Computational Tools for 3D Printing

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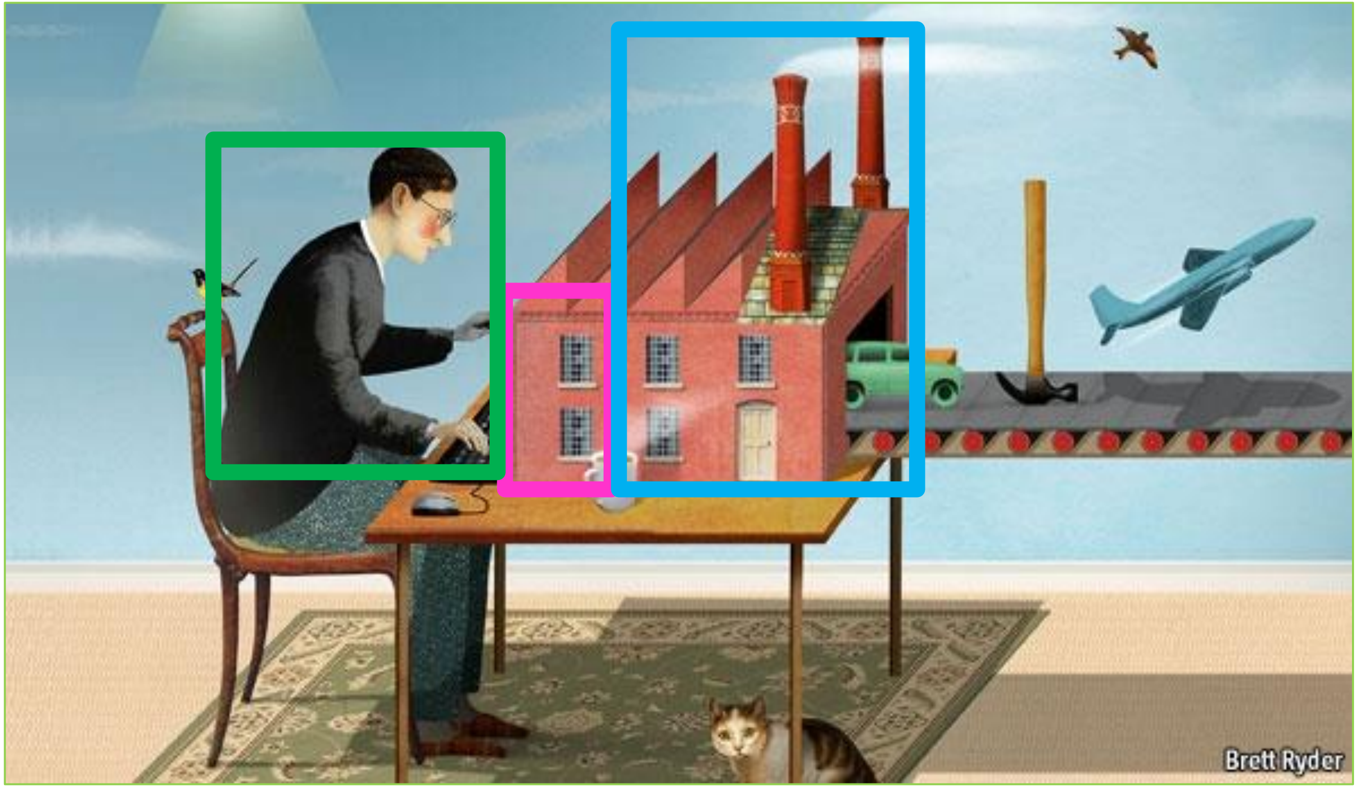
About This Course

- Basics of 3D printing hardware and software
- Computation, 3D printing, interactive techniques
- Overview of latest research

Source: The Economist (Cover)

About This Course



Source: The Economist (Cover)

Course Website

- http://www.computational-fabrication.com/
- Includes the course material

Other 3D Printing Courses at Siggraph/ Siggaph Asia

- Siggraph Asia 2014
  - **3D printing oriented design: geometry and optimization** http://staff.ustc.edu.cn/~lgliu/Courses/SigAsia_2014_course_3Dprinting/index.html
- Siggraph 2015
  - **Modeling and Toolpath Generation for Consumer-Level 3D Printing**
  - http://webloria.loria.fr/~slefebvr/sig15fdm/

Lecturers

- Ariel Shamir
  - Interdisciplinary Center Herzliya
  - http://www.faculty.idc.ac.il/arik/
- Bernd Bickel
  - Institute of Science and Technology, Austria
  - http://berndbickel.com/
- Wojciech Matusik
  - Massachusetts Institute of Technology
  - http://people.csail.mit.edu/wojciech/

Course Schedule

9:00 am - 9:10 am Welcome and Introductions, **Matusik**

9:10 am - 10:00 am 3D Printing Hardware/Software, **Matusik**

10:00 am - 10:30 am Appearance Fabrication for 3D Printing, **Bickel**

10:30 am - 10:45 am Break

10:45 am - 11:15 am Design and Fabrication of Deformable Objects, **Bickel**

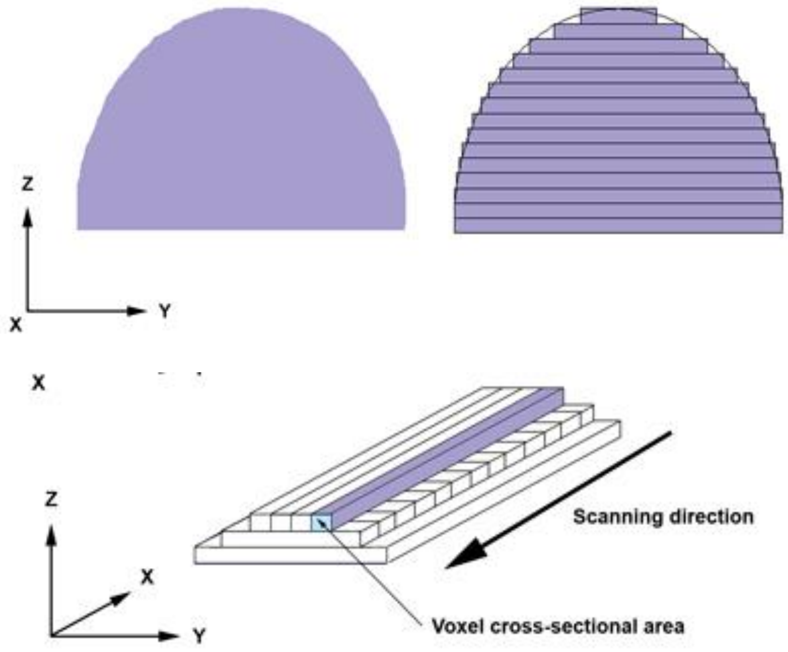
11:15 am - 12:10 am Modeling and Analysis, **Shamir**

12:10 pm – 12:15pm Conclusions, Q&A, **All**

Course Overview

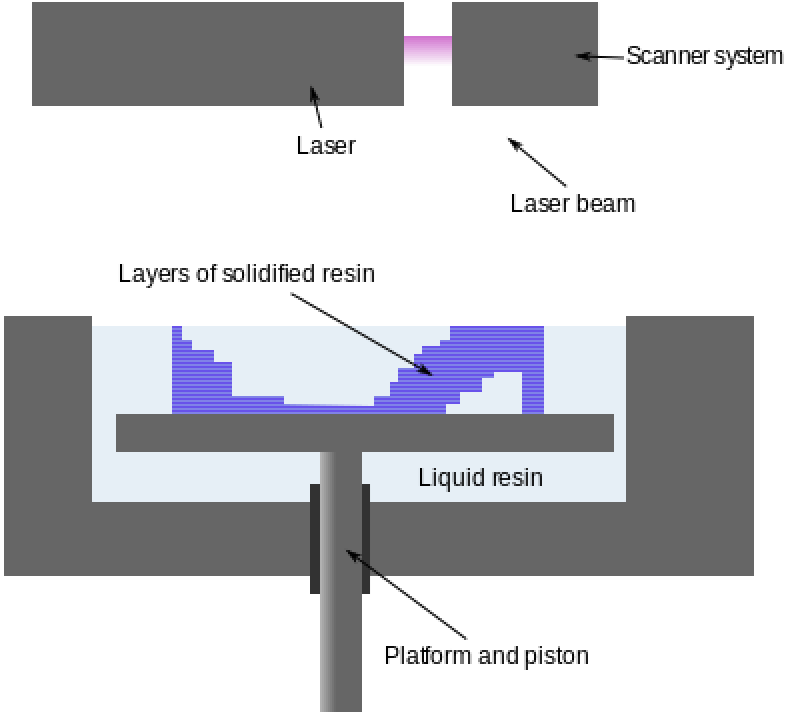
Basics of 3D Printing

- What 3D printing is?
- How does it work?
- What are the applications?



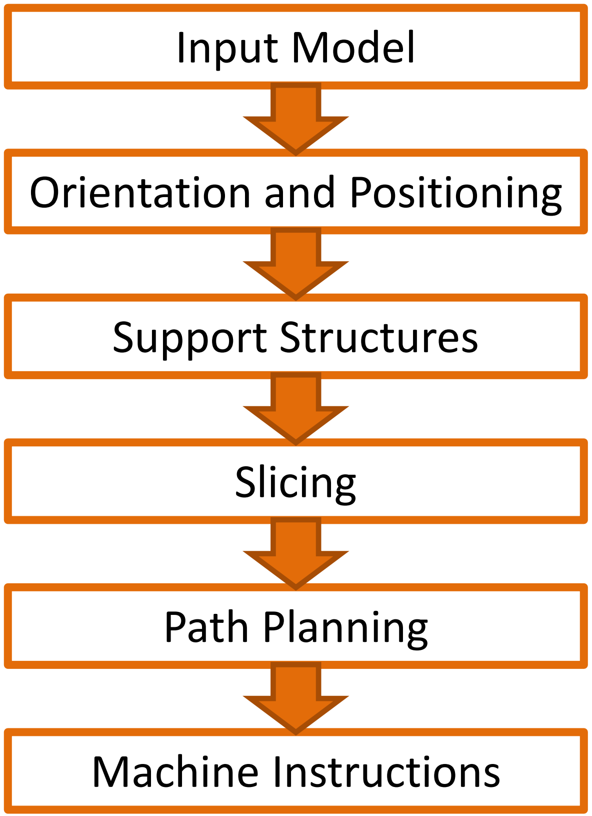
3D Printing Hardware and Materials

Fused deposition modeling

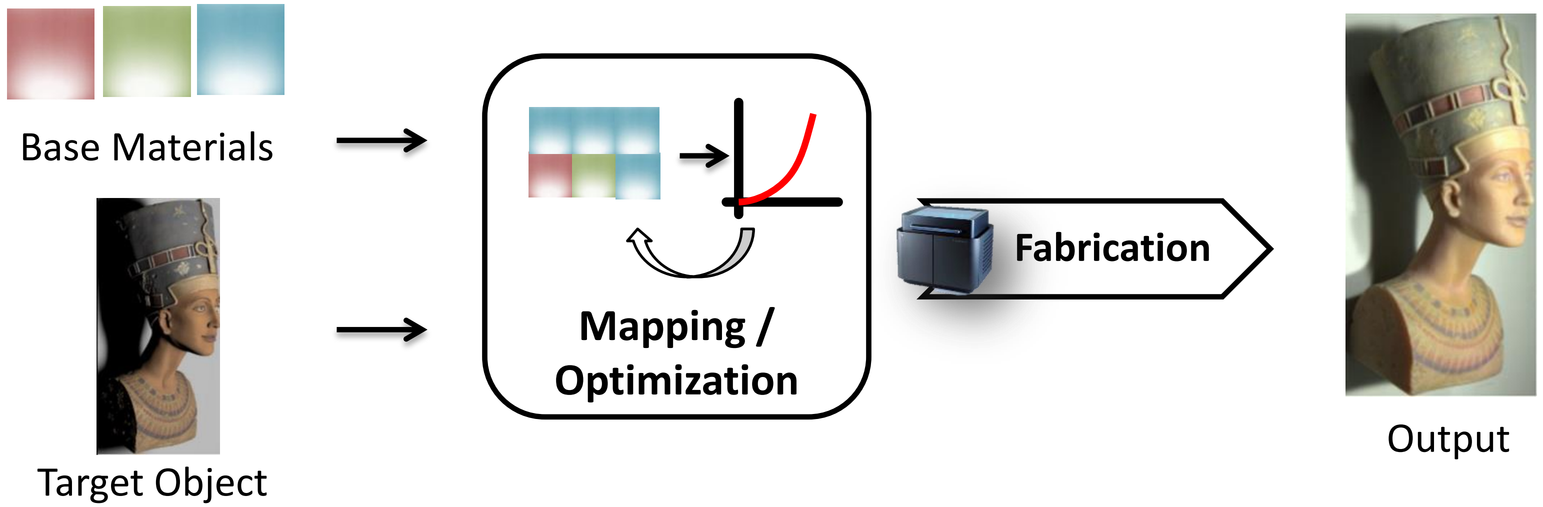


Stereolithography

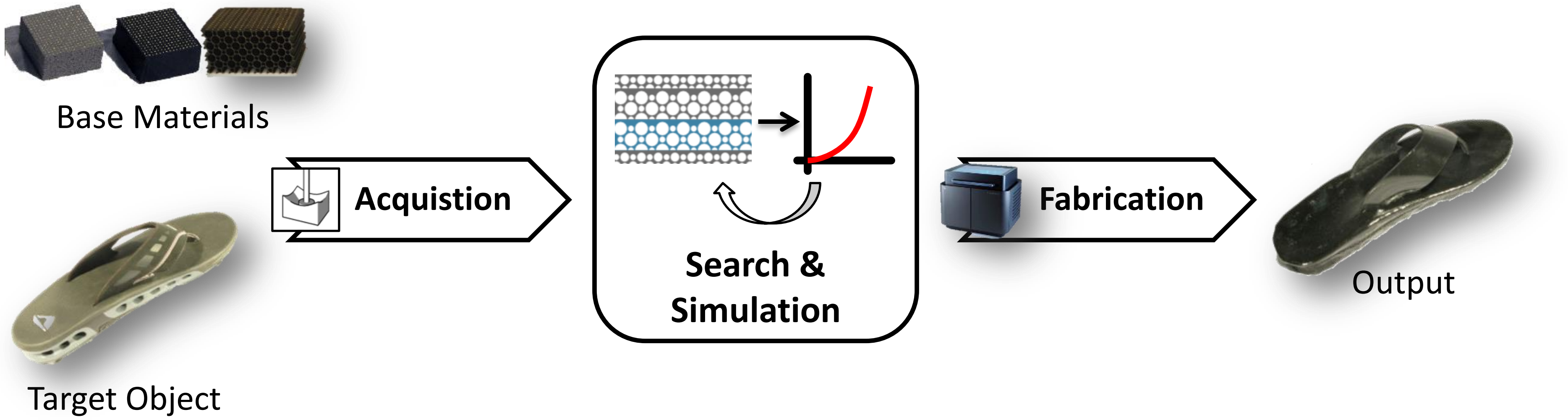
3D Printing Software Pipeline



Appearance Fabrication for 3D Printing

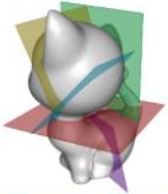


Designing Deformations for 3D Printing



More Inverse Modeling Examples

Specification → Optimization → Model



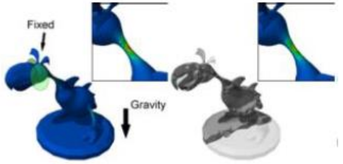
Specification: shape and size

Specification: balance

Specification : strength to a given weight

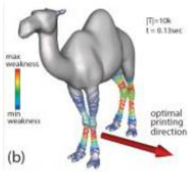
Structural Analysis for Fabrication

- Need to analyze the “strength” or “weakness” of the shape



Stress Relief: Improving Structural Strength of 3D Printable Objects [Stava et al. SIG 2012]

Worst-case Structural Analysis [Zhou et al. SIG 2013]

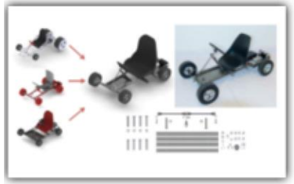


Cross-sectional Structural Analysis for 3D Printing Optimization [Umetani & Schmidt SIGA 2013]

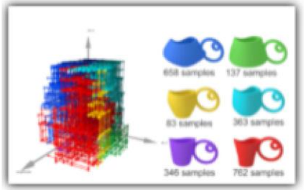
Interactive Modeling for Fabrication

- Examples of interactive tools

Modeling from Photographs



Modeling by (Part) Examples



Customization of Models

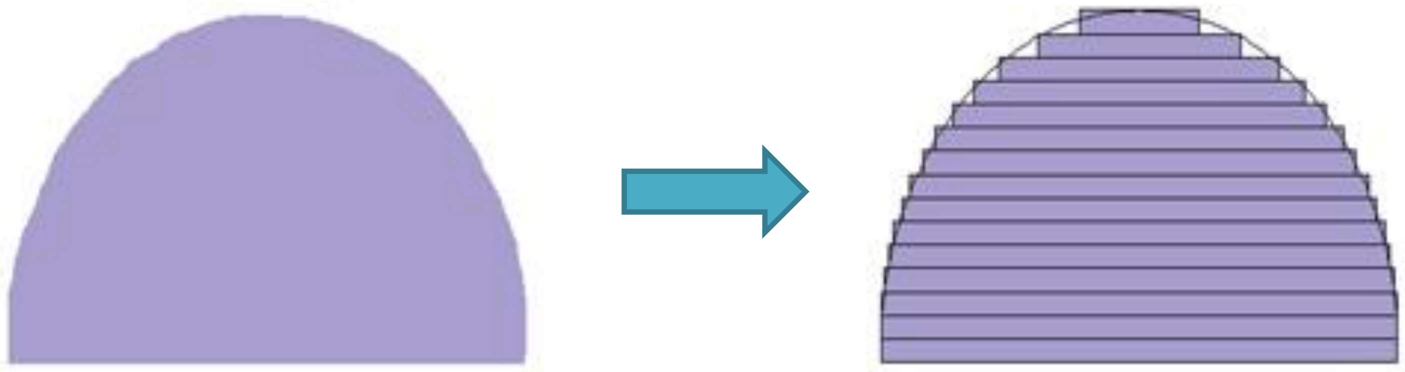
3D Printing Basics

3D Printing = Additive Manufacturing

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

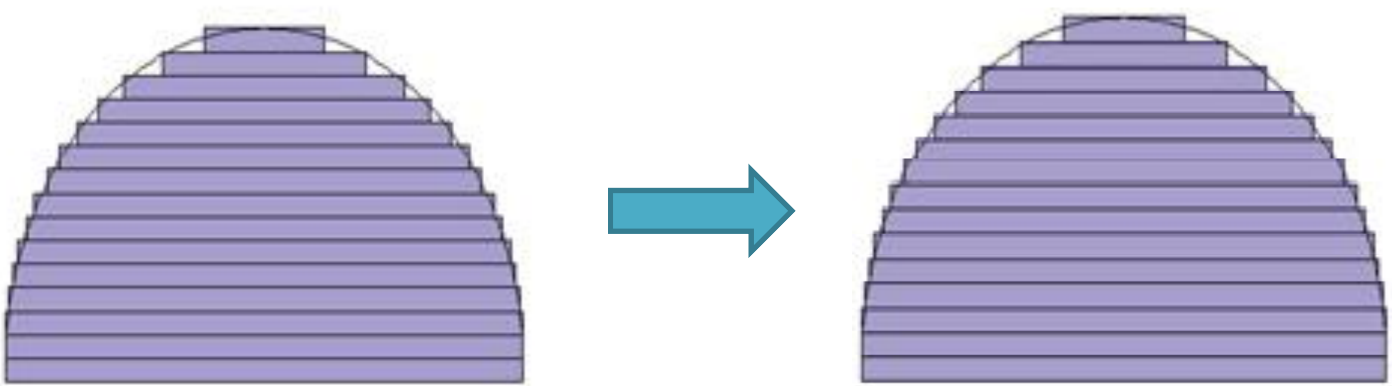
3D Printing Process

- Slice 3D model into layers



3D Printing Process

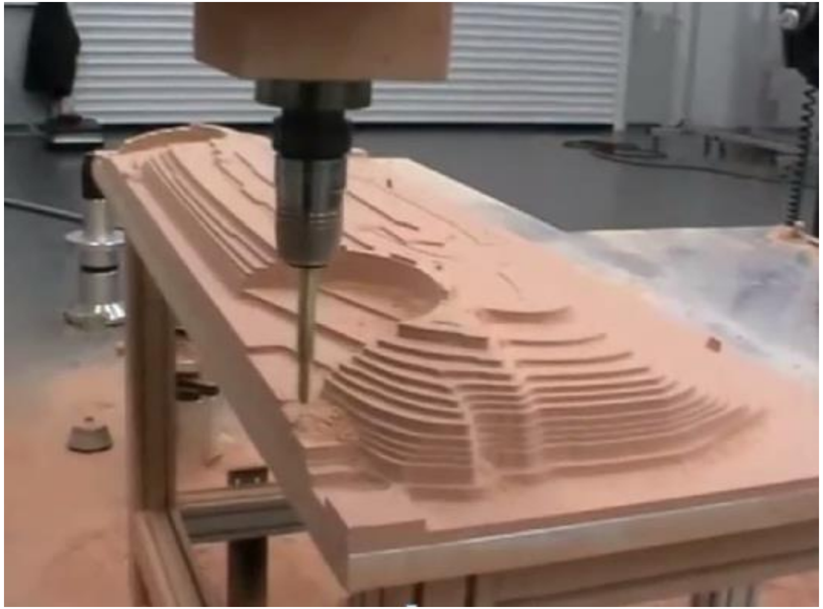
- Slice 3D model into layers
- Manufacture layers one by one (e.g., bottom-up)



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

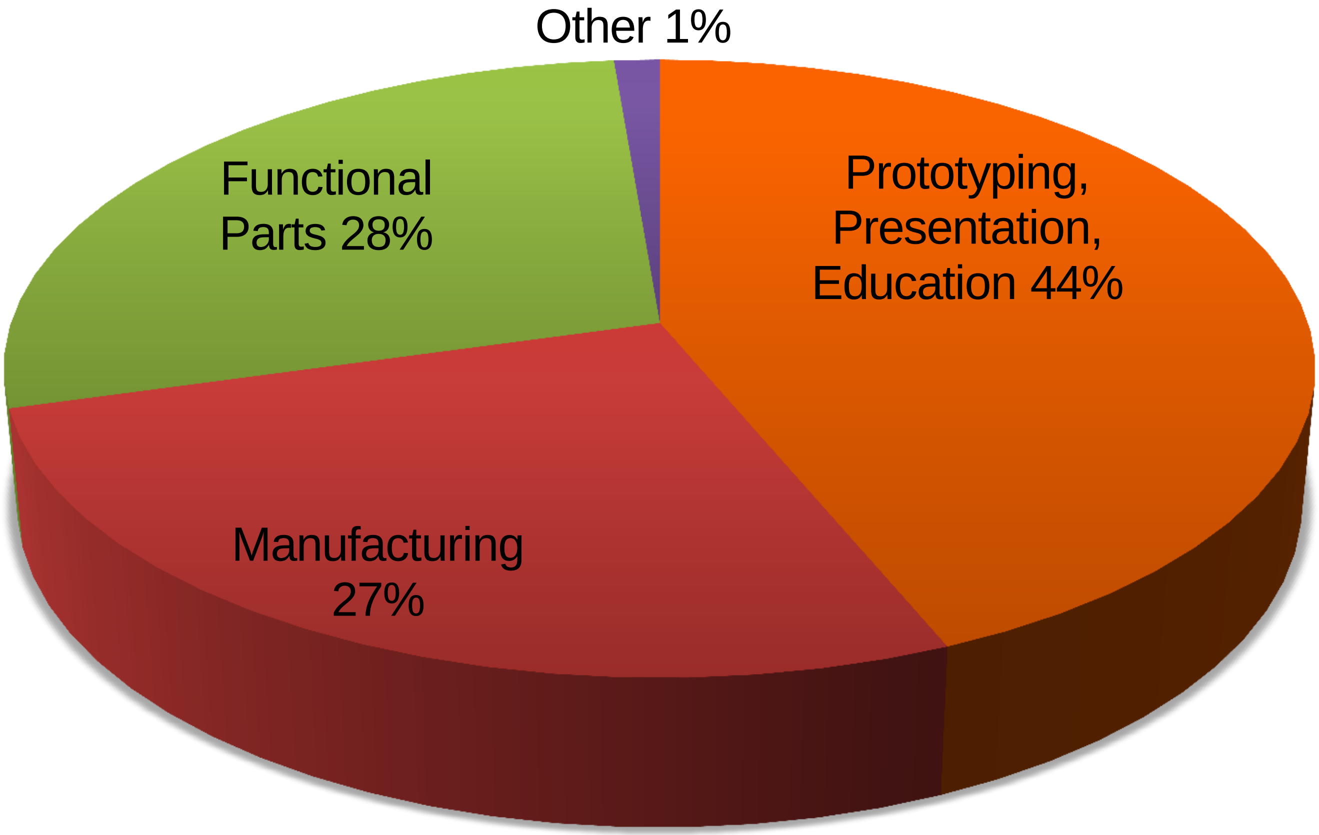
- Fused deposition modeling (FDM)
- Stereolithography (SLA)
- DLP 3D printing
- Selective laser sintering (SLS)
- Direct metal laser sintering (DMLS)
- Plaster-based 3D printing (PP)
- Photopolymer Phase Change Inkjets
- Thermal Phase Change Inkjets
- Laminated object manufacturing (LOM)

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: Automotive

Honeycomb
Tires

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

Source: www.uprint3dprinting.com, gizmodo.com

Applications: Automotive

Source: https://3dprint.com/36433/3d-printed-shelby-cobra/

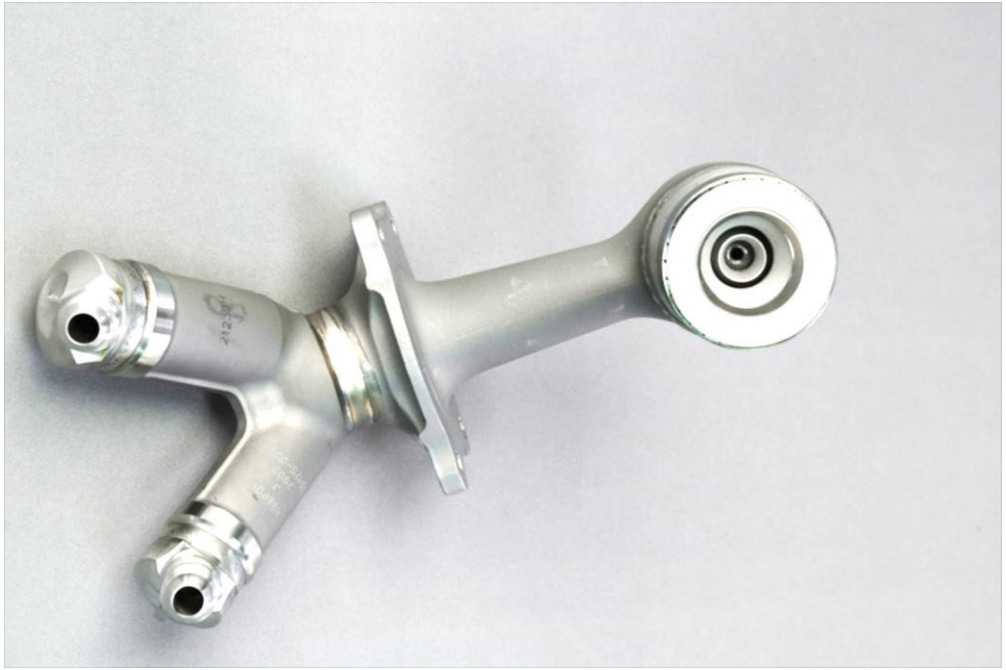
Applications: Architecture

Source: http://web.ornl.gov/sci/eere/amie/

Applications: Architecture & Design

Source: aecbytes.com, Z Corp, object.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



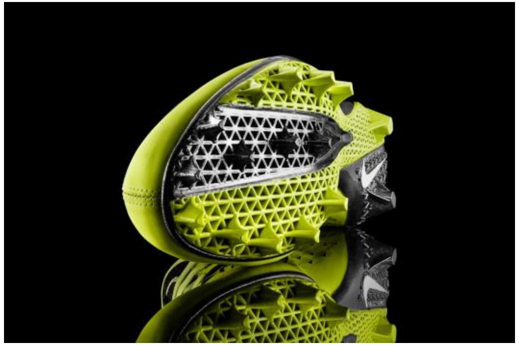


Source: Shapeways, replicatorinc.com

Applications: Footwear





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

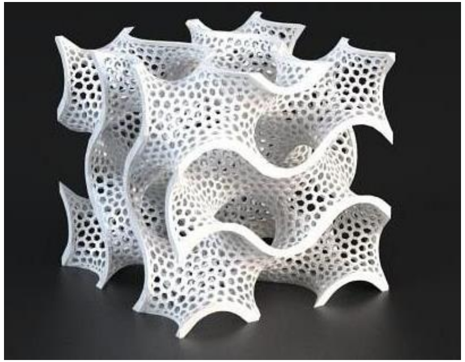
Applications: Consumer Home Products

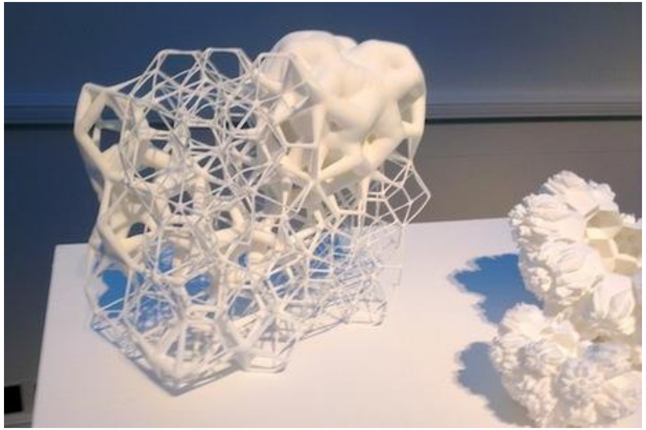




Source: Shapeways

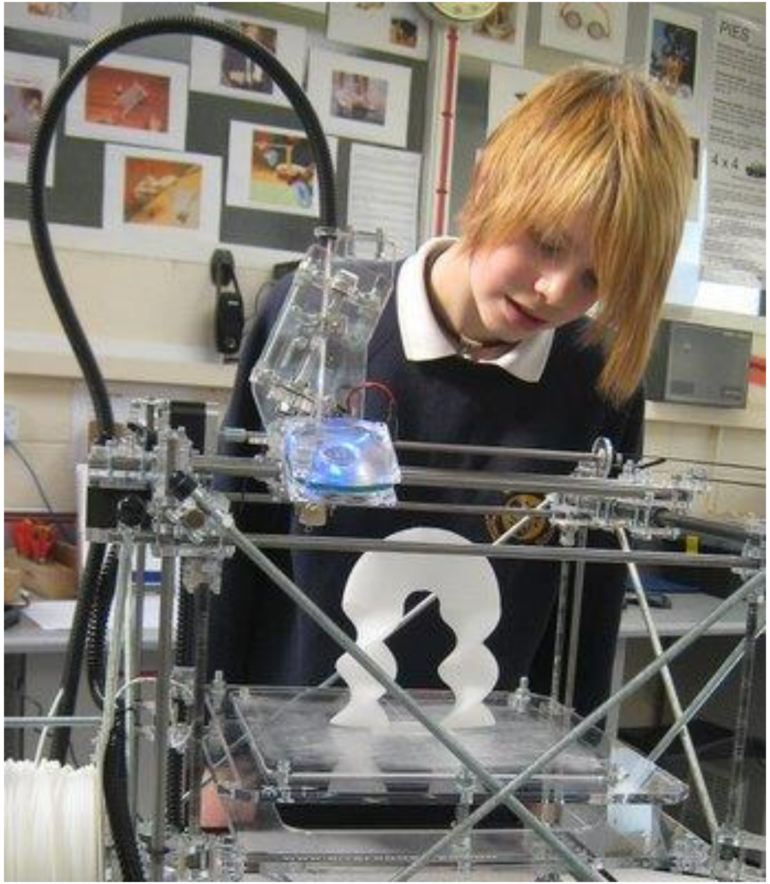
Applications: Art

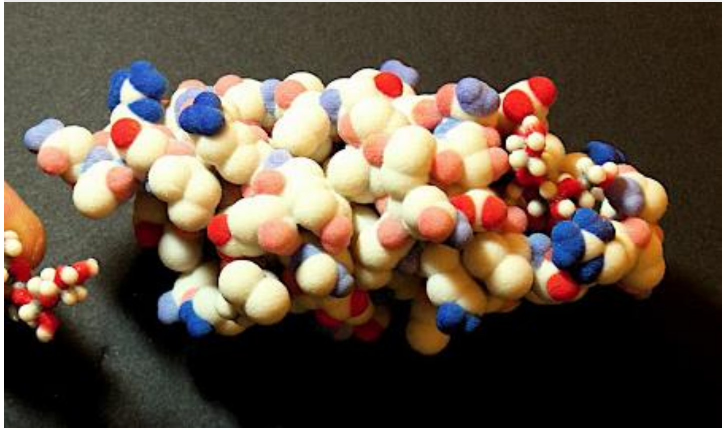




Source: Shapeways, Carlo Sequin, techdigest.tv

Applications: Education





Source: printcountry.com, designfax.net

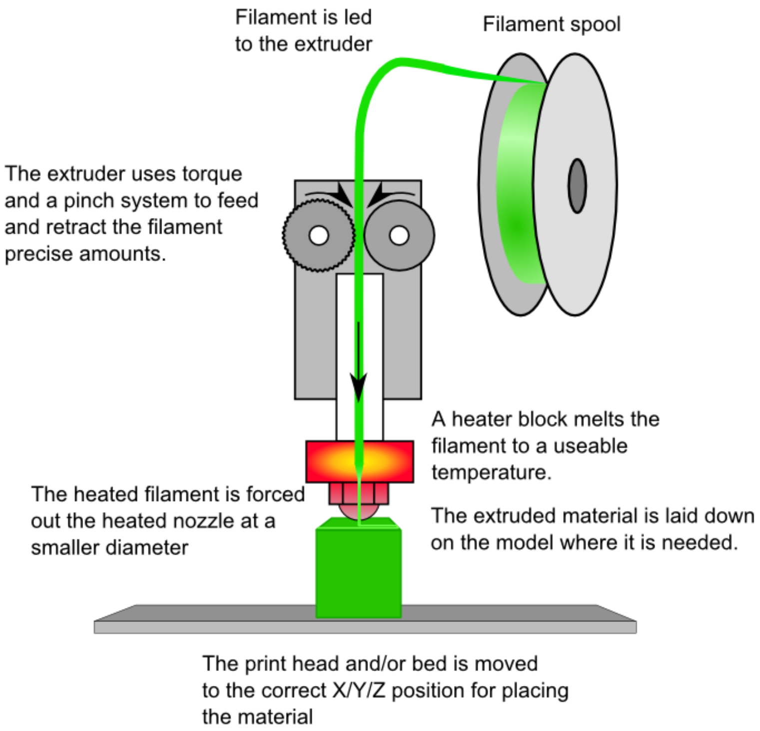
3D Printing Hardware and Materials

Additive Manufacturing Encompasses Many Different 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)

Fused Deposition Modeling (FDM)

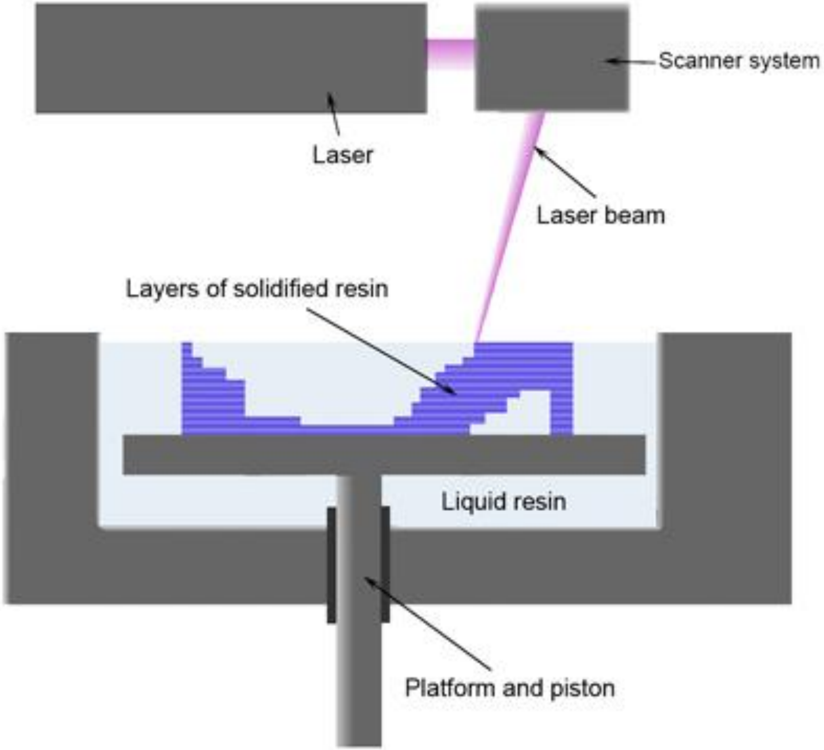
- Fused Filament Fabrication (FFF)
- Filament is made of thermoplastic materials
  - e..g., ABS, polycarbonate, PLA
- Temporary support structure can be made from water-soluble material such as PVA
  - removed using heated sodium hydroxide solution



Source: http://reprap.org

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



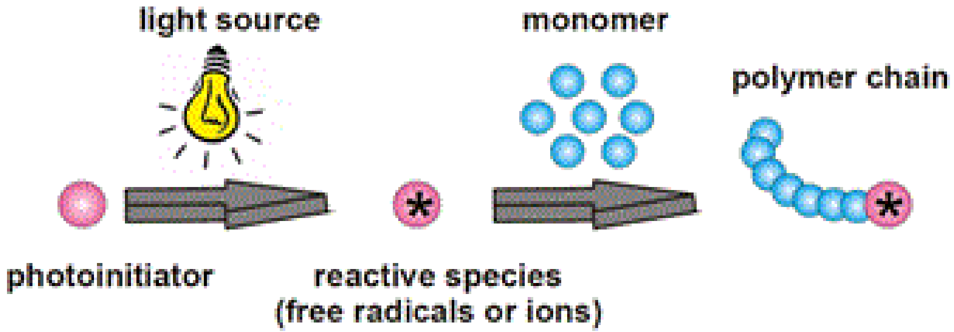
Source: http://en.wikipedia.org/

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

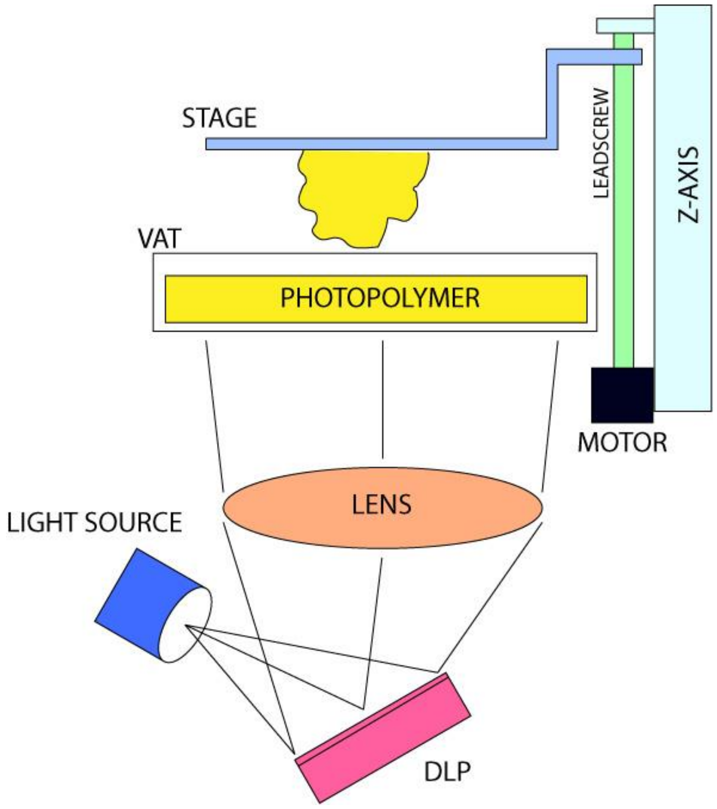


Source: http://www.additive3d.com/photo.htm

Stereolithography Process

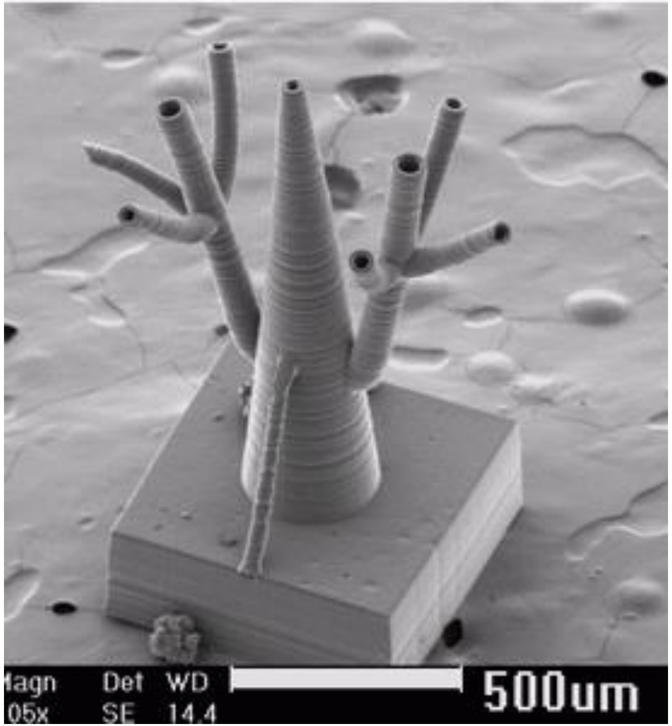
Digital Light Projector (DLP) 3D Printing

- 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



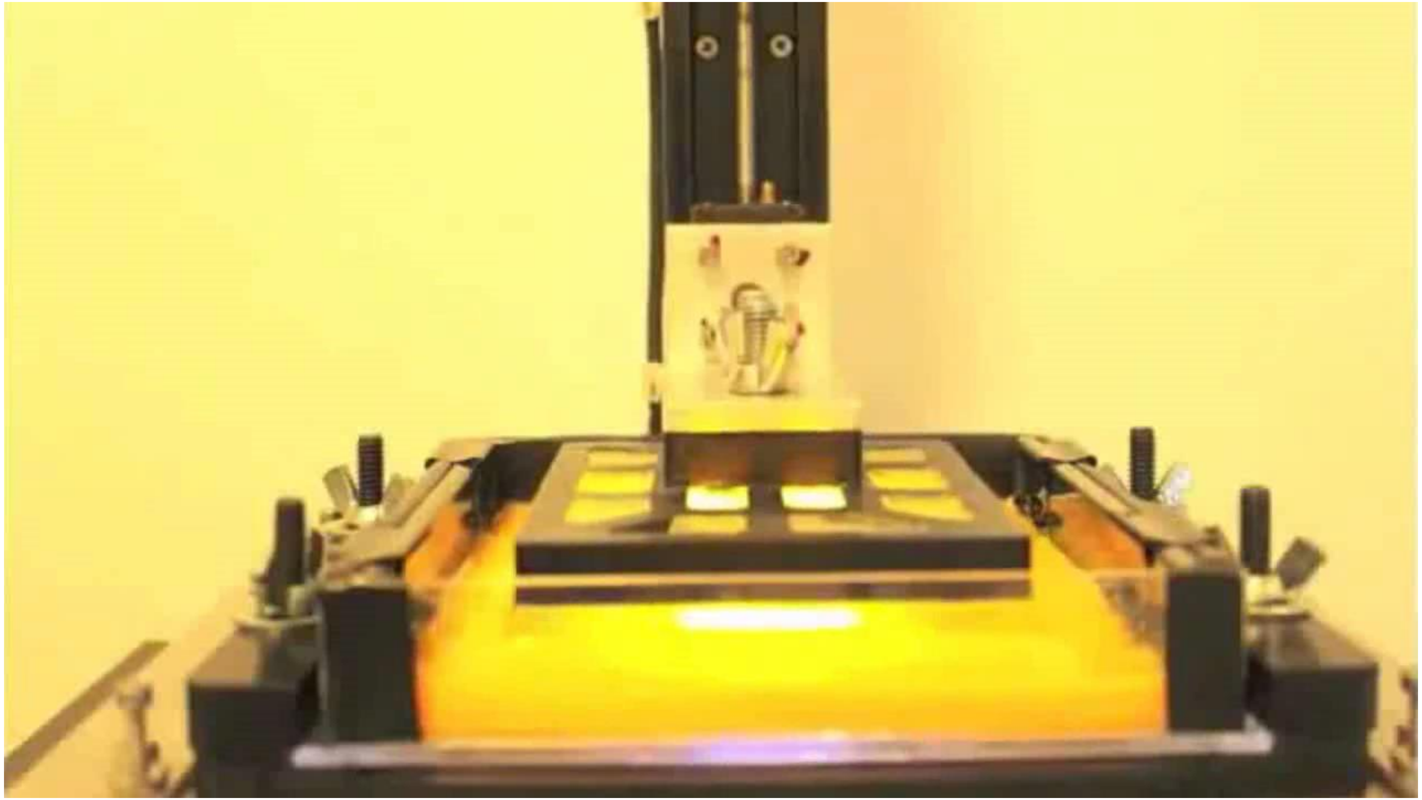
DLP 3D Printing Features

- 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



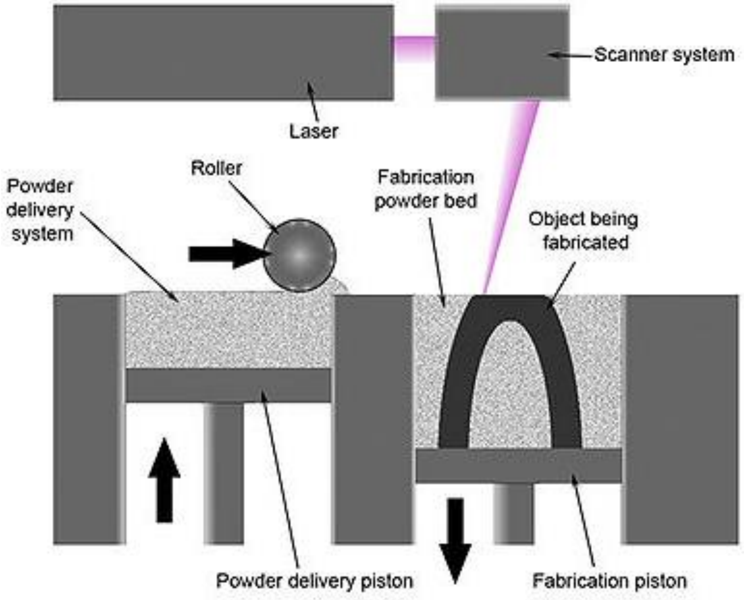
Source: Nicholas Fang, MIT

DLP 3D Printing Process



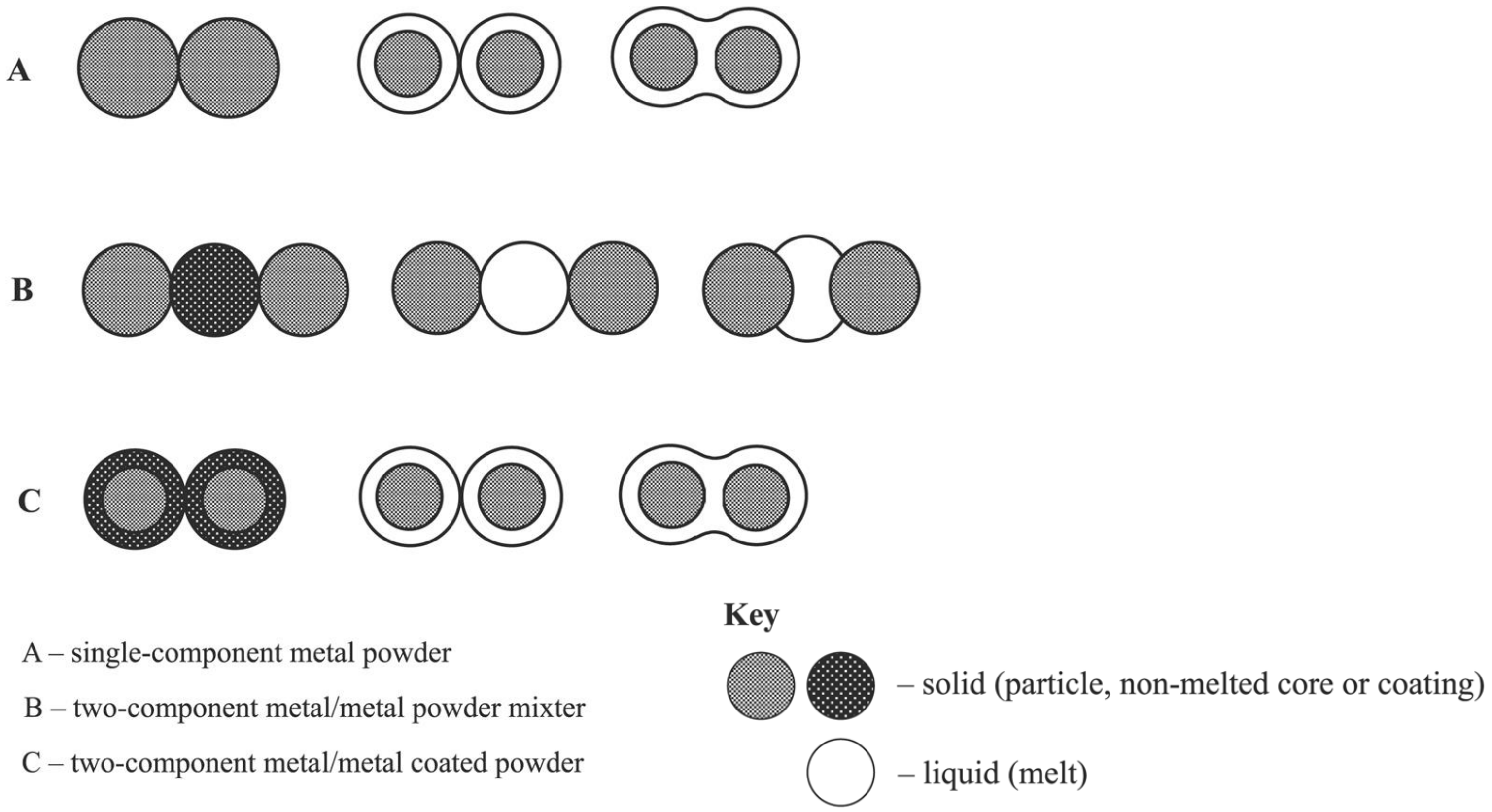
Selective Laser Sintering (SLS)
Direct Metal Laser Sintering (DMLS)

- 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



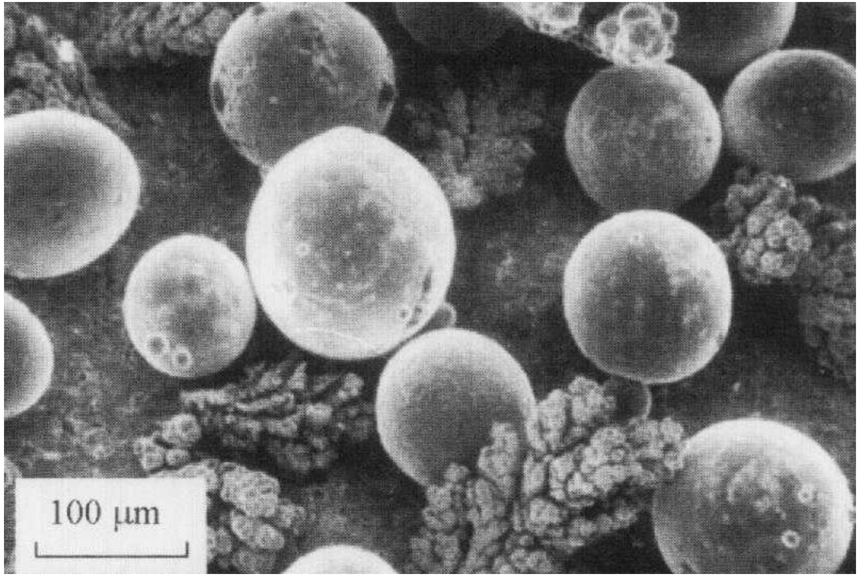
Source: http://en.wikipedia.org/wiki/Selective_laser_sintering

Single- and Two-Component Powders

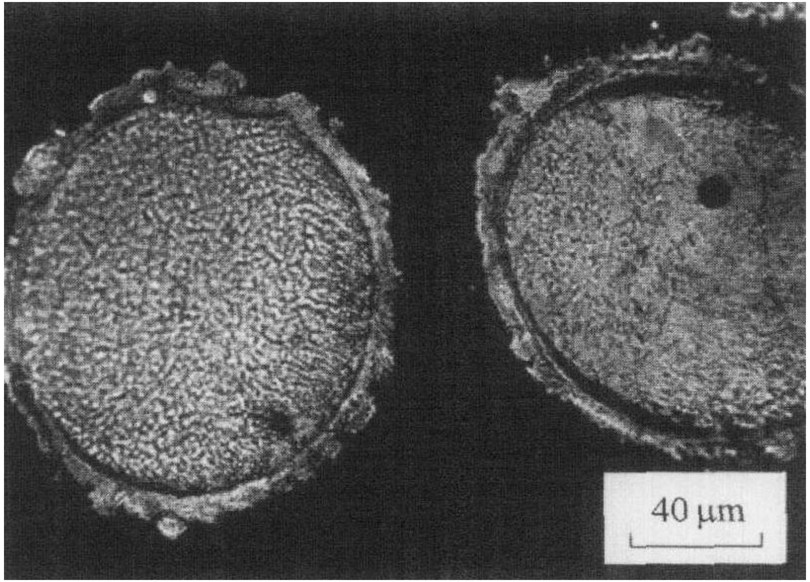


Source: Tolochko et al. 2003

Raw Powder Particles



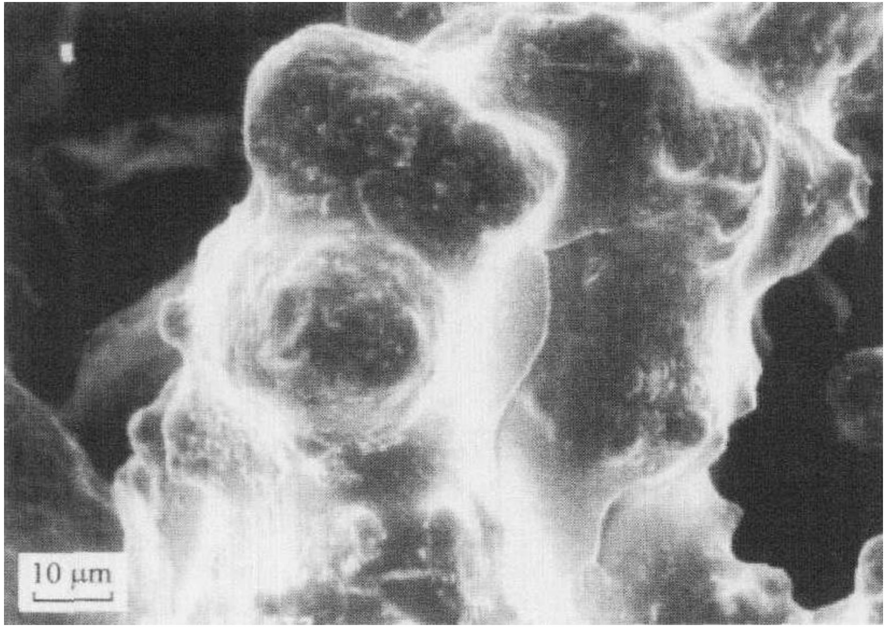
Raw Ni-alloy-Cu powder mixture

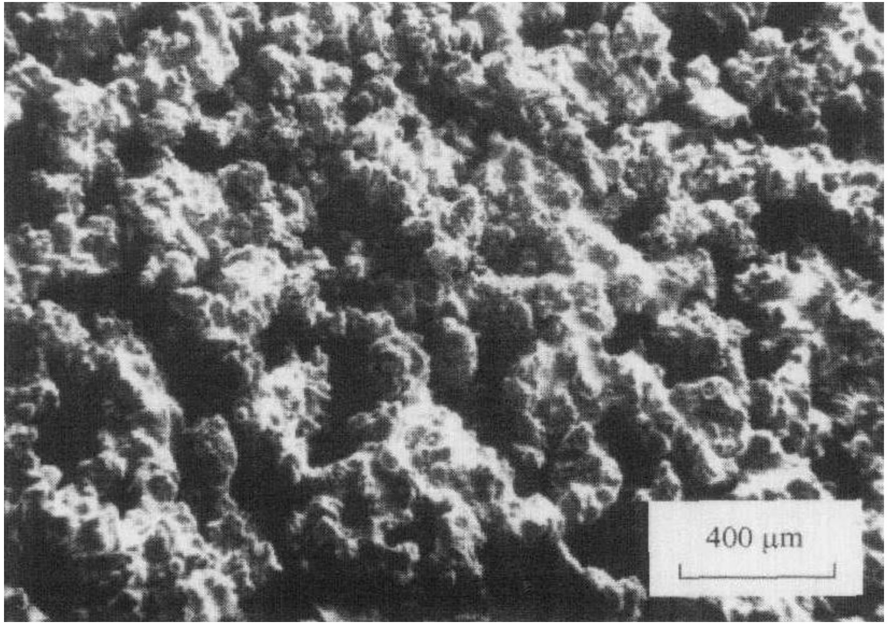


Raw Cu-coated Ni-alloy powder

Source: Tolochko et al. 2003

Sintered Materials





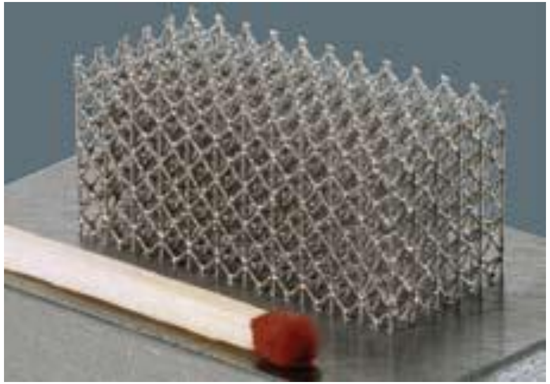
Fe-Cu powder mixture **after** sintering

Source: Tolochko et al. 2003

SLS & DMLS Process

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

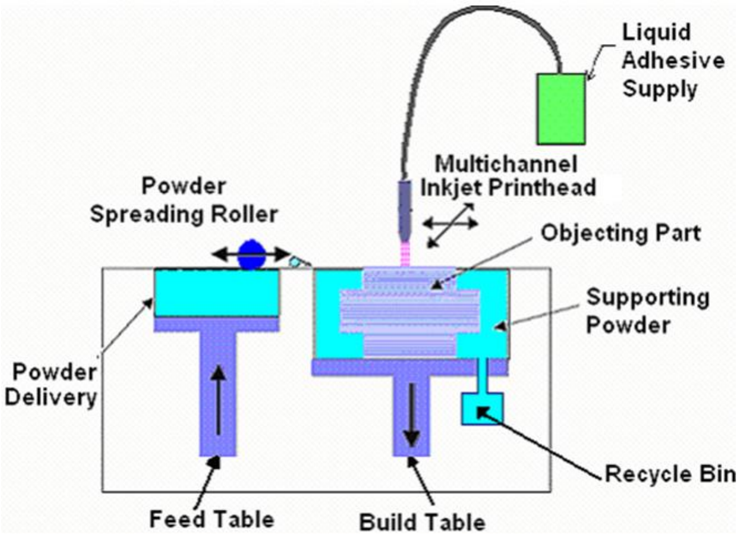
Sample Fabricated Parts



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

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)

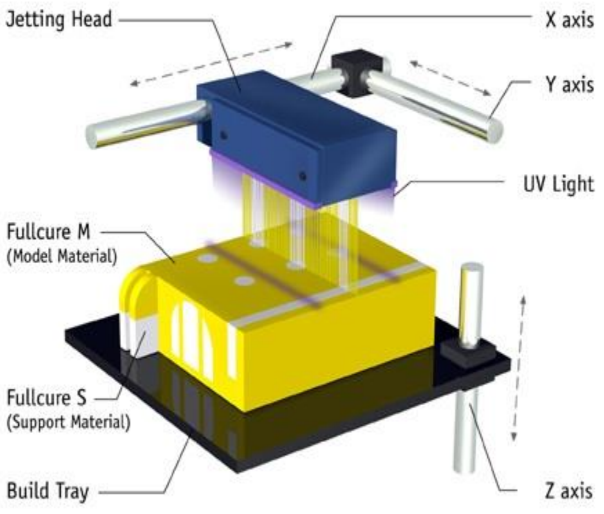
Source: Z corporation

Plaster-based 3D Printing Process

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

Photopolymer Phase Change Inkjets

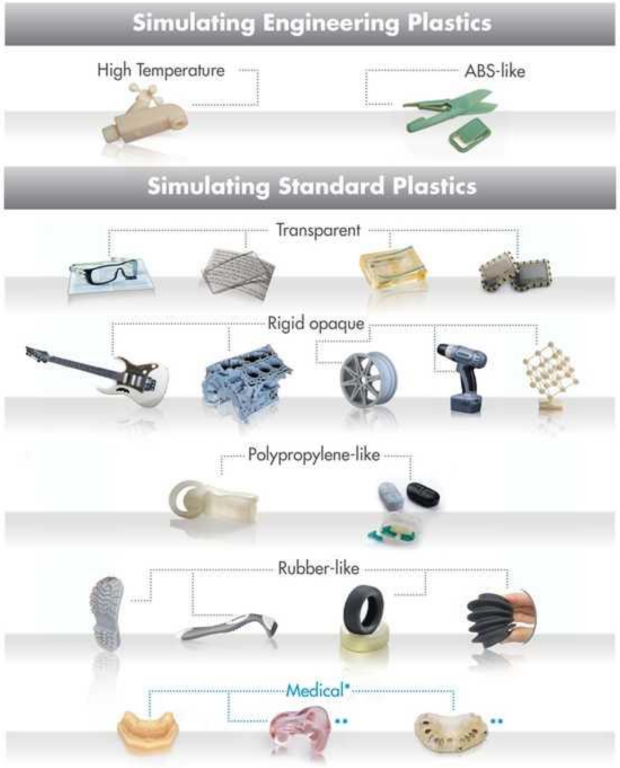
- Inkjet printhead jets liquid photopolymer and support material
- UV light cures photopolymer and support material
- Excess material is removed using a roller
- The platform descends by one layer



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

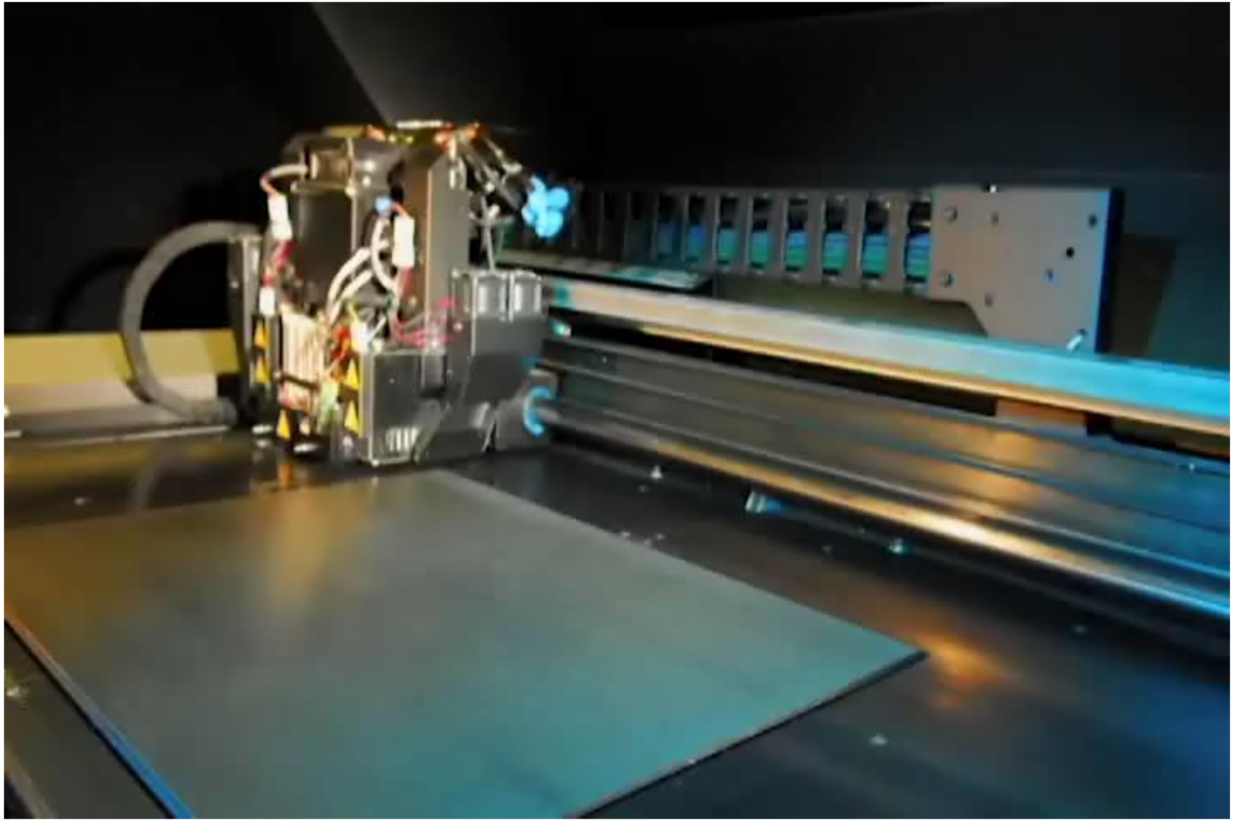
Materials

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



Source: Objet Geometries

Photopolymer Phase Change Inkjet 3D Printing



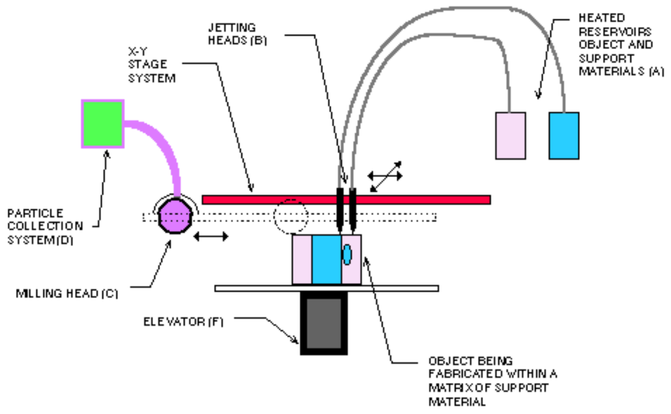
Source: https://www.youtube.com/watch?v=XLLq9SwSTpM

Sample Fabricated Objects

Source: Objet Geometries

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

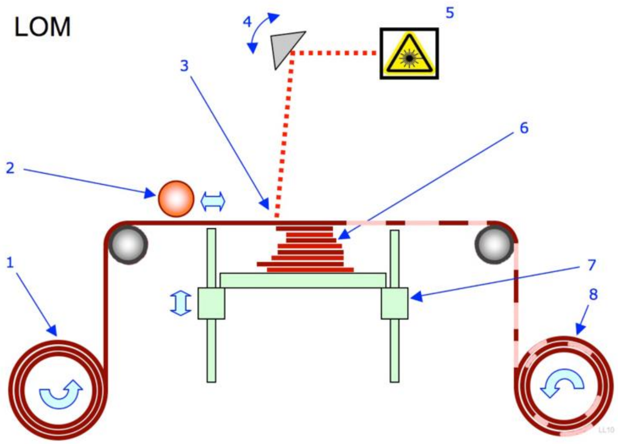
Thermal Phase Change Inkjets Features

- 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

Source: http://www.protojewel.com

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

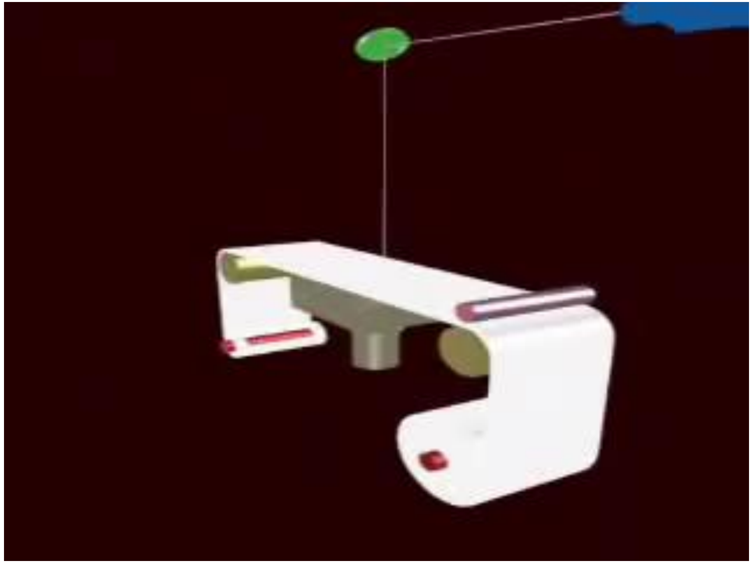
Laminated Object Manufacturing Features

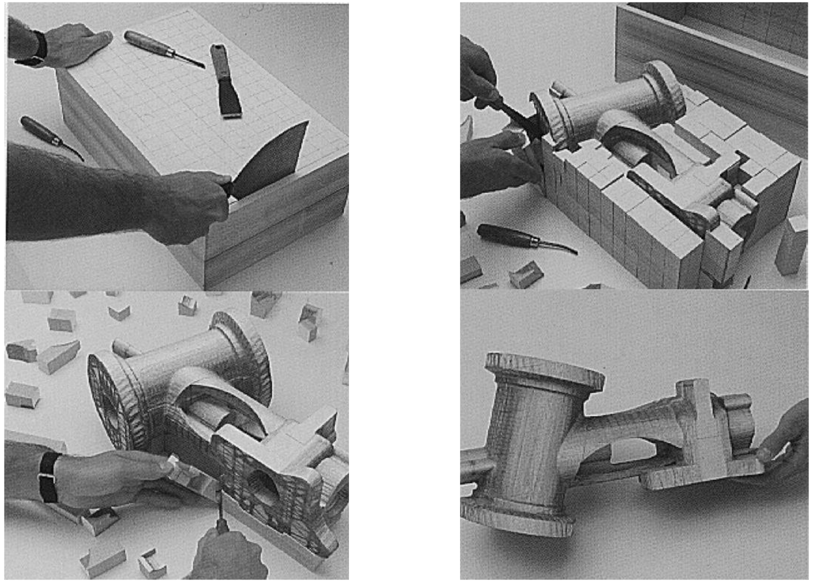
- Inexpensive – low material cost
- Color can be added using additional printhead
- Materials
  - Paper (most common), plastics, composites
- Support material
  - The same material can be used as support




Source: http://www.solido3d.com

LOM Printing Process



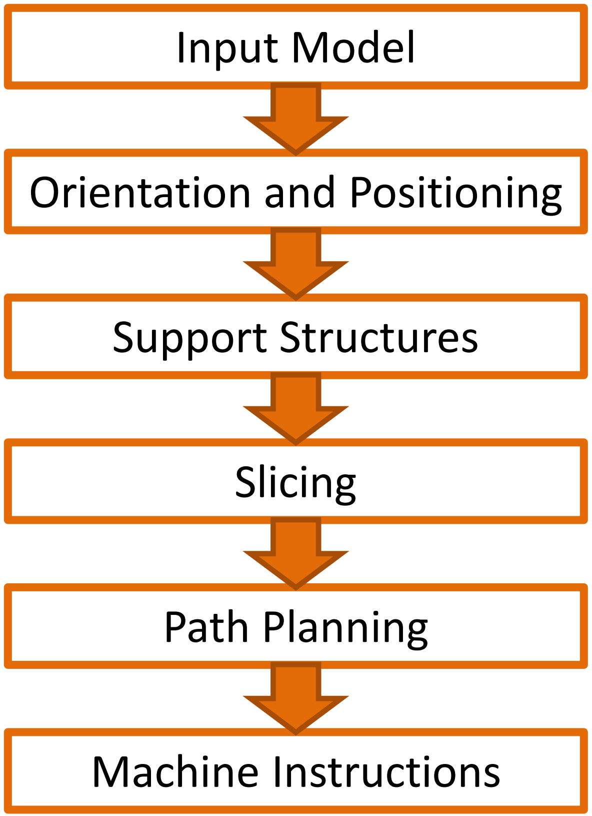


Source: http://www.youtube.com/watch?v=Z1WNA6tdfWM

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

3D Printing Software Pipeline

3D Printing Software Pipeline



Input File Formats

- STL (Stereolithography)
  - Triangle "soup" – an unordered list of triangular facets
  - Vertices ordered by the right hand rule

ASCII

solid *name*

facet normal n_i n_j n_k
outer loop
vertex $v1_x$ $v1_y$ $v1_z$
vertex $v2_x$ $v2_y$ $v2_z$
vertex $v3_x$ $v3_y$ $v3_z$
endloop
endfacet

repeat for each triangle

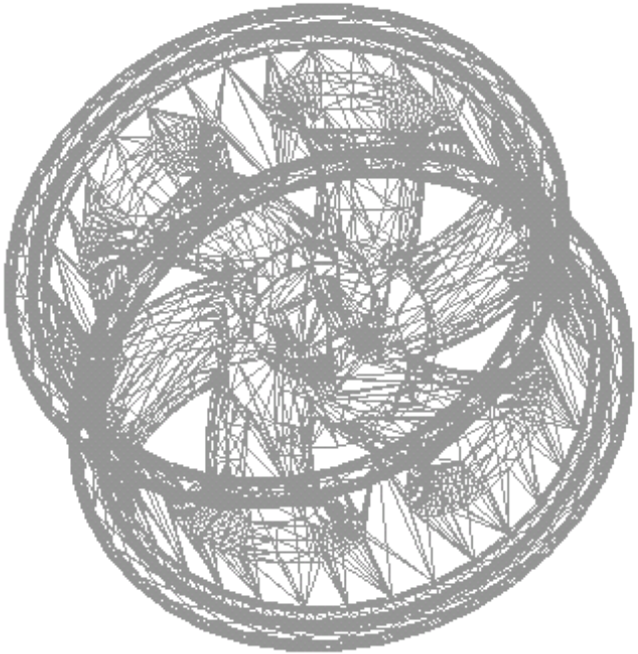
endsolid *name*

binary

UINT8[80] – Header
UINT32 – Number of triangles

foreach triangle
REAL32[3] – Normal vector
REAL32[3] – Vertex 1
REAL32[3] – Vertex 2
REAL32[3] – Vertex 3
UINT16 – Attribute byte count (0)
end

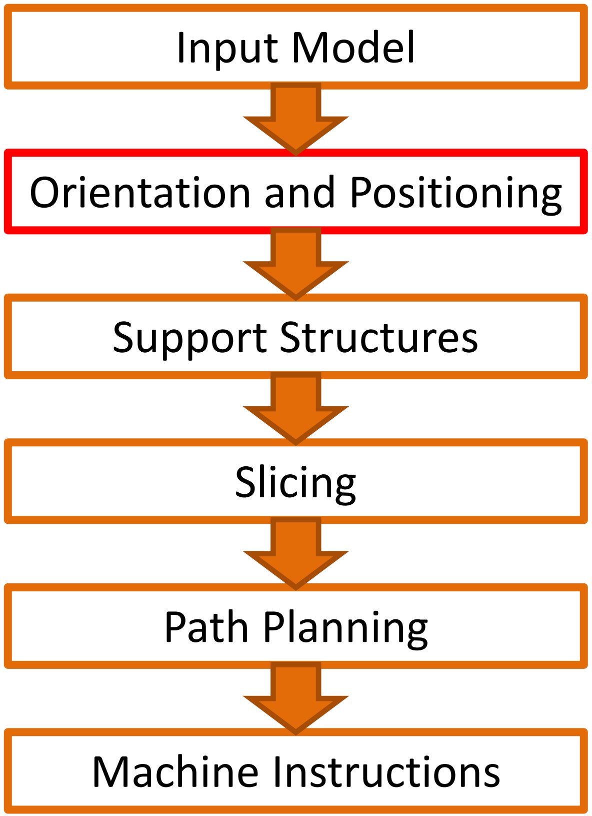
STL (Stereolithography) File Format



```
solid Wheel
   facet normal -1.000000e+000 0.000000e+000 0.000000e+000
      outer loop
         vertex 7.095000e+001 2.913194e+002 7.026579e+001
         vertex 7.095000e+001 2.914028e+002 7.636772e+001
         vertex 7.095000e+001 3.106206e+002 8.149973e+001
      endloop
   endfacet
   facet normal -1.000000e+000 0.000000e+000 0.000000e+000
      outer loop
         vertex 7.095000e+001 3.106206e+002 8.149973e+001
         vertex 7.095000e+001 2.914028e+002 7.636772e+001
         vertex 7.095000e+001 2.882984e+002 1.048139e+002
      endloop
   endfacet
   facet normal -1.000000e+000 0.000000e+000 0.000000e+000
      outer loop
         vertex 7.095000e+001 3.106206e+002 8.149973e+001
         vertex 7.095000e+001 2.882984e+002 1.048139e+002
         vertex 7.095000e+001 2.795565e+002 1.320610e+002
      endloop
   endfacet
   facet normal -1.000000e+000 0.000000e+000 0.000000e+000
      outer loop
         vertex 7.095000e+001 2.685262e+002 2.101446e+002
         vertex 7.095000e+001 2.845330e+002 1.940968e+002
         vertex 7.095000e+001 2.647845e+002 1.974923e+002
      endloop
                  .
                  .
                  .
   facet normal -1.000000e+000 0.000000e+000 0.000000e+000
      outer loop
         vertex 7.095000e+001 2.647845e+002 1.974923e+002
         vertex 7.095000e+001 2.845330e+002 1.940968e+002
         vertex 7.095000e+001 3.011244e+002 1.720122e+002
      endloop
   endfacet
endsolid
```

Source: Jackson 2000

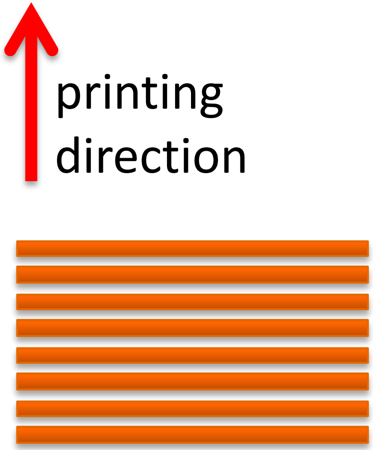
3D Printing Software Pipeline

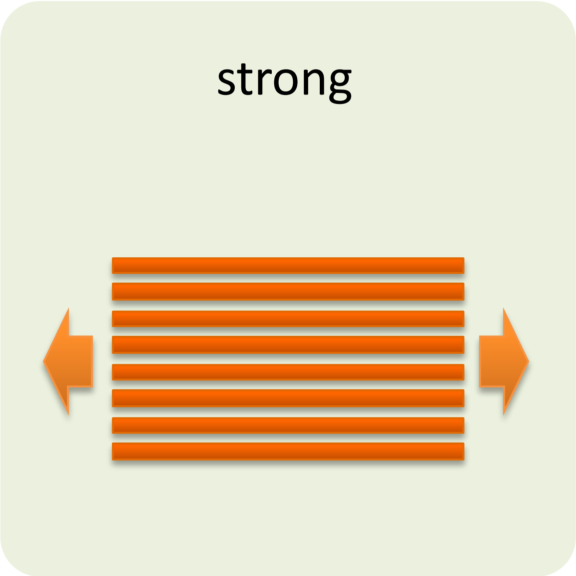


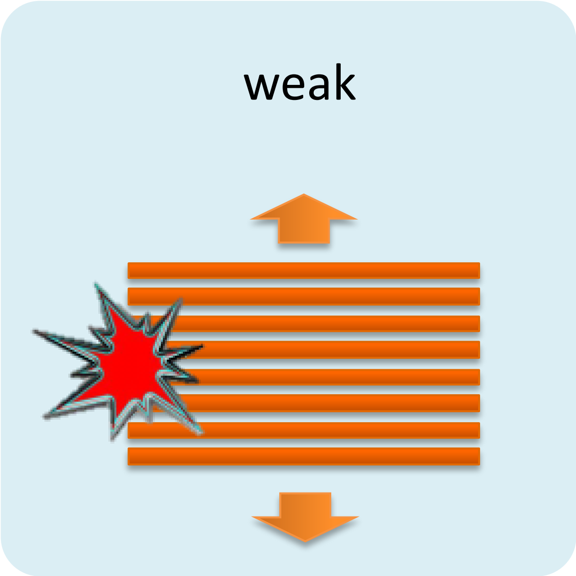
Model Orientation

- Model orientation on the build platform influences
  - Mechanical properties
  - Build time
  - Support volume
  - Surface accuracy
  - Support contact area

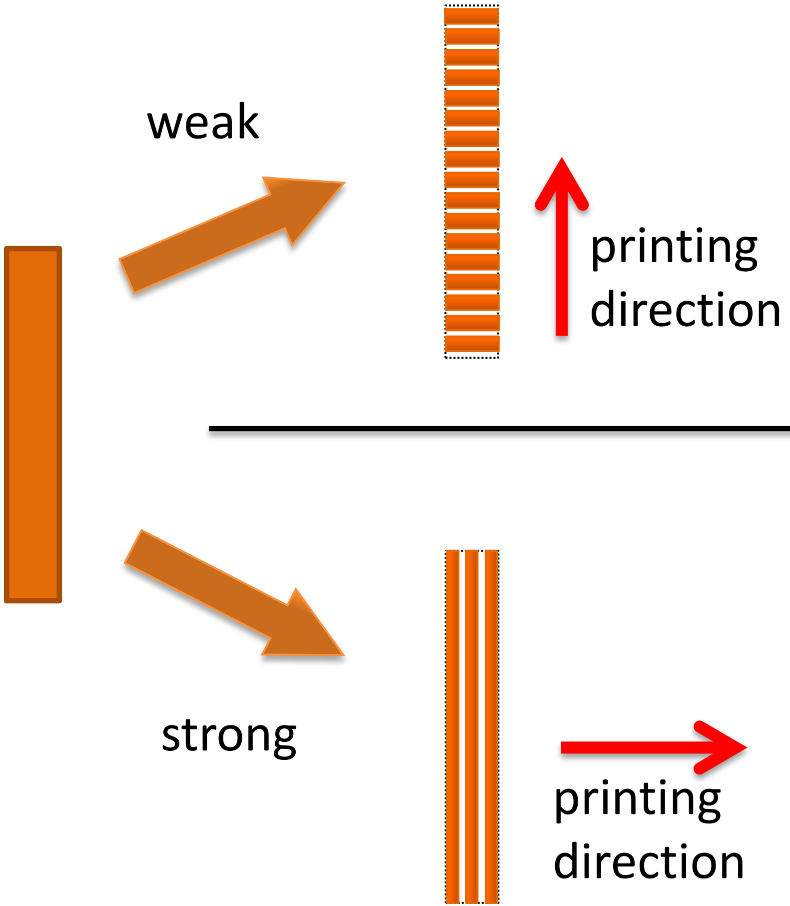
Model Orientation: Mechanical Properties

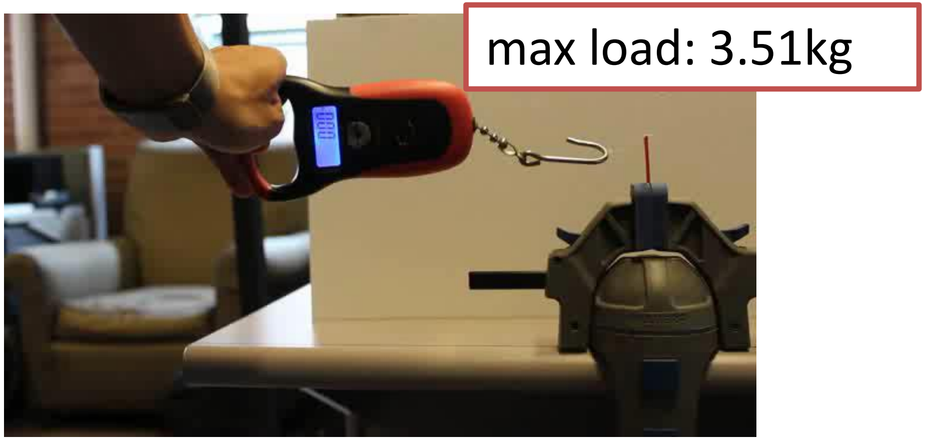






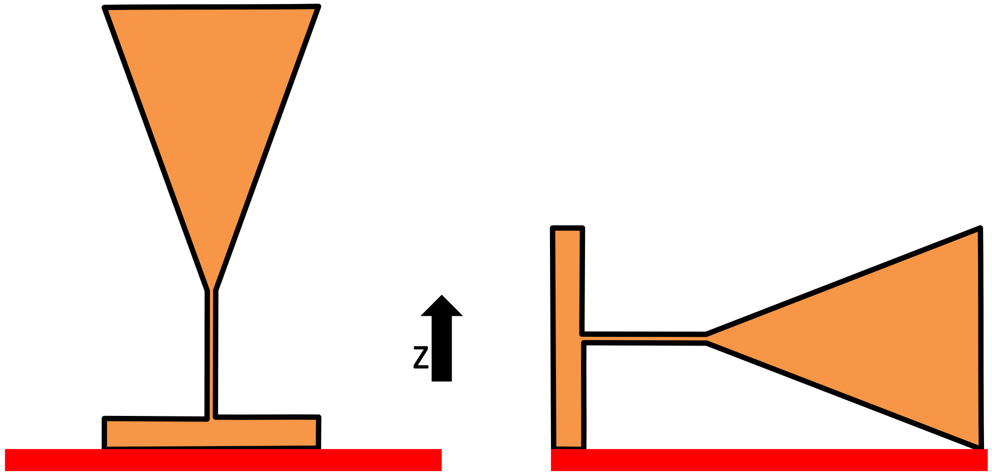
Model Orientation: Mechanical Properties





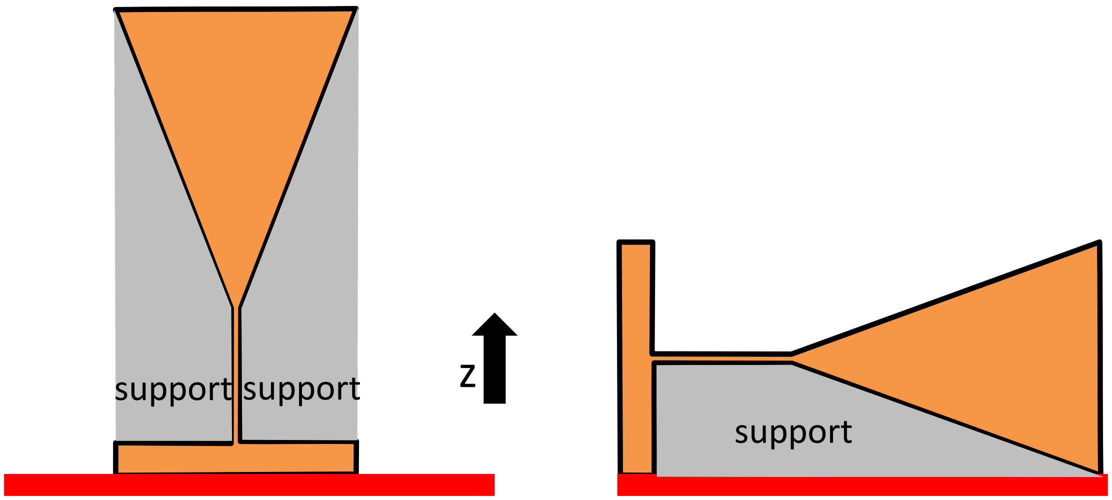
Model Orientation: Build Time

- Build speed is slower for the z direction compared to the xy direction



longer build time shorter build time

Model Orientation: Support Volume



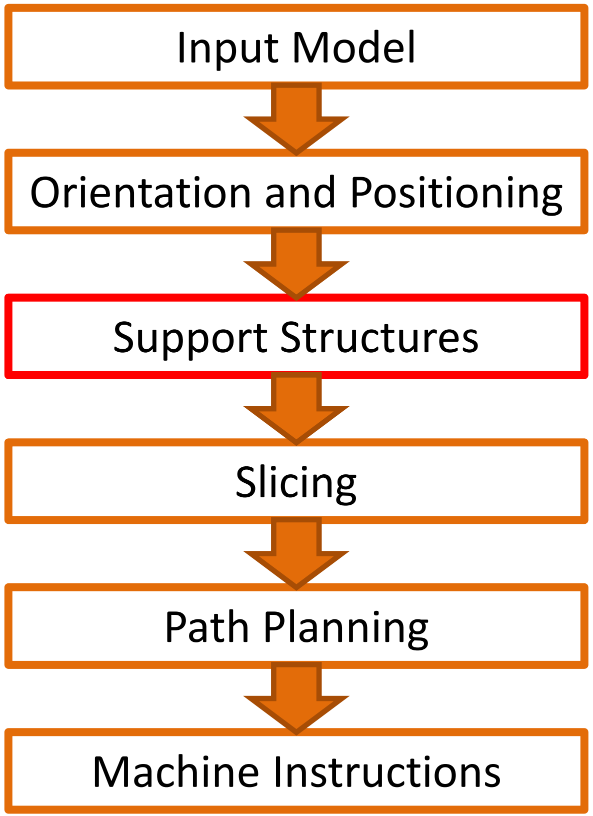
more support volume

less support volume

Algorithms for Specifying Model Orientation

- Manual placement
  - User is responsible for placing parts on the build tray
- Semi-automated placement
  - User places parts on the build tray
  - System provides feedback on build time, support volume, support contact area, mechanical properties
- Automated placement
  - orientation is computed using optimization according to one or more objectives (build time, support volume, support area, mechanical properties)

3D Printing Software Pipeline

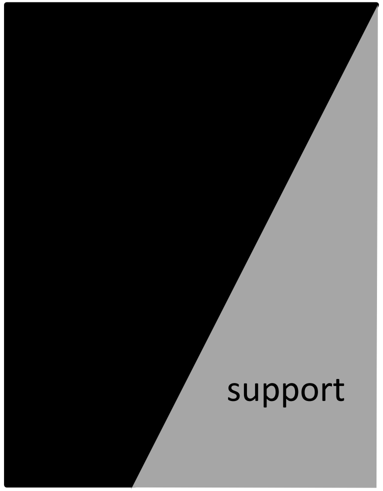


Support Structure Generation

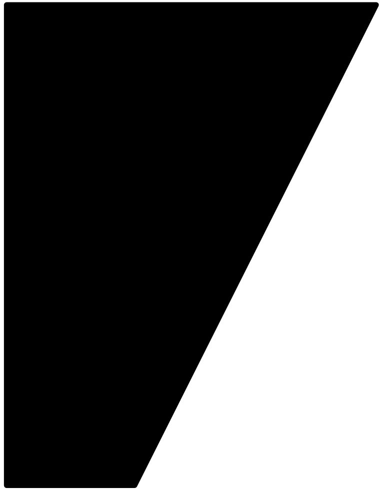
- Do not require special support
  - SLS, DMLS, LOM, Plaster-based
- Require support
  - SLA, DLP, FDM, phase-change inkjet
- Different goals
  - Prevent curling as the resin hardens
  - Supporting overhangs
  - Maintaining stability (part does not move or tip over)
  - Supporting large flat walls
  - Preventing excessive shrinkage
  - Supporting slanted walls

Support Structure Generation Depends on Manufacturing Method

- Different for FDM, SLA/DLP, inkjet printing



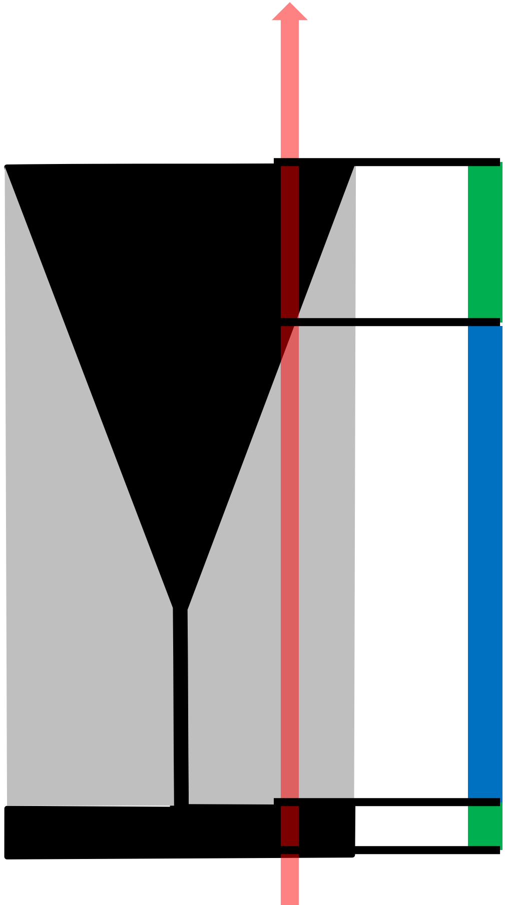
inkjet



FDM

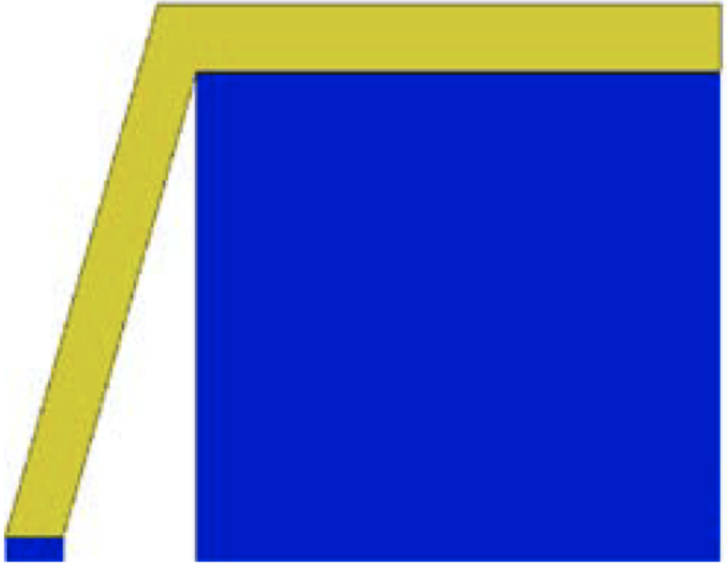
Simple Conservative Algorithm

- Use ray casting in the z direction to compute all intersections for a ray
- Sort intersections in the increasing z to determine intervals inside/outside of the object
- Any outside intervals before the last inside interval should contain support



Support Generation For FDM

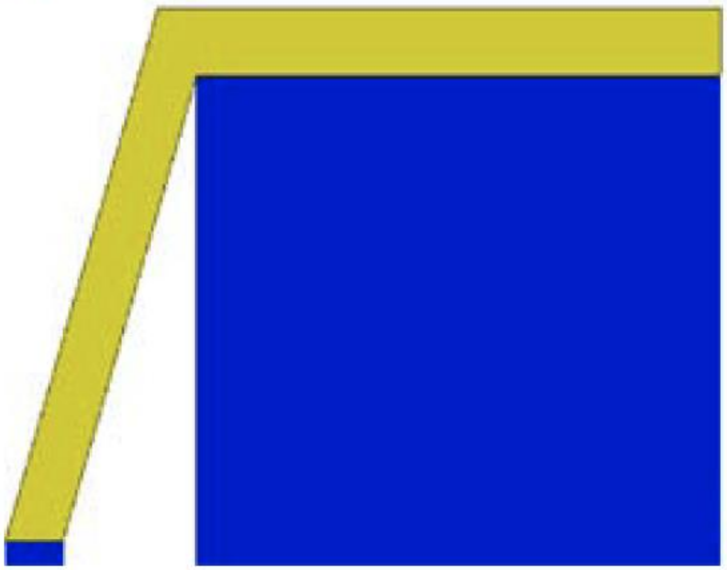
- FDM printers can print at some draft angle



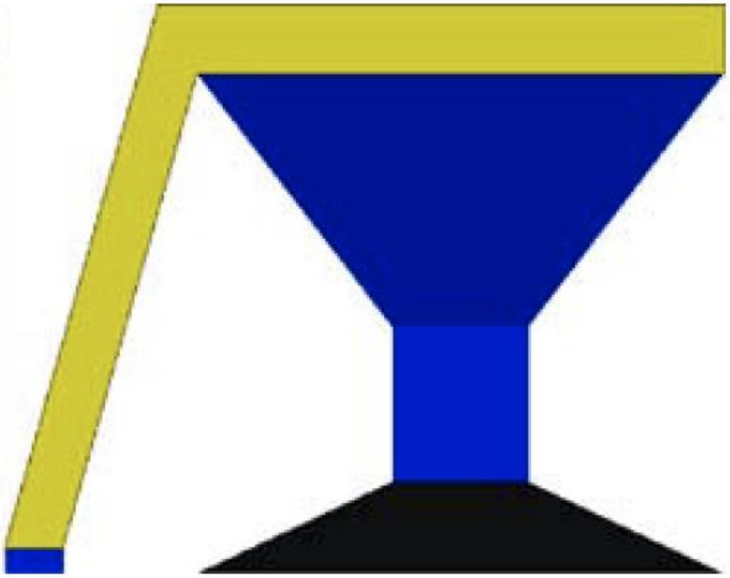
Huang et al. 2009

Support Generation For FDM

- Minimize the use of support material



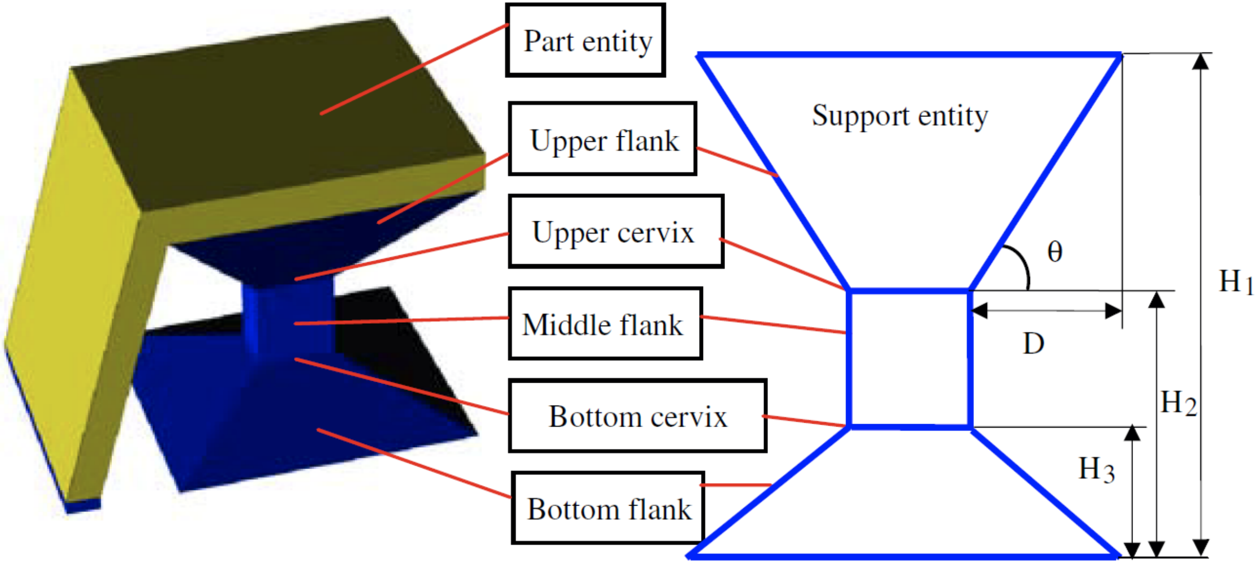
unoptimized support



optimized support

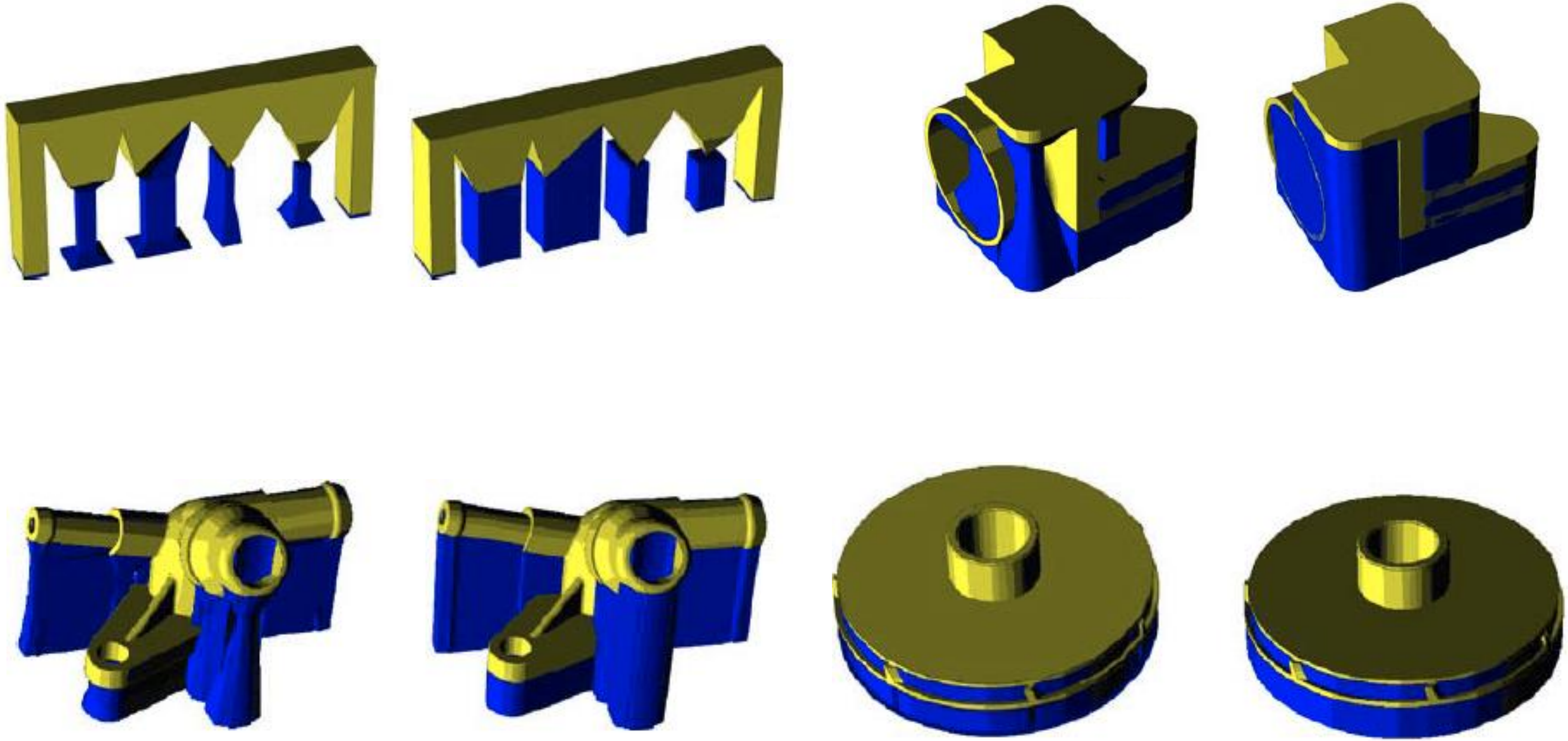
Huang et al. 2009

Optimized Support Structures



Huang et al. 2009

Unoptimized vs. Optimized Support Structure



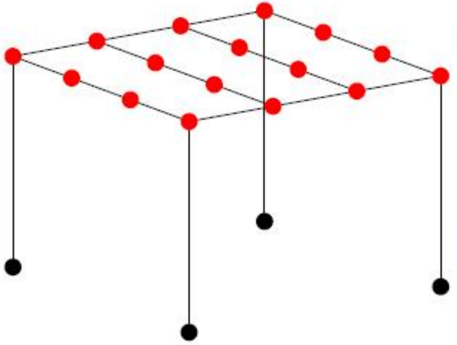
Huang et al. 2009

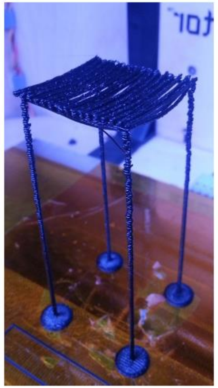
Advanced Algorithms: Photoshop

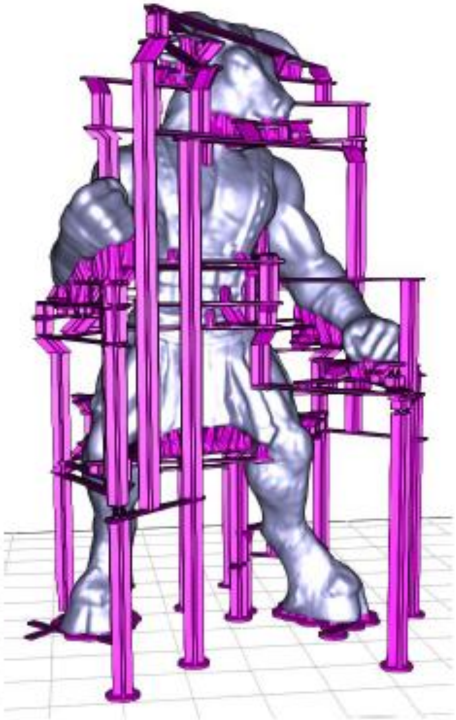
Advanced Algorithms: MeshMixer

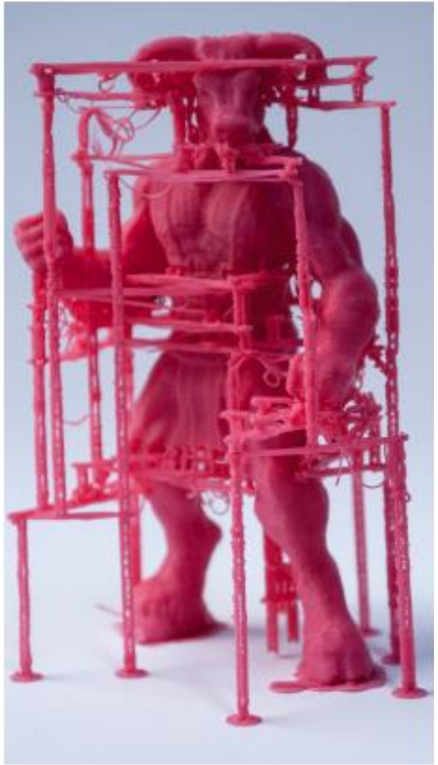
Source: http://www.youtube.com/watch?v=aFTyTV3wwsE

Advanced Algorithms: Bridging the Gap



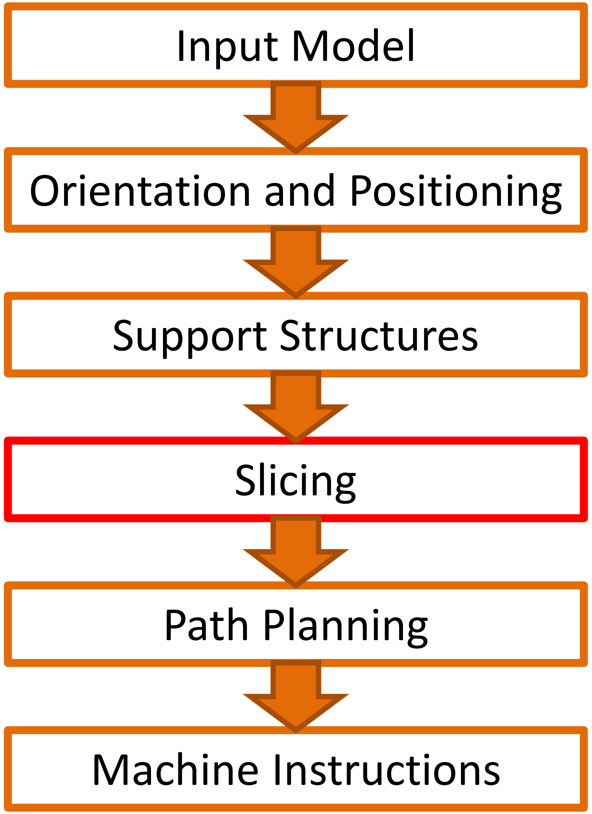






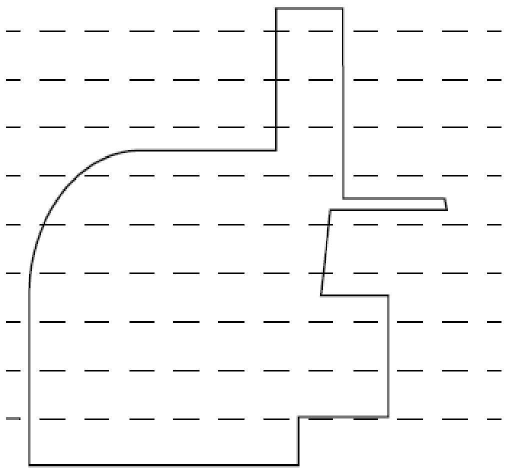
Source: Dumas, Siggraph 2014

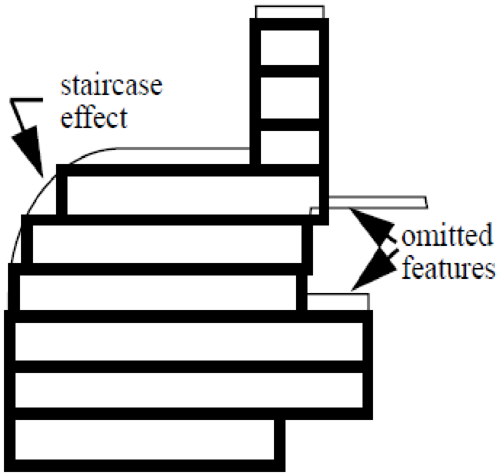
3D Printing Software Pipeline



Slicing

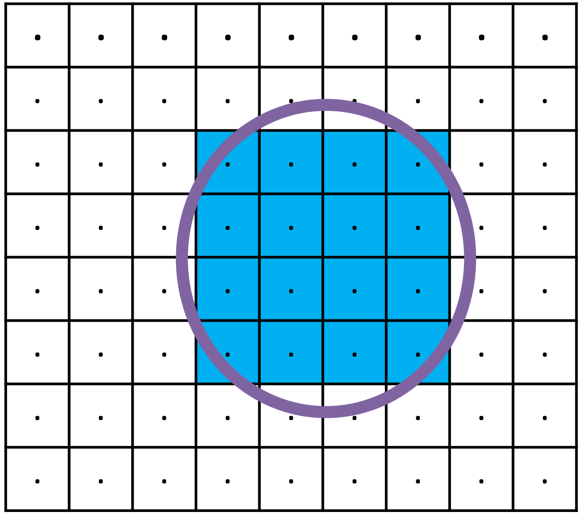
- For a discrete z value, compute an intersection of a plane with a model





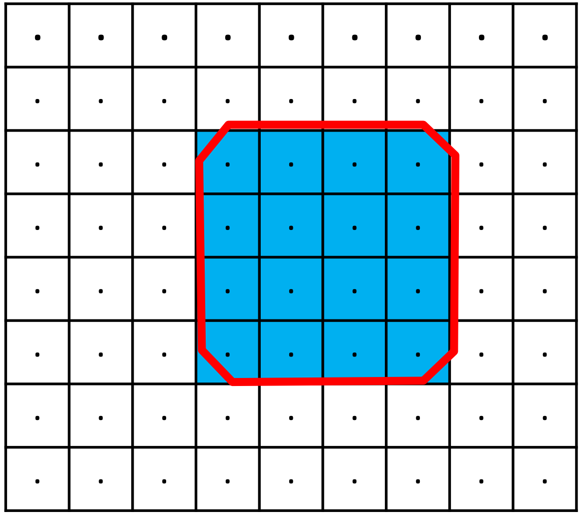
Slicing Algorithms: Voxelization

- **For each voxel compute inside/outside**
- Extract contours



Slicing Algorithms: Voxelization

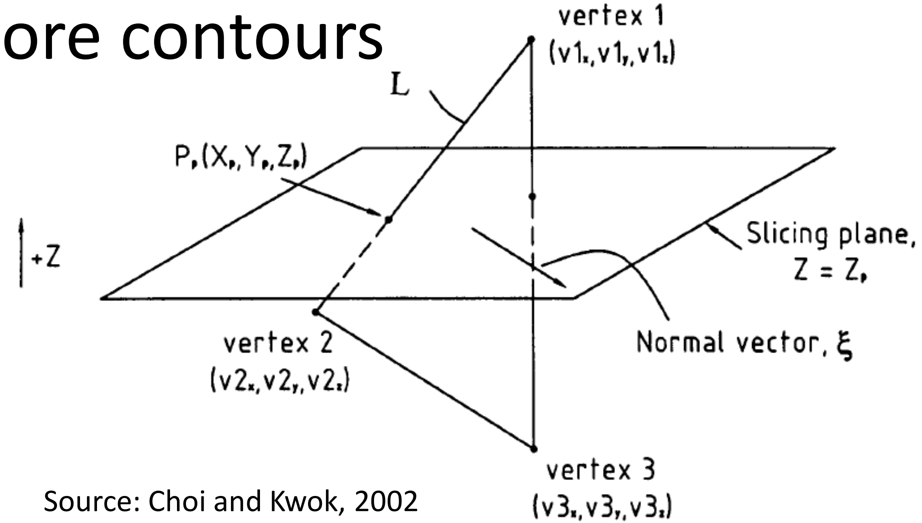
- For each voxel compute inside/outside
- **Extract contours (e.g., Marching Squares)**



Slicing Algorithms: Direct Plane-Triangle Intersection

- For each triangle
  - Intersect triangle with the z plane
  - If they intersect, store the line segment
- Connect line segments, store contours

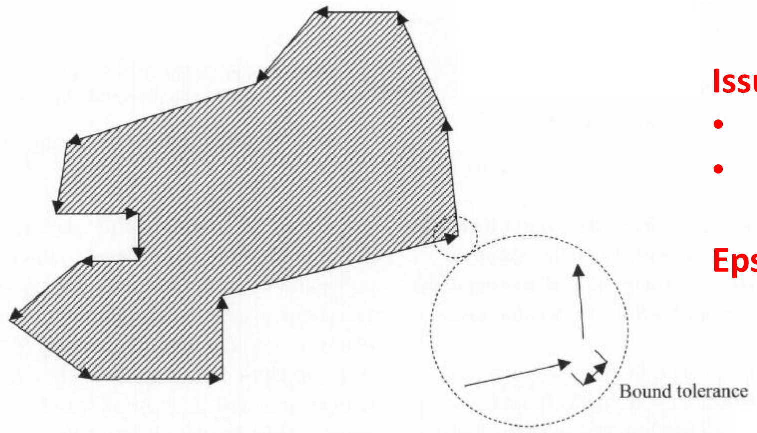
1. **Intersect each edge with the plane**
2. **If two intersection points, connect them to form a line segment**



Source: Choi and Kwok, 2002

Slicing Algorithms: Direct Plane-Triangle Intersection

- For each triangle
  - Intersect triangle with the z plane
  - If they intersect, store the line segment
- Connect line segments, store contours

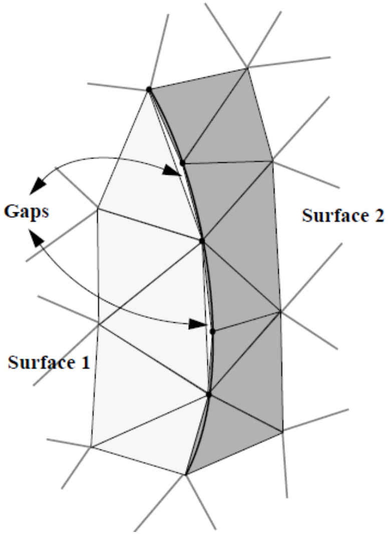


Issues
- **spurious line segments**
- **missing line segments**

Epsilons

Slicing Algorithms: Direct Plane-Triangle Intersection

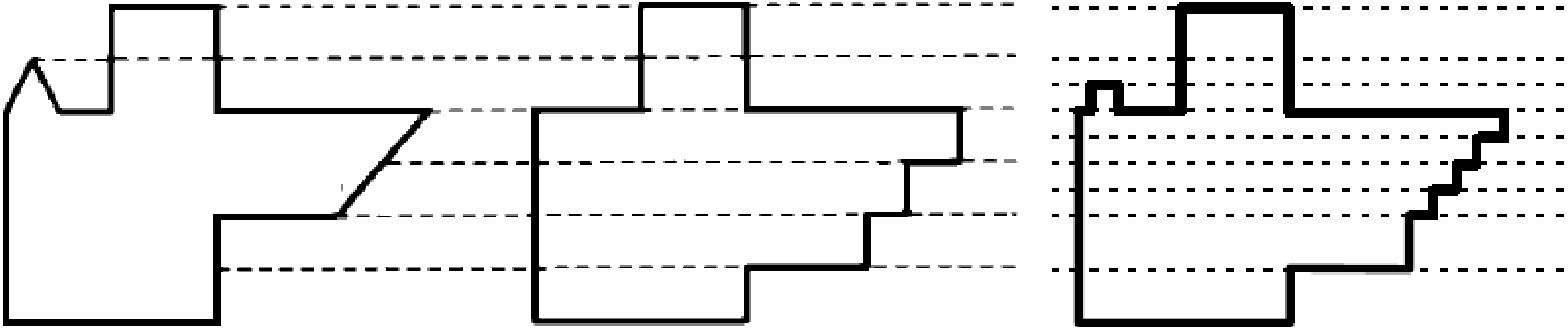
- STL models are not always watertight -> epsilons



Source: Marsan et al, 1998

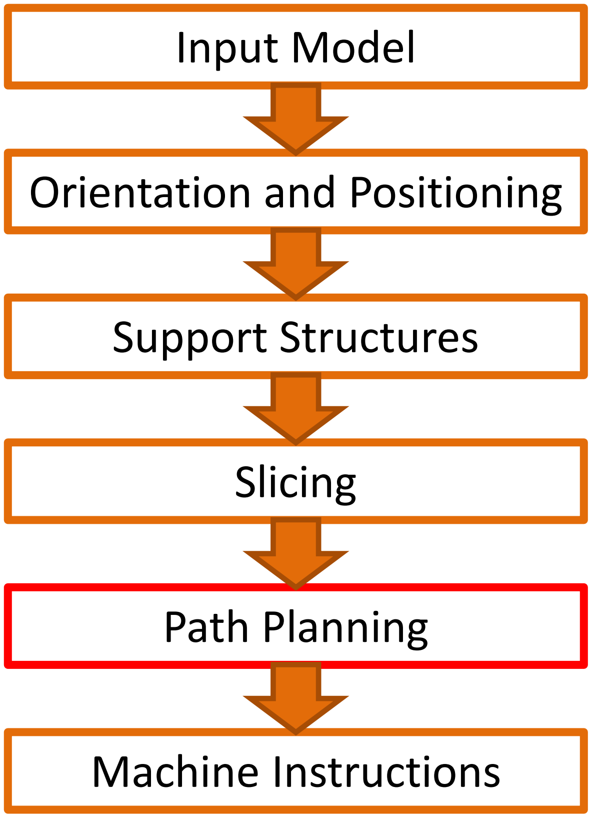
Adaptive Slicing

- Slice height is adapted to the input geometry
- Adaptive slicing is rarely used



input model uniform slicing adaptive slicing

3D Printing Software Pipeline

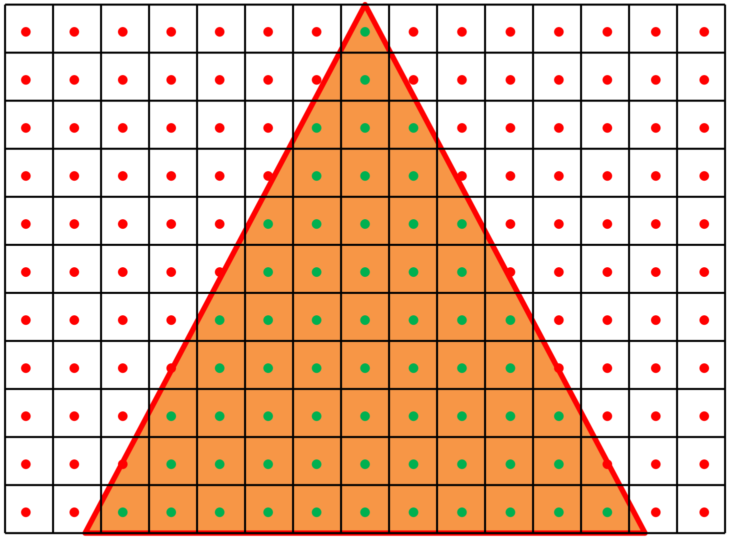


What Does Path Planning Influence?

- Build time
  - repositioning the tool at the start of a new path
  - accelerating and decelerating for direction changes
- Surface accuracy
  - the filament size
- Distortion
  - materials with a high coefficient of thermal expansion
  - the top layer shrinks when it hardens and it distorts since it is tied to the bottom layer
- Stiffness and strength
  - fill pattern
  - the area and strength of bonds depends on spacing and the time interval between the tool traversal

Path Planning for Raster-based 3D Printing

- Superimpose a voxel grid and test whether a voxel is inside/outside the model
- Trivial for DLP 3D printing
- For inkjet-based 3D printing requires computing print head movement (many nozzles, distances between nozzles)



Path Planning for Vector-based 3D Printing

- Contour
- Contour + solid interior
- Contour + interior fill pattern

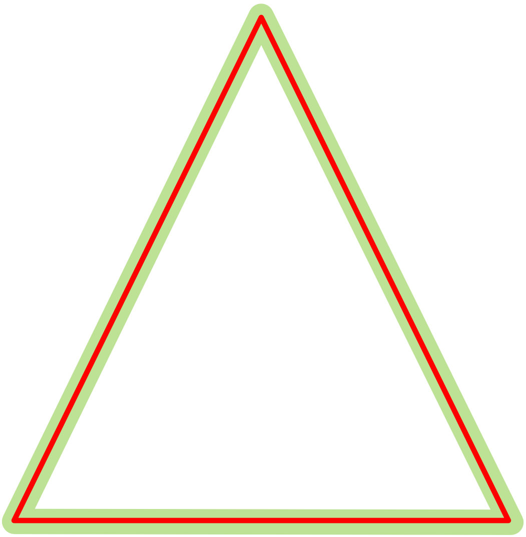
Path Planning for Vector-based 3D Printing: Contour

- Allows manufacturing hollow objects, some overhangs, some tilted surfaces
- Reduces frequency of tool repositioning
- Reduces support structures

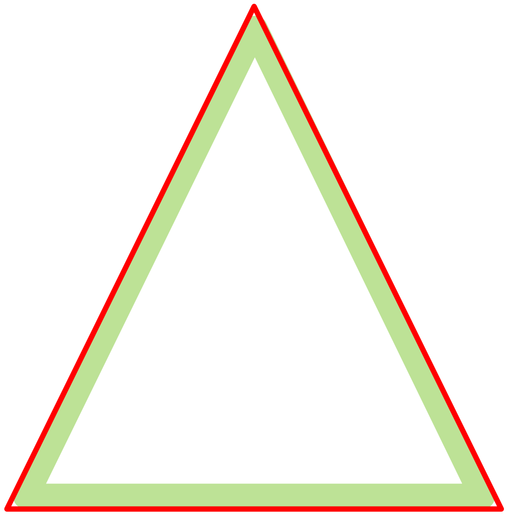
Source: http://www.3ders.org

Path Planning for Vector-based 3D Printing: Contour

- Offset inwards by distance equal to the filament radius



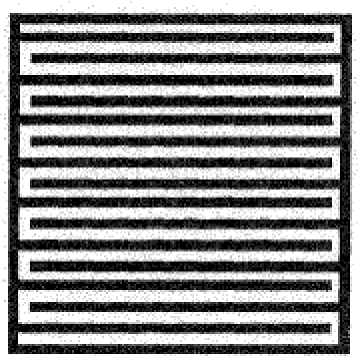
no offset

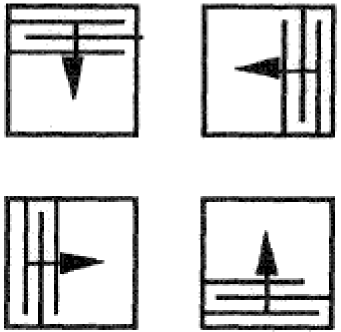


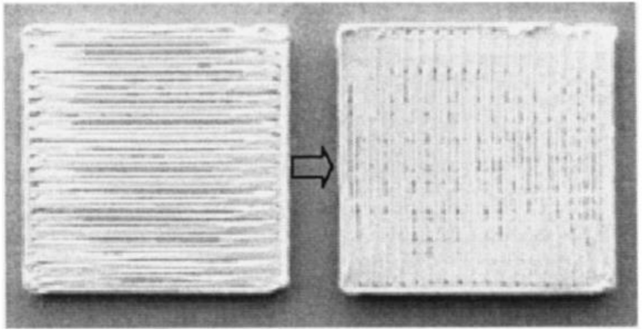
offset inwards

Path Planning for Vector-based 3D Printing: Interior

- Tracing contours is combined with filling the interior
- The interior can be completely filled





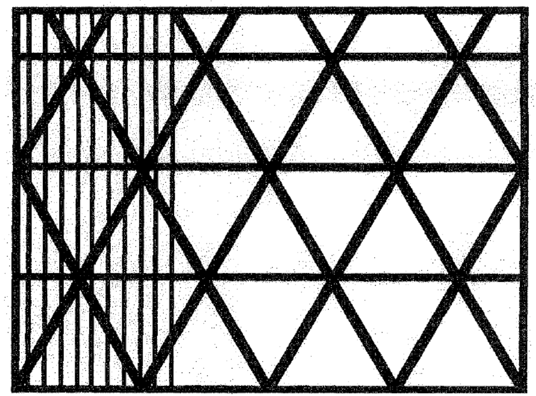


Horton et al 1993

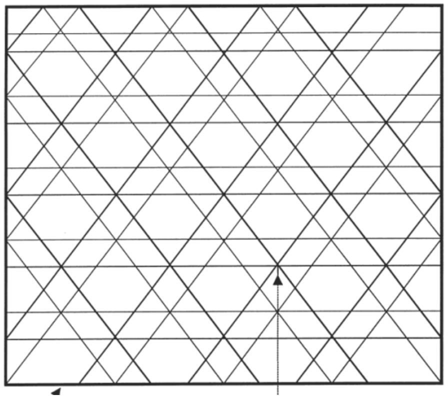
Han et al 2002

Path Planning for Vector-based 3D Printing: Interior

- Tracing contours is combined with filling the interior
- Many different fill patterns can be used



TriHatch

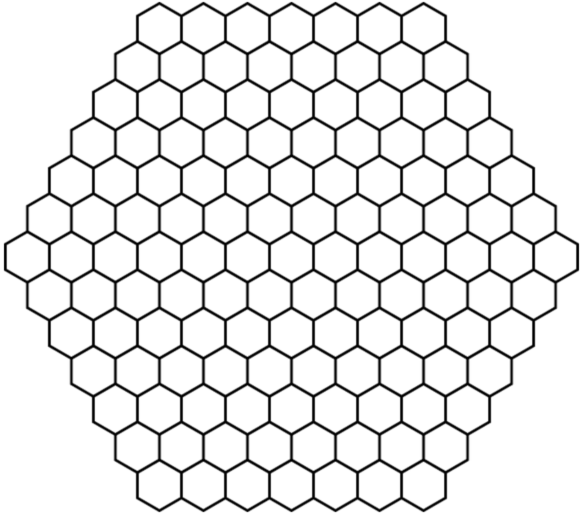


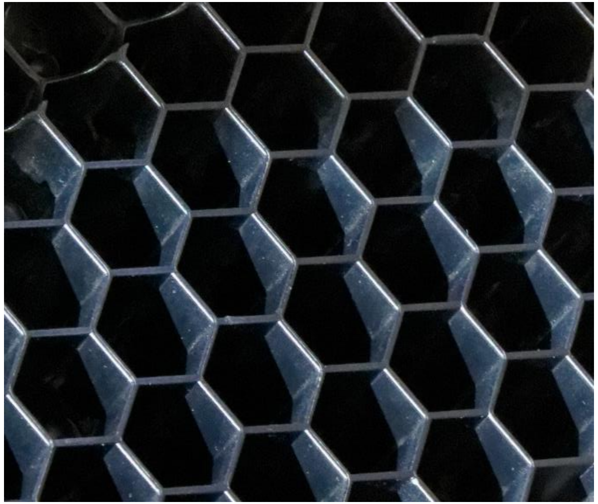
QuickCast

Horton et al 1993

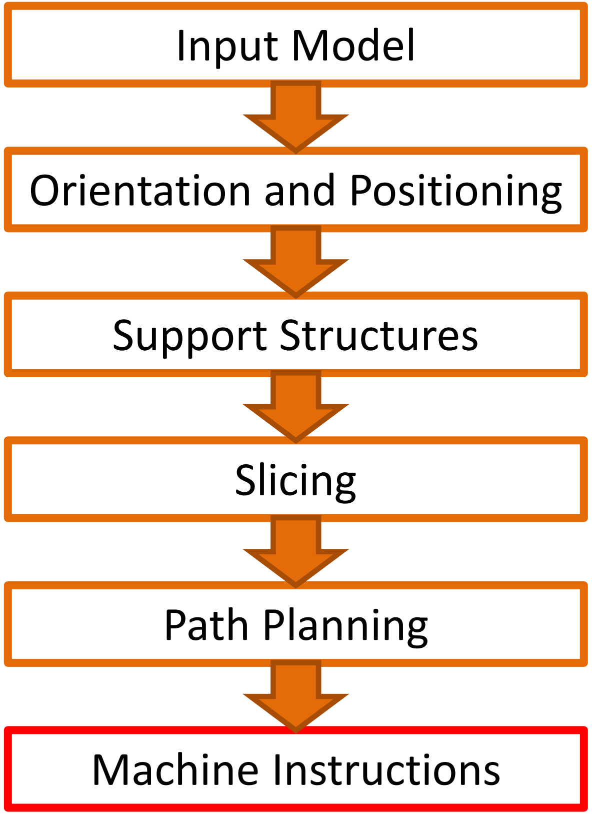
Path Planning for Vector-based 3D Printing: Interior

- A ***honeycomb-cell structure*** a good trade-off between overall weight and strength





3D Printing Software Pipeline



Machine Instructions

- Raster file formats
  - DLP 3D printing, plaster-based 3D printing, phase-change inkjets
  - Proprietary, not exposed
  - Can be exported as image files (e.g., PNG, BMP)
- Vector file formats
  - G-Code
  - SLI by 3D Systems – machine-specific 2D format for the vector commands that control the laser beam

G-code

- Numerical control (NC) programming language
- Developed at MIT in 1950s
- Used for CNC milling machines, now for many 3D printers
- Sample Instructions
  - **G00: Rapid move**
    - does not necessarily move in a single straight line between start point and end point. It moves each axis at its max speed until its vector is achieved.
  - **G01: Linear interpolation**
    - specify the start and end points, and the control automatically calculates the intermediate points to pass through that will yield a straight line
  - **G02: Circular interpolation, clockwise**

G-code Example

This program draws a 1" diameter circle about the origin in the X-Y plane.

```
G17 G20 G90 G94 G54
G0 Z0.25
X-0.5 Y0.
Z0.1
G01 Z0. F5.
G02 X0. Y0.5 I0.5 J0. F2.5
X0.5 Y0. I0. J-0.5
X0. Y-0.5 I-0.5 J0.
X-0.5 Y0. I0. J0.5
G01 Z0.1 F5.
G00 X0. Y0. Z0.25
```

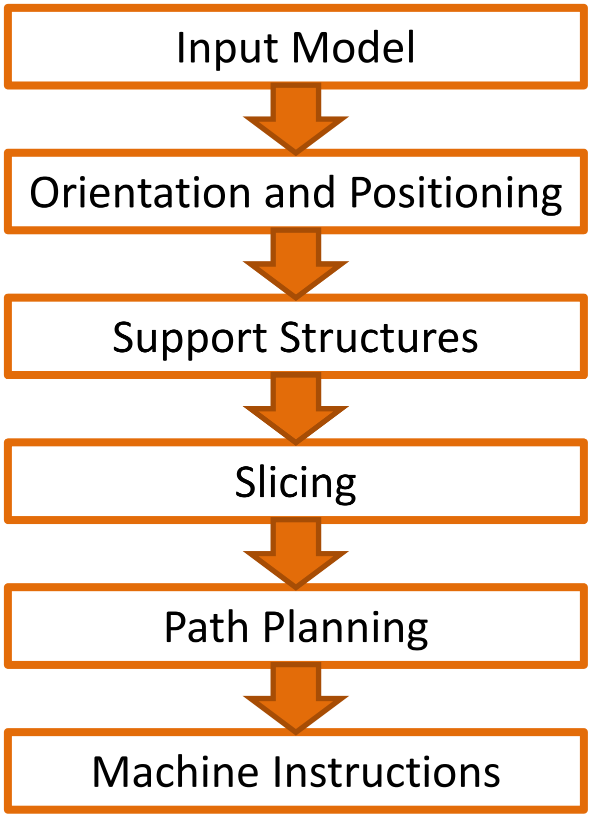
seek the Z-axis to 0.25“
travel to X=-0.5 and Y=0.0

lower back to Z=0.0.
draw a clockwise circle at a slow feed rate.

lift the Z-axis up 0.1“
seek back to X=0.0, Y=0.0, and Z=0.25

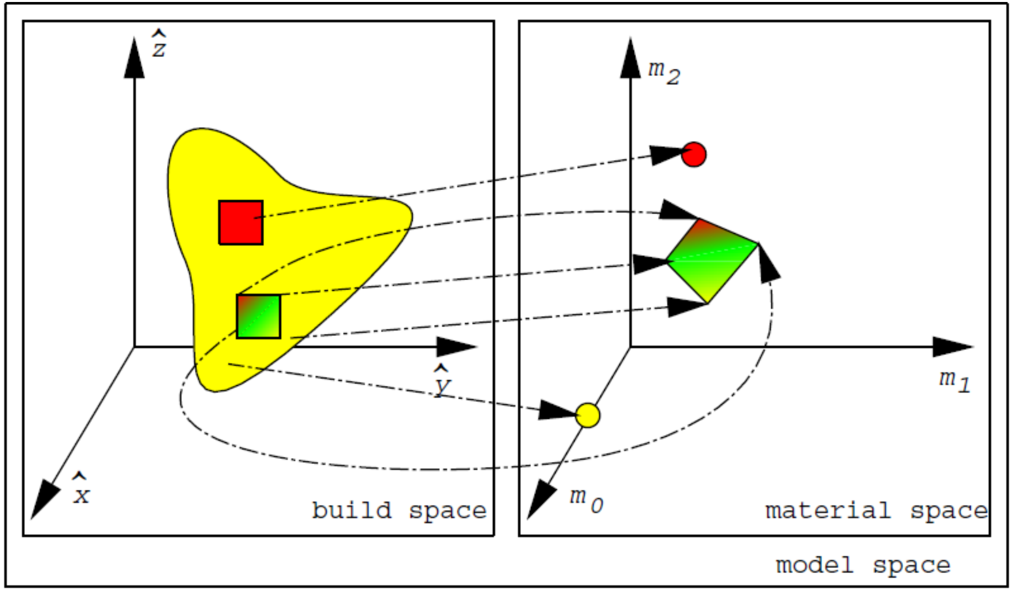
https://github.com/grbl/grbl/wiki/G-Code-Examples

3D Printing Software Pipeline



Representation of Multi-material Objects

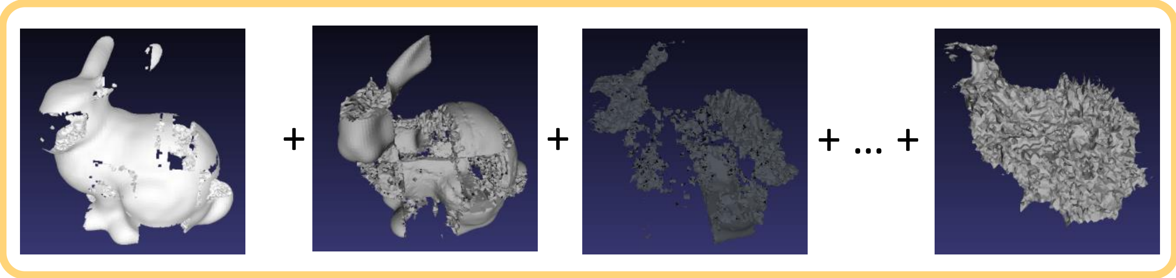
- Each point in the Build Space (**x** ∈ **X**) must map to a composition in the Material Space (**m**(**x**) ∈ **M**)



Source: Jackson 2000

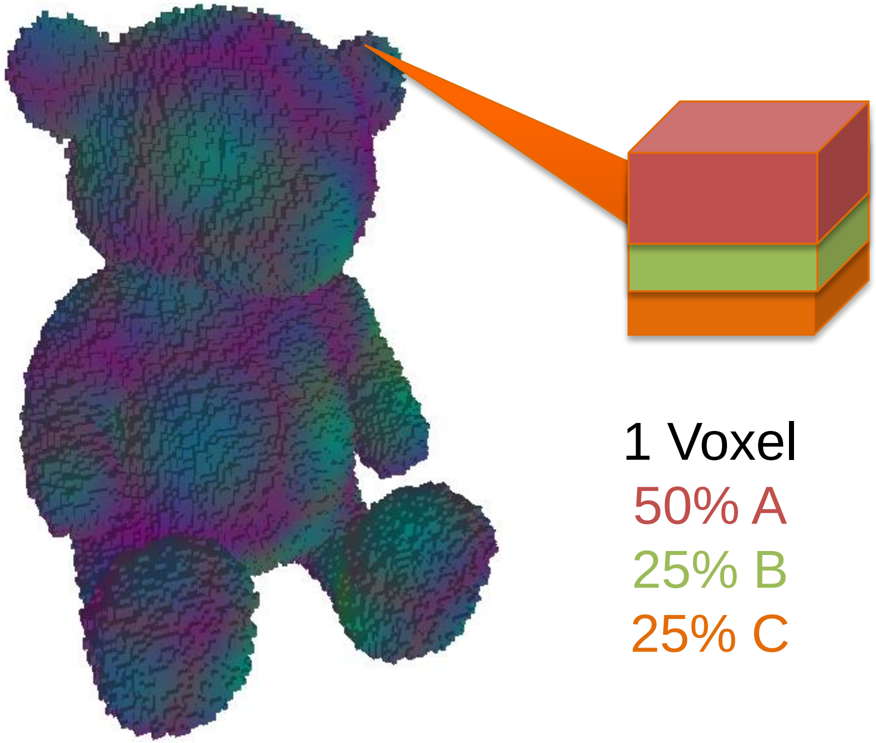
Basic Multi-Material 3D Printing Software Pipeline

- Input
  - A separate boundary representation for each material (e.g. an STL file)
- The rest of the pipeline is similar



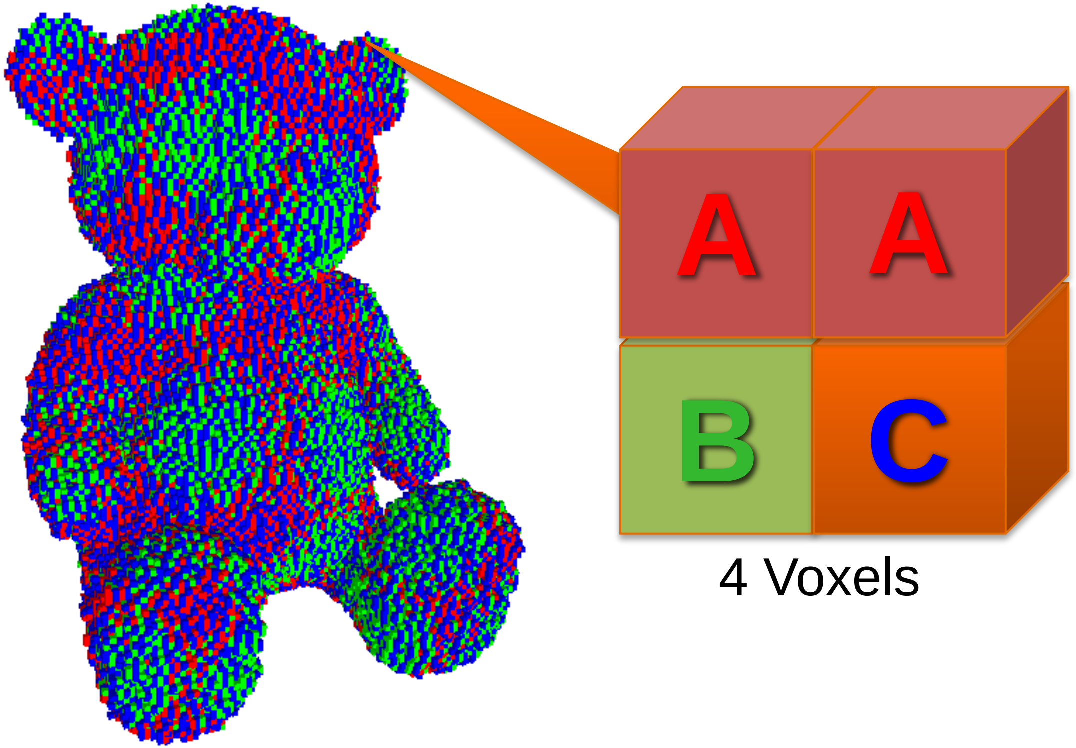
Voxel Representation of Multi-material Objects

- Voxel-based modeling
  - Each voxel maintains information about its composition



Voxel Representation of Multi-material Objects

- Voxel-based modeling
  - Each voxel maintains information about its composition
  - When printing this volume is dithered to obtain a halftoned representation



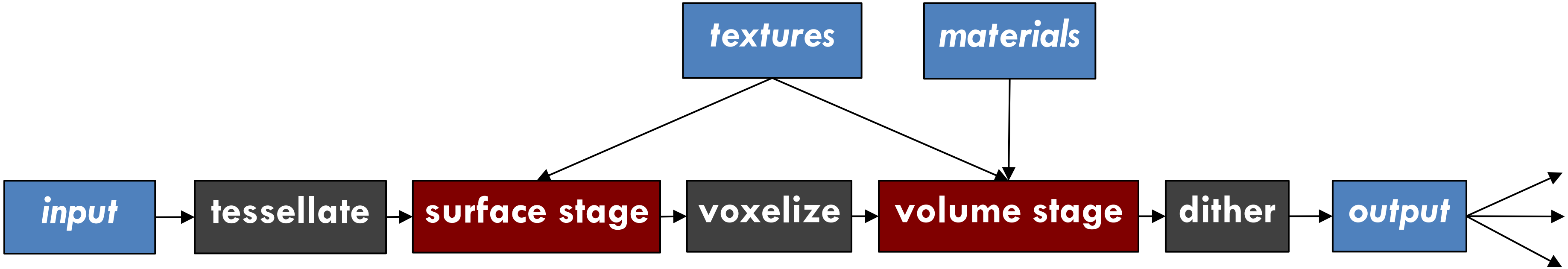
Software Architecture Challenges

- Giga voxels/inch^3, Tera voxels/foot^3
- Continuous gradation between materials
- Reusable material definitions
- Resolution and printer independence

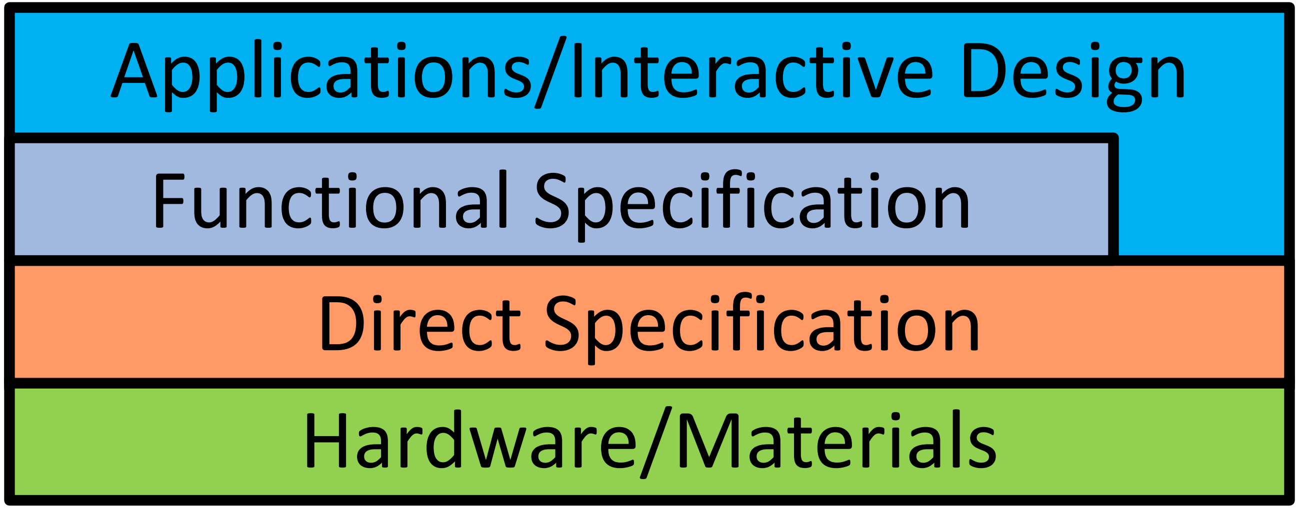
OpenFab [Vidimce 2013]

- Inspired by rendering pipelines
- Fixed stages and programmable stages
- Procedural surface and material definitions
- Resolution independence
- Streaming architecture

OpenFab [Vidimce 2013]



Extended 3D Printing Pipeline



Questions?