Additive Manufacturing

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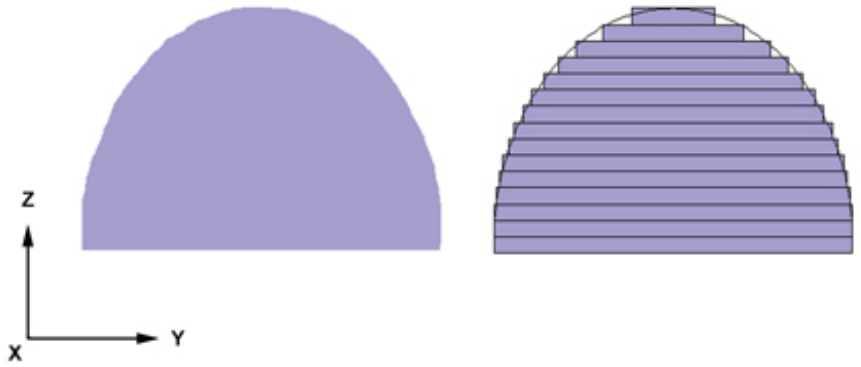
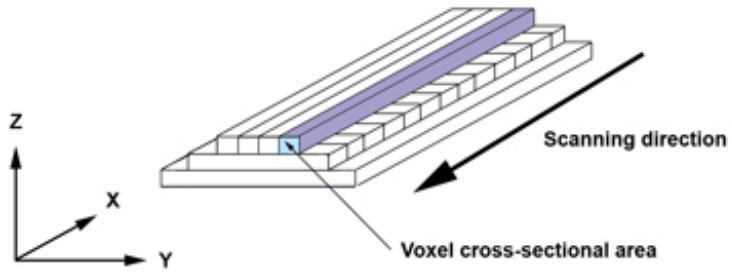
Today: 3D Printing

- Overview
- Technologies
  - Hardware
  - Materials
- Applications

The Additive Manufacturing Process

- Additive vs. Subtractive
  - Most of current manufacturing is subtractive
- “3D Printing” coined at MIT in 1995

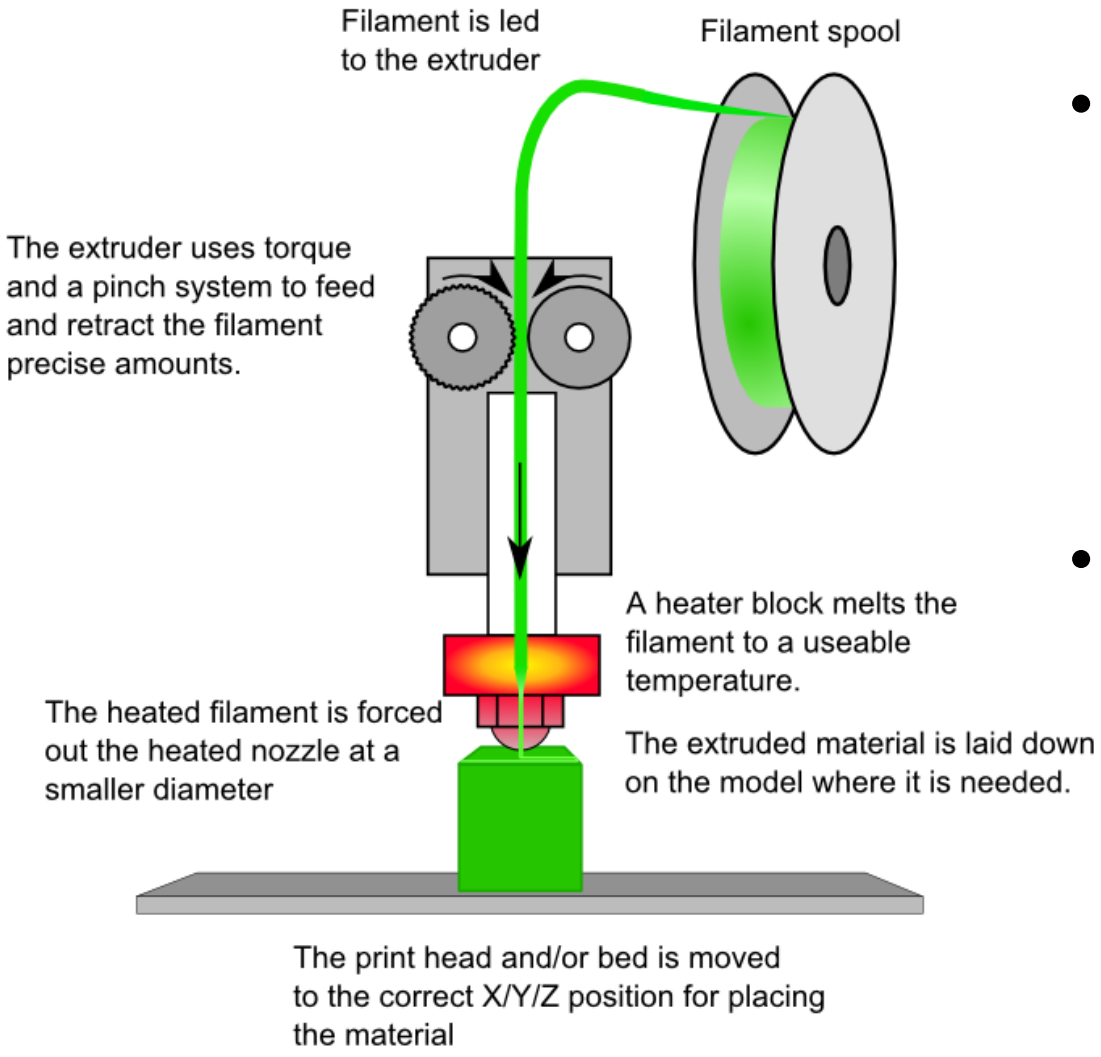




3D Printing Technologies

- 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)



source: http://reprap.org

- Filament is made of thermoplastic materials
  - ABS, polycarbonate, polycaprolactone, polyphenylsulfones and waxes
- Temporary support structure can be made from water-soluble material such as PVA
  - removed using heated sodium hydroxide solution

Fused Deposition Modeling (FDM)

Extruder Head

source: makerbot.com

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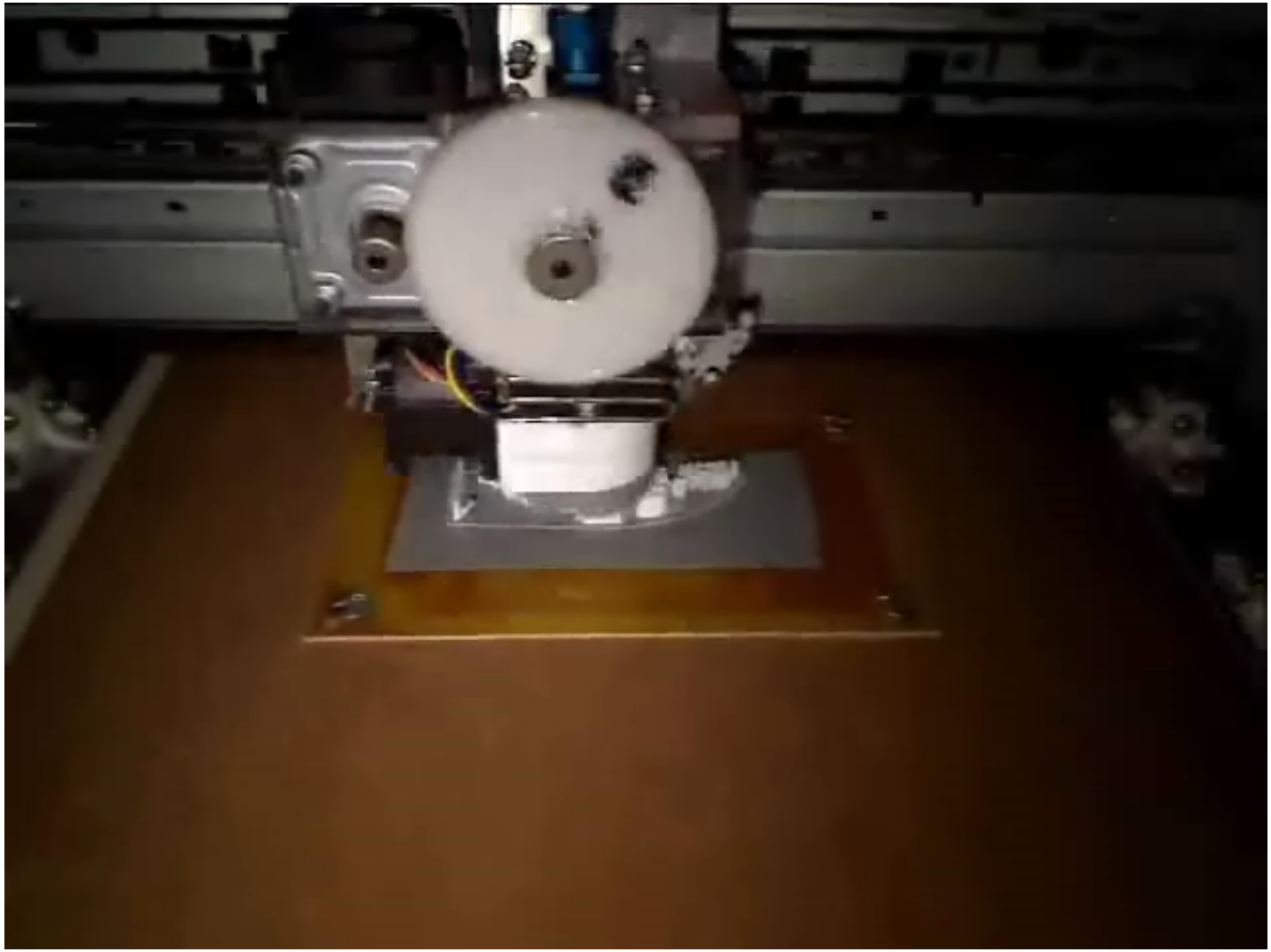
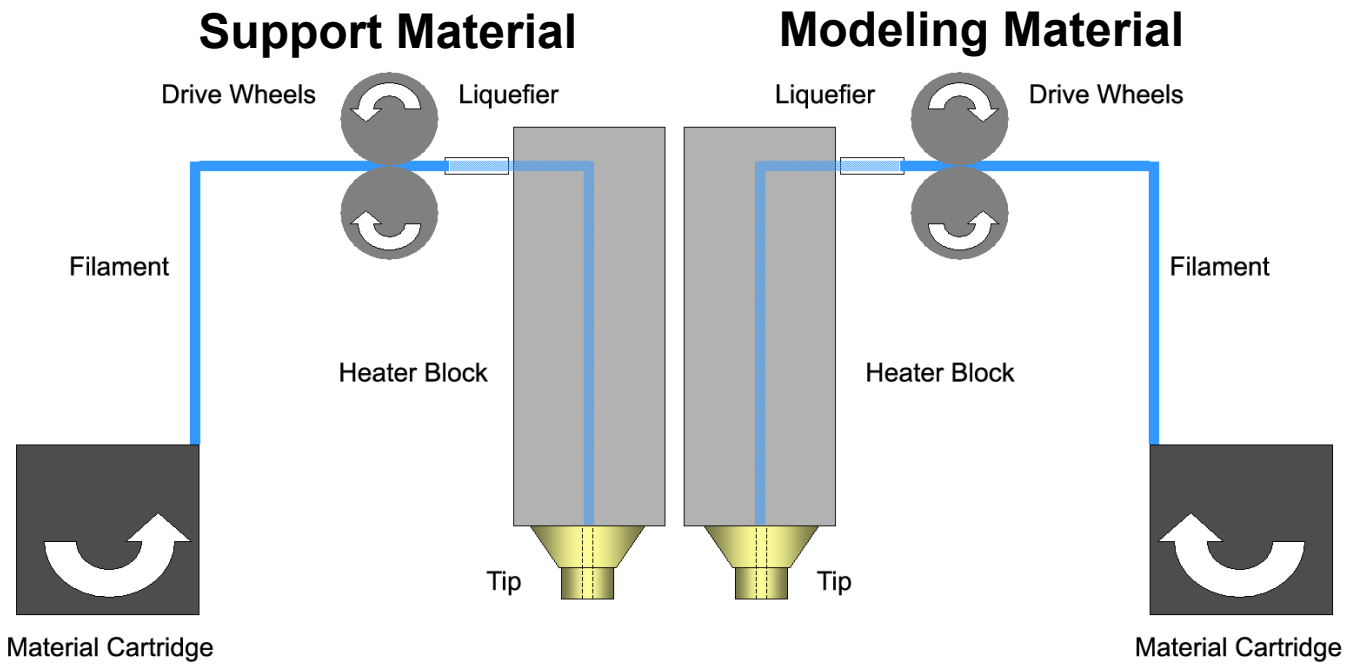
FDM Process Timelapse



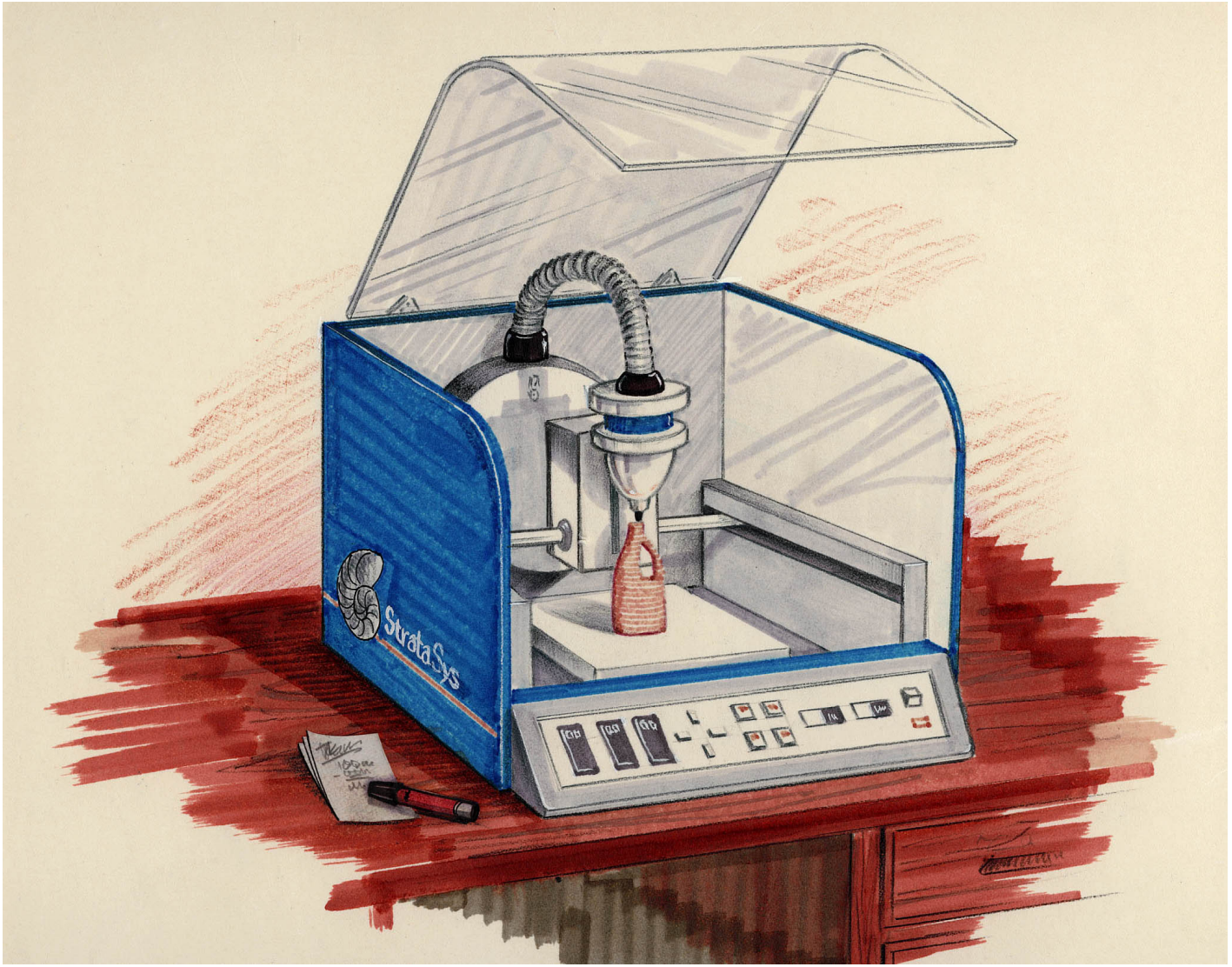
- http://www.youtube.com/watch?v=rUiehGVRrXU

Fused Deposition Modeling - History

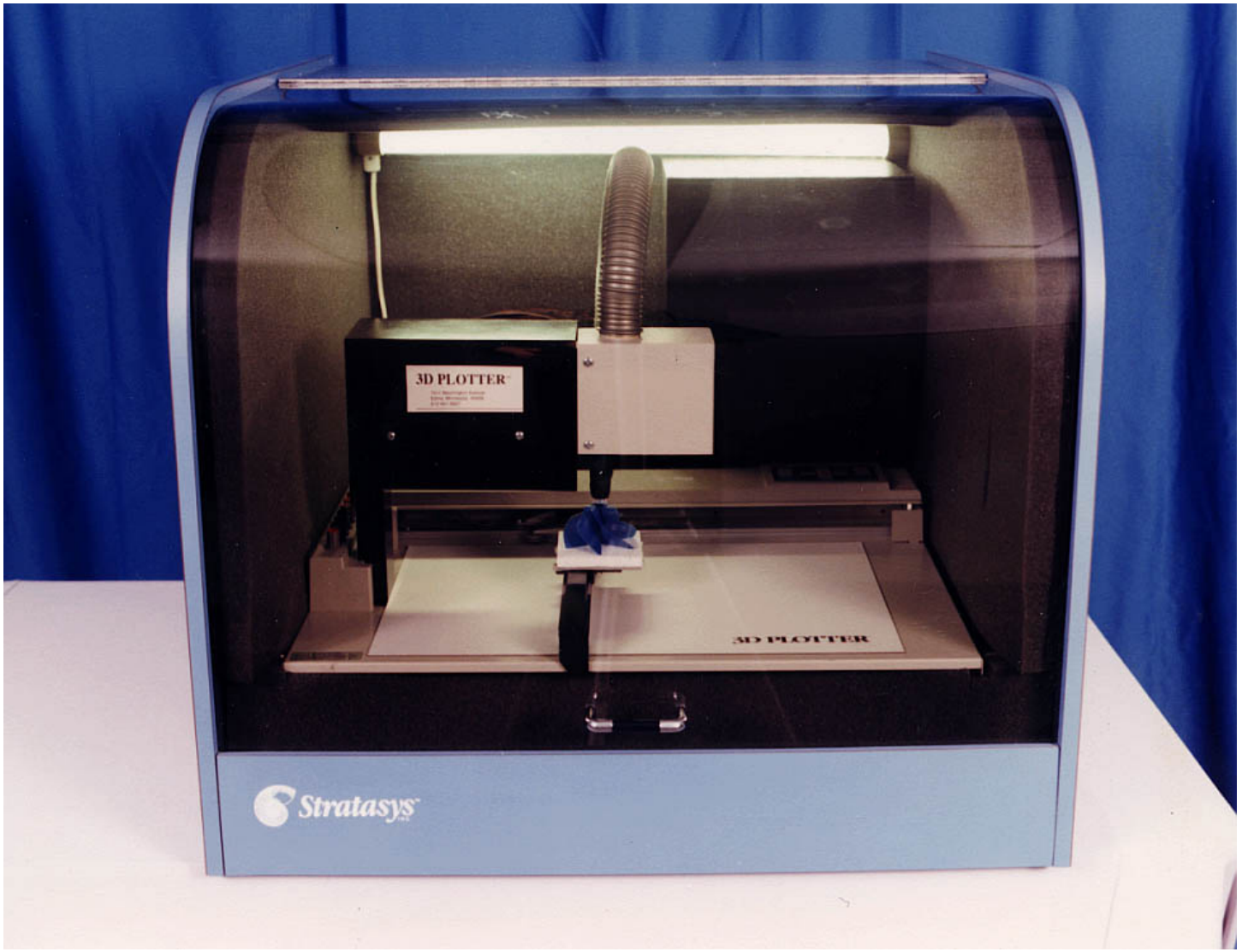
- Developed by Scott and Lisa Crump in the late 80s
  - Founded Stratasys
  - FDM is trademarked by Stratasys
    - Fused Filament Fabrication (FFF) should be used instead



3D Plotter - Vision



Operating 3D Plotter Prototype

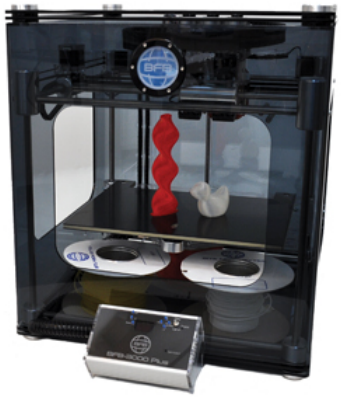


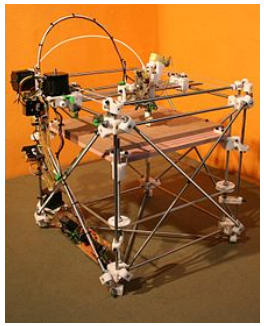
Fused Deposition Modeling – Commercial Systems

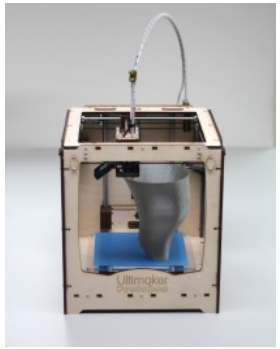
- Stratasys
  - Dimension family
- Z resolution: 0.18 mm
- Build size: 8 x 8 x 12 inches
- Limited color
- Limited material types

Fused Deposition Modeling - Clones

- MakerBot
  - http://*www.makerbot.com/*
- Bits from Bytes BFB-3000
  - http://www.bitsfrombytes.com
- RepRap
  - http://*reprap.org*
- Ultimaker
  - http://*ultimaker.com/*
- And Many More







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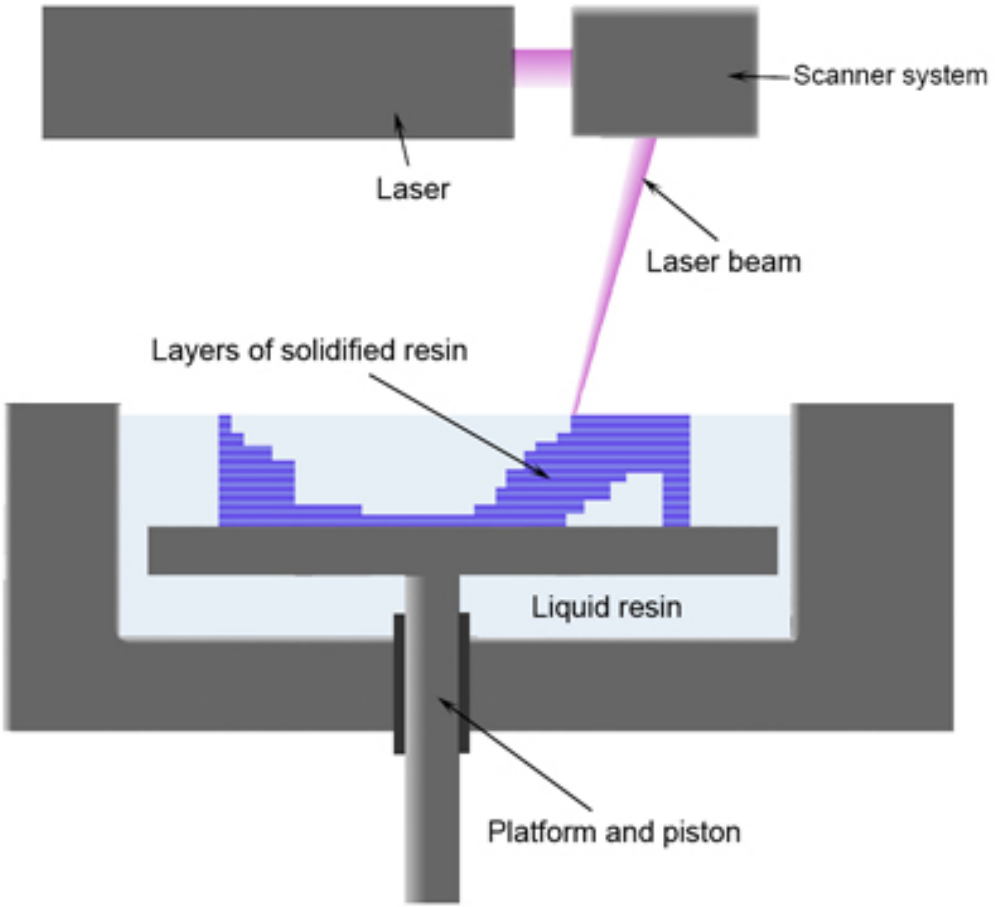
Stereolithography (SLA)



- 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

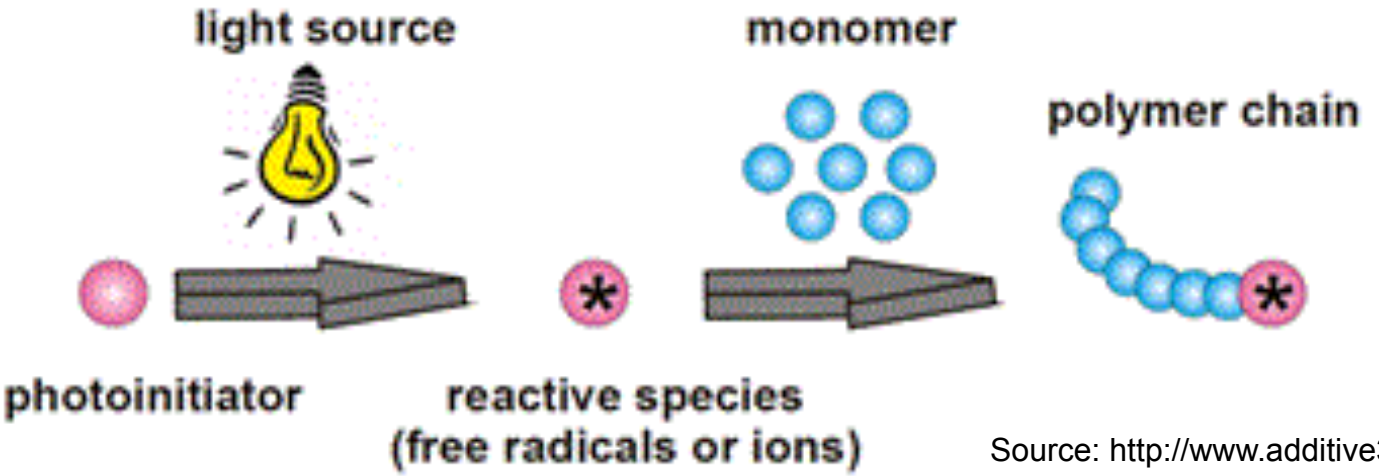
How Photopolymers Work

- Change from a liquid state to solid state when exposed with light of a certain wavelength
  - Wavelength is dependent on the photopolymer type
- A “soup” of ingredients
  - **Binders**/Oligomers: long, chain-like, chemically-reactive molecules
    - Acrylates, expoxies, urethanes
  - **Monomers**: small molecules, lower viscosity
  - **Photoinitiators:** split into 2 or more parts under light exposure, these parts react with both monomers and binders to link them together

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

How Photopolymers Work

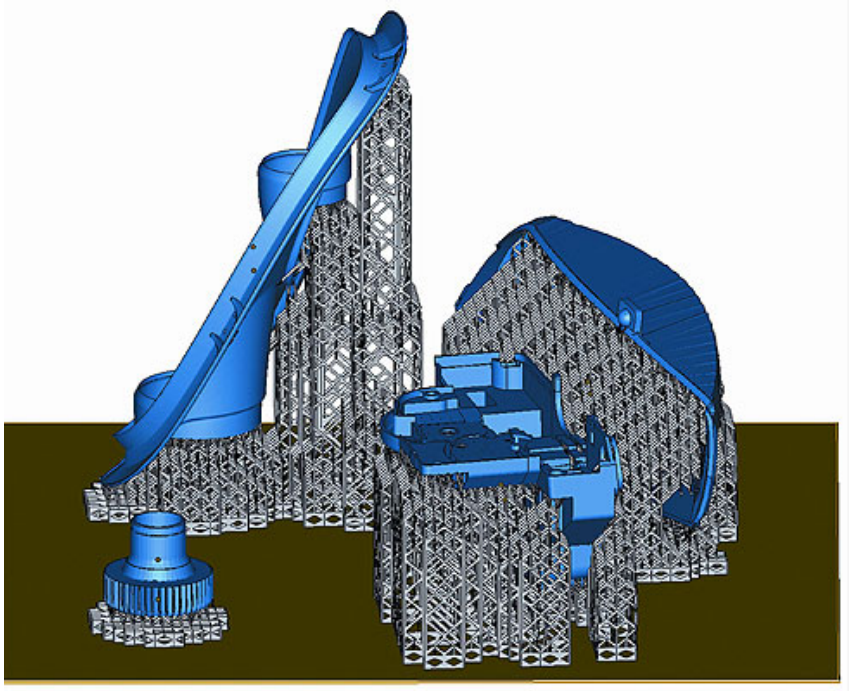
- **Radical Polymerization (more common)**
  - Free radical/complex ion is split off the initiator by light radiation
  - Radical combines with monomer or binder molecule to start reaction
  - Monomer/binder combine to make longer chain
  - Polymer chains **cross-link** – bond from chain to chain
  - Chain reaction: when monomer/binder link they release more radicals; reaction continues until radicals recombine or are trapped
- Catonic Polymerization (less common)
  - Initiator releases strong acid by light radiation; this starts the bonding

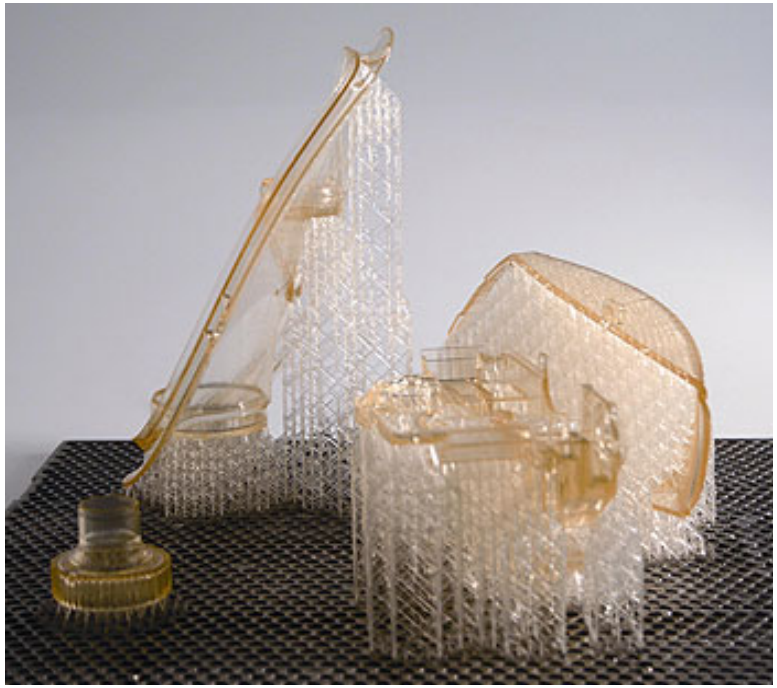


Source: http://www.additive3d.com/photo.htm

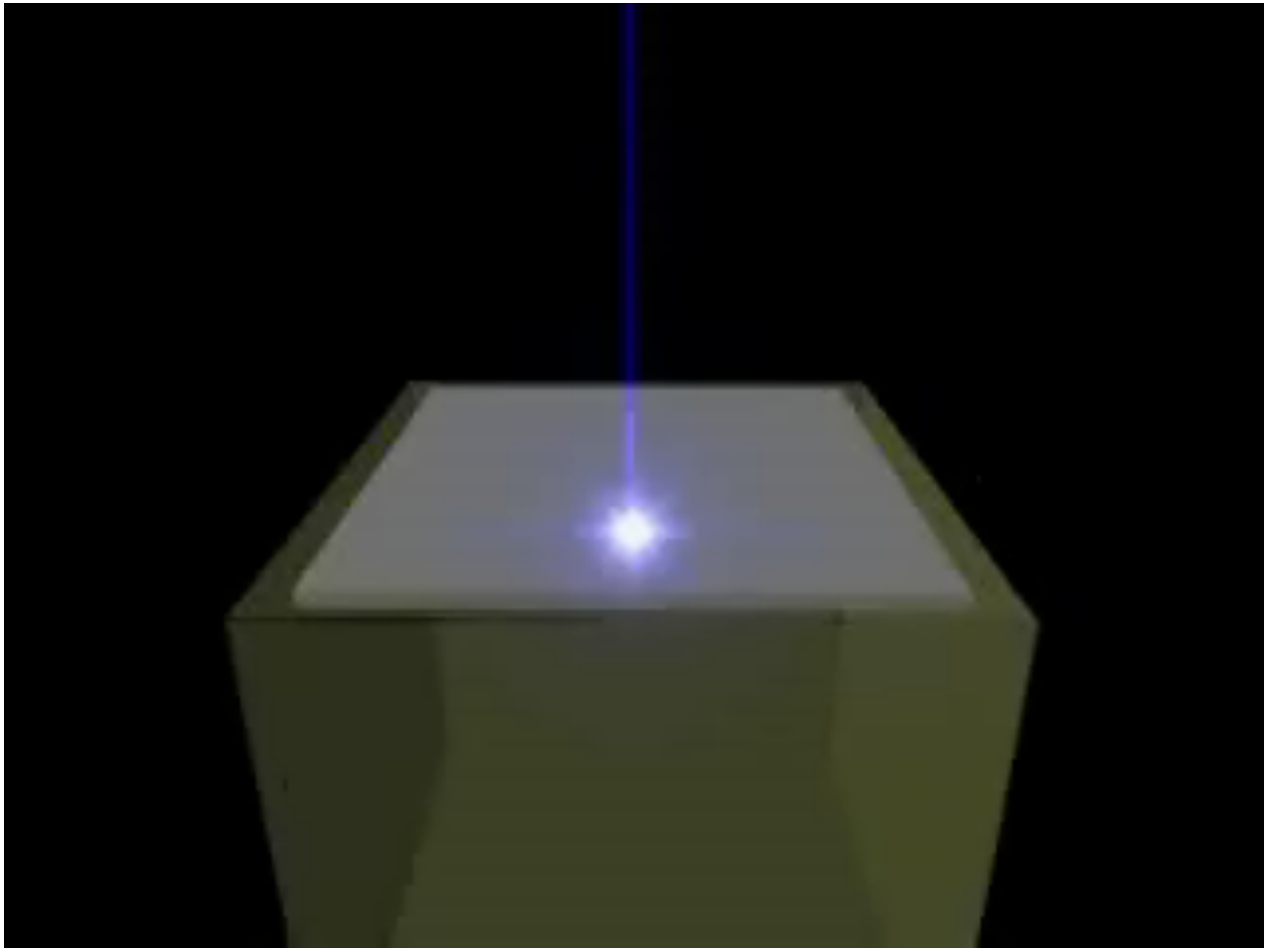
Stereolithography (SLA)

- Support structure
  - thin support lattice can be broken off



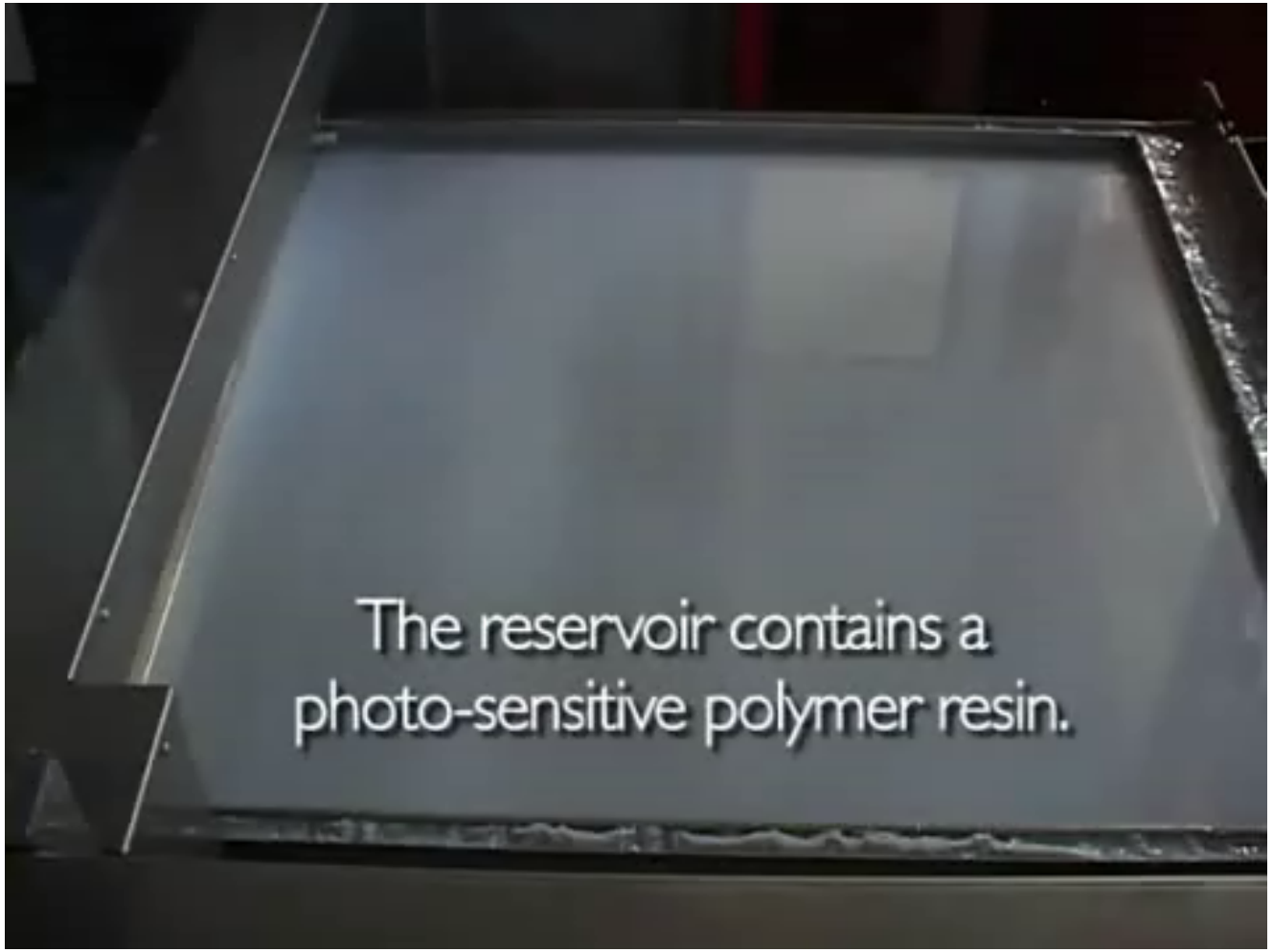


Stereolithography Process



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

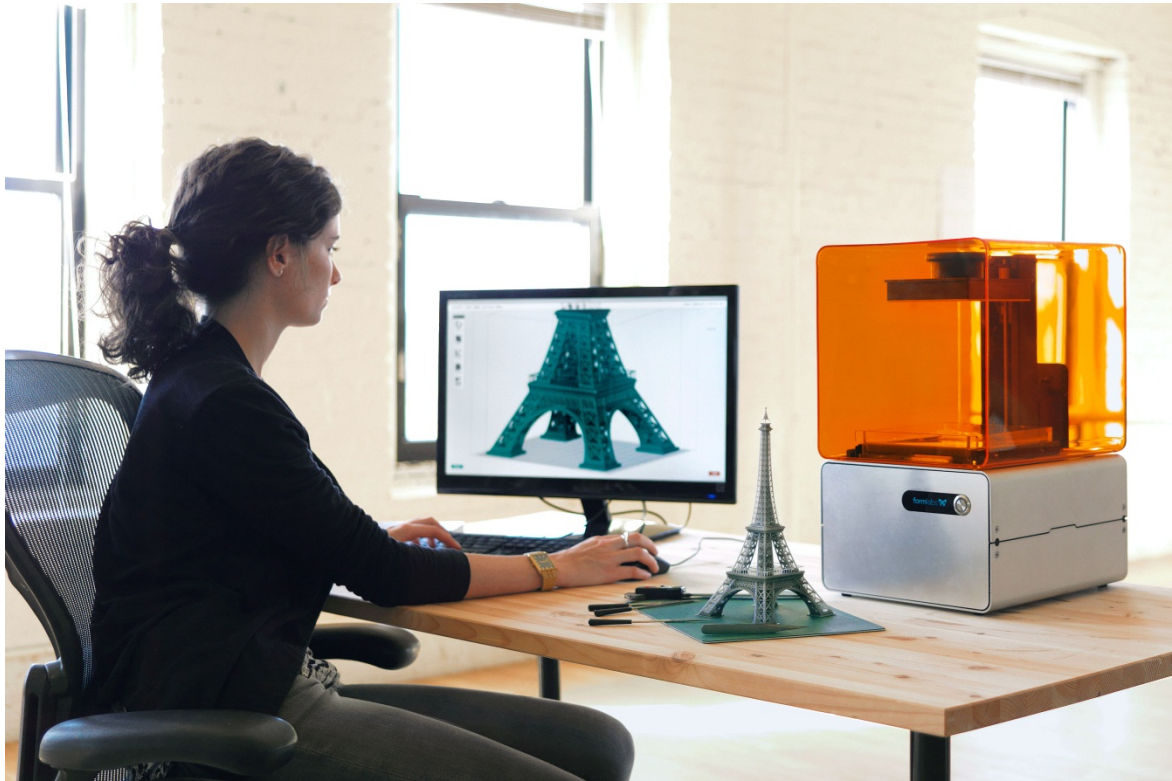
Stereolithography – 3D Systems

- 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



Stereolithography - Clones

- Autodesk Ember
  - X-Y: 50um
  - Z: 10-100um
  - Open firmware

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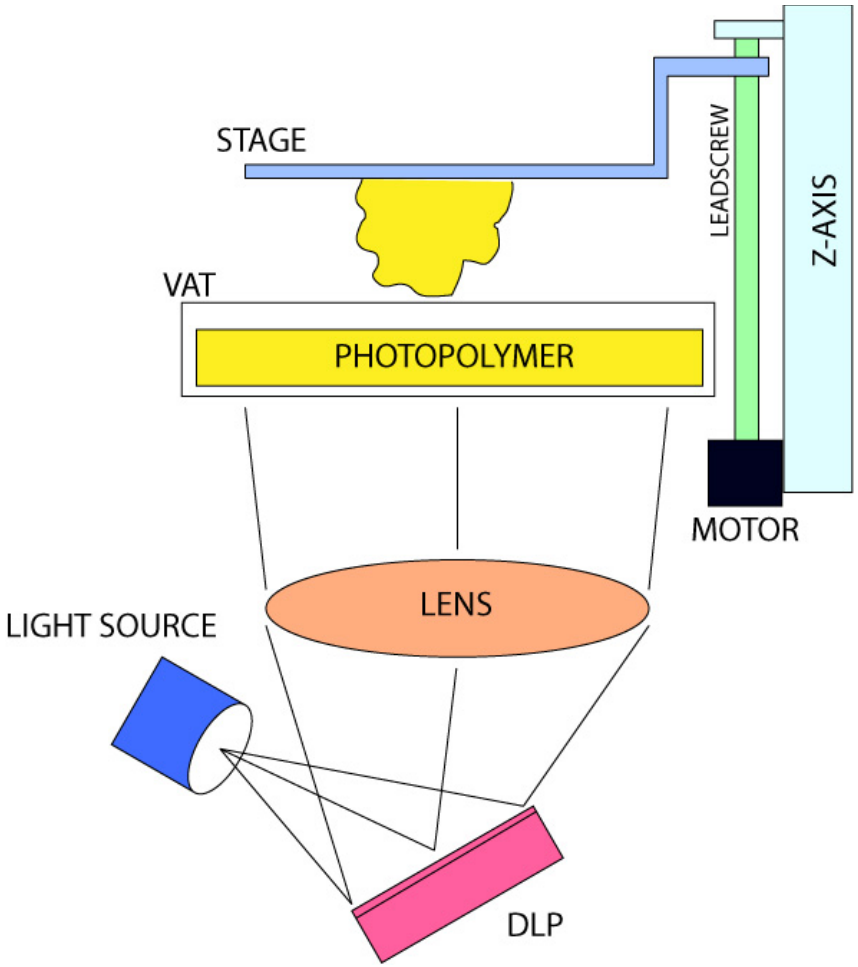
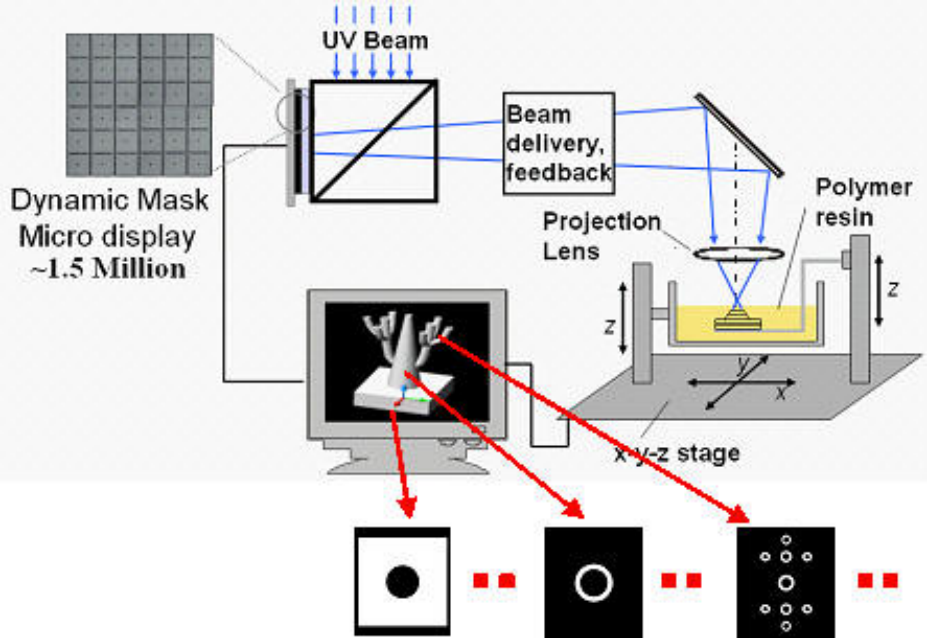
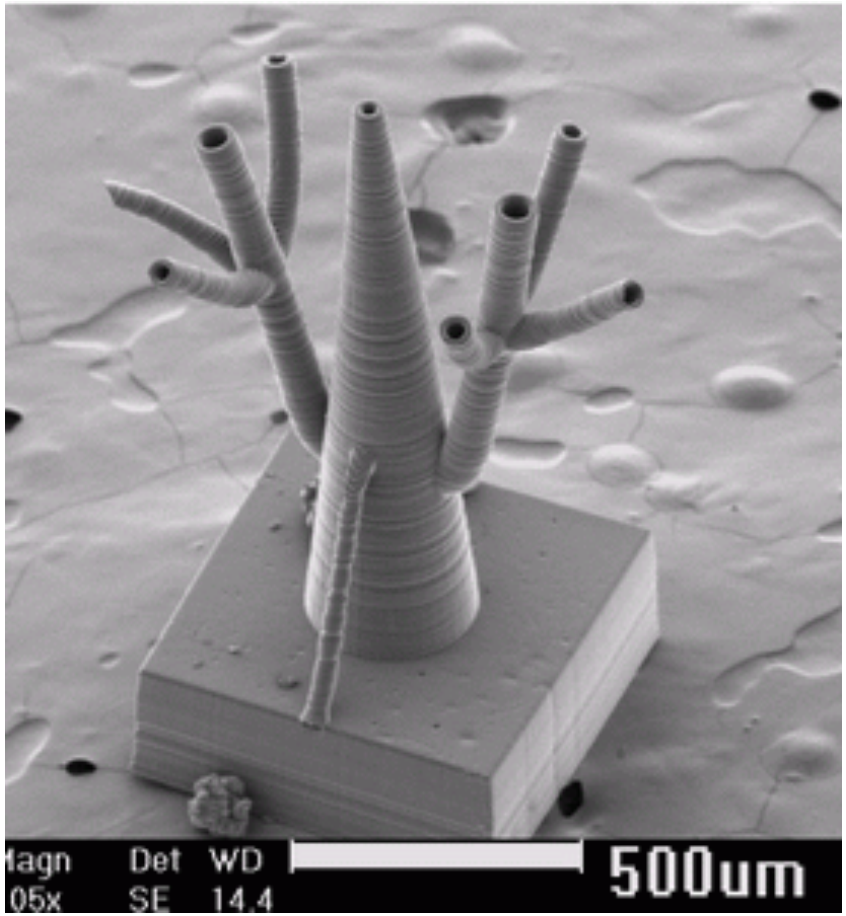
Digital Light Projector (DLP) 3D Printing



- 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

Digital Light Projector (DLP) 3D Printing





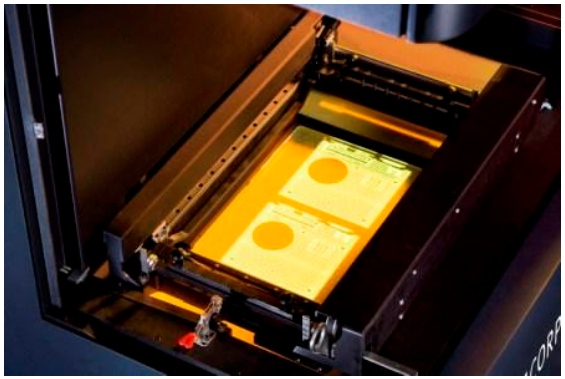
Nicholas Fang, MIT

DLP 3D Printing Features

- Similar to SLA
  - Laser+mirror is replaced by a projector
- Simple design
  - 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

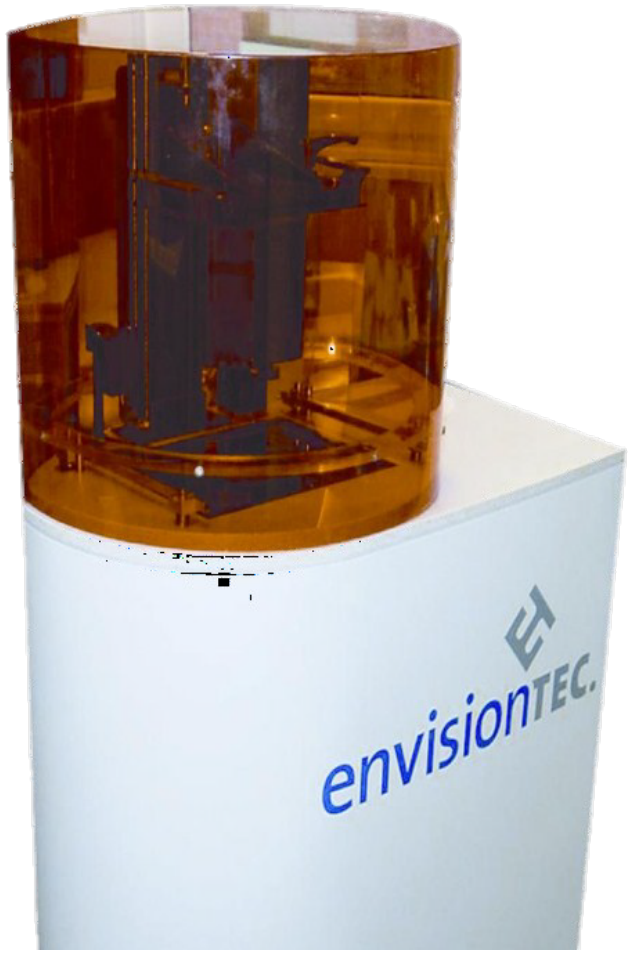
DLP 3D Printing – Commercial Systems

- 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
  - Price ~40K

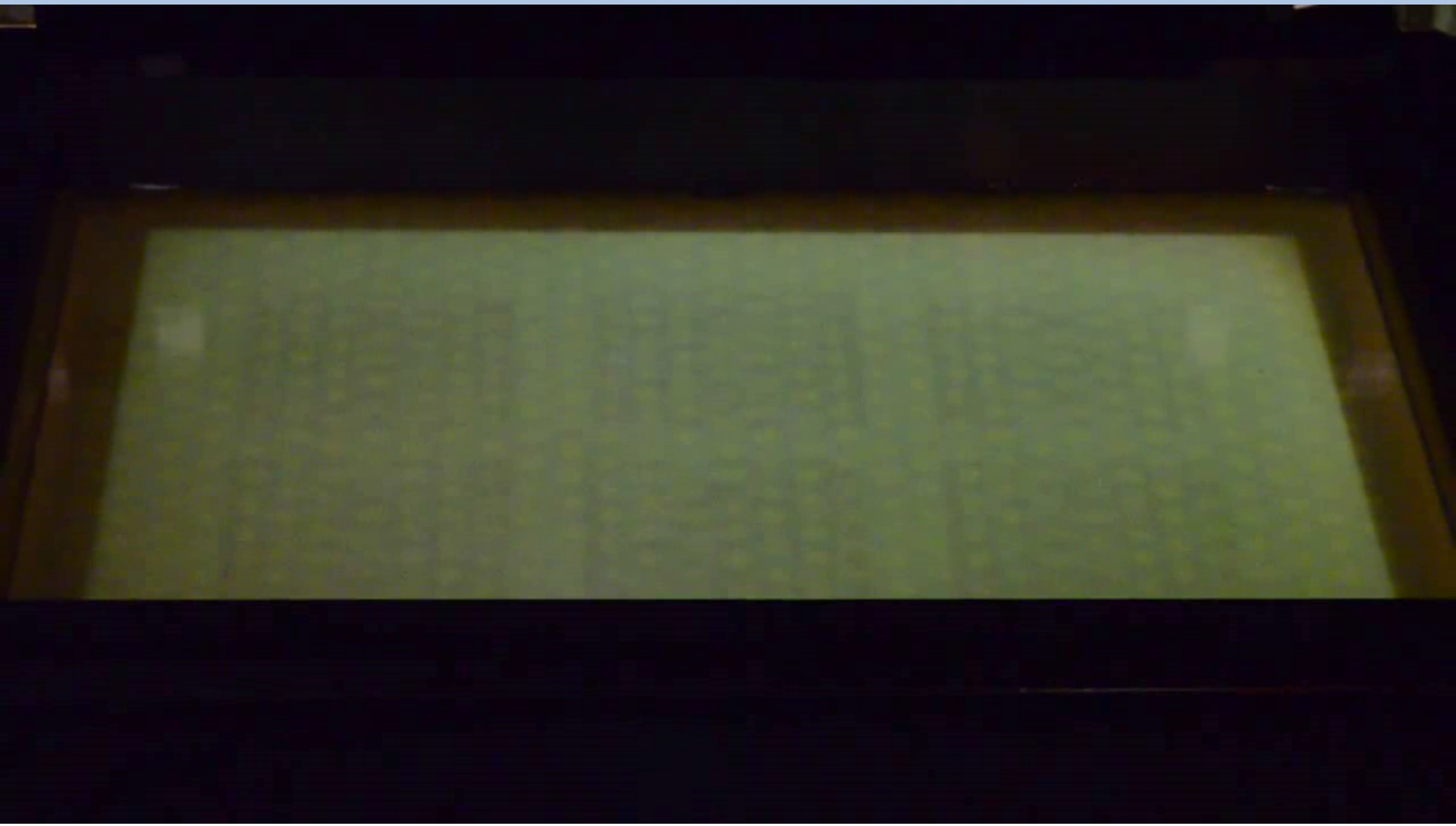


DLP 3D Printing – Commercial Systems

- 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

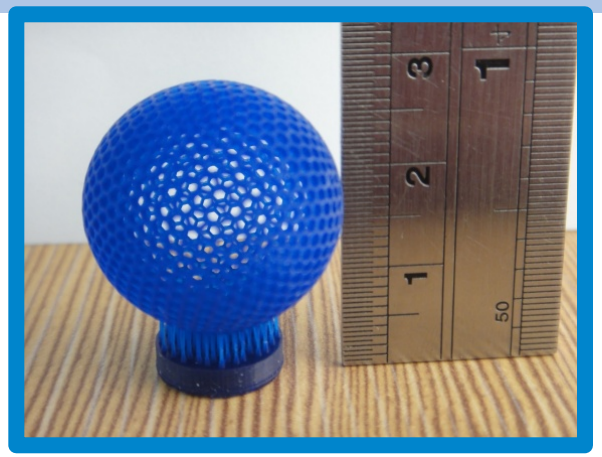


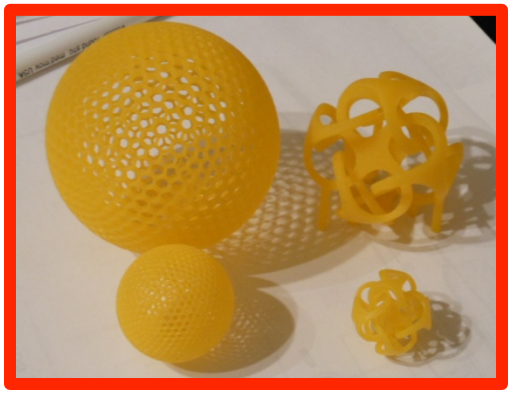
https://www.youtube.com/watch?v=HbUuv_3Jw7M

DLP 3D Printing - DIY

B9Creator

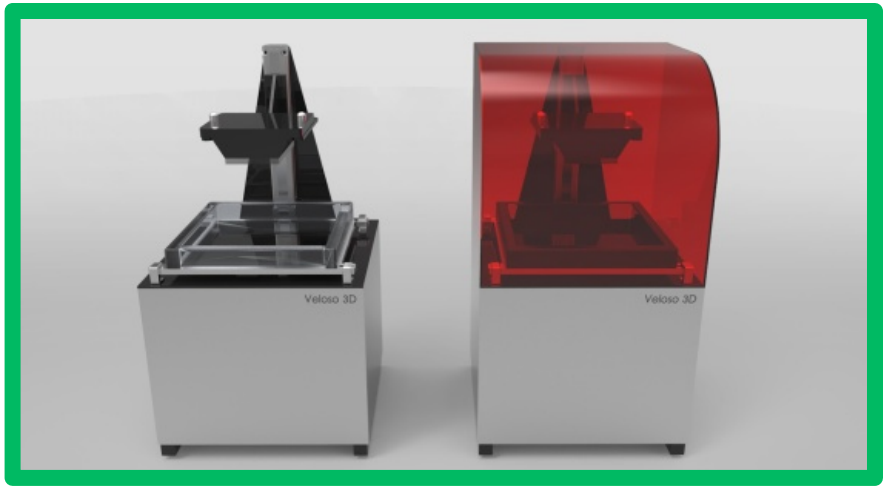
MiiCraft





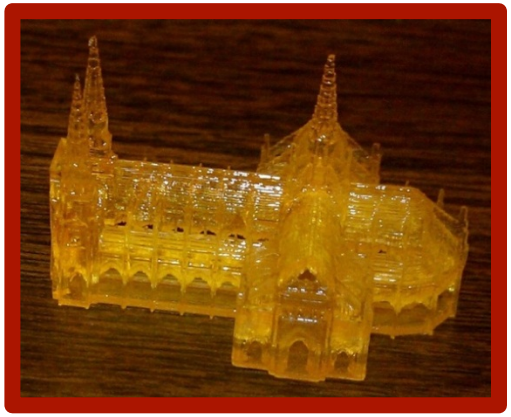
http://www.3ders.org/articles/20120911-a-list-of-diy-high-resolution-dlp-3d-printers.html

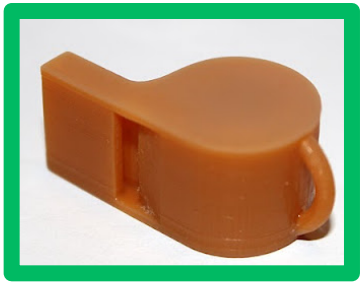
DLP 3D Printing - DIY



3D Home Made

Sedgwick





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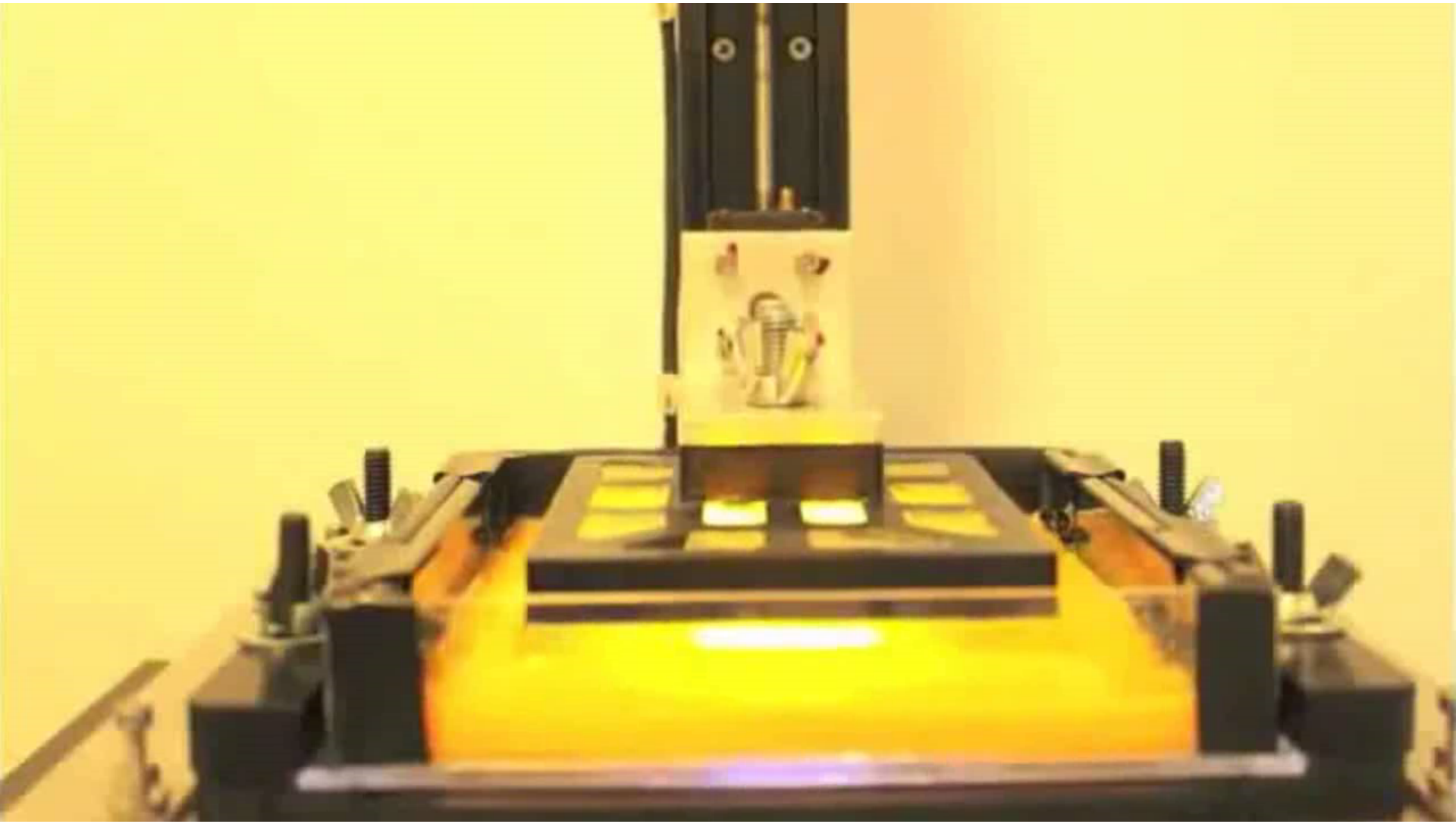
DLP 3D Printing – DIY Video



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

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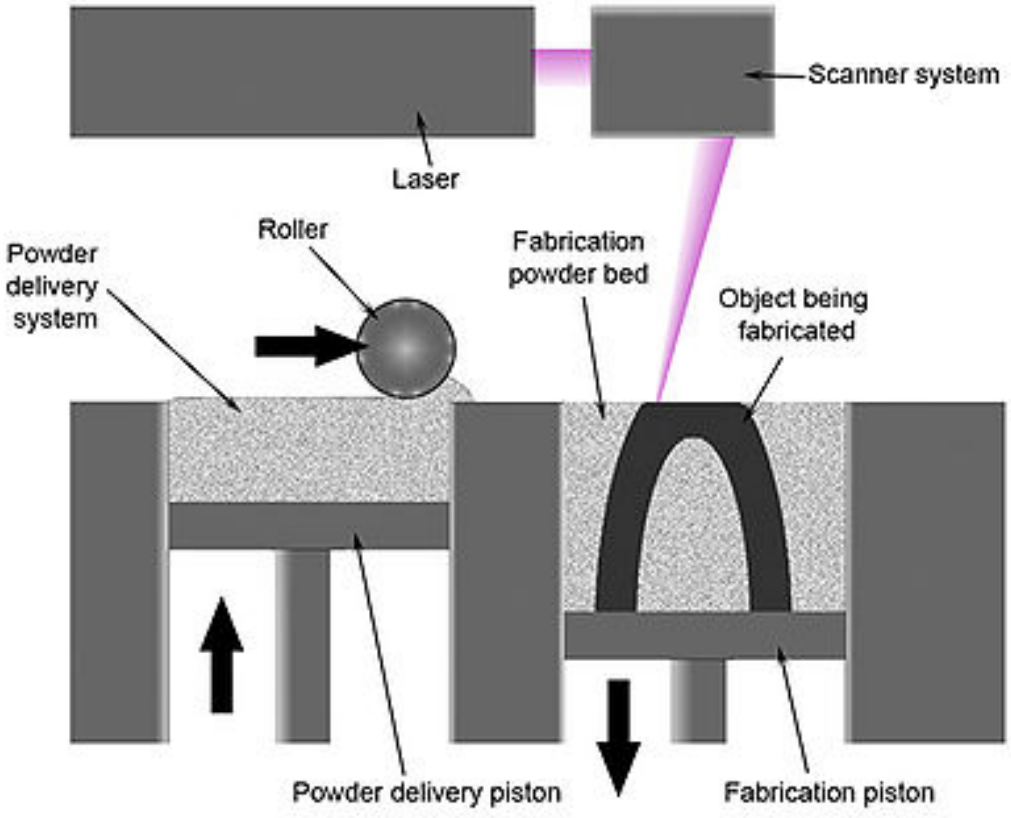
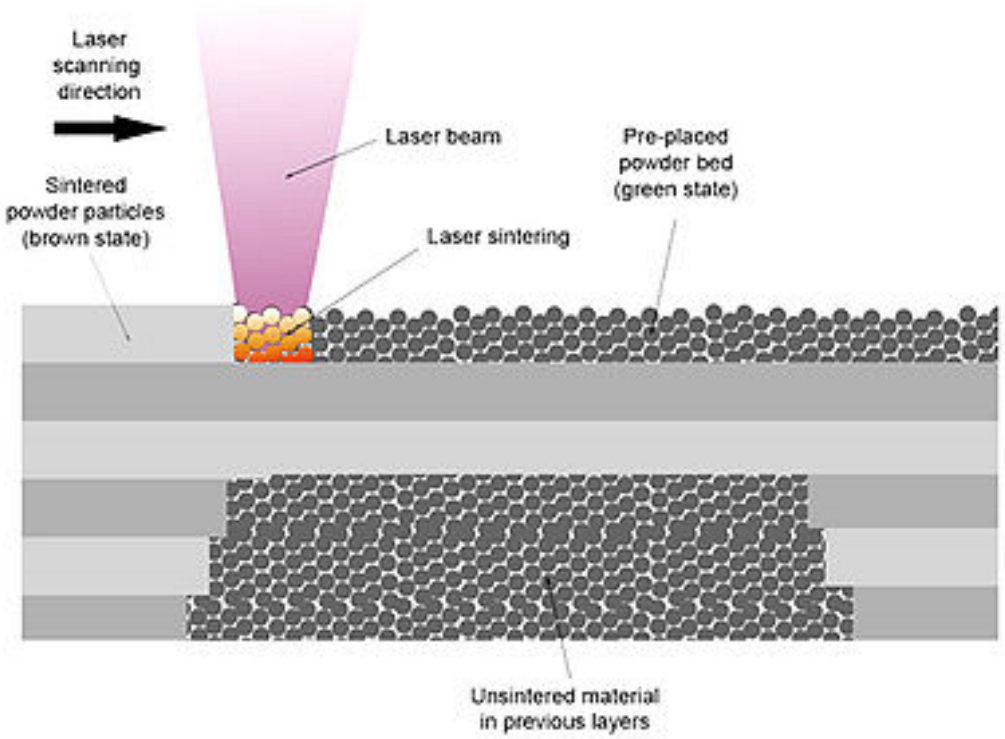


- SLS and DMLS use a bed of small particles (made of plastic, metal, ceramic, or glass)
- High-power laser traces one layer on the surface of the powder bed melting/fusing the particles
- The platform descends by one layer and more material is added

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

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



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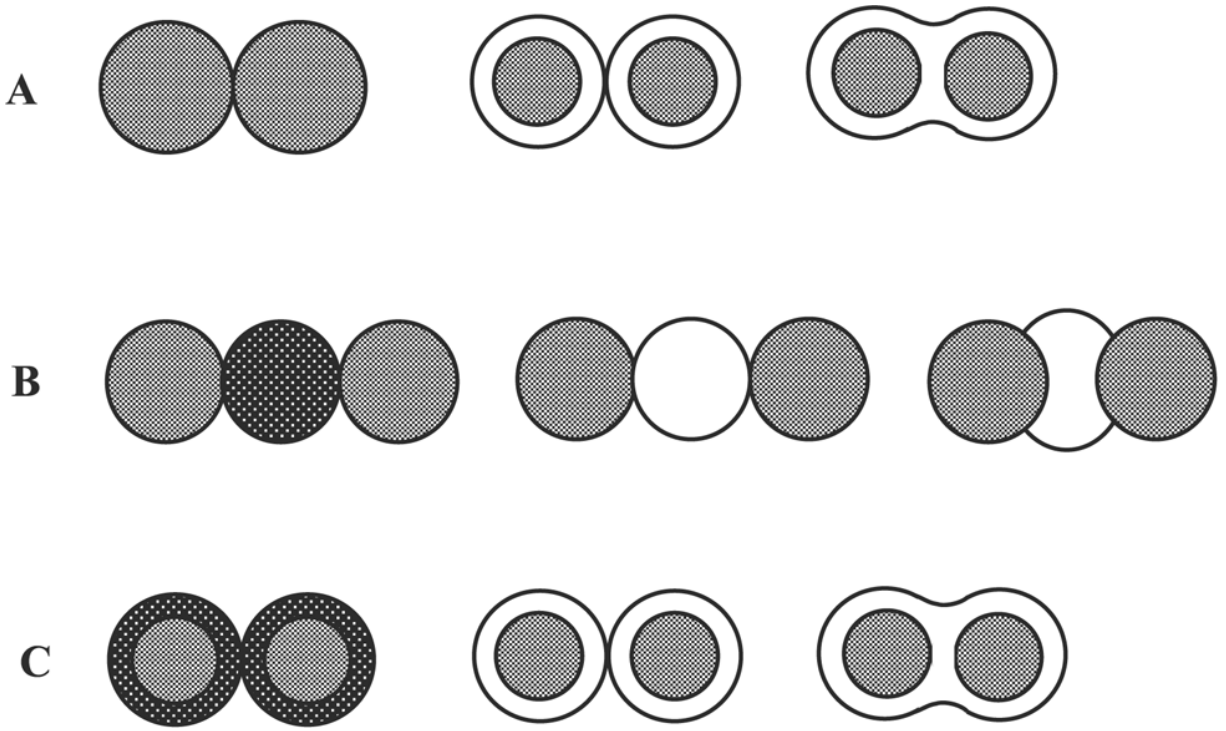
SLS & DMLS Features

- 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

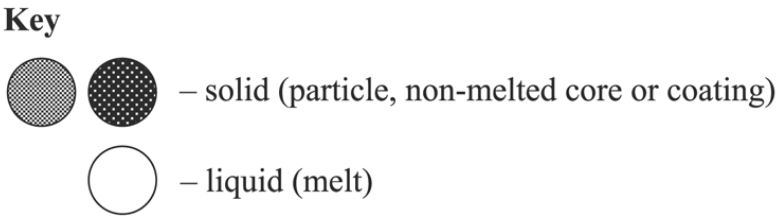
Single- and Two-Component Powders



A – single-component metal powder

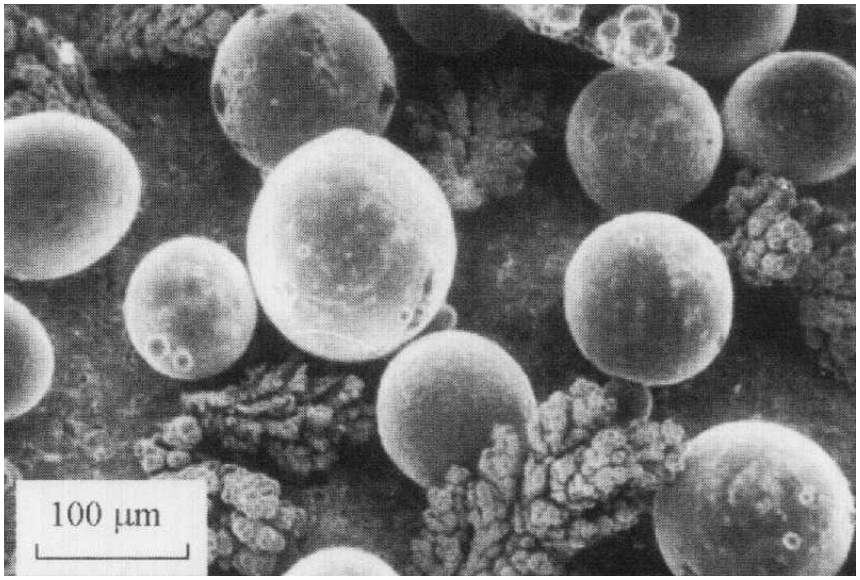
B – two-component metal/metal powder mixter

C – two-component metal/metal coated powder

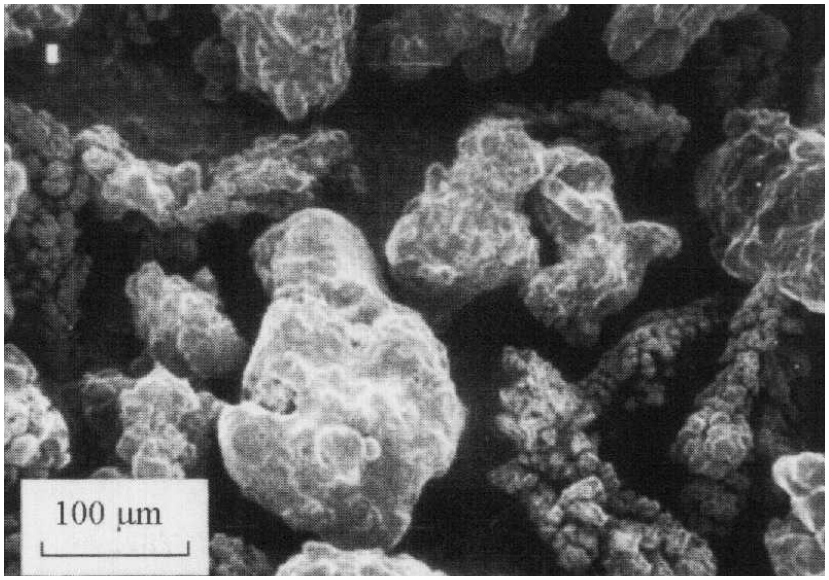


Source: Tolochko et al. 2003

Raw Powder Particles



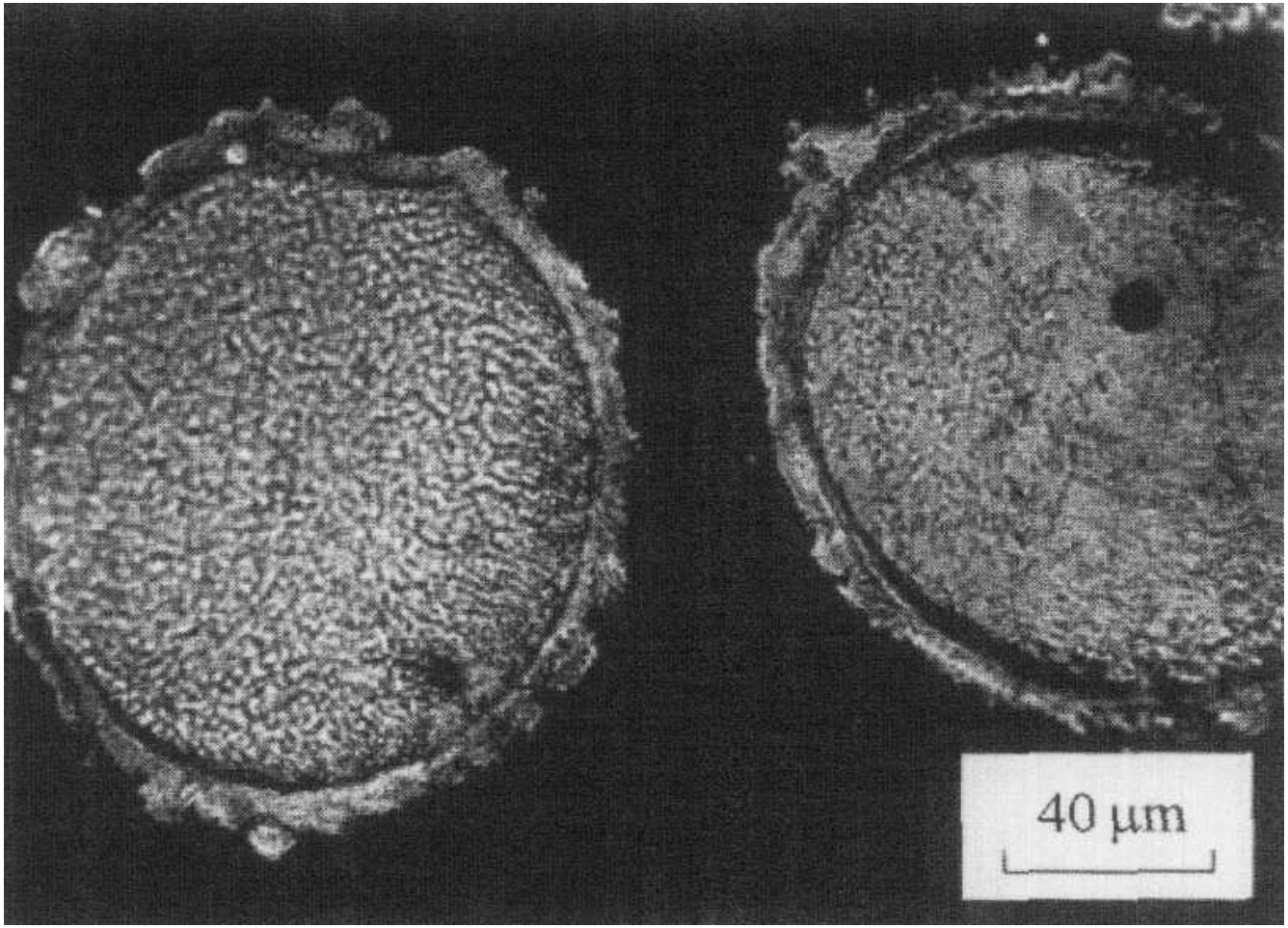
Raw Ni-alloy-Cu powder mixture



Raw Fe-Cu powder mixture

Source: Tolochko et al. 2003

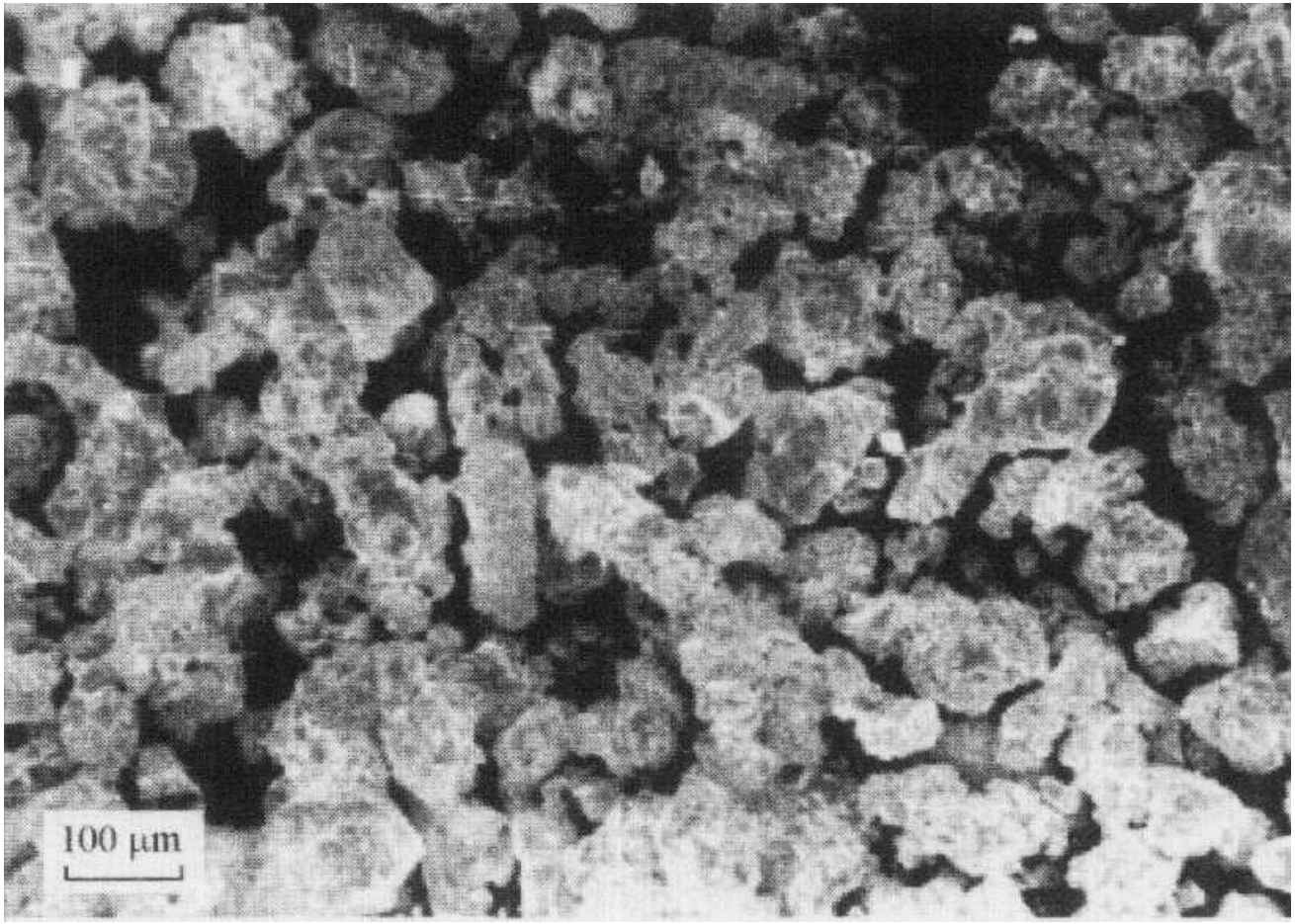
Raw Powder Particles



Raw Cu-coated Ni-alloy powder

Source: Tolochko et al. 2003

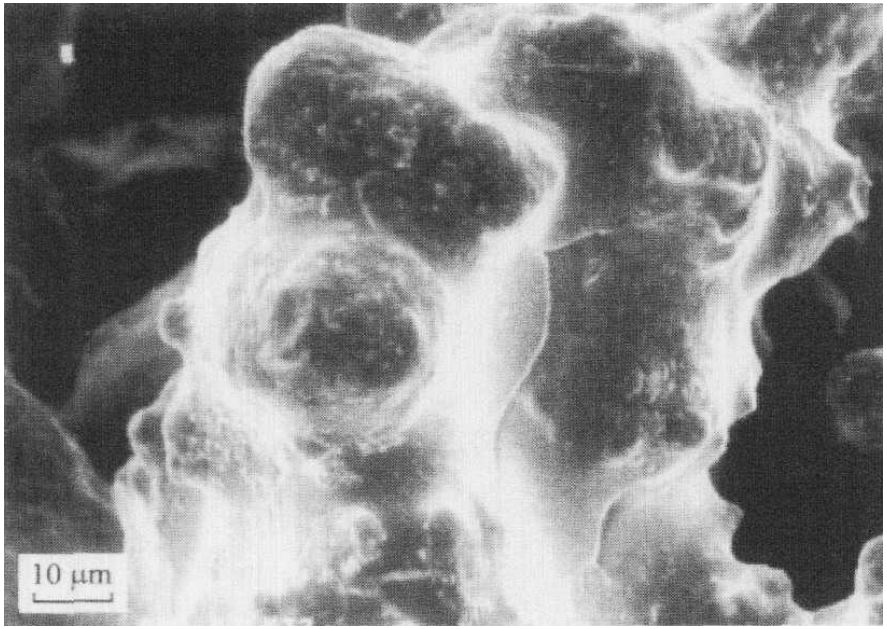
Sintered Powders

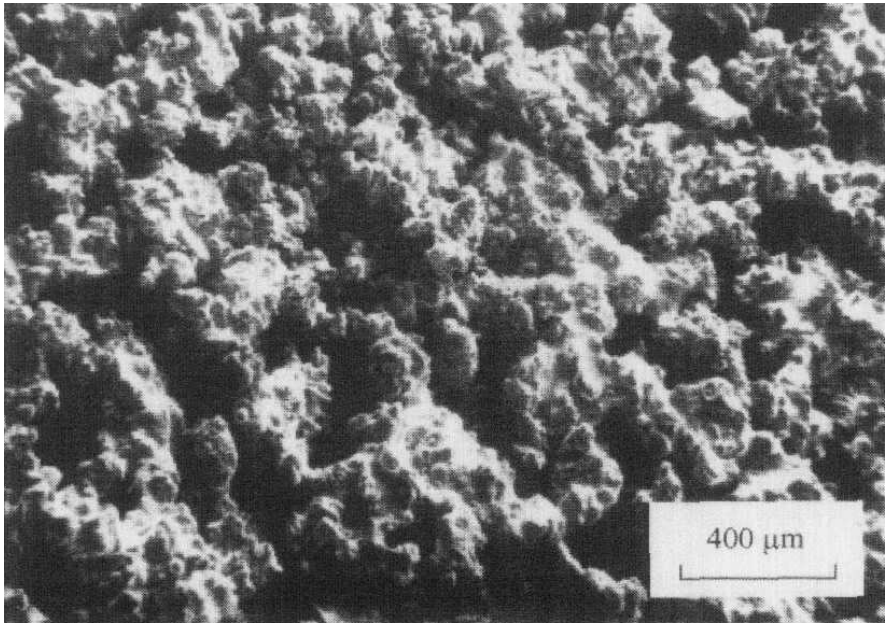


Single component Fe powder **after** sintering

Source: Tolochko et al. 2003

Sintered Powders

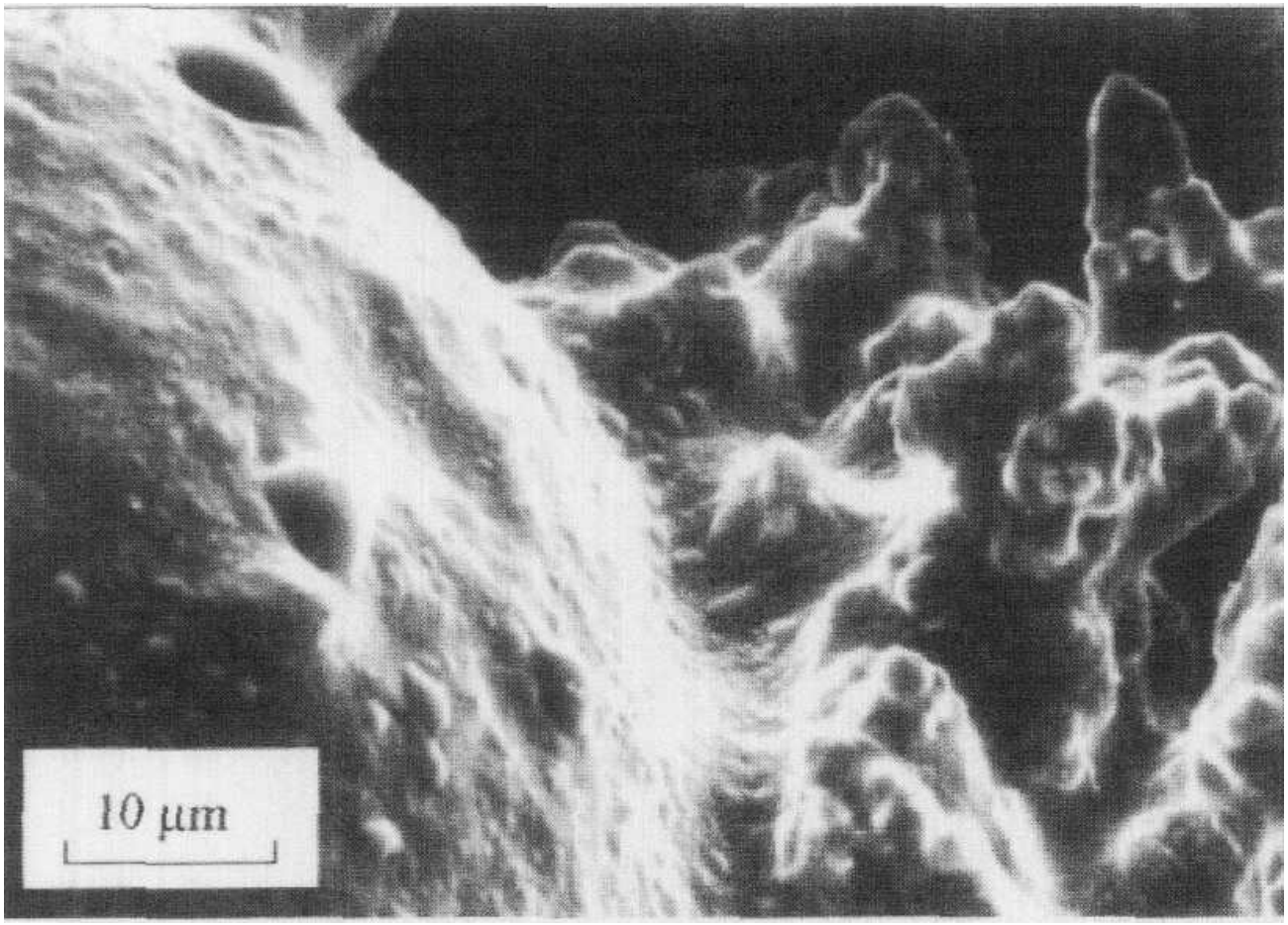




Fe-Cu powder mixture **after** sintering

Source: Tolochko et al. 2003

Sintered Powders



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

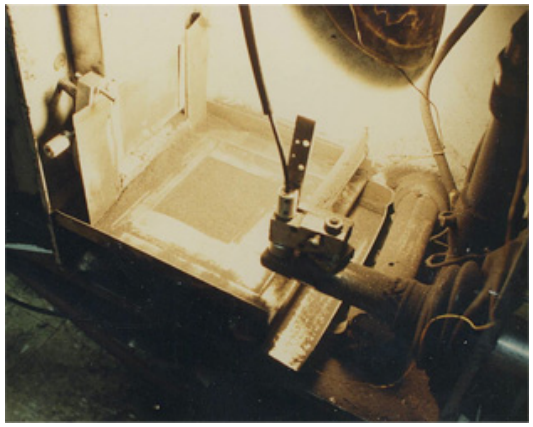
Source: Tolochko et al. 2003

SLS & DMLS Process

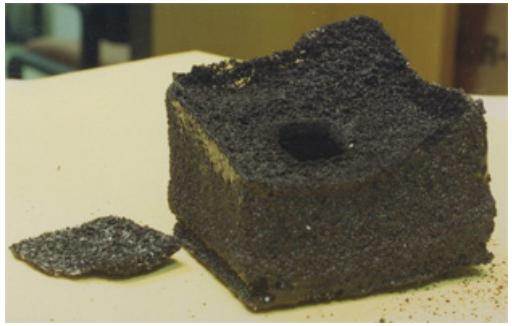
https://www.youtube.com/watch?v=BZLGLzyMKn4

SLS & DMLS - History

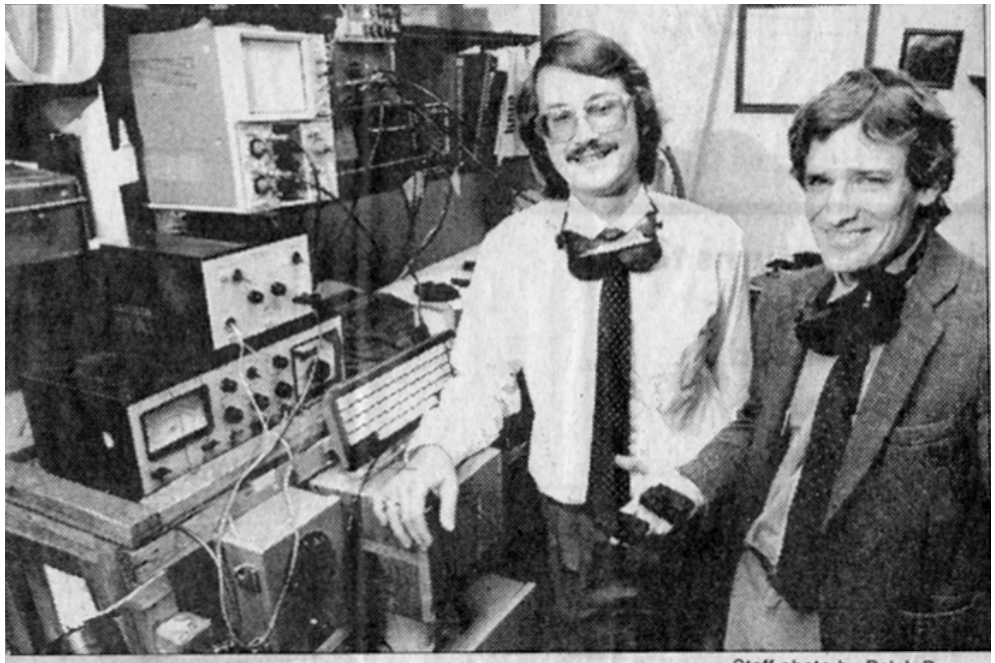
- Invented at UT Austin by Joe Beaman and Carl Deckard (80s)



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

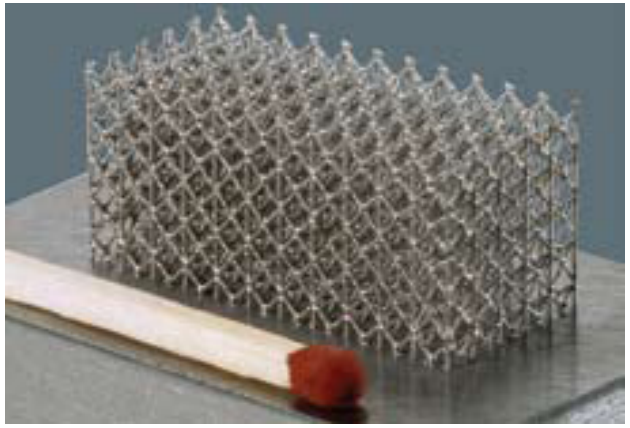
Associate Professor Joe Beaman shows some three-dimensional plastic models made by the 'selective laser centering' device developed by Carl Deckard, left.

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

SUTD DmanD Center

EOSINT M 280, Direct Metal Laser Sintering

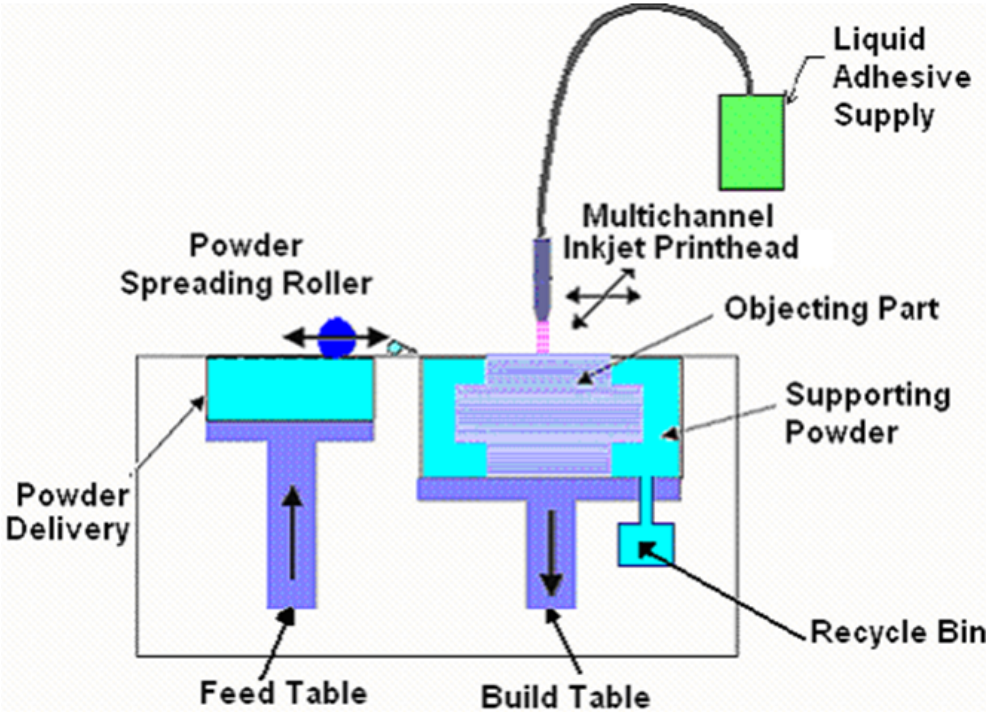
Produces metals with high mechanical quality

Materials: Maraging Steel, Stainless Steel, Nickel Alloy
Resolution: 40µm layers
Build Size: 250 x 250 x 325 mm
URL: Click here

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)

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

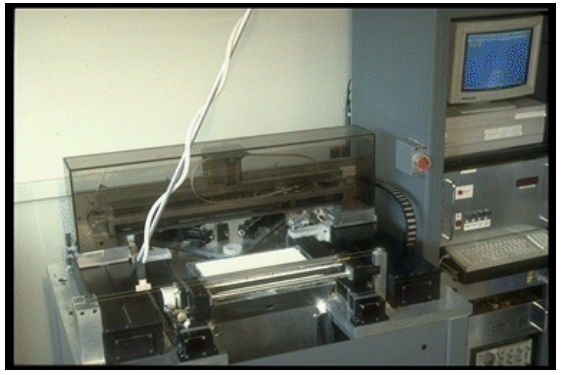
- Similar to SLS and DMLS
  - Also uses granular materials
  - Uses inkjet printhead instead of laser
  - Glues particles instead of melting them
- Does not require support structure
  - Overhangs are supported by powder material
- The only technology supporting full-color printing
- Materials
  - Plaster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

Plaster-based 3D Printing Process

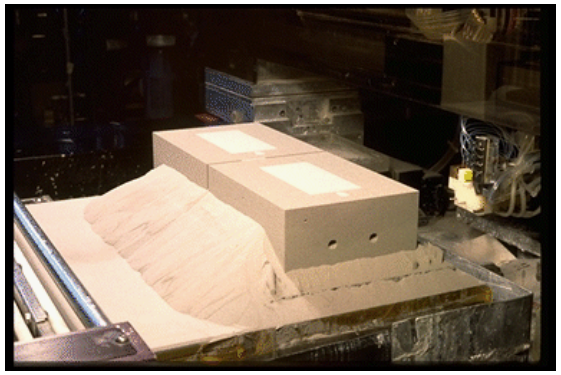
https://www.youtube.com/watch?v=GnFxujCyD70

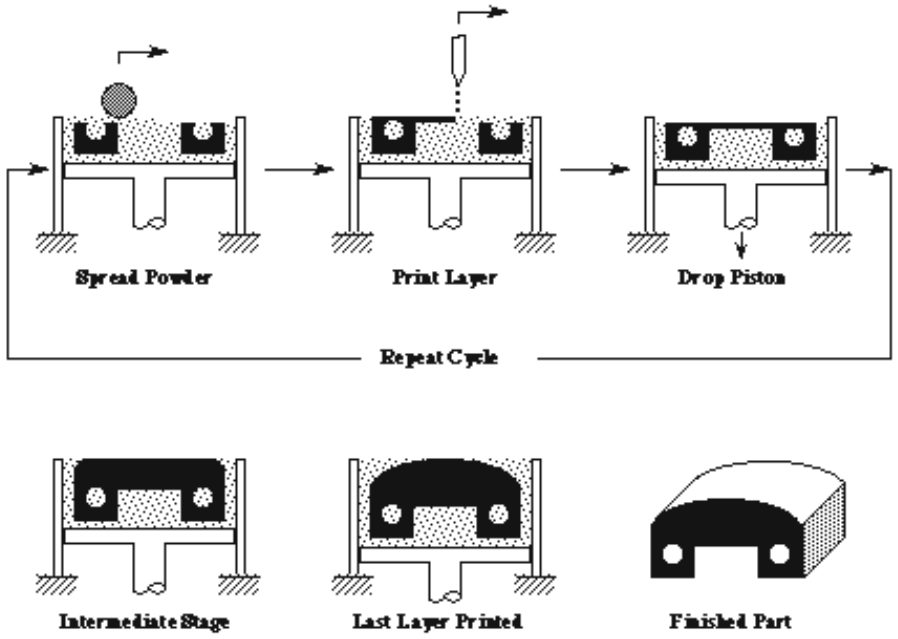
Plaster-based 3D Printing - History

- 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

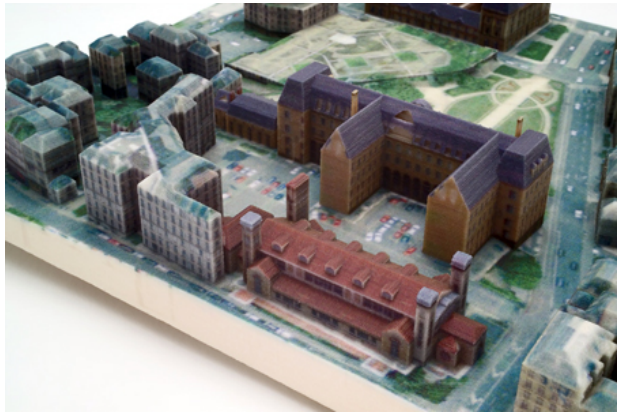
Source: Z corporation

SUTD Fab Lab

- Z Corporation ZPrinter 350

Source: Z corporation

Fabricated Parts



Source: Z corporation

3D Printing Technologies

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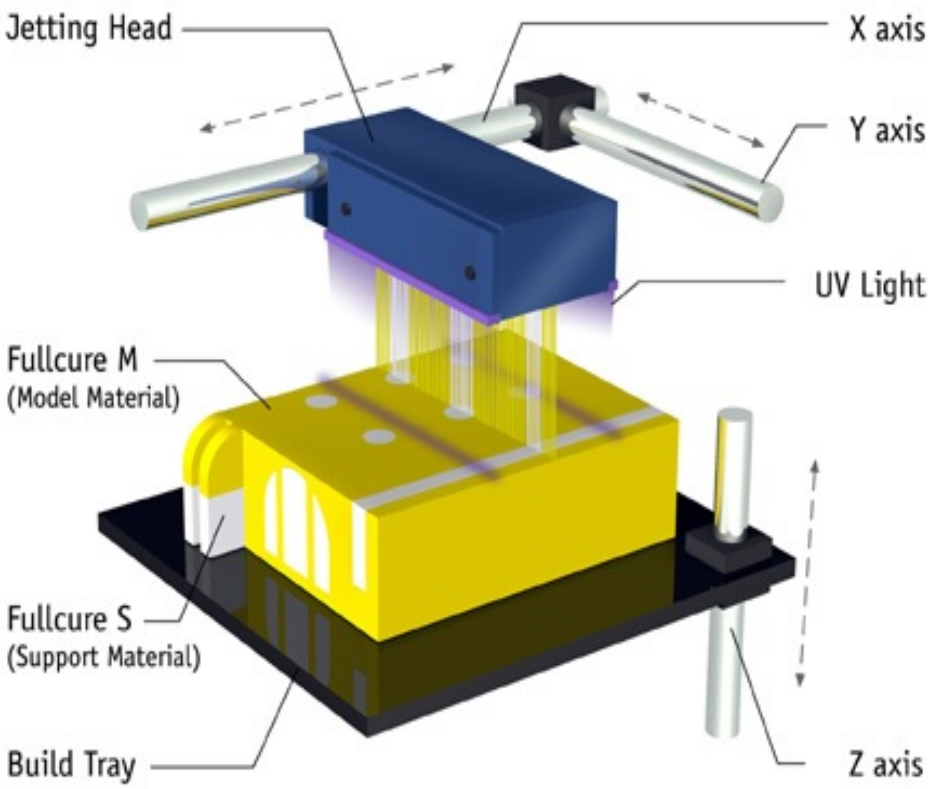
Photopolymer Phase Change Inkjets



- 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

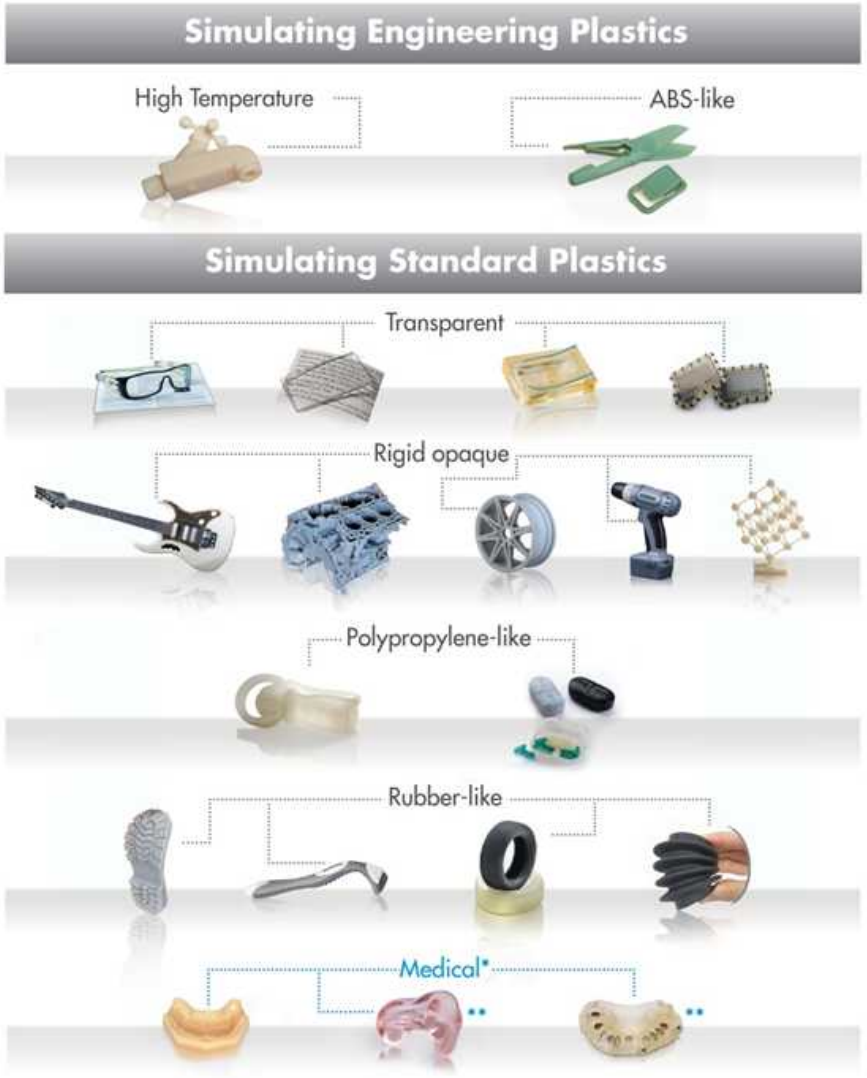
- Somewhat similar to plaster-based 3D printing
  - Also uses inkjet printhead
  - Jets material not binder
- Somewhat similar to SLA
  - Also uses photopolymers
- The only technology supporting multiple materials
  - Currently two + support material
- Materials
  - Photopolymers only
  - Can be mixed 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

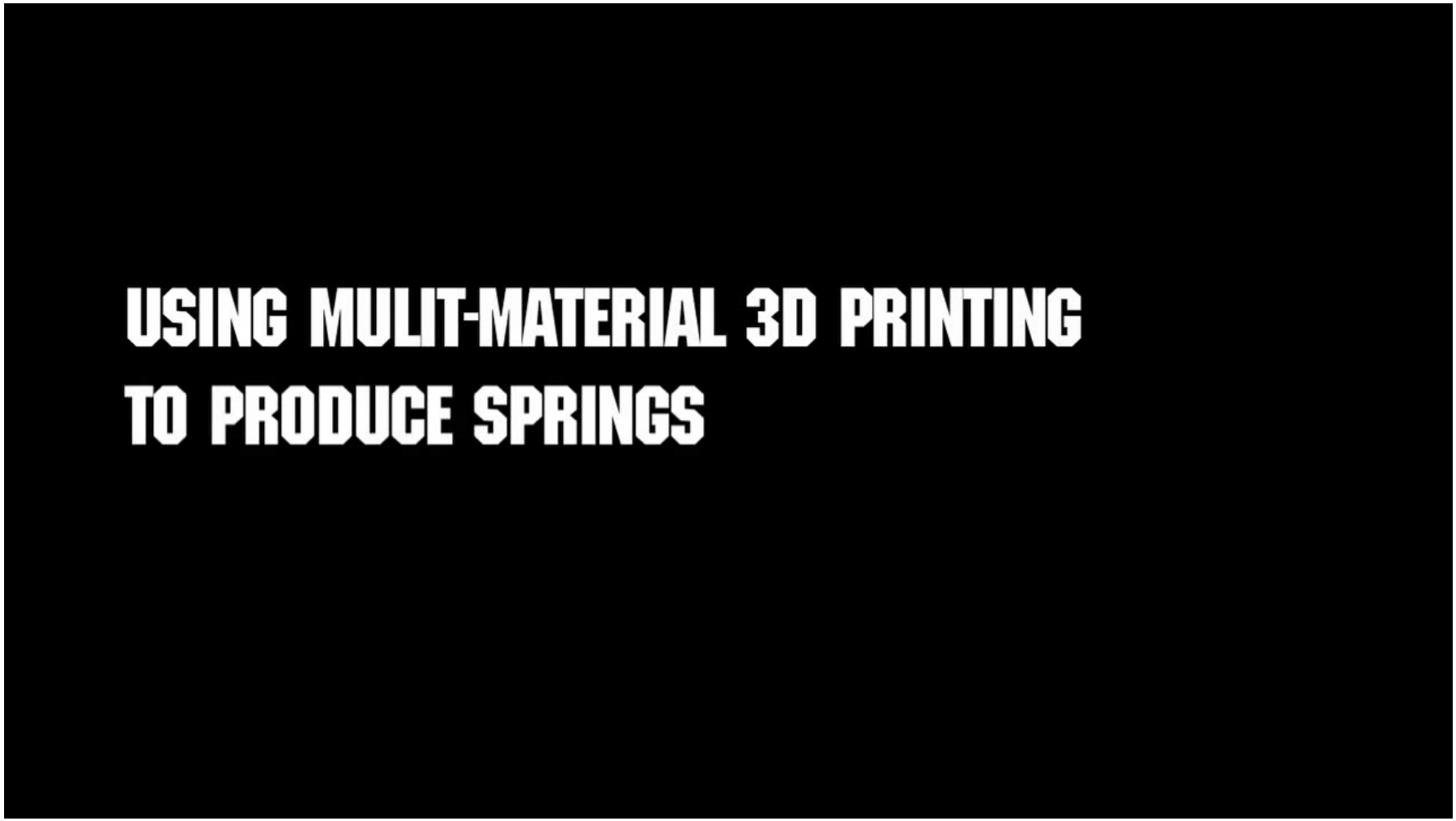
- Bio-compatible
- High-temperature
- ABS-like
- Transparent
- Opaque
- Rigid
- Polypropylene-like
- Rubber-like



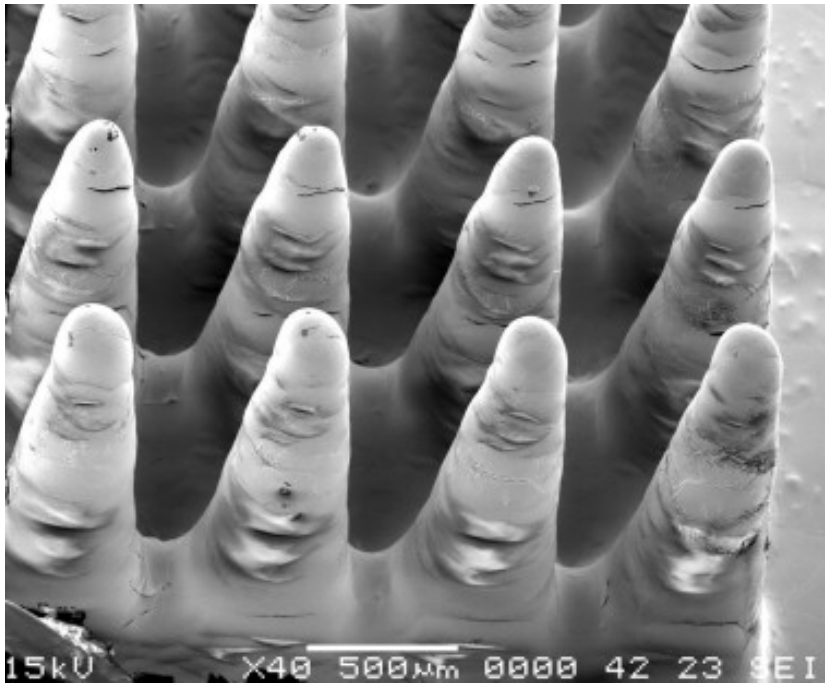
Source: Objet Geometries

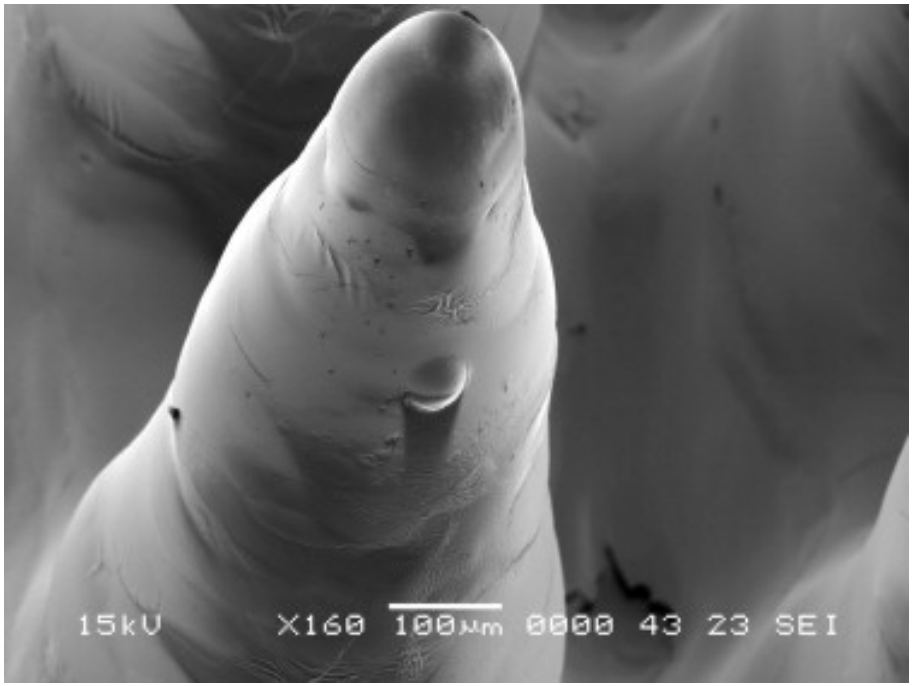
Rubber-like Materials

Multiple Materials

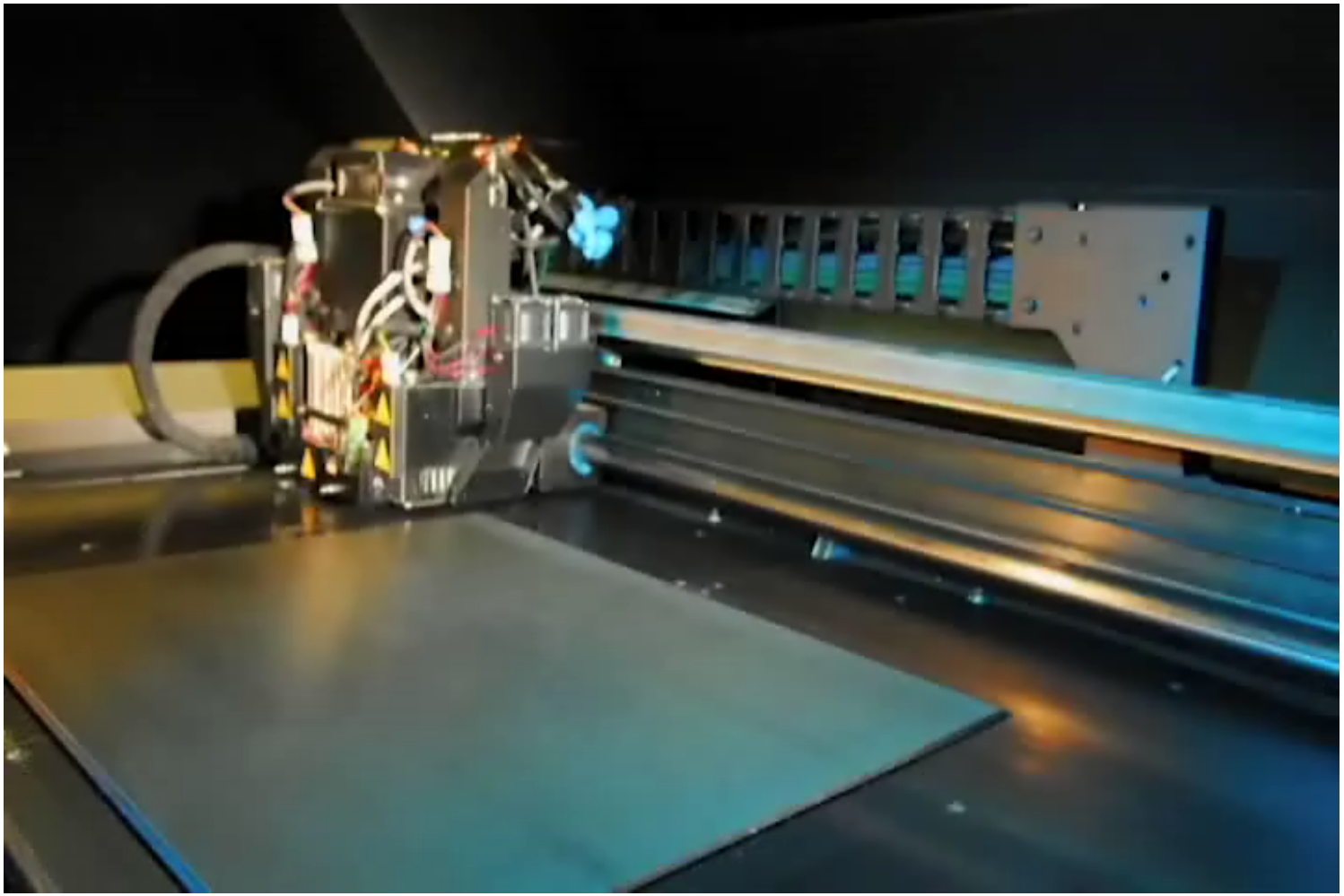


Printing Resolution





Printing Process



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

Sample Fabricated Objects

Source: Objet Geometries

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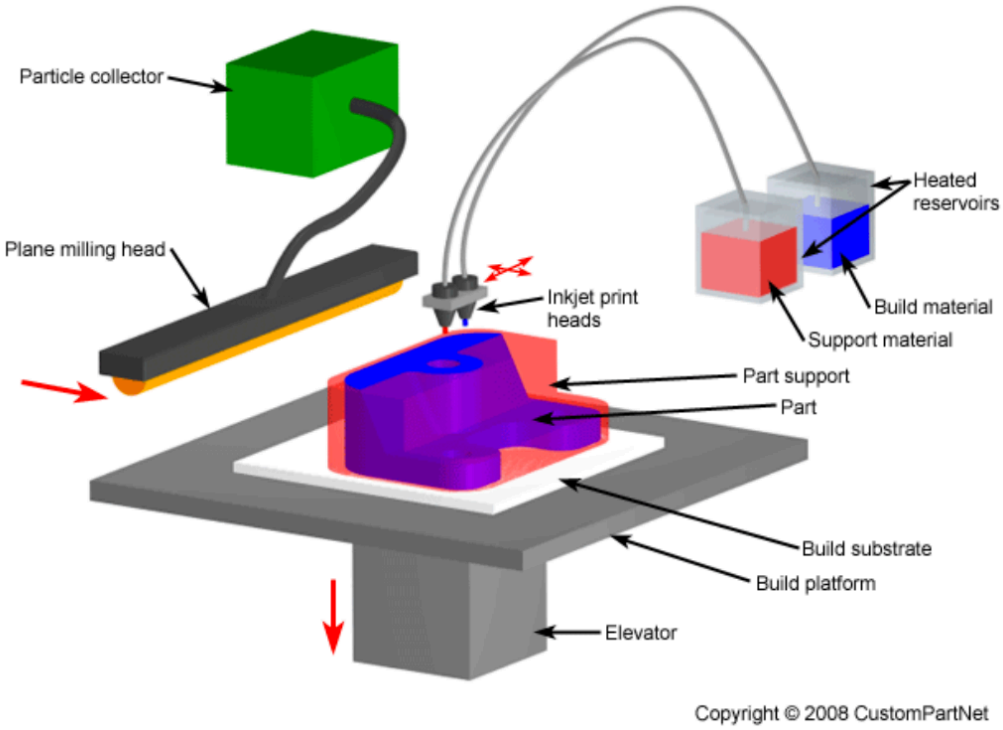
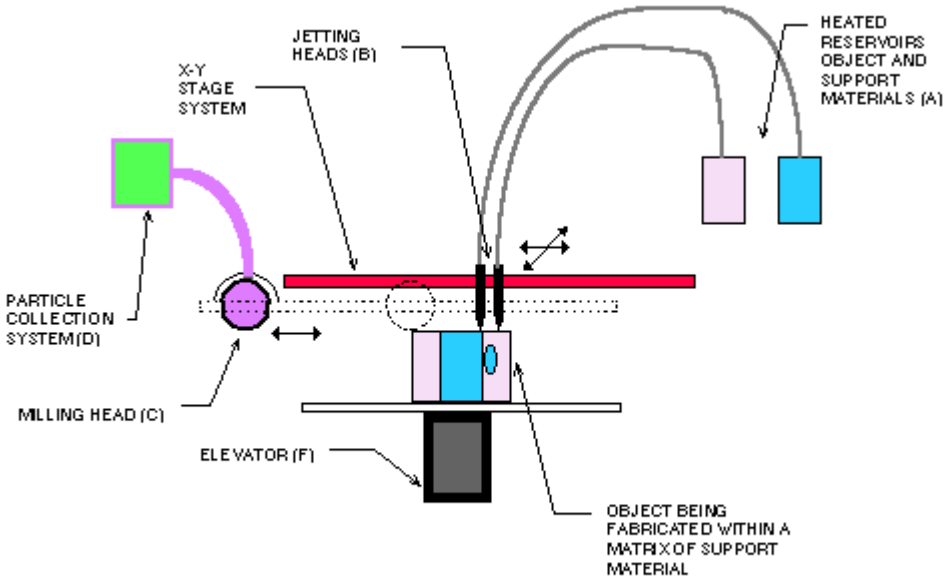
Thermal Phase Change Inkjets



- 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



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- The platform descends by one layer

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

Thermal Phase Change Inkjets Features

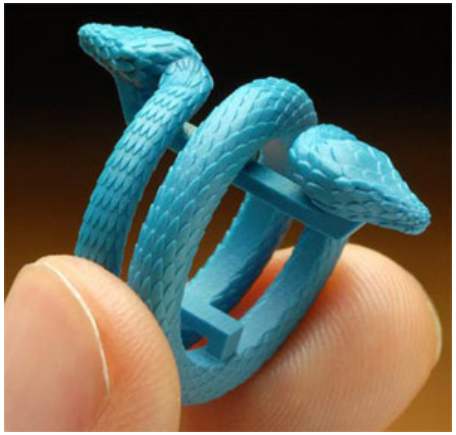
- Extremely high resolution
- Slow printing time
- Materials
  - Limited: plastics and waxes
- Support material
  - Wax: easy to remove
- Manufactured objects are used as casting pattern but almost never as final functional parts

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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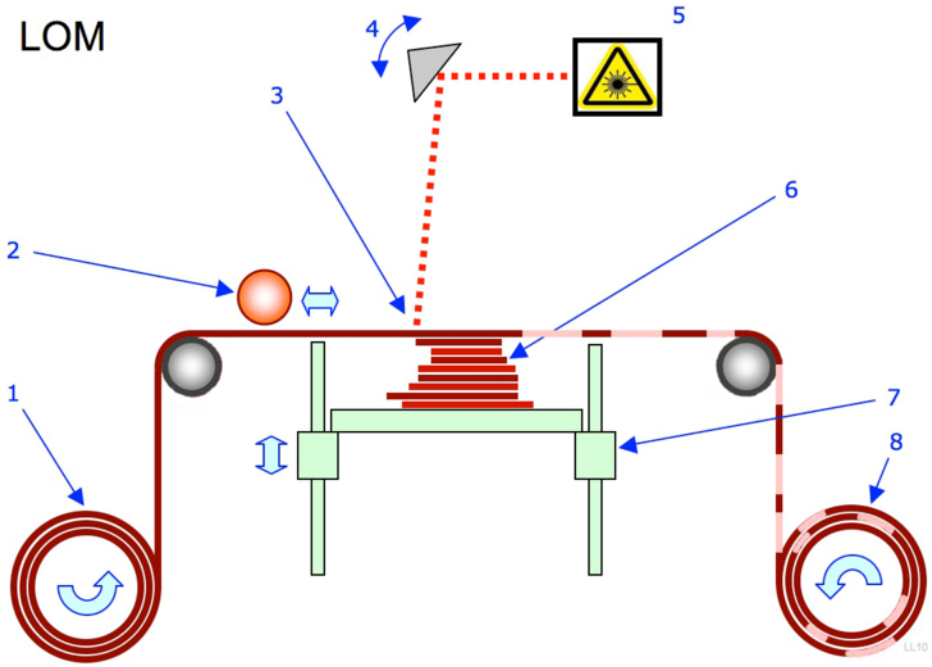
Laminated Object Manufacturing (LOM)

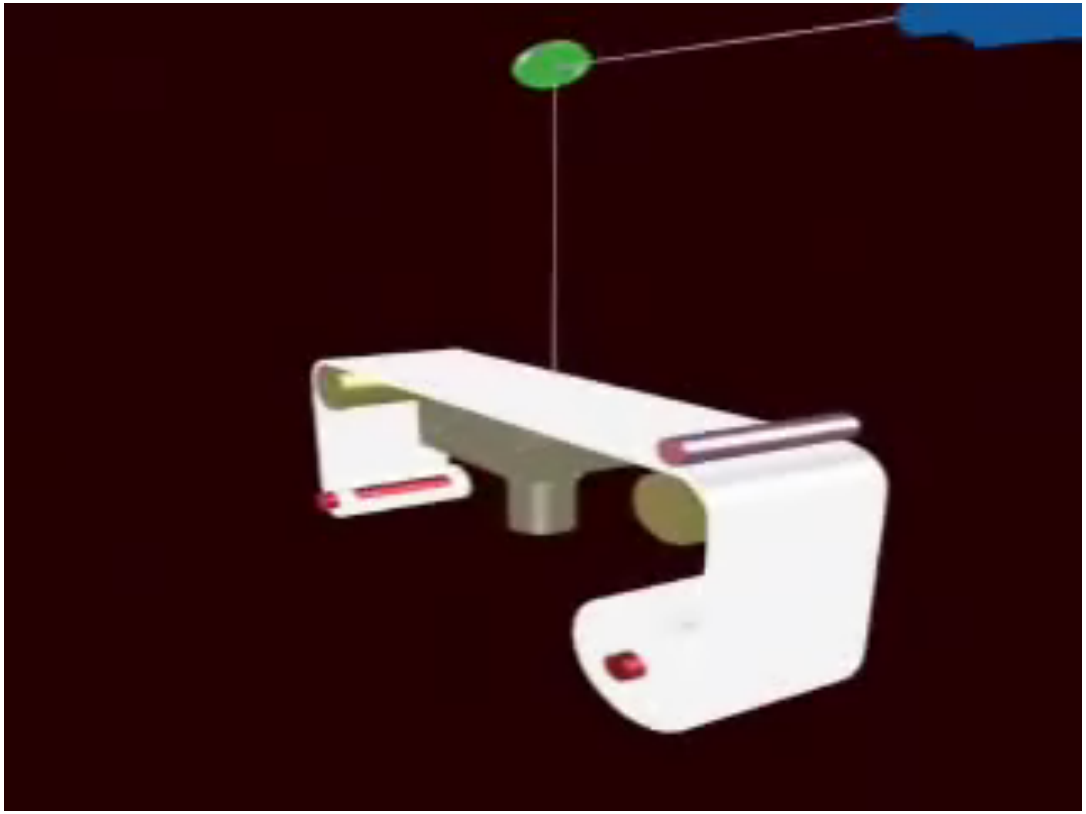


1 Foil supply. 2 Heated roller. 3 Laser beam. 4. Scanning prism. 5 Laser unit. 6 Layers. 7 Moving platform. 8 Waste.

- 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

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

Printing Process

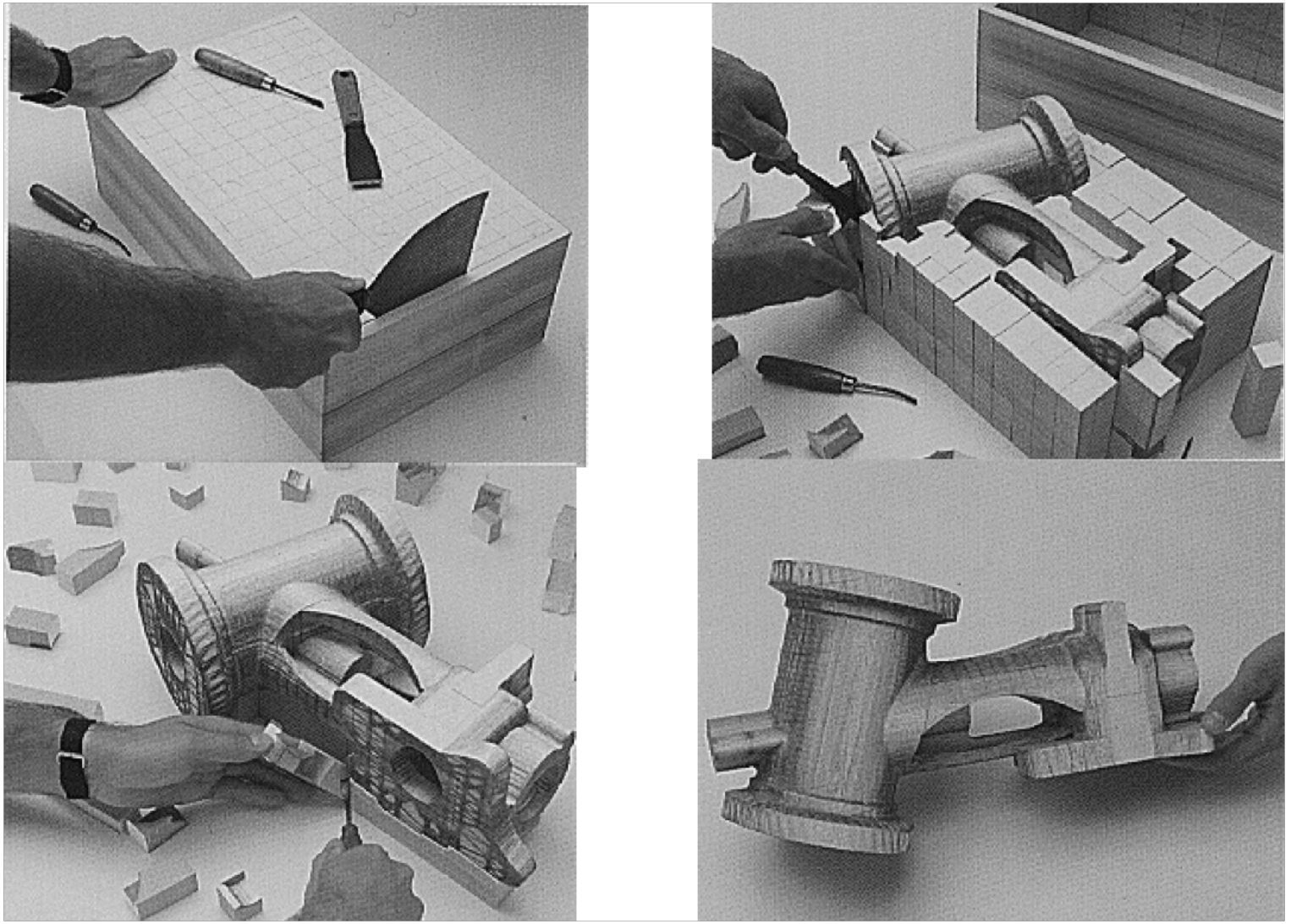


http://www.youtube.com/watch?v=Z1WNA6tdfWM

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

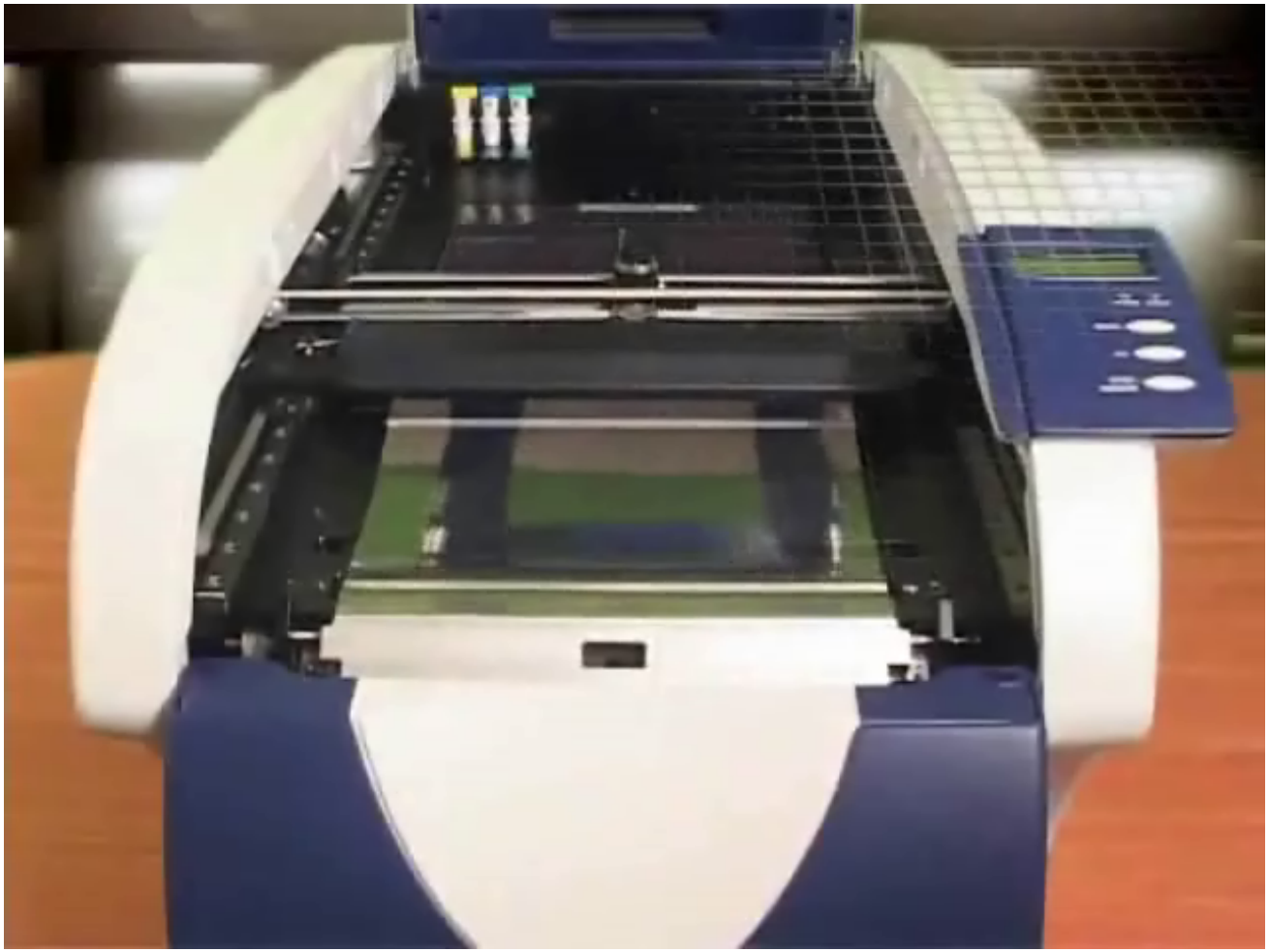


Source: http://blog.nus.edu.sg/u0804594/common-rp-techniques/laminated-object-manufacturing-lom/

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

Printing Process



https://www.youtube.com/watch?v=nE-8Wnz9-Qc

Sample Fabricated Objects






Source: http://www.solido3d.com

Today: 3D Printing

- Overview
- Technologies
  - Hardware
  - Materials
- Applications

Applications

- Jewelry
- Dental and Medical Industries
- Footwear
- Architecture, Engineering and Construction
- Aerospace
- Automotive
- Consumer Home Products
- Toys and Gadgets
- Art
- Education

Applications: Jewelry

- direct metal printing and casting patterns






Source: Shapeways, replicatorinc.com

Applications: Dental and Medical Industries

Crowns, copings, bridges

Custom Hearing Aids

Implants

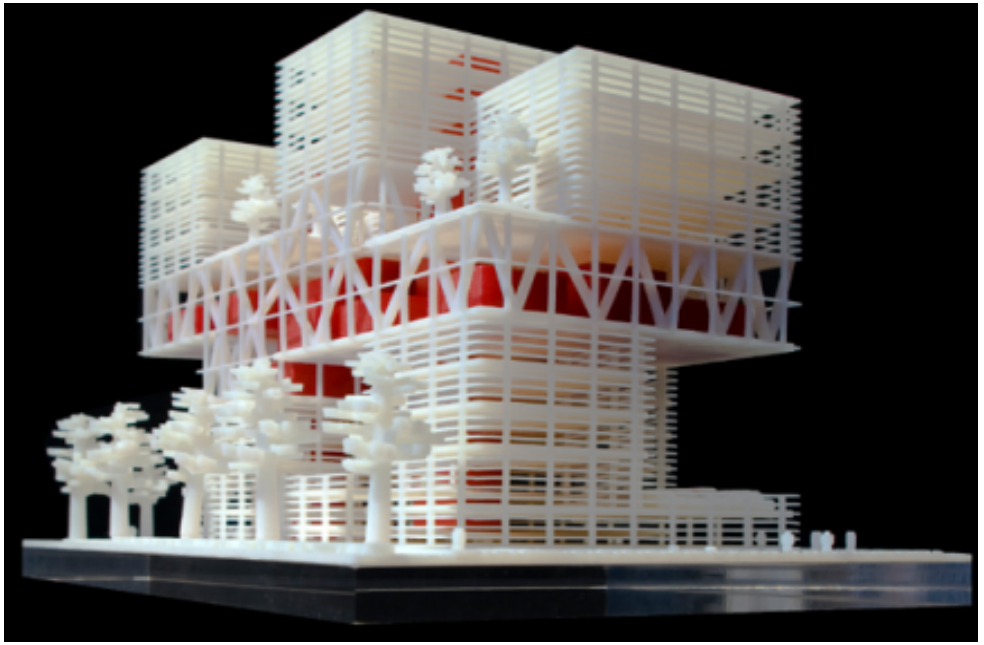
Prosthetics

Source: Envisiontec, on3dprinting.com

Applications: Footwear

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

Applications: Architecture, Engineering & Construction



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

Applications: Aerospace

3D printed, titanium central wing spar

Airbus wing brackets

Source: ponoko.com, 3dprintingindustry.com

Applications: Automotive

Honeycomb Tires

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

Source: www.uprint3dprinting.com, gizmodo.com

Applications: Consumer Home Products

Lamp

Egg cup

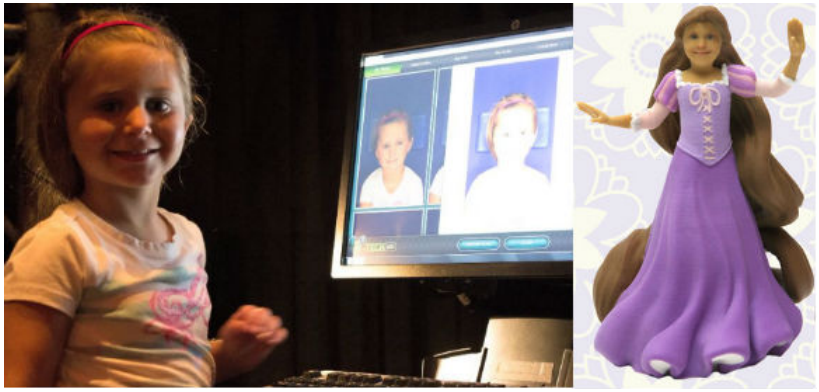
Espresso Cup

Platter

Pencil bowl

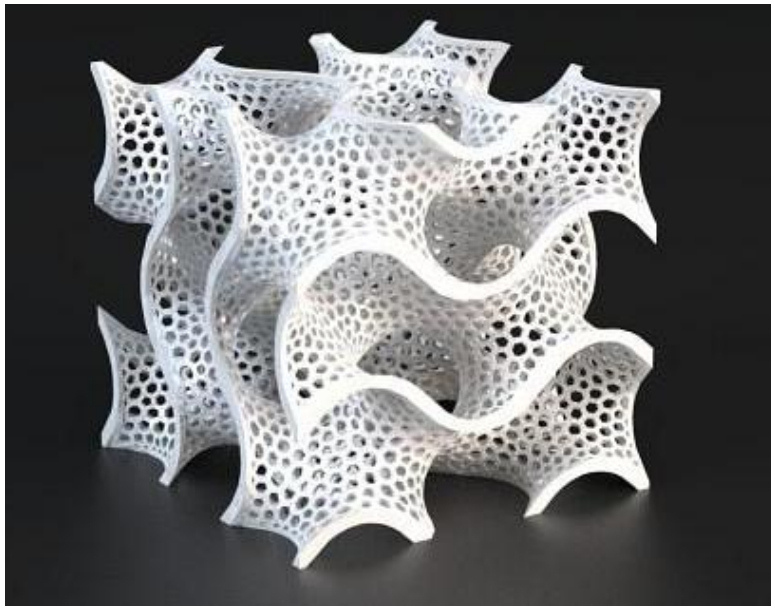
Source: Shapeways

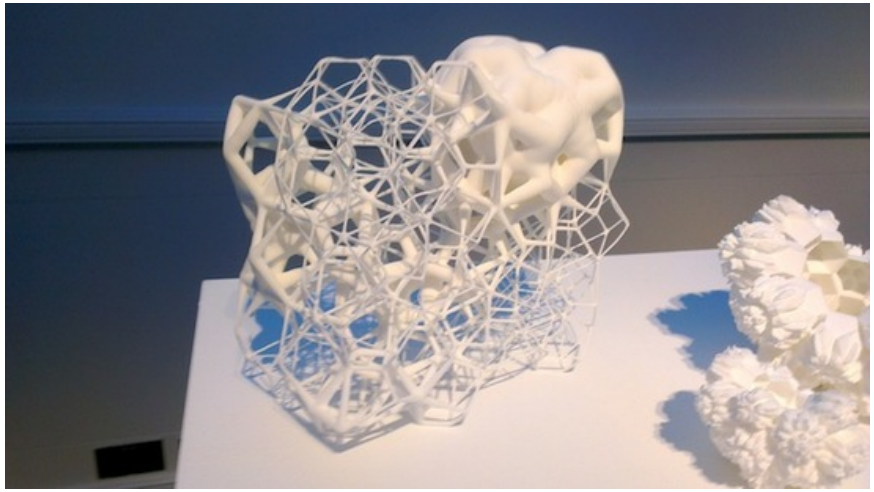
Applications: Toys & Gadgets



Source: Shapeways, singularityhub.com, MyRobotNation.com

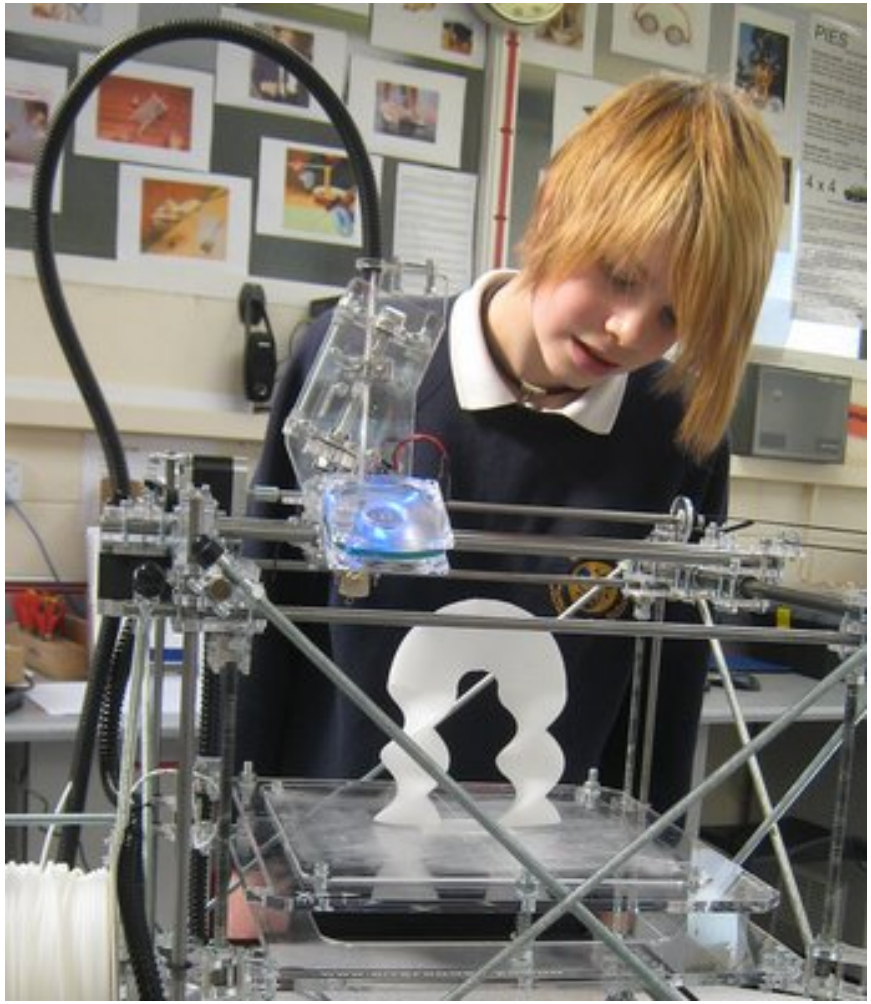
Applications: Art

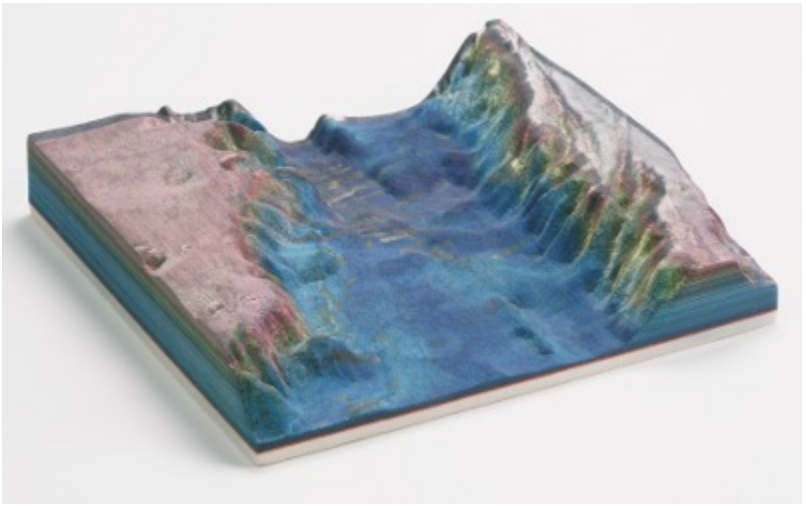


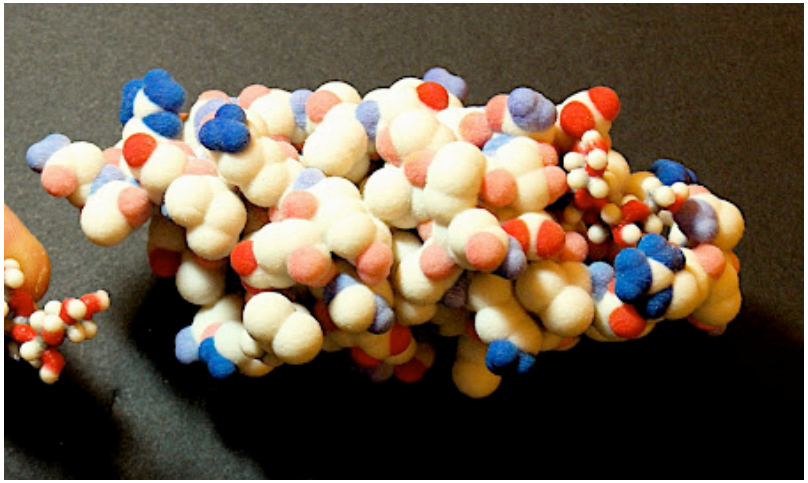


Source: Shapeways, Carlo Sequin, techdigest.tv

Applications: Education







Source: printcountry.com, designfax.net

That’s All for Today