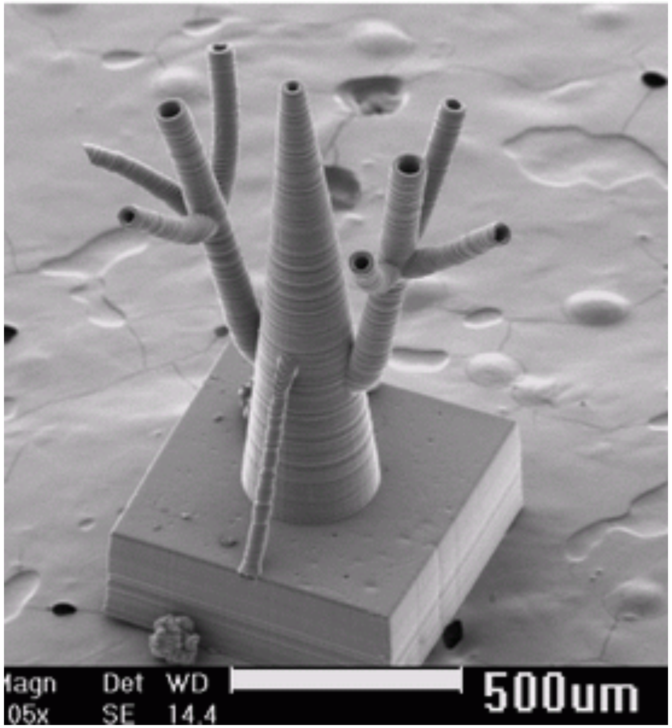
Digital Light Projector (DLP) 3D Printing

- DLP 3D printer uses liquid ultraviolet curable photopolymer resin
- DLP exposes and solidifies one layer at a time on the surface of the resin
- The Z-axis moves by one layer



DLP 3D Printing Features

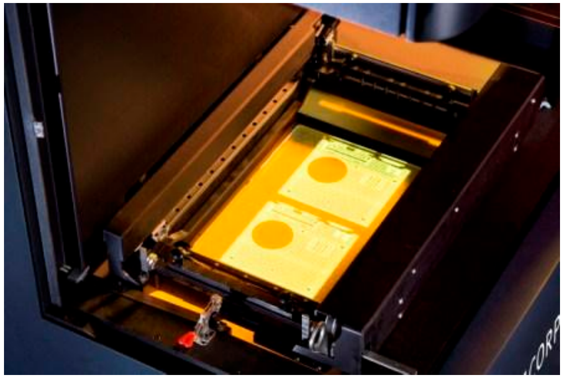
- Simple design
  - laser+mirror are replaced by a projector
  - only one degree of freedom
- Faster than SLA
  - exposes one layer at a time
- Materials
  - The same as SLA
- No additional support material
  - Lattice structure similar to SLA



Source: Nicholas Fang, MIT

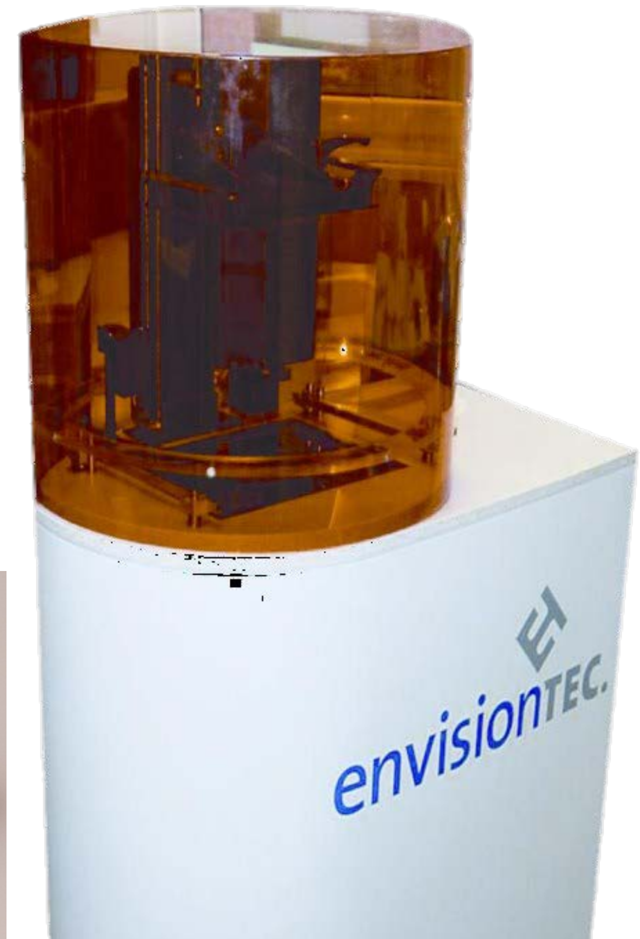
DLP 3D Printing - Commercial Systems

- ZBuilder Ultra from Z-Corp/3D Systems
  - ZBuilder Ultra
  - Z resolution: 50 – 100 microns
  - XY resolution: 138 microns
  - Build volume 10.2 x 6.3 x 7.5 inches
  - Vertical build speed 0.5 inches/hour

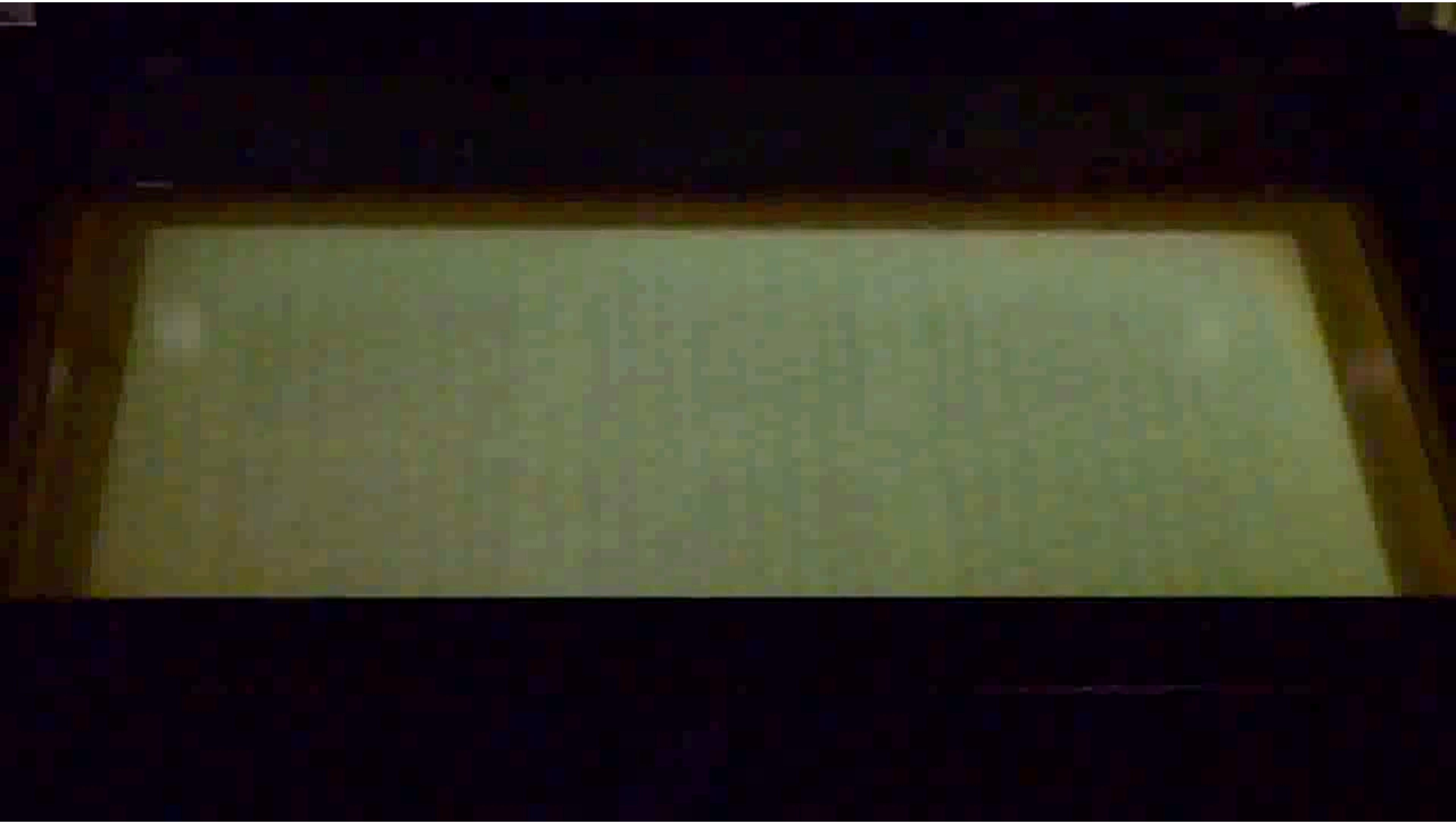


DLP 3D Printing - Commercial Systems

- Perfactory from EnvisionTec
  - http://www.envisiontec.de
  - Z resolution 50 microns
  - XY resolution 50 microns
  - projector resolution (2800x2100 pixels)
  - Build volume 5.5 x 4.1 x 9.1 inches



DLP 3D Printing - Process

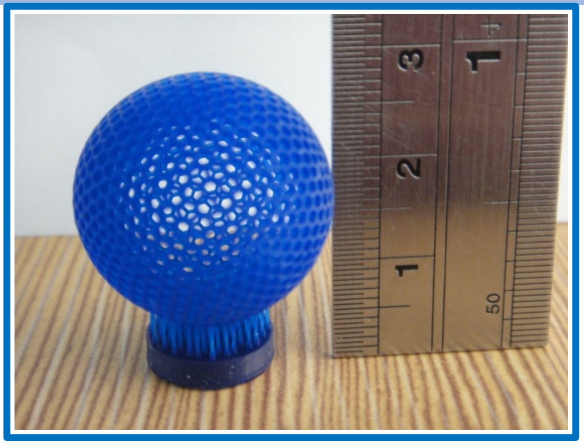


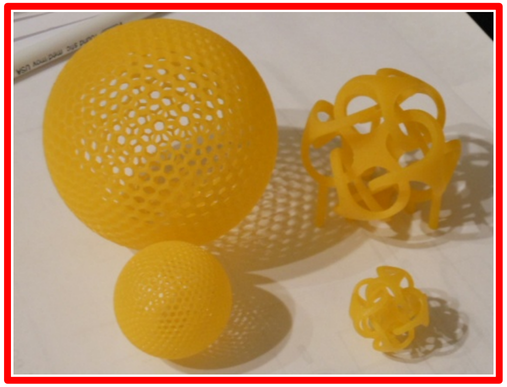
https://www.youtube.com/watch?v=HbUuv_3Jw7M

DLP 3D Printing - DIY

B9Creator

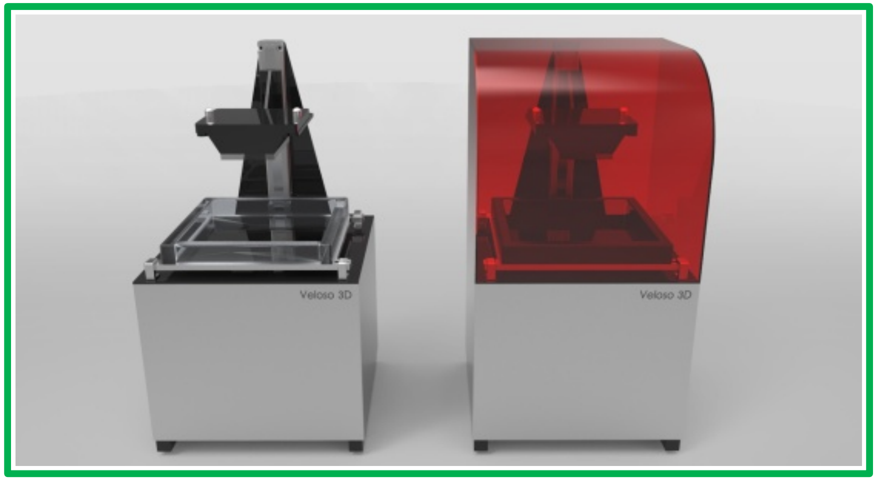
MiiCraft





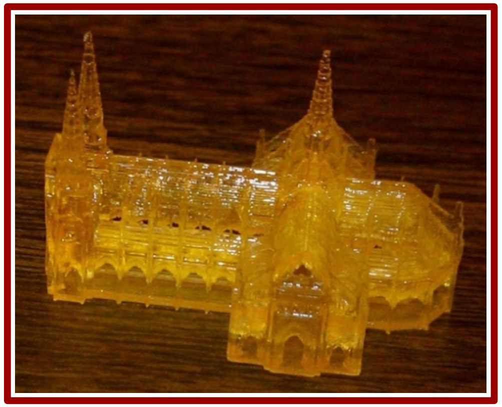
http://www.3ders.org/articles/20120911-a-list-of-diy-high-resolution-dlp-3d-printers.html

DLP 3D Printing - DIY



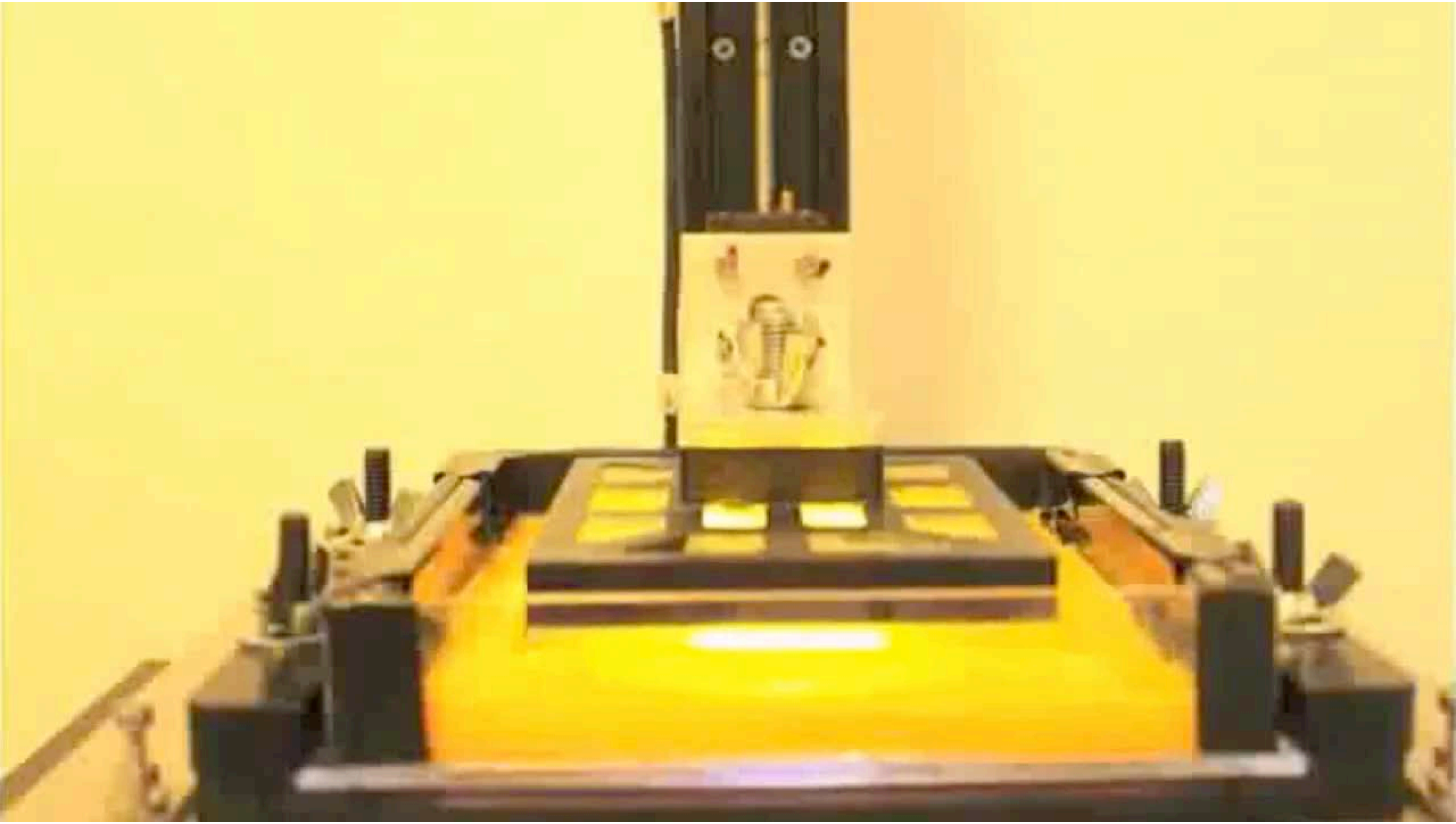
3D Home Made

Sedgwick



http://www.3ders.org/articles/20120911-a-list-of-diy-high-resolution-dlp-3d-printers.html

DLP 3D Printing - DIY Video



http://www.youtube.com/watch?v=o2uy6WaGhxs&feature=player_embedded

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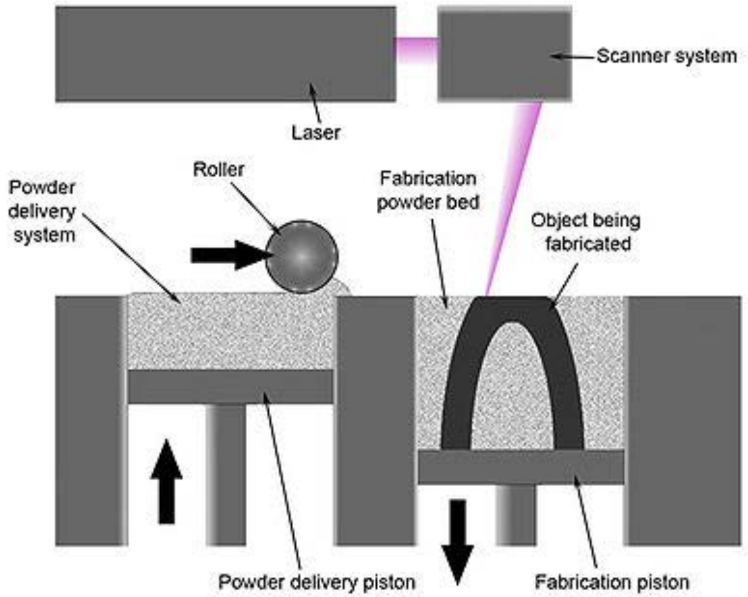
Selective Laser Sintering (SLS)
Direct Metal Laser Sintering (DMLS)

- SLS and DMLS use a bed of small particles (made of plastic, metal, ceramic, or glass)
- High-power laser traces one layer on the surface of the powder bed melting/fusing the particles
- The platform descends by one layer and more material is added

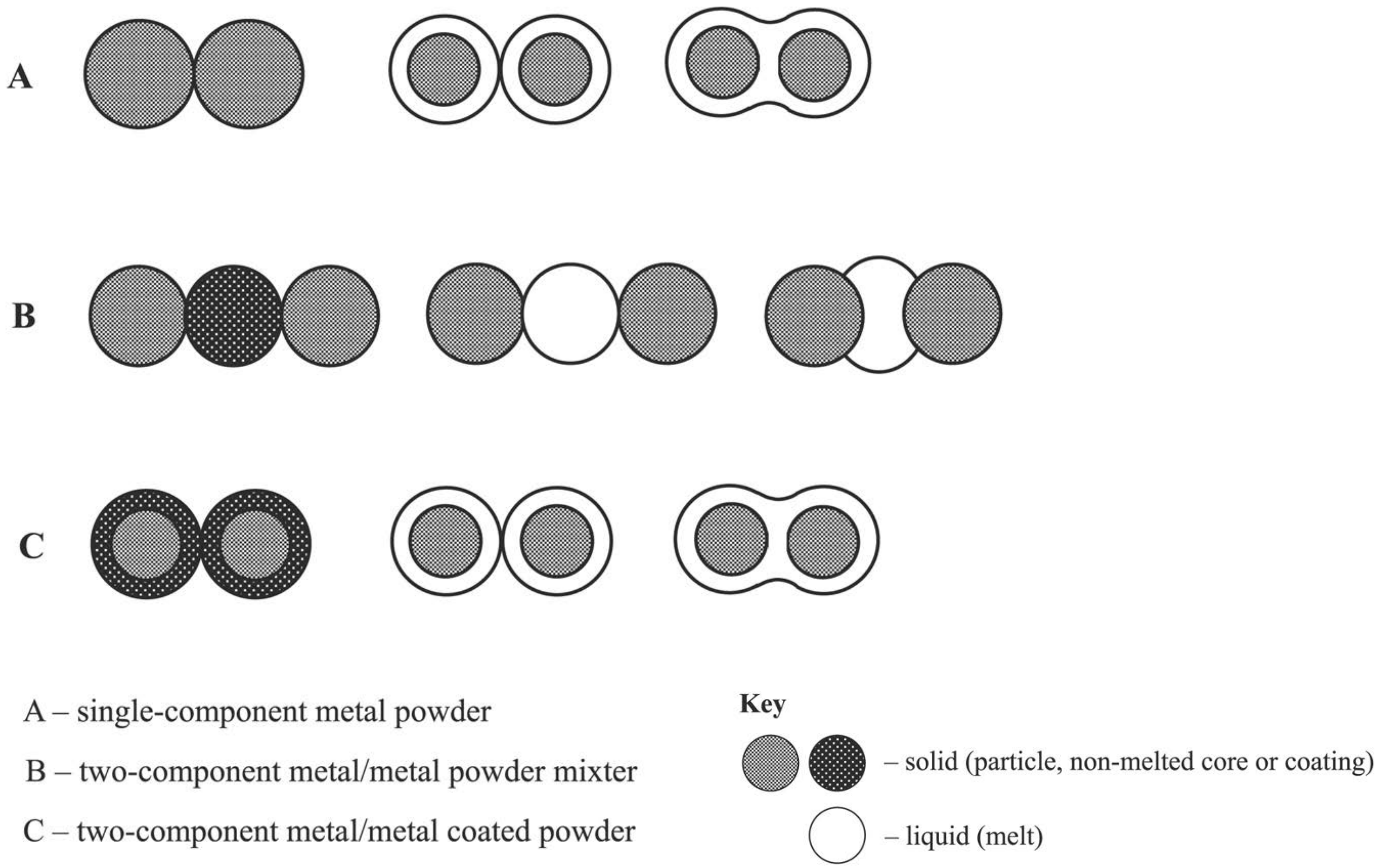


Source:
http://en.wikipedia.org/wiki/Selective_laser_sintering

SLS & DMLS Features

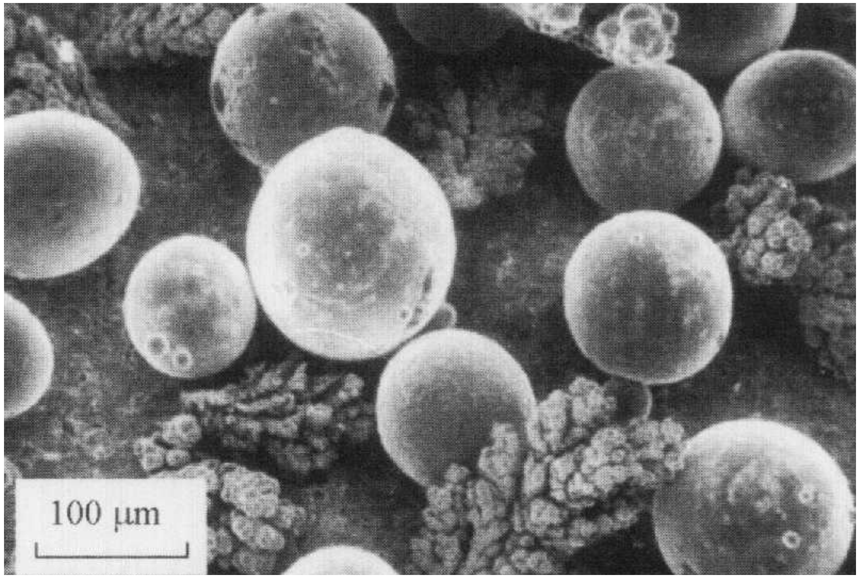
- Laser and scanner system
  - Similar do SLA but laser is more powerful
- Bulk material can be preheated
  - Reduces the required energy to melt it
- Materials
  - One material at a time
  - Glass, polymers (e.g., nylon, polysterine), metals (e.g., steel, titanium, alloys), ceramic
- Does not require support structure
  - Overhangs are supported by powder material

Single- and Two-Component Powders

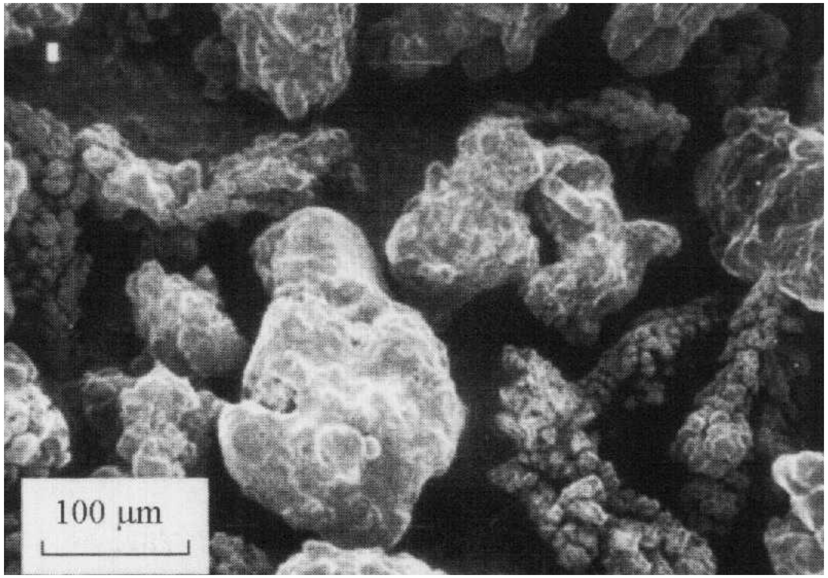


Source: Tolochko et al. 2003

Raw Powder Particles



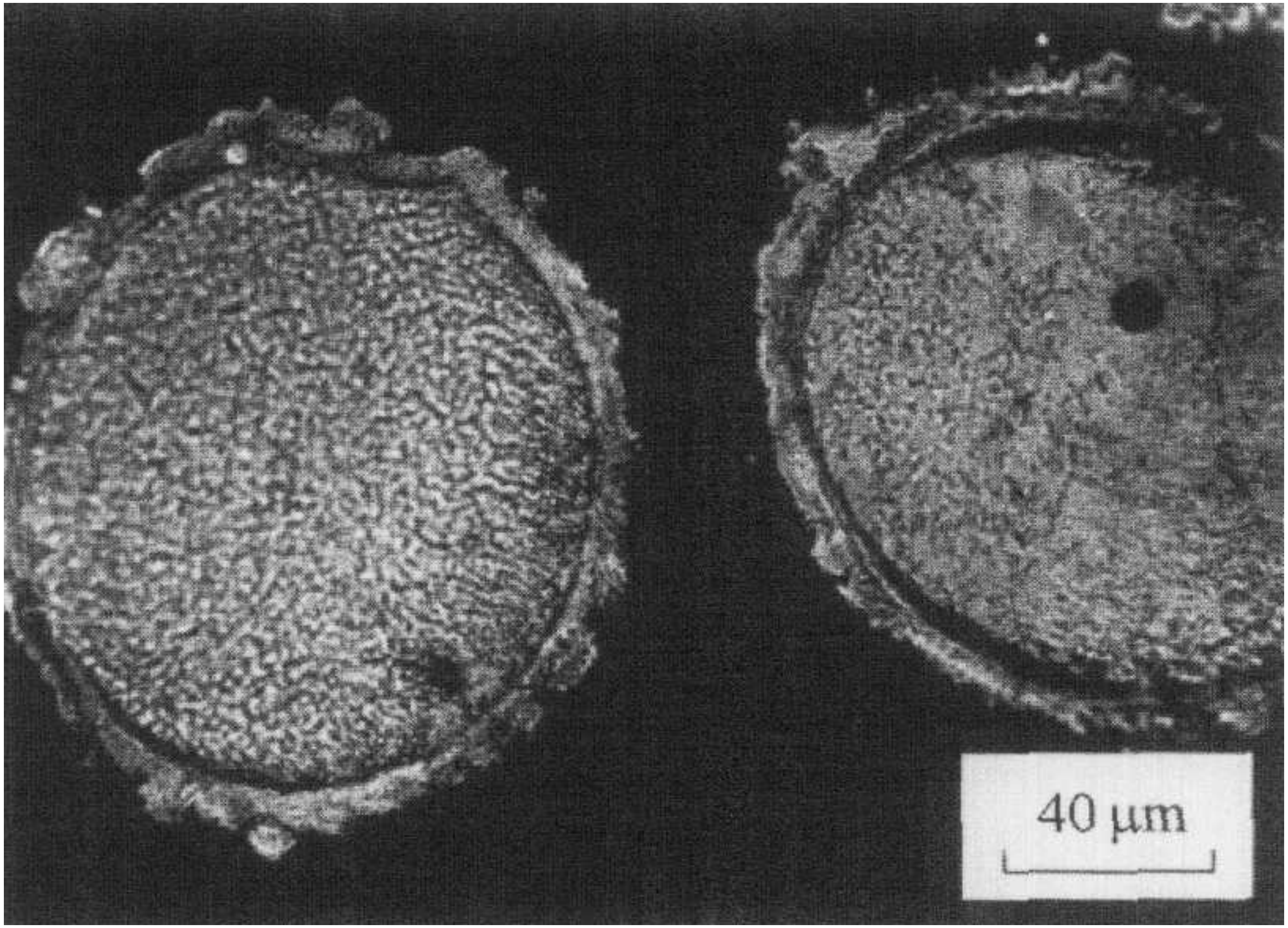
Raw Ni-alloy-Cu powder mixture



Raw Fe-Cu powder mixture

Source: Tolochko et al. 2003

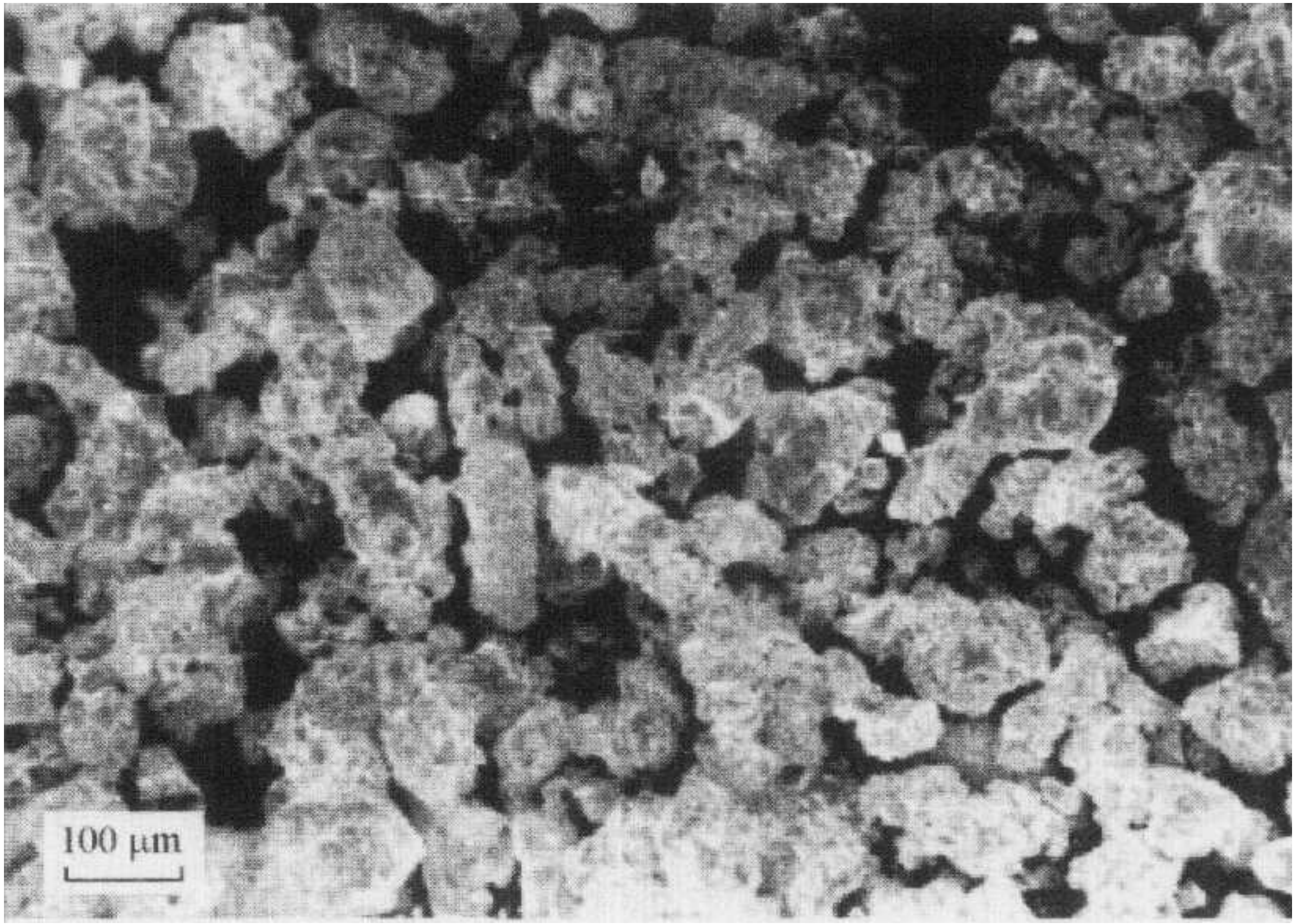
Raw Powder Particles



Raw Cu-coated Ni-alloy powder

Source: Tolochko et al. 2003

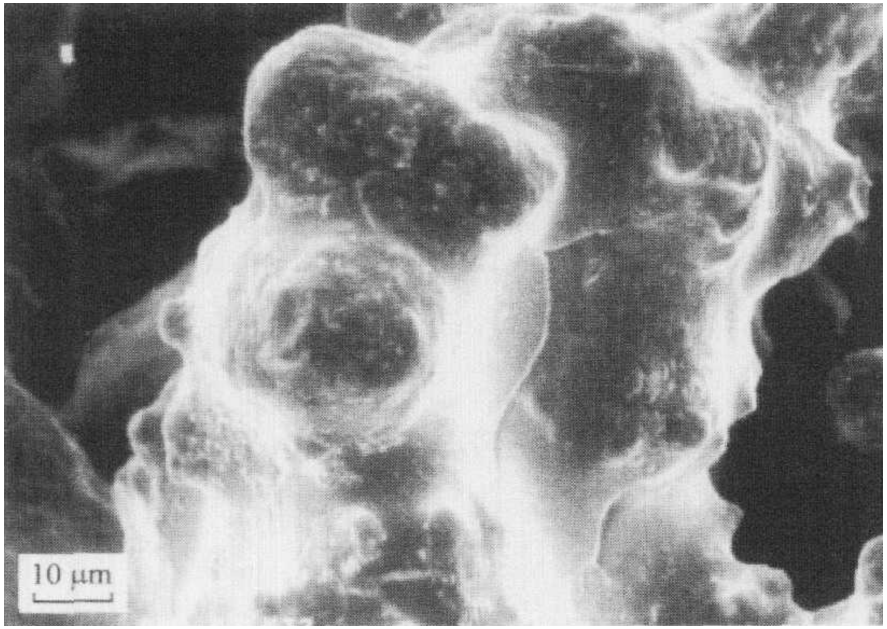
Sintered Powders

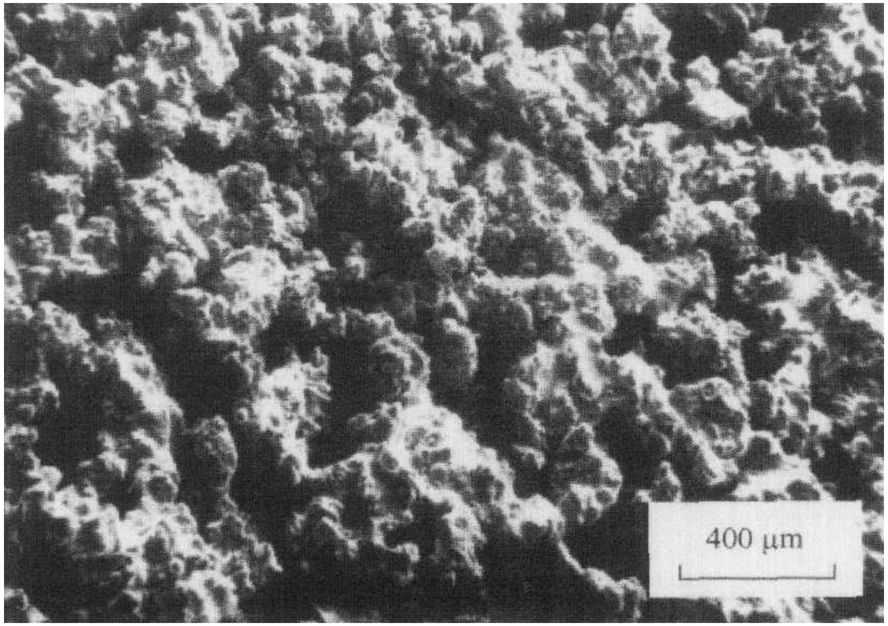


Single component Fe powder **after** sintering

Source: Tolochko et al. 2003

Sintered Powders

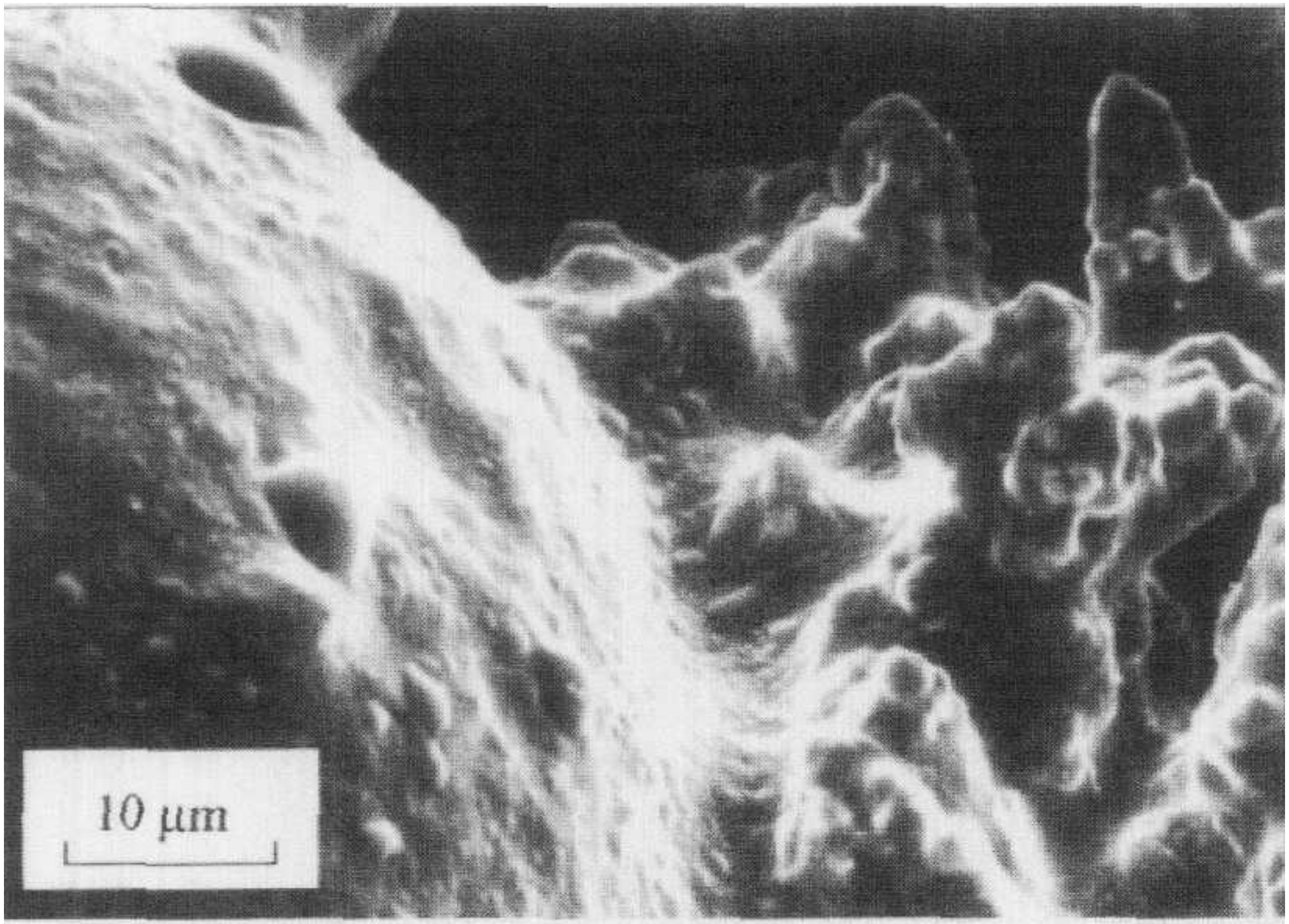




Fe-Cu powder mixture **after** sintering

Source: Tolochko et al. 2003

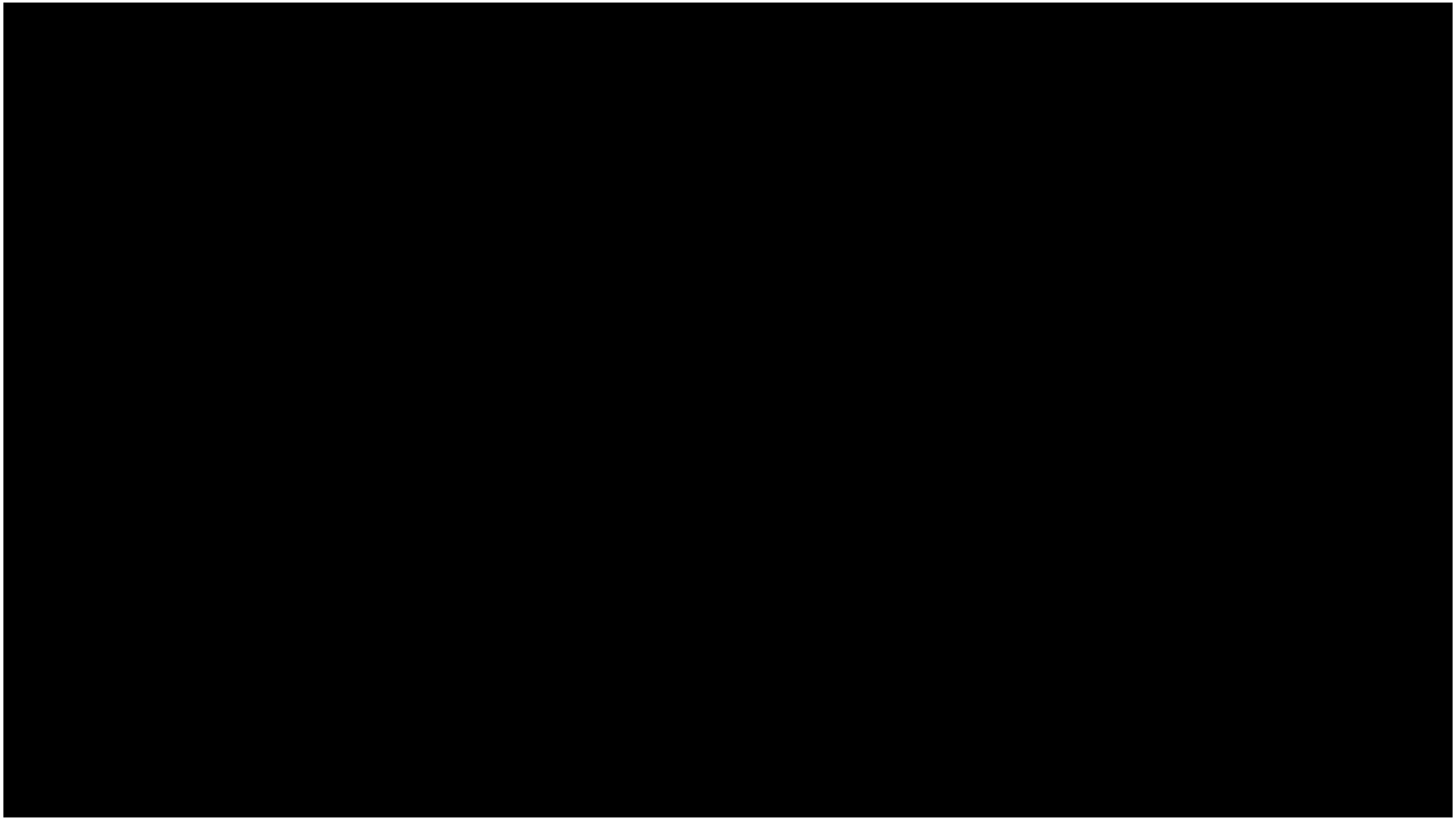
Sintered Powders



Ni-alloy-Cu powder mixture **after** sintering

Source: Tolochko et al. 2003

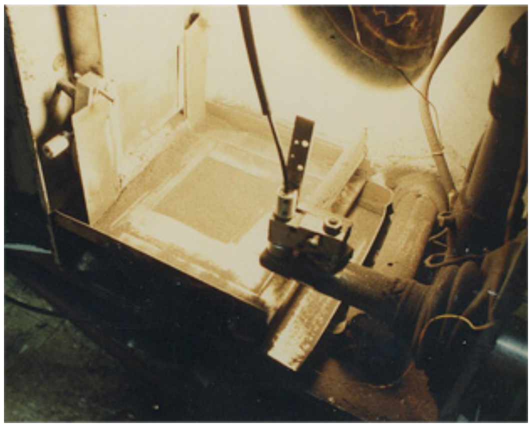
SLS & DMLS Process



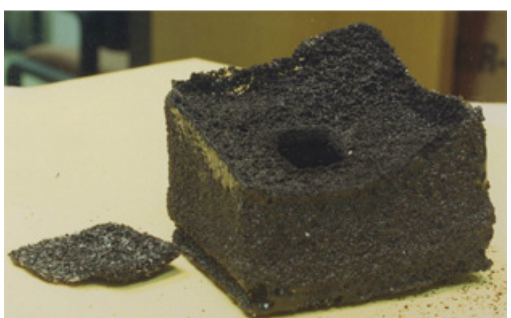
https://www.youtube.com/watch?v=BZLGLzyMKn4

SLS & DMLS - History

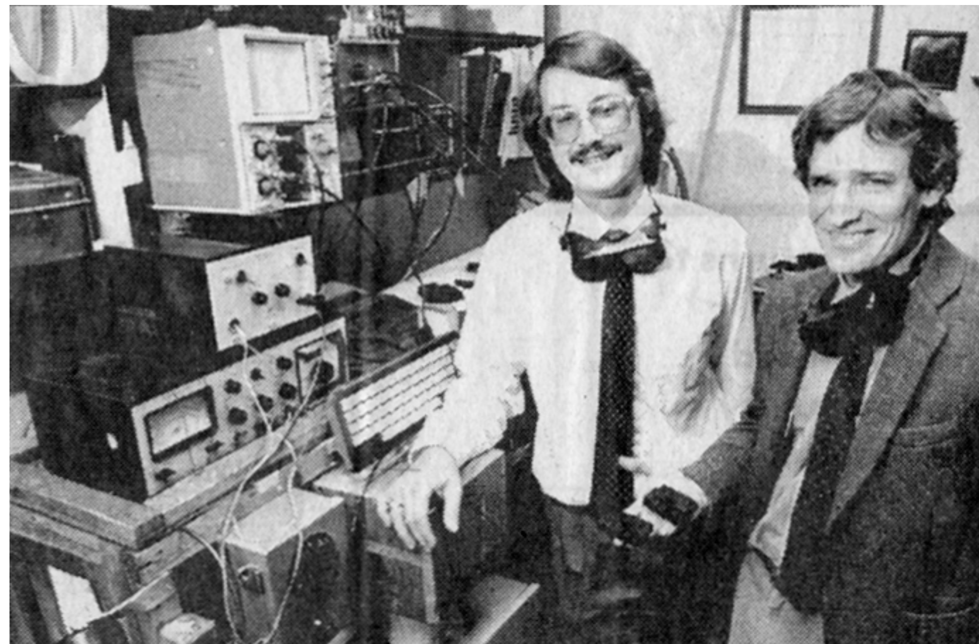
- Invented at UT Austin by Joe Beaman and Carl Deckard (80s)



This is part of the original machine, nicknamed Betsy, made by Carl Deckard as a graduate student in 1986.



One of the first attempts at making an object with selective laser sintering.



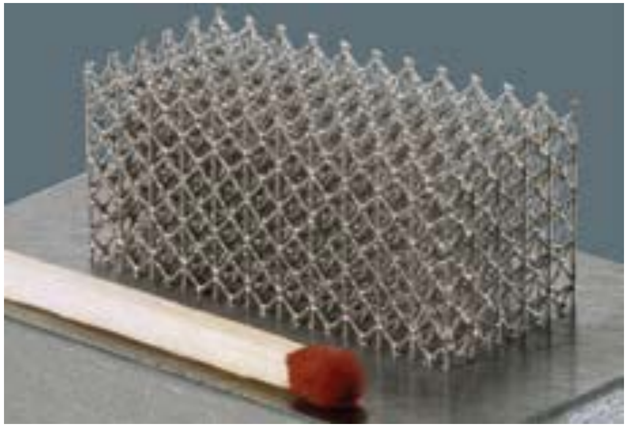
Staff photo by Ralph Barrera
Associate Professor Joe Beaman shows some three-dimensional plastic models made by the 'selective laser centering' device developed by Carl Deckard, left.

Source:
http://www.me.utexas.edu/news/2012/0612_selective_laser_sintering.php

Commercial Systems

- 3D Systems
  - sPro family & Pro DM
- EOS GmbH
  - Formiga and EOSINT family
- Requires powerful laser
  - 30W for SLS
  - 400W for DMLS
- Layer thickness: 0.02 – 0.08mm

Sample Fabricated Parts



Sources: http://www.bridgesmathart.org , http://www.freedomofcreation.com

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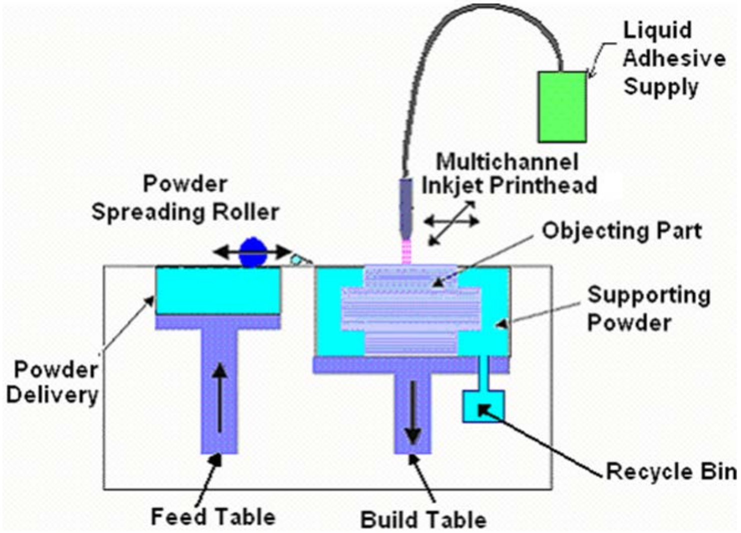
Plaster-based 3D Printing

- This method uses a bed of small plaster particles
- Inkjet printhead prints with liquid (possibly colored) adhesive one layer on the surface of the powder bed fusing the particles
- The platform descends by one layer and more material is added



Source: Zhou and Lu, 2011

Plaster-based 3D Printing Features

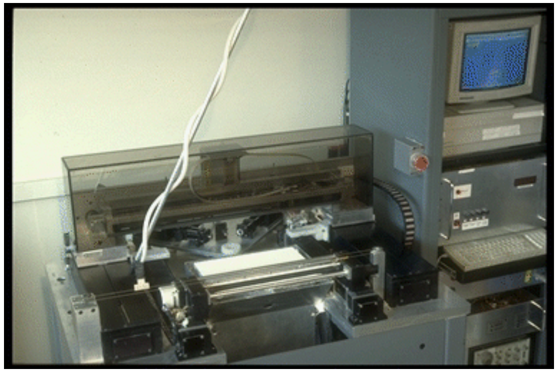
- Similar to SLS and DMLS
  - Also uses granular materials
  - Uses inkjet printhead instead of laser
  - Glues particles instead of melting them
- Does not require support structure
  - Overhangs are supported by powder material
- The was the only technology supporting full-color printing
- Materials
  - Plaster only
  - Color can be applied (typically on/near the surface)

Plaster-based 3D Printing Process

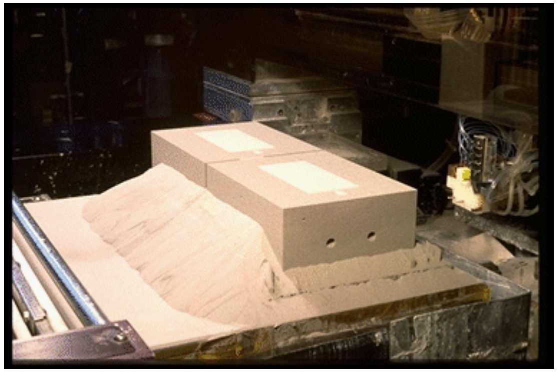
https://www.youtube.com/watch?v=GnFxujCyD70

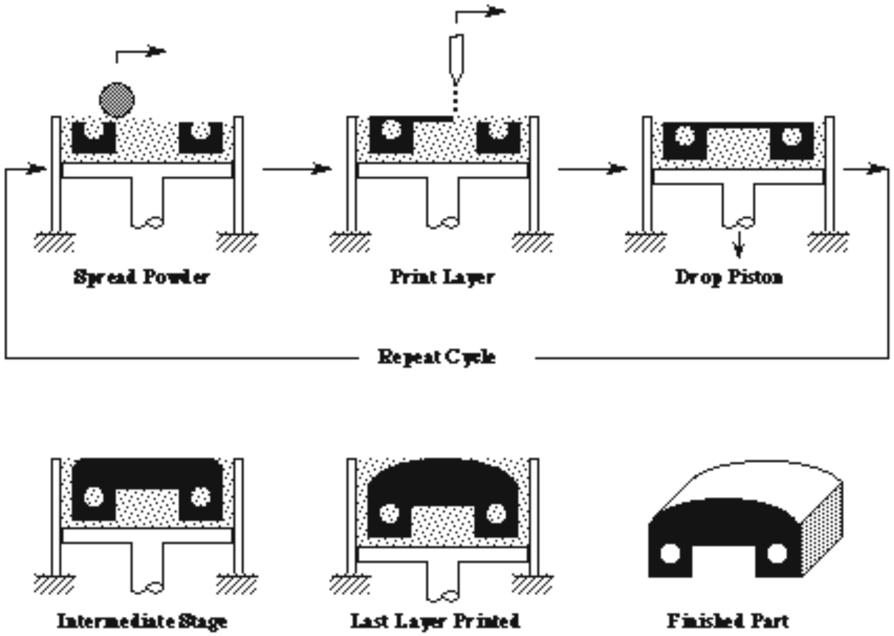
Plaster-based 3D Printing - History

- Developed at MIT
  - http://web.mit.edu/tdp/www/whatis3dp.html
- Commercialized by Z Corporation in 1995



MIT Alpha Machine





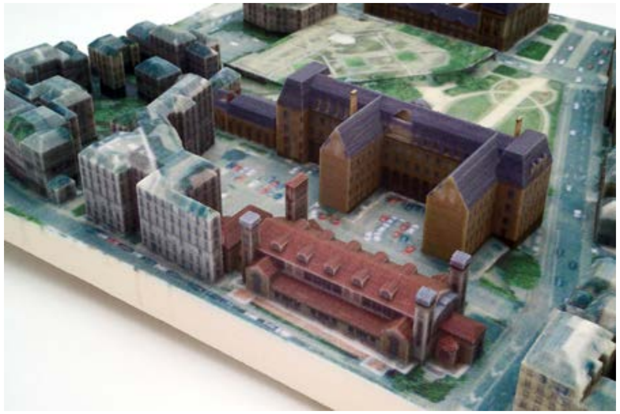
Plaster-based 3D Printing - Commercial Systems

- Z Corporation (now 3D Systems)
  - Z-Printer family
  - Uses HP inkjet print heads
  - 390K colors
  - XY resolution: 600 x 540dpi
  - Z resolution: 0.1mm
  - Build size: 20 x 15 x 9 inches

ZPrinter® 250 **ZPrinter® 850**

Source: Z corporation

Fabricated Parts



Source: Z corporation

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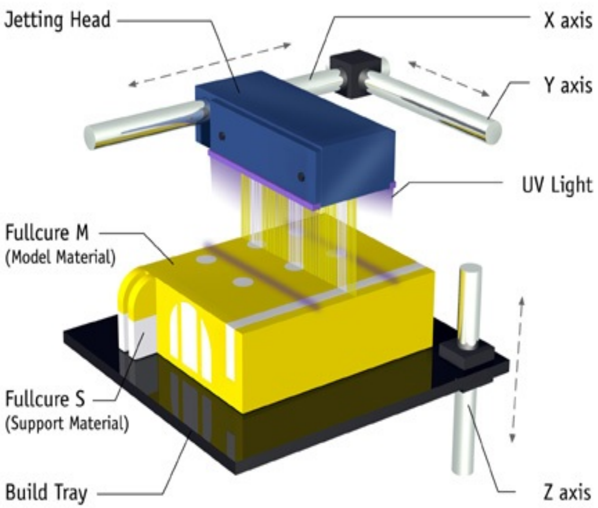
Photopolymer Phase Change Inkjets

- Inkjet printhead jets liquid photopolymer and support material
- UV light cures photopolymer and support material
- Excess material is removed using a roller
- The platform descends by one layer



Source: http://www.engatech.com/Objet-3D-Printing-Technology.asp

Photopolymer Phase Change Inkjets Features

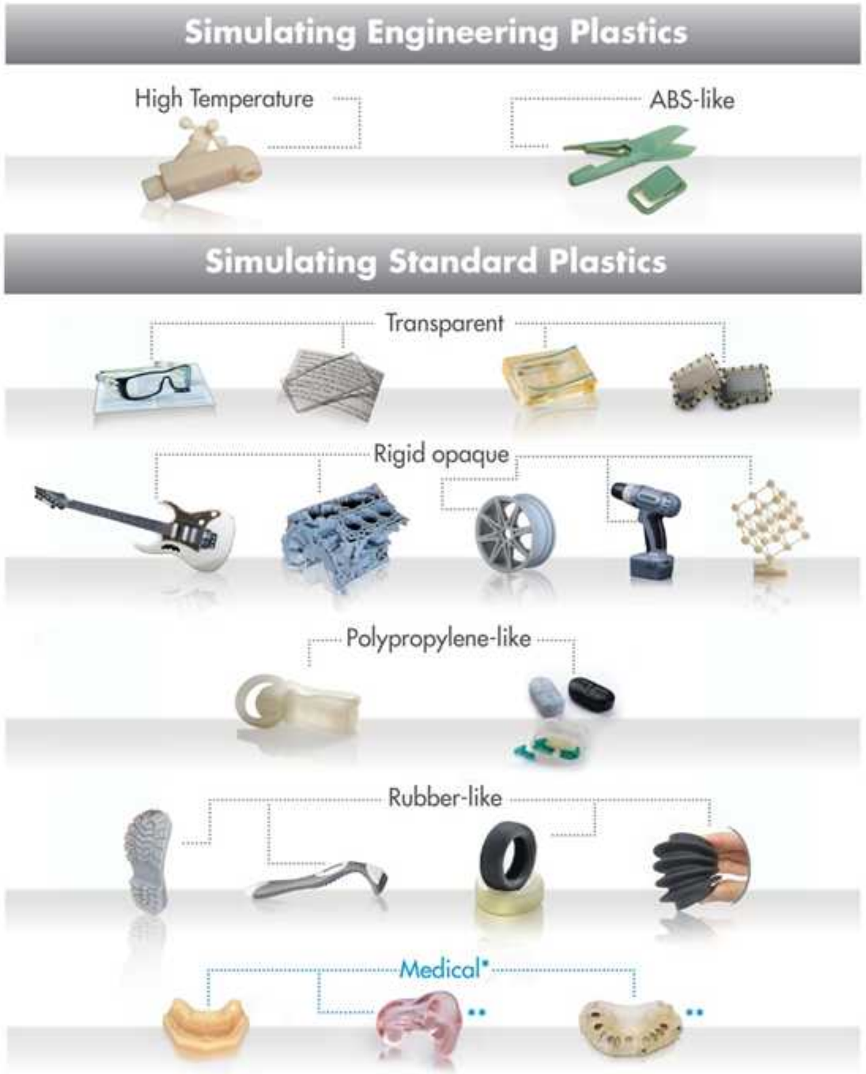
- Somewhat similar to plaster-based 3D printing
  - Also uses inkjet printhead
  - Jets material not binder
- Somewhat similar to SLA
  - Also uses photopolymers
- The only technology supporting multiple materials
  - Currently two + support material
- Materials
  - Photopolymers only
  - Can be mixed before curing -> graded materials
  - Soft, rigid, opaque, transparent, different colors

Photopolymer Phase Change Inkjets - Commercial Systems

- Objet (now Stratasys)
  - Called PolyJet
  - Eden series (one material + support)
  - Connex series (two materials + support)
  - Build size: 19.3 x 15.4 x 7.9 inches
  - Z resolution: up to 16 microns (1600 dpi)
  - XY resolution 600 dpi

Materials

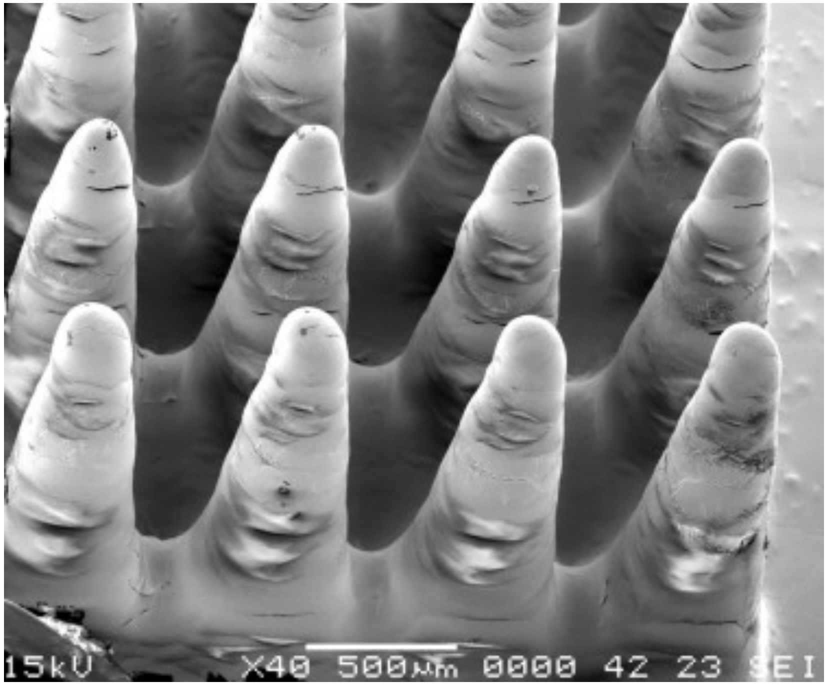
- Bio-compatible
- High-temperature
- ABS-like
- Transparent
- Opaque
- Rigid
- Polypropylene-like
- Rubber-like

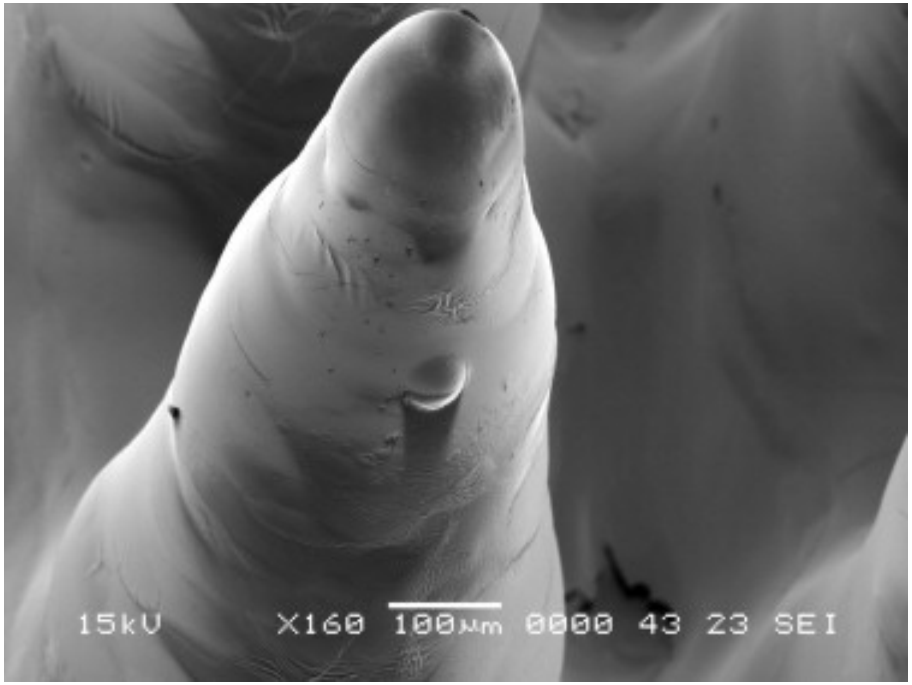


Source: Objet Geometries

Rubber-like Materials

Printing Resolution





Printing Process

https://www.youtube.com/watch?v=XLLq9SwSTpM

Sample Fabricated Objects

Source: Objet Geometries

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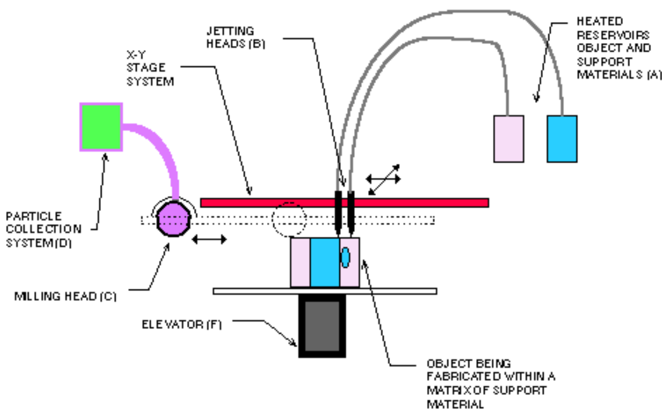
Thermal Phase Change Inkjets

- Inkjet printhead jets heated liquid plastic and support material (wax)
- Material droplets solidify as they cool down
- Excess material is removed using a milling head to make a uniform thickness layer
- Particles are vacuumed away
- The platform descends by one layer



Source: http://www.additive3d.com/bpm.htm

Thermal Phase Change Inkjets Features

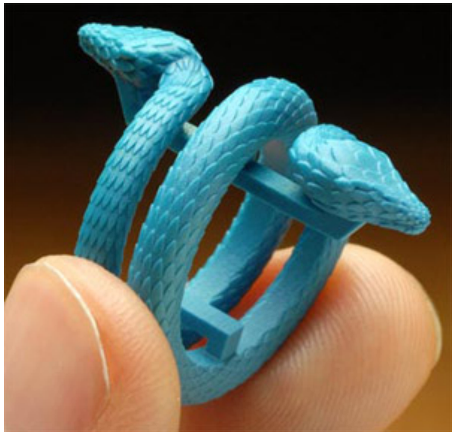
- Extremely high resolution
- Slow printing time
- Materials
  - Limited: plastics and waxes
- Support material
  - Wax: easy to remove
- Manufactured objects are used as casting pattern but almost never as final functional parts

Thermal Phase Change Inkjets - Commercial Systems

- Produced by Solidscape (now Stratasys)
  - 3Z Pro
  - XY resolution: 5000 x 5000 dpi
  - Y resolution: 8000 dpi
  - Build volume: 6 x 6 x 4 inches

Source: http://www.solid-scape.com

Sample Fabricated Parts



Source: Solidscape

Source: http://www.protojewel.com

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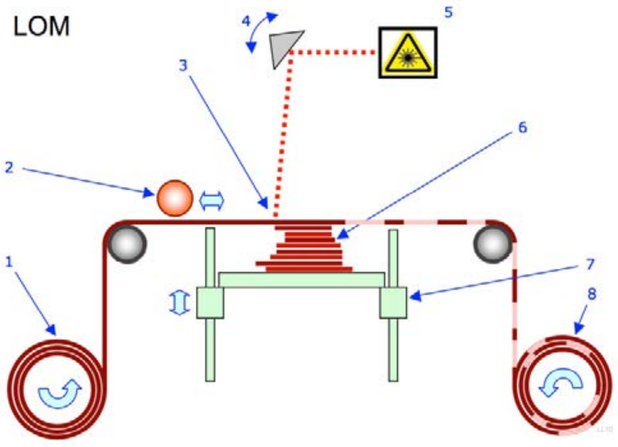
Laminated Object Manufacturing (LOM)

- Sheet is adhered to a substrate with a heated roller
- Laser traces desired dimensions of prototype
- Laser cross hatches non-part area to facilitate waste removal
- Platform with completed layer moves down out of the way
- Fresh sheet of material is rolled into position
- Platform moves up into position to receive next layer



1 Foil supply. 2 Heated roller. 3 Laser beam. 4. Scanning prism. 5 Laser unit. 6 Layers. 7 Moving platform. 8 Waste.

Source: http://en.wikipedia.org/wiki/Laminated_object_manufacturing

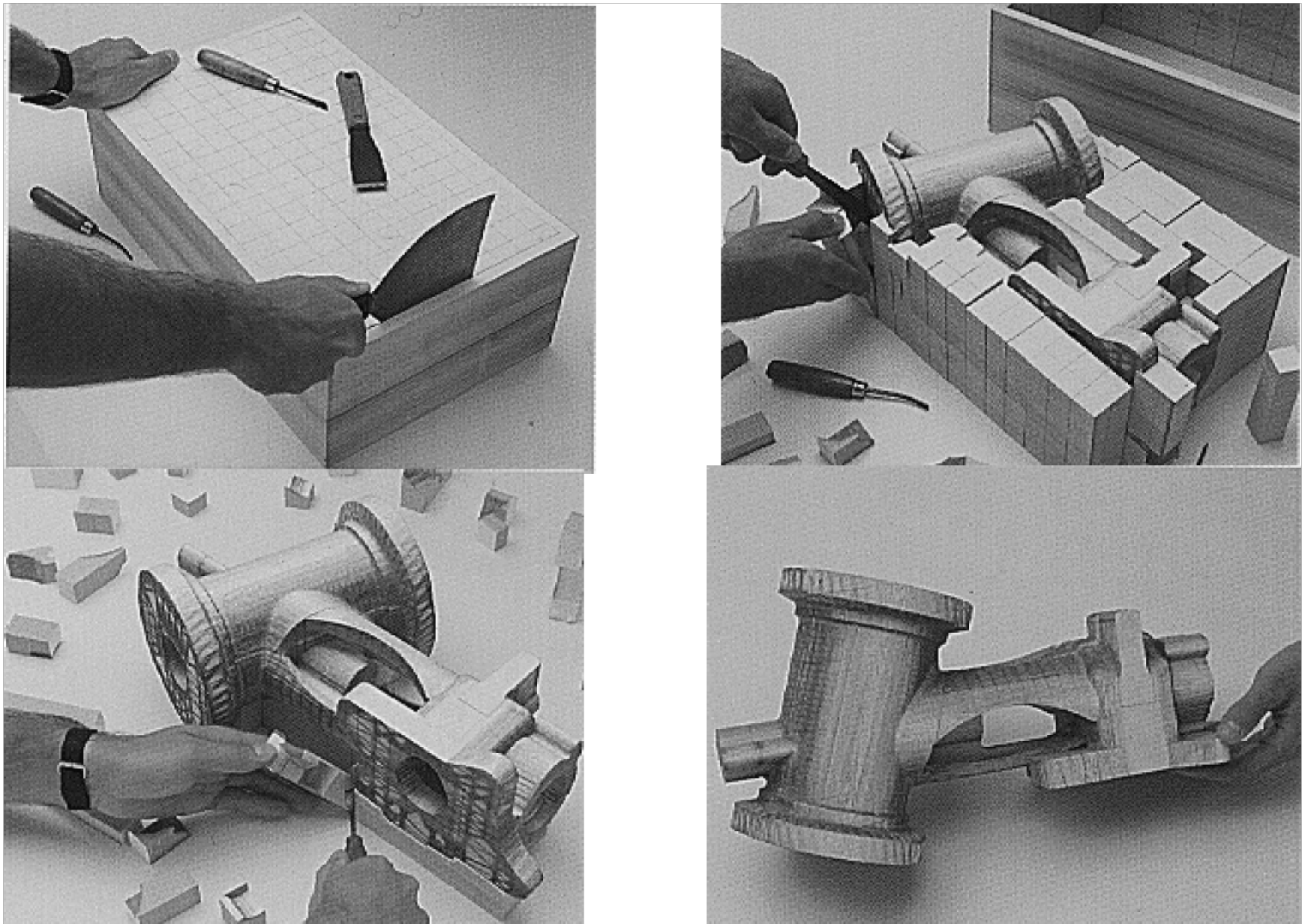
Printing Process

http://www.youtube.com/watch?v=Z1WNA6tdfWM

Laminated Object Manufacturing Features

- Inexpensive – low material cost
- Print resolution is lower than other methods
- Color can be added using additional printhead
- Materials
  - Paper (most common), plastics, composites, metal, ceramics
- Support material
  - Same material can be used as support

Support Material



Source: http://blog.nus.edu.sg/u0804594/common-rp-techniques/laminated-object-manufacturing-lom/

Commercial Systems

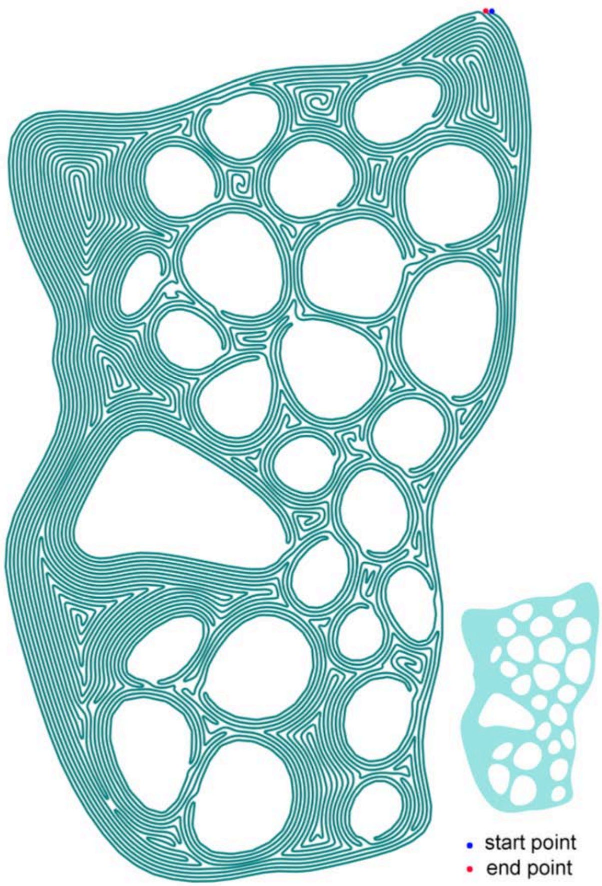
- Helisys (now Cubic Technologies)
  - SD300
  - Build Size 160 x 210 x 135 mm
  - Z resolution: 0.3 mm
  - XY resolution 0.2 mm
  - Build material – plastics

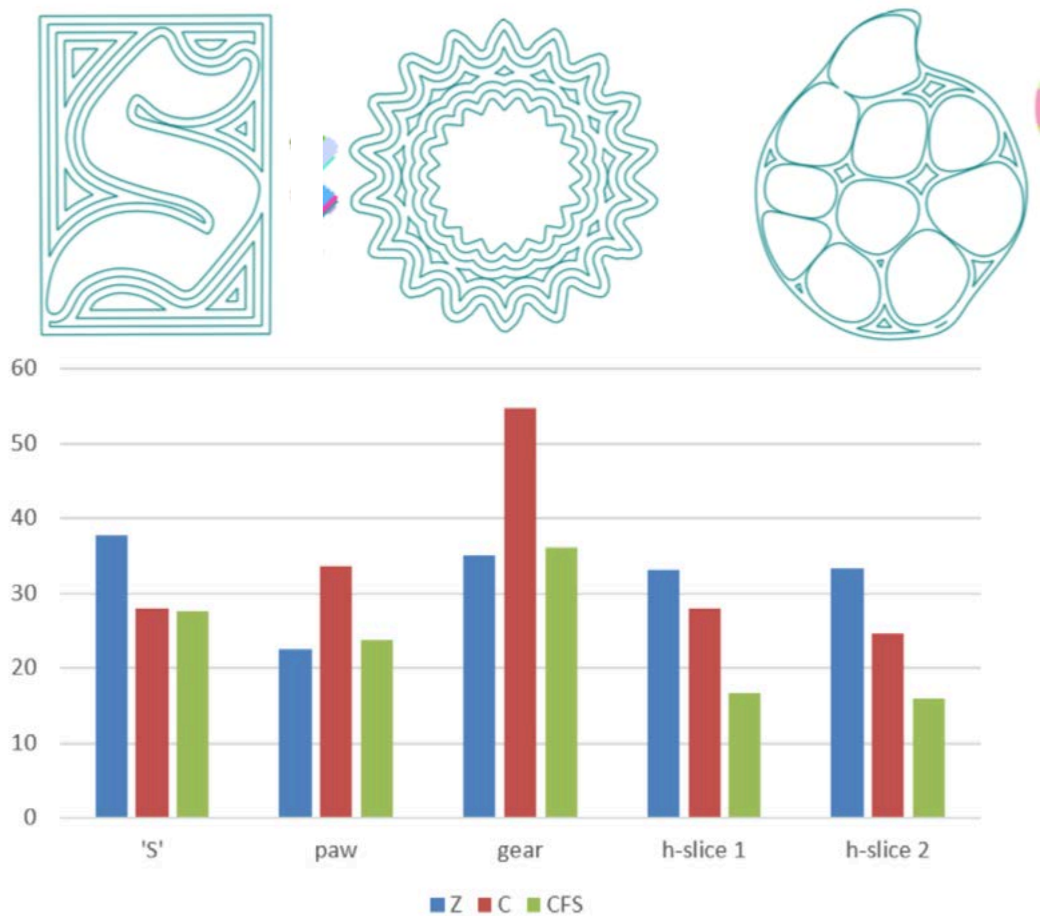
Sample Fabricated Objects

Source: http://www.solido3d.com

Recent Hardware Centric Research

- Better Printing Motions

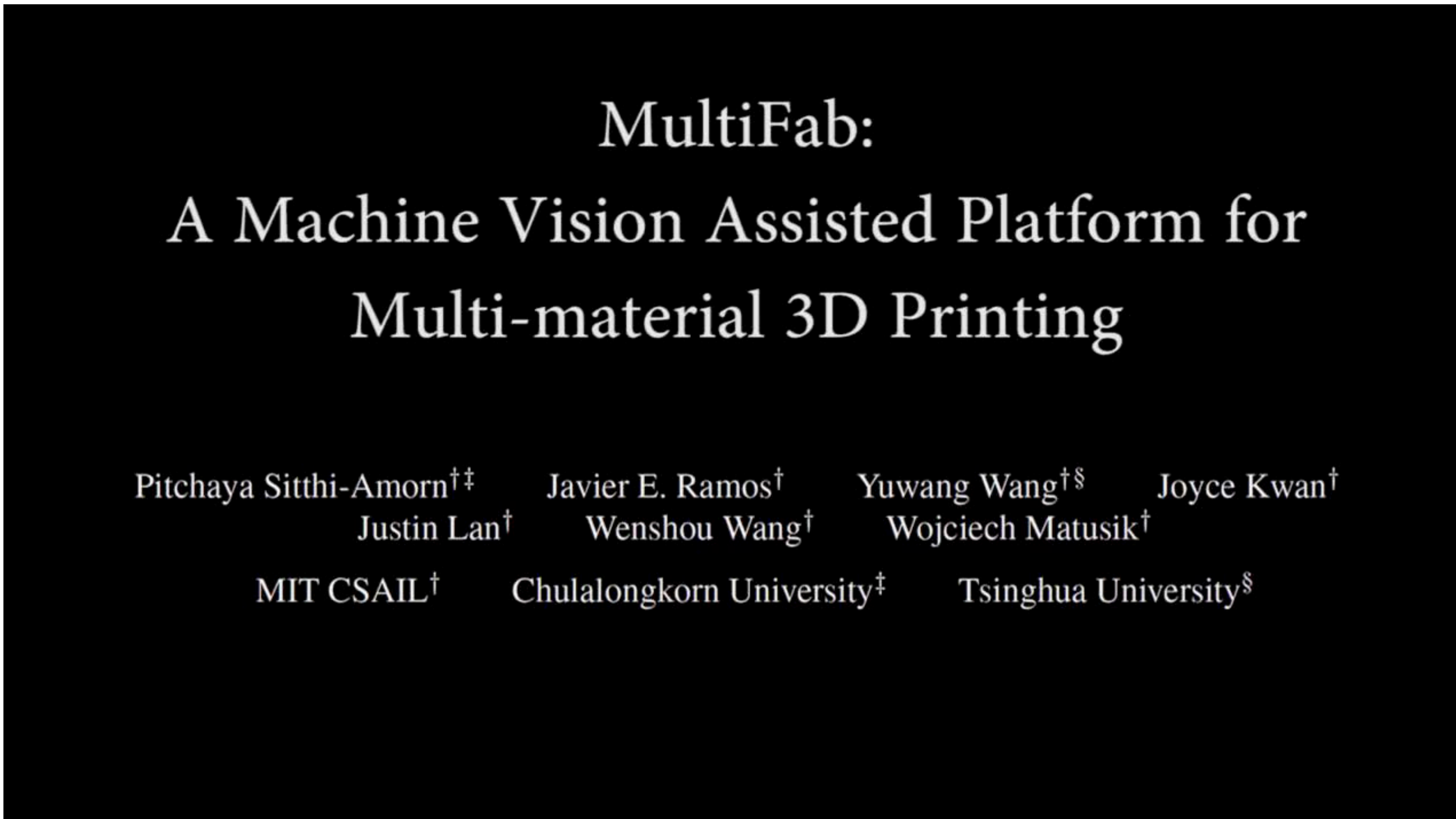




Zhao et al. Connected Fermat Spirals for Layered Fabrication. SIGGRAPH 2016

Recent Hardware Centric Research

- Smarter Printers



Sitthi-Amorn et al. MultiFab: a machine vision assisted platform for multi-material 3D printing

That’s All for Today