Additive Manufacturing Technology and Trends

MCA Session Topic: CAM for CAD

4/21/24

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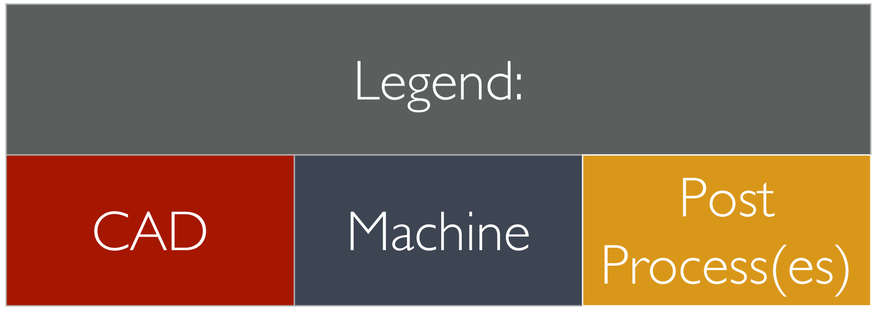
Eight Steps[1] in Additive Manufacturing

1. Conceptualization and CAD
2. Conversion to STL/AMF
3. Transfer to AM Machine and STL File Manipulation
4. Machine Setup
5. Build
6. Removal and Cleanup
7. Post-Processing
8. Application

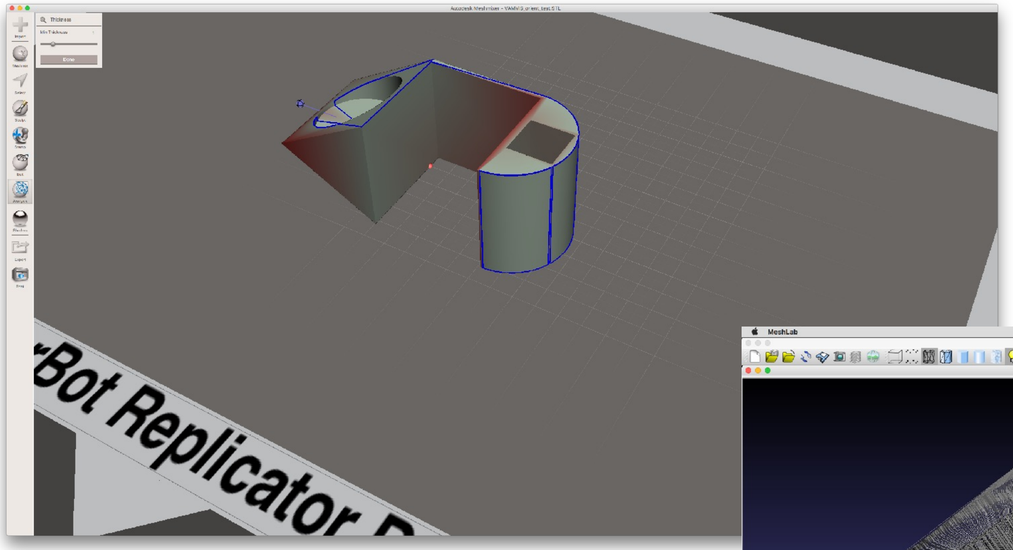


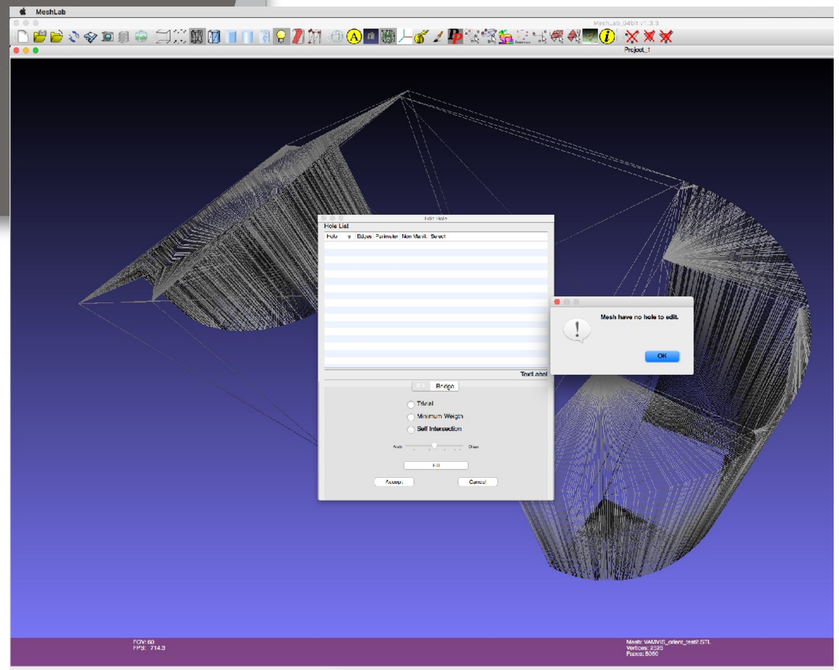
- The **rapid** part of the process
- Users **assume** Additive Manufacturing is the **best** solution.
- Expenses and potential cost savings are **high**.

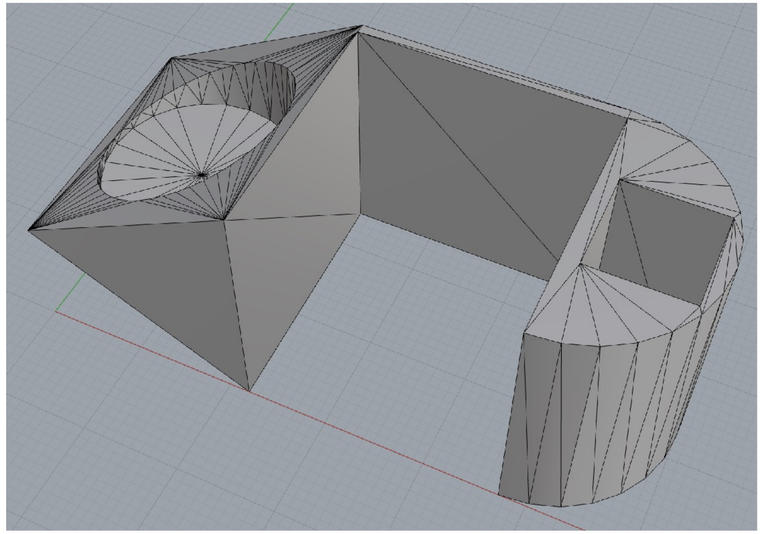
1) Gibson, Ian, David W. Rosen, and Brent Stucker. *Additive manufacturing technologies*. Vol. 238. New York: Springer, 2010.

Near-CAD Model Analyses

- Does not open in 3D printer software?
- Does open but does not print “well”?
- Is there an intermediate step?
- If so: what else can you do as the designer…?



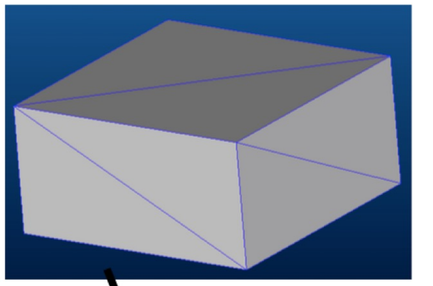


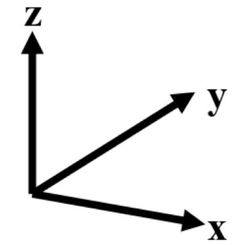


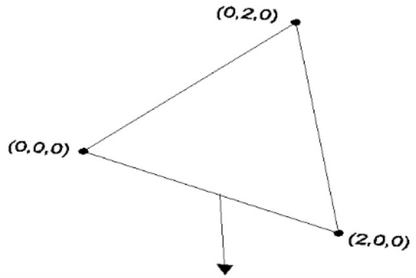
Rules Make STL Files Good

- Calculated Normals
  - Normals calculated with cross-product
  - Normals generated during export and stored with each facet's vertex information
- Vertex to Vertex Rule
  - Every triangle must share exactly two vertices with each adjacent triangle.
  - Every segment must be shared by two and only two triangles

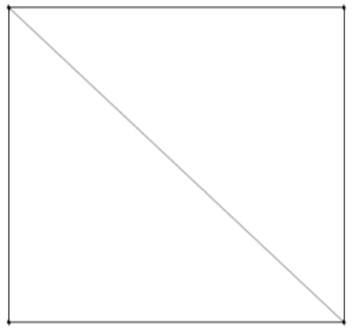
```
solid BOX3
  facet normal 0.000000e+00 0.000000e+00 -1.000000e+00
    outer loop
      vertex 2.000000e+00 0.000000e+00 0.000000e+00
      vertex 0.000000e+00 0.000000e+00 0.000000e+00
      vertex 0.000000e+00 2.000000e+00 0.000000e+00
    endloop
  endfacet
```



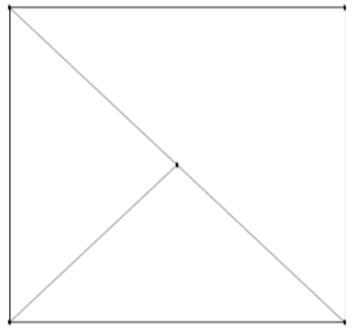




*The facet normal always points to the "outside"



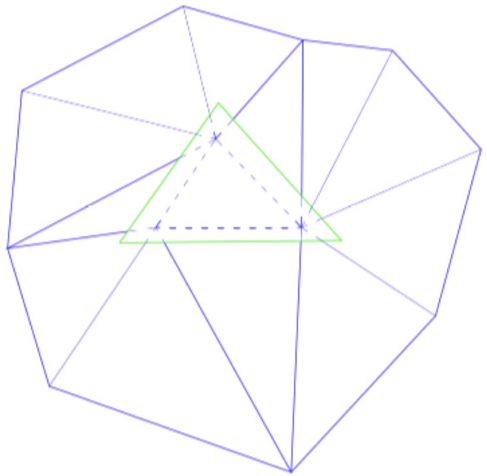
VALID



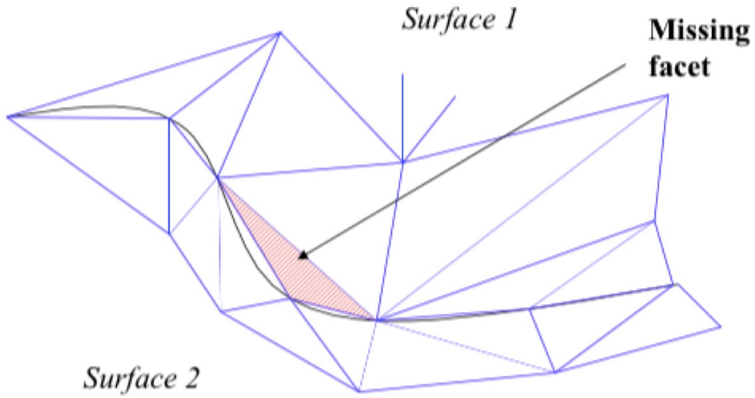
INVALID

STL Tessellation Errors

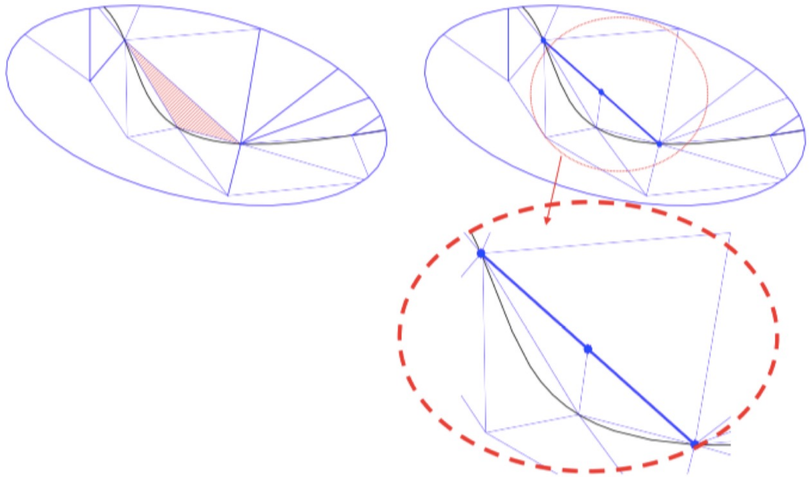
Overlapping Facets



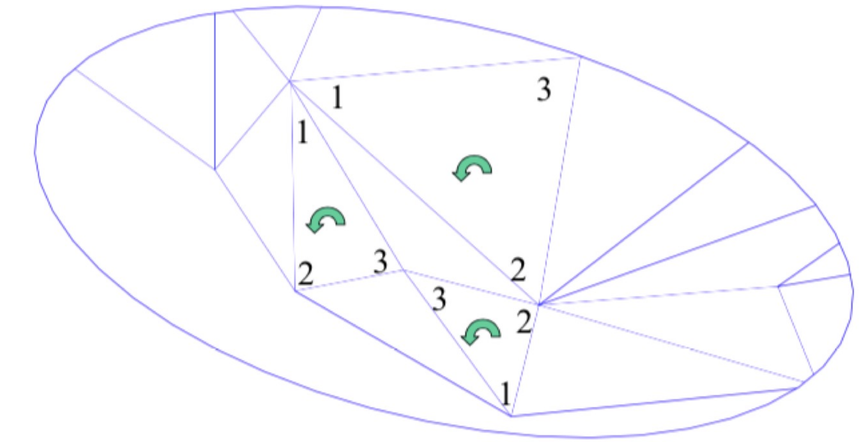
Missing Facets

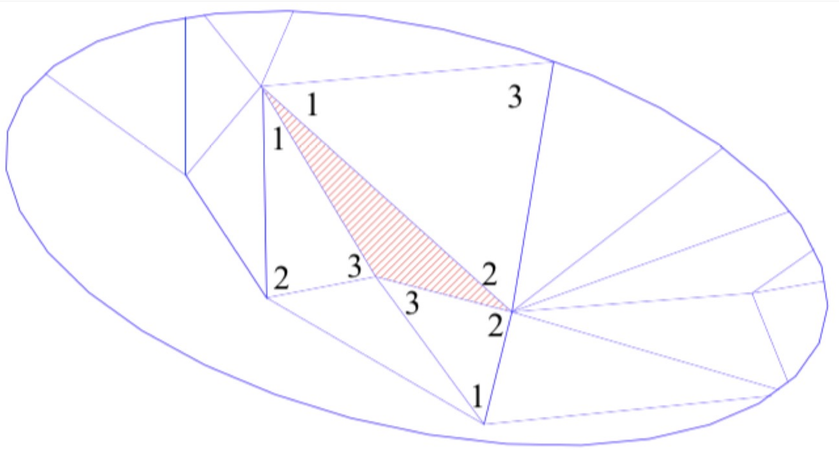


Degenerate Facets

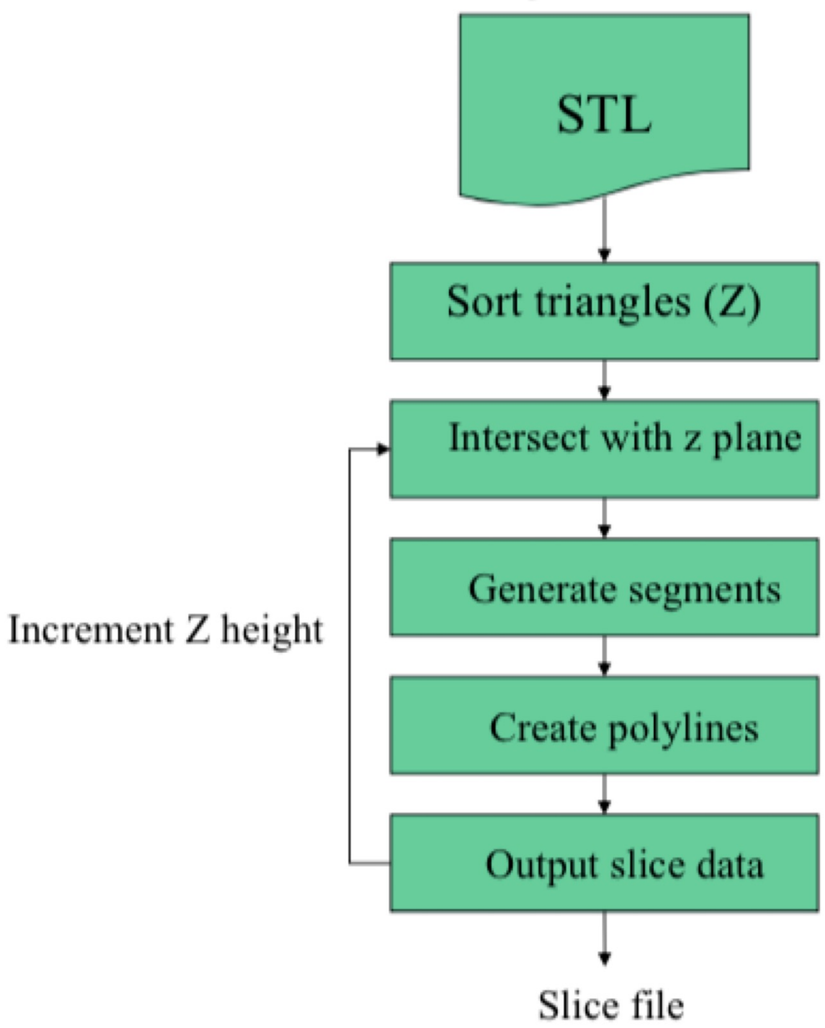


Cannot Slice if not Watertight

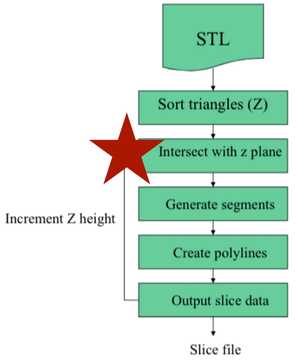




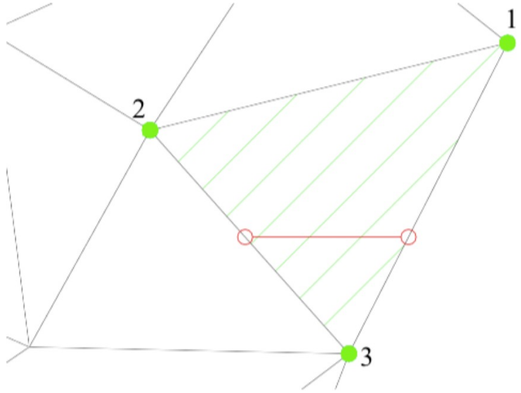
Slicing an STL File



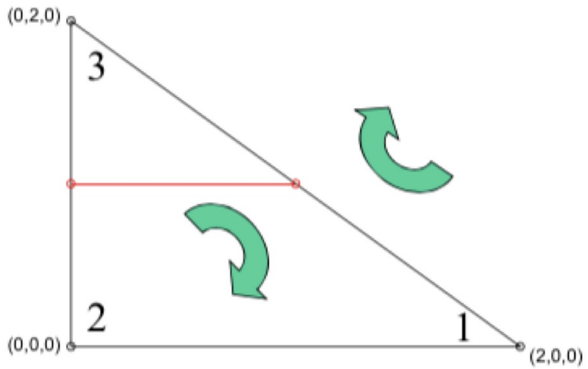
Intersect With Z-Plane



- Every segment belongs to exactly two triangles (vertex to vertex rule)
- Right hand rule…
- STL facet normals always point to the “outside” of the 3D model
- Now we can find the adjacent facet…
- If segment 3-1 exists, then segment 1-3 must exist, otherwise?

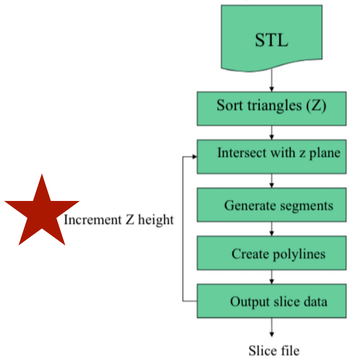



```
solid BOX3
  facet normal 0.000000e+00 0.000000e+00 -1.000000e+00
    outer loop
      vertex 2.000000e+00 0.000000e+00 0.000000e+00
      vertex 0.000000e+00 0.000000e+00 0.000000e+00
      vertex 0.000000e+00 2.000000e+00 0.000000e+00
    endloop
  endfacet
  facet normal -1.000000e+00 0.000000e+00 0.000000e+00
    outer loop
      vertex 0.000000e+00 2.000000e+00 1.000000e+00
      vertex 0.000000e+00 2.000000e+00 0.000000e+00
      vertex 0.000000e+00 0.000000e+00 0.000000e+00
    endloop
  endfacet
  facet normal 0.000000e+00 0.000000e+00 -1.000000e+00
    outer loop
      vertex 2.000000e+00 2.000000e+00 0.000000e+00
      vertex 2.000000e+00 0.000000e+00 0.000000e+00
      vertex 0.000000e+00 2.000000e+00 0.000000e+00
    endloop
  endfacet
  ...
...
...
endsolid BOX3
```

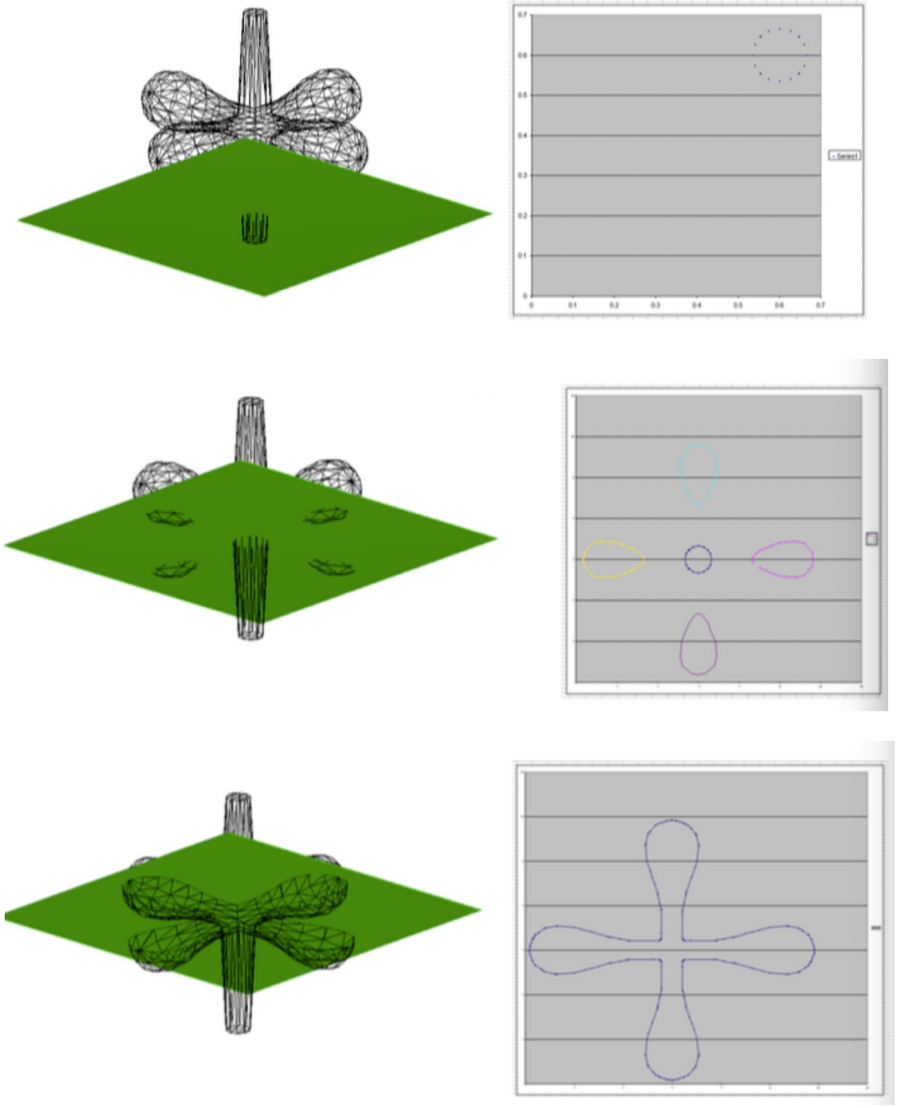


If Segment 3-1 exists, then segment 1-3 must also exist…else?

Increment Z height

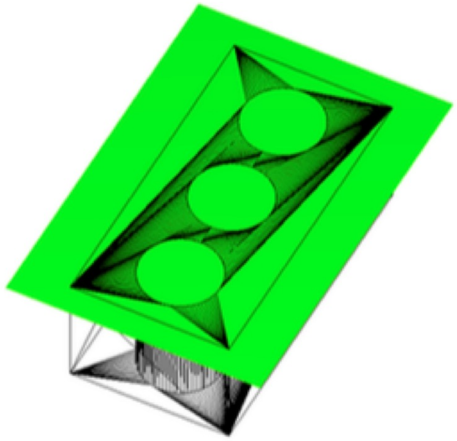


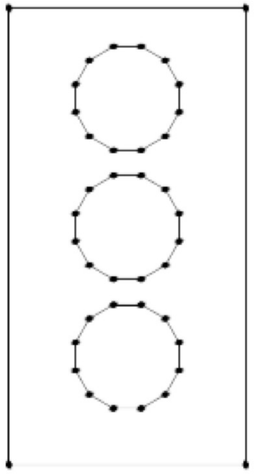
1. Green plane slices through STL
2. Resulting 2D contour Plotted
3. Change Z position
4. Repeat

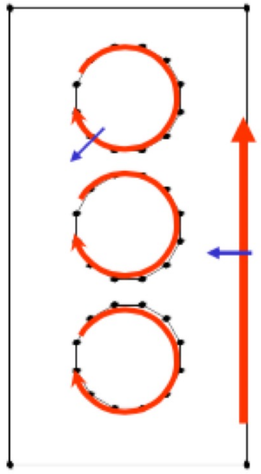


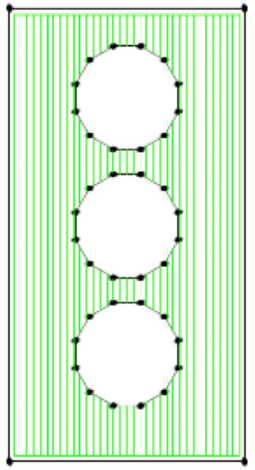
Color In-Between The Slice File Lines

- CCW polygonal chains are exterior chains
- CW polygonal chains are interior chains
- Machine fills in using slice file polygon chain
- Fill based on polygon chain CW or CCW calculation
- “Raster” is the term for how filling occurs





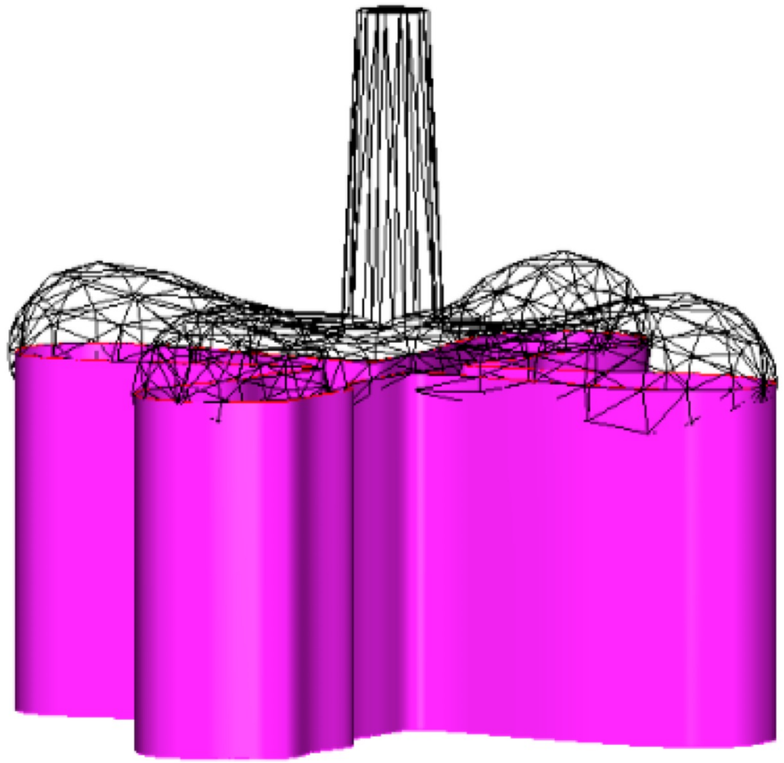




What's Up?

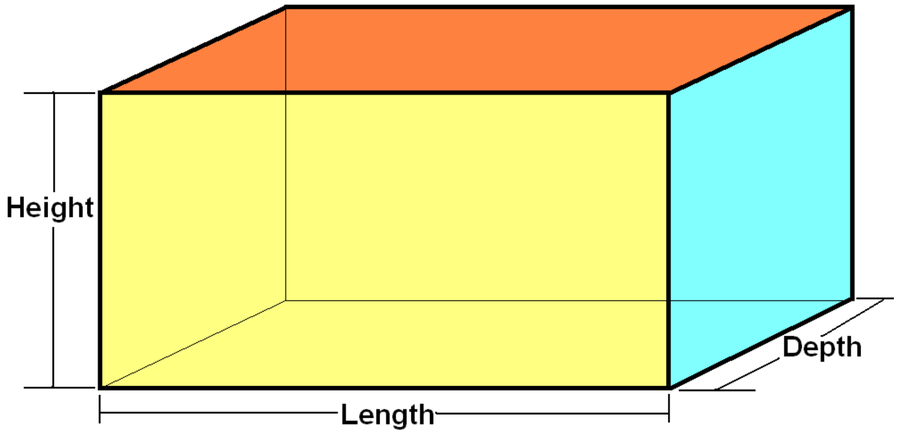
- Once you slice, you defined what's up*
  - Must re-slice the 3D model for any and every orientation change
  - Beneficial if you know how orientation changes
- 3D Models can be sliced from any orientation
  - AM user's "Best" orientation depends on slices and layers
  - Designer's "Best" orientation depends on features/aspects of the design

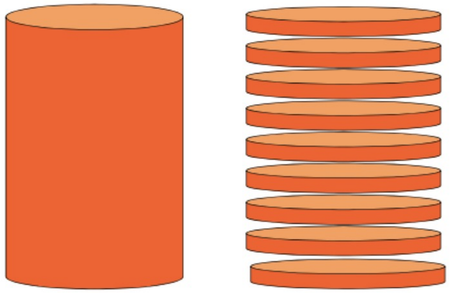
```
facet normal 0.000000e+00 0.000000e+00 -1.000000e+00
  outer loop
    vertex 2.000000e+00 0.000000e+00 0.000000e+00
    vertex 0.000000e+00 0.000000e+00 0.000000e+00
    vertex 0.000000e+00 2.000000e+00 0.000000e+00
  endloop
endfacet
facet normal -1.000000e+00 0.000000e+00 0.000000e+00
  outer loop
    vertex 0.000000e+00 2.000000e+00 1.000000e+00
    vertex 0.000000e+00 2.000000e+00 0.000000e+00
    vertex 0.000000e+00 0.000000e+00 0.000000e+00
  endloop
endfacet
facet normal 0.000000e+00 0.000000e+00 -1.000000e+00
  outer loop
    vertex 2.000000e+00 2.000000e+00 0.000000e+00
    vertex 2.000000e+00 0.000000e+00 0.000000e+00
    vertex 0.000000e+00 2.000000e+00 0.000000e+00
  endloop
endfacet
...
```

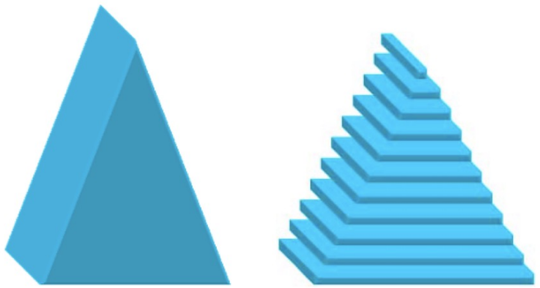


Activity #1

- Sketch the cylinder and triangular extruder shape
- Sketch hyperrectangle shapes inside the cylinder and extruded triangle shapes

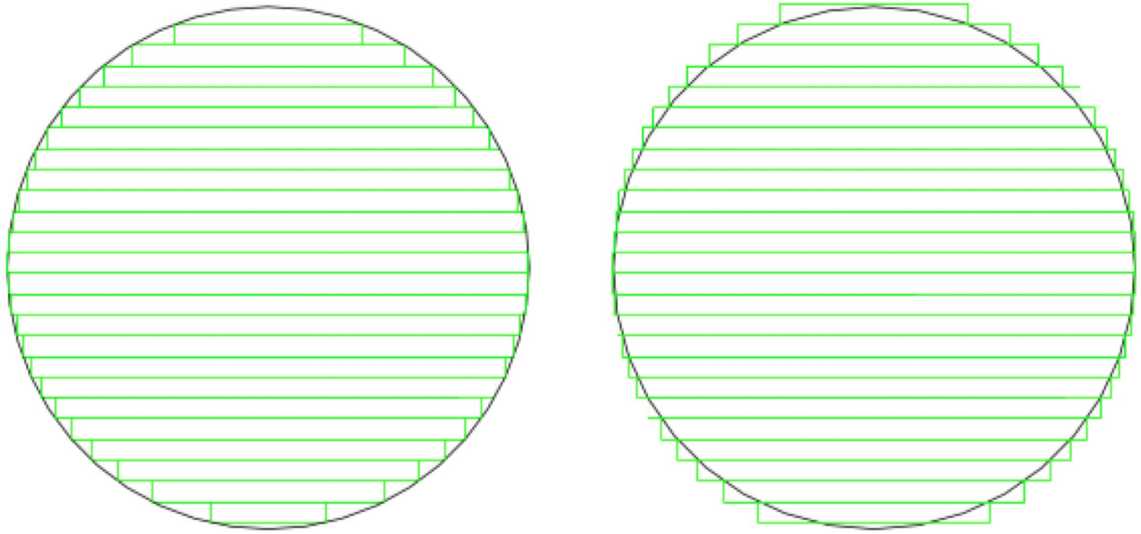




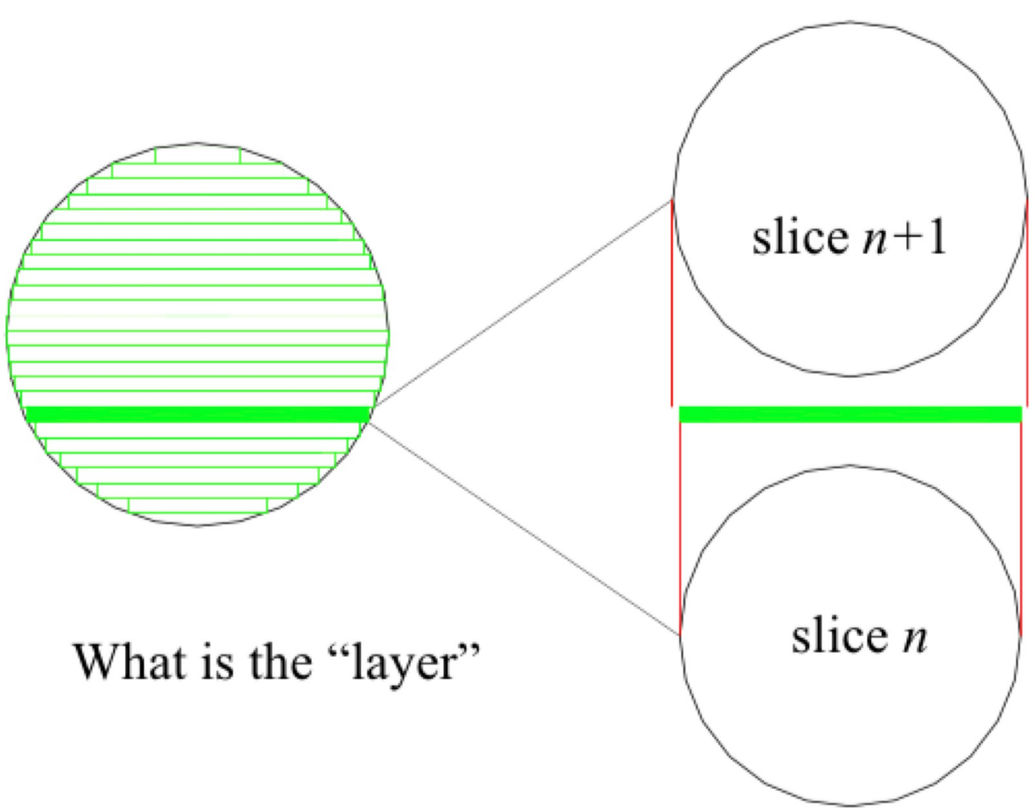


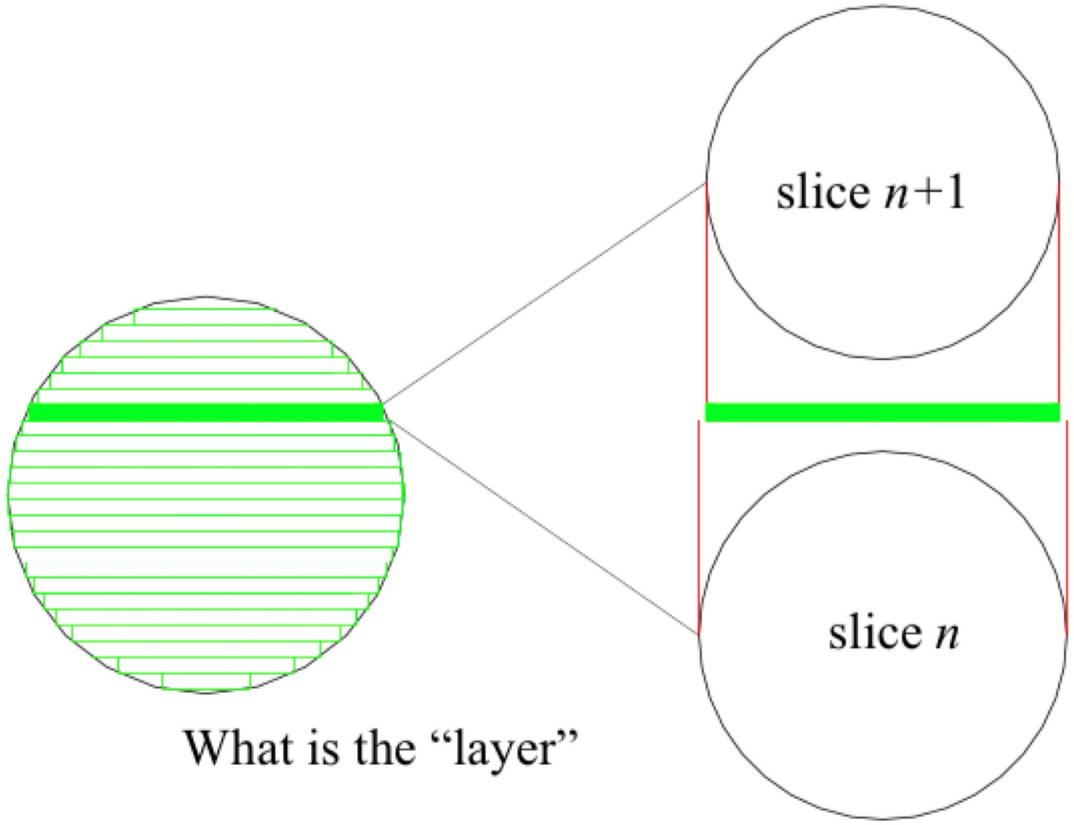
From Slices to Layers

- Slices and layers are not the same thing
- Slice is a 2D cross-section of the CAD (STL) model
- Layer is a 2.5D thin slab of material between two slices
- Slice exists at the top and bottom of a layer…
- Important question then becomes: which slice corresponding to a layer (top or bottom)
- The same slices can create different layers

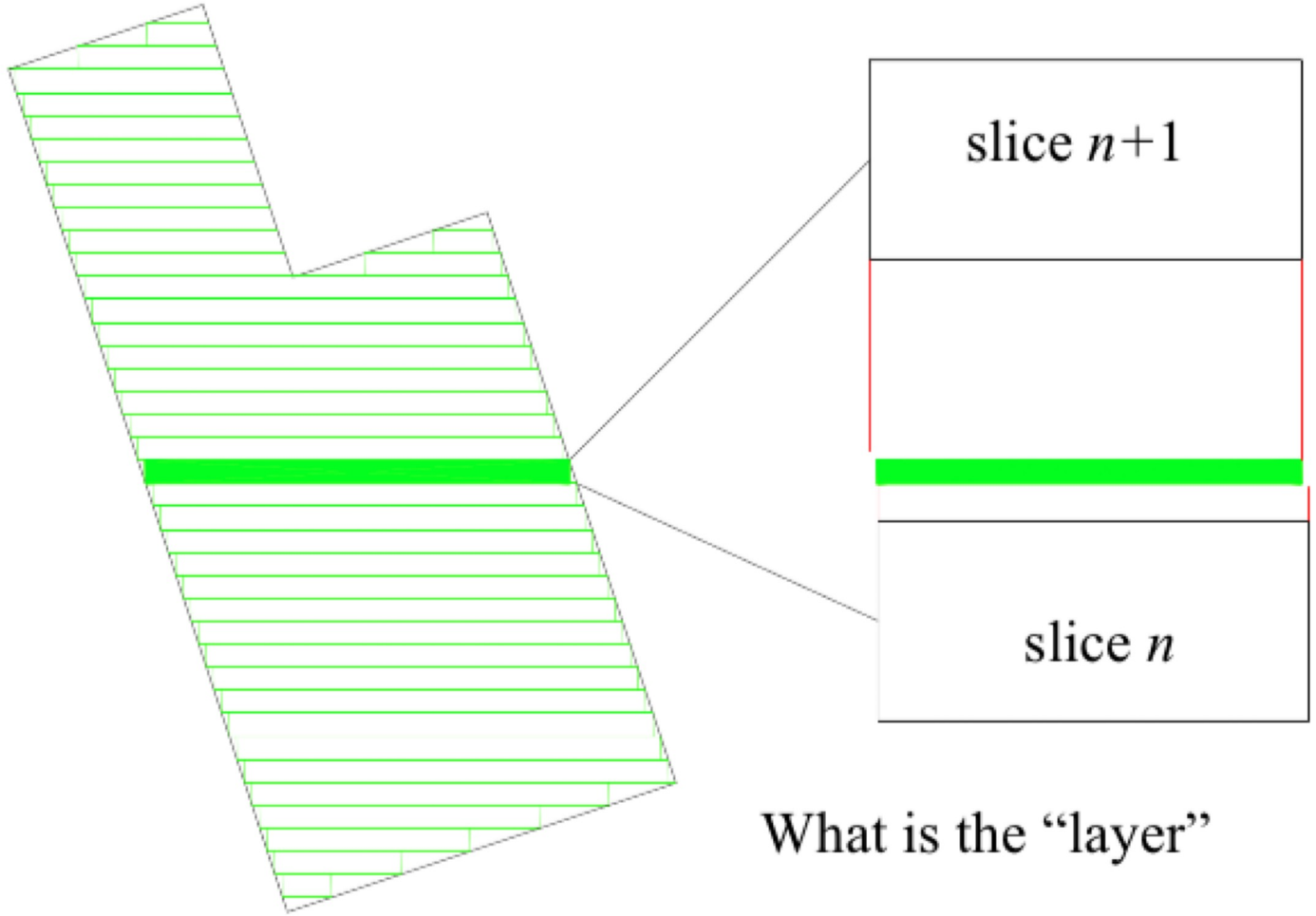


Over and Under Approximation Error





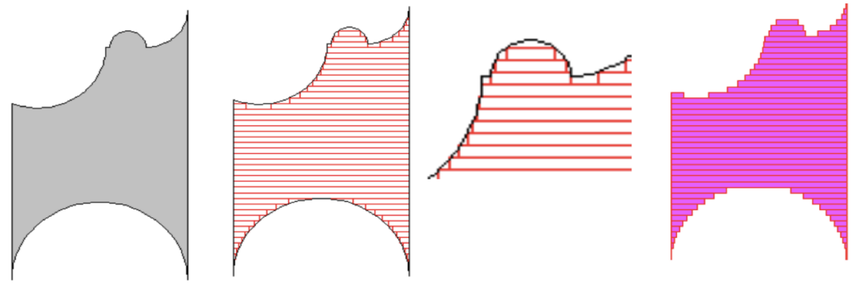
Different Geometry, Similar Slice/Layer Problems

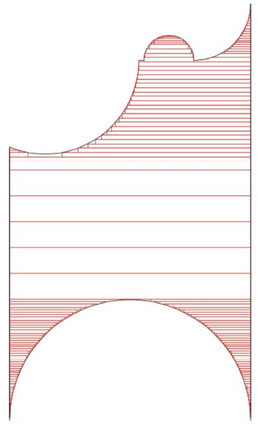


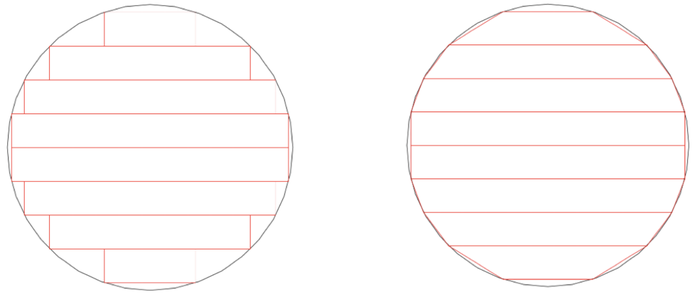
What is the “layer”

Layer Generation Techniques

- Most layers are 2.5 D objects (x-y contour and some constant depth)
- Creating each layer is significantly easier than creating 3D freeform shape
- Some systems can perform “Adaptive Slicing” to change the thickness of a layer
- Layers are zeroth order approximations of 3D models
- Some of the best systems can perform First-order ruled approximations of the shape







Zeroth-order

First-order

Layers vs. 3D Shapes

- Isometric views of the two shapes on the right highlight the importance of orienting a part for 3D printing
- Which part will be “near net shape”?
- (Hint: layer thickness is almost always larger than X-Y positional tolerance)

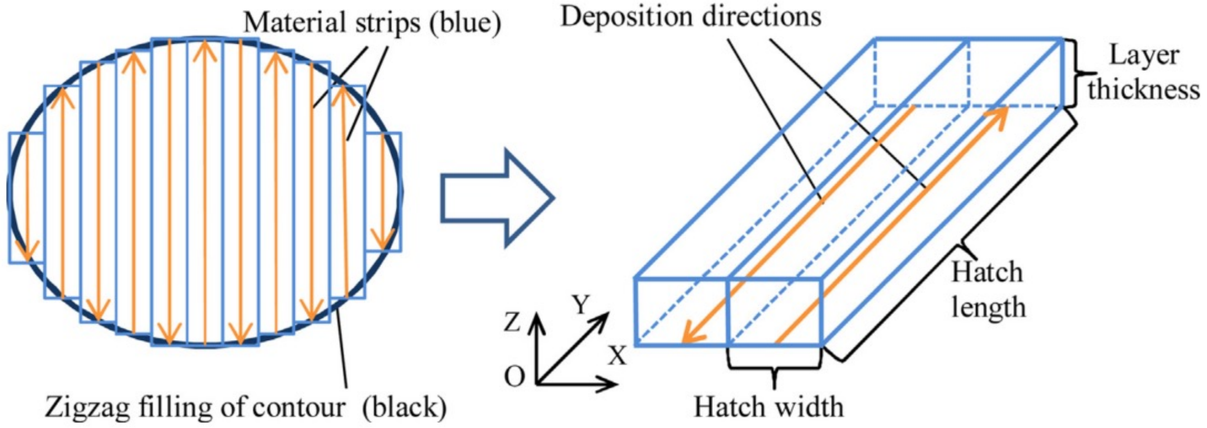
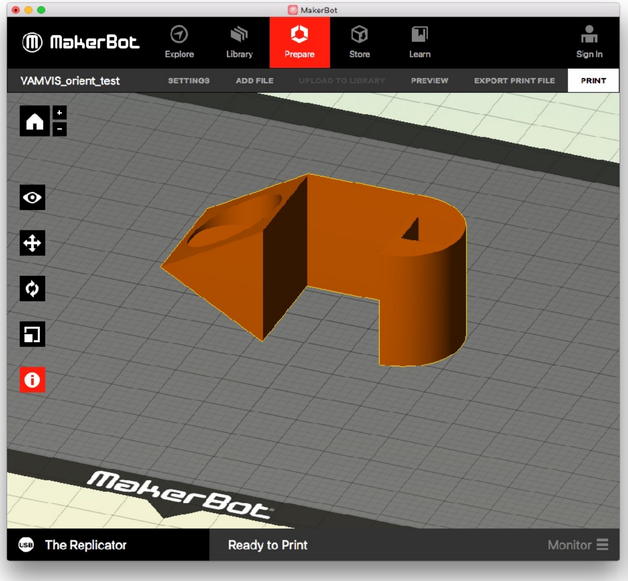
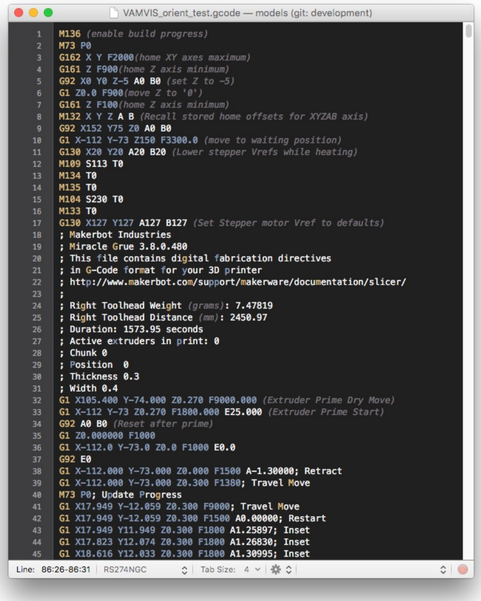


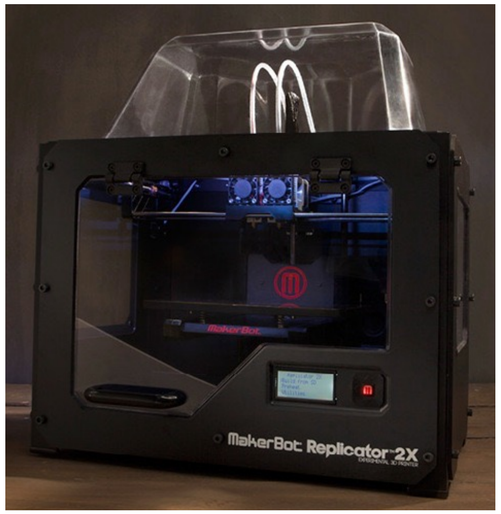
Fig. 10. Cuboid dexel-based simulation for vector-based MMLM process.

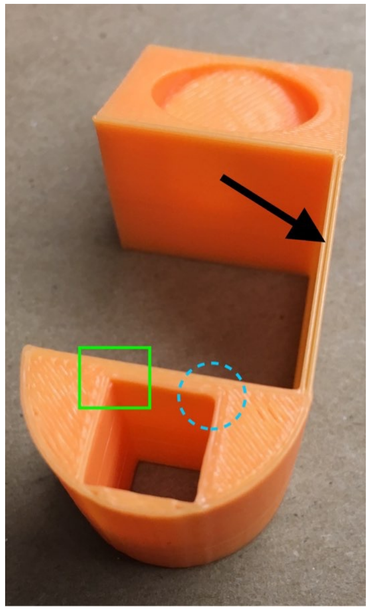
Deep Dive Take-Away

- “Better methods are needed that enable users to explore trade-offs (compromises) among build goals and to find machine settings that enable them to best meet their goals.” [Gibson, 2010]









What Caused Printed Part Errors?

Activity #2: 3D print training readiness test

- One-on-one training with Alex + software training with Chloe and Spencer
- Download a small/simple part (less than 2 hours to print)
- Choose a printer and material (you'll load the filament and Alex will show you the required steps)
- Use the DABL PCs to prepare your part for printing (extra instruction will be provided if you choose Prusa XL, Ultimaker UM3, MakerBot(s), Creality K1)
- Send your print job to an Octoprint server (Cura plugin or manual upload), Prusalink, Creality connect, Ultimaker digital factory

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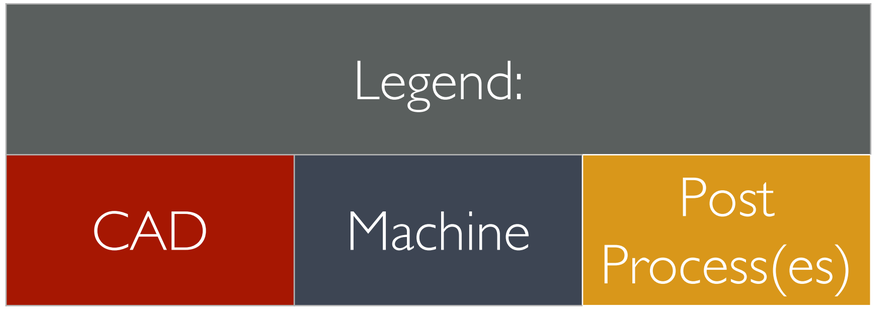
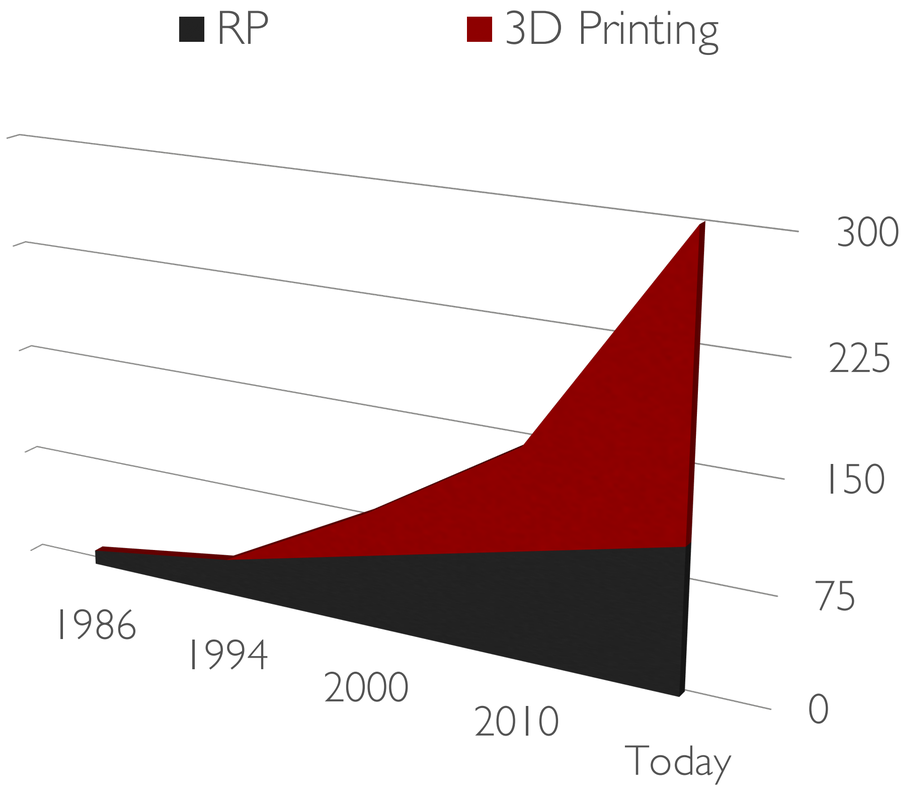


- Process iterations are rarely performed.
- Software tools require previous user experience to prevent print failures before printing.
- Potential cost savings are very high.

1) Gibson, Ian, David W. Rosen, and Brent Stucker. *Additive manufacturing technologies*. Vol. 238. New York: Springer, 2010.

“Desktop 3D Printing”: RP and DDM

“Desktop” used as term for systems < $5,000
Used for same reasons Rapid Prototyping (RP) machines were used and for Direct Digital Manufacturing (DDM) making the final part
Fundamental manufacturing processes have not changed



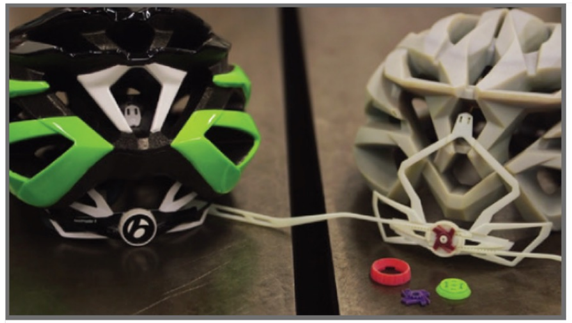
3D Printing Myths - Expert List

1. AM is a low-labor content, “pushbutton” technology.
2. Additive manufacturing is fast.
3. AM is greener than conventional manufacturing.
4. AM systems can produce anything.
5. With AM, it’s just as efficient to build one part at a time as it is to build many.
6. AM systems and materials are inexpensive.
7. AM will replace conventional manufacturing.
8. AM can print guns.
9. Every household will own a 3D printer.

Wohlers, Terry, and Tim Caffrey. "Additive manufacturing: going mainstream." Manufacturing Eng 151.6 (2013): 67-73.

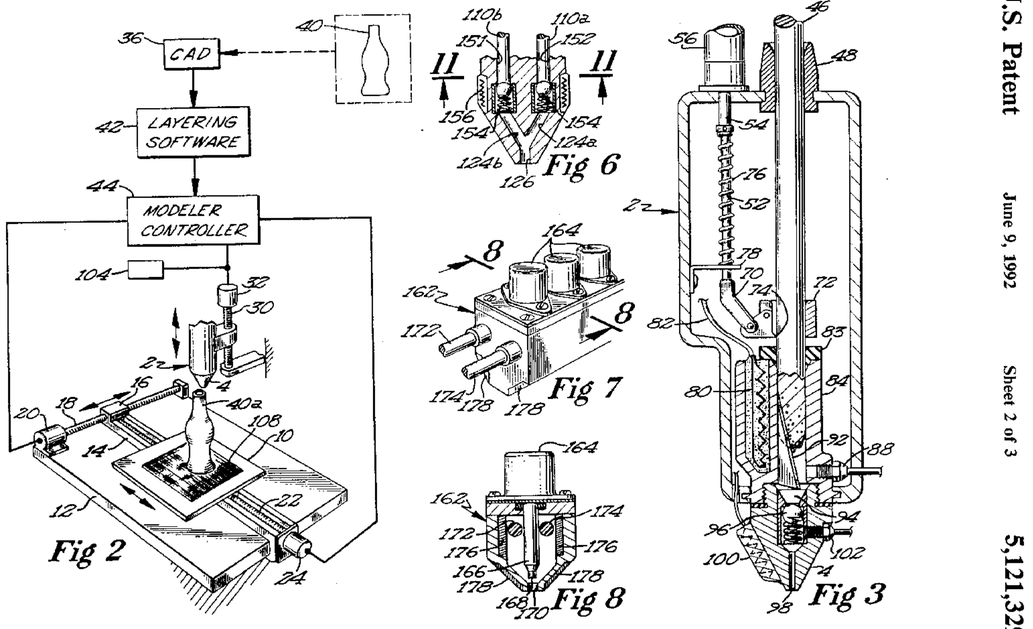
RP and 3D Printed Part Examples

- Mass Customization
- Truly “Rapid” Prototyping
- One of One
- “Mass Production”



Trek’s prototype development department uses multi-material 3D printing to achieve final-product realism.

Old School Ideas vs. New School Challenges



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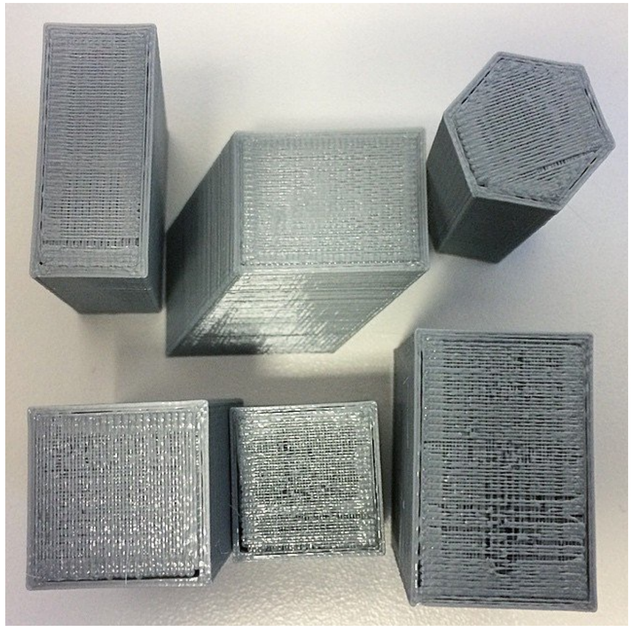
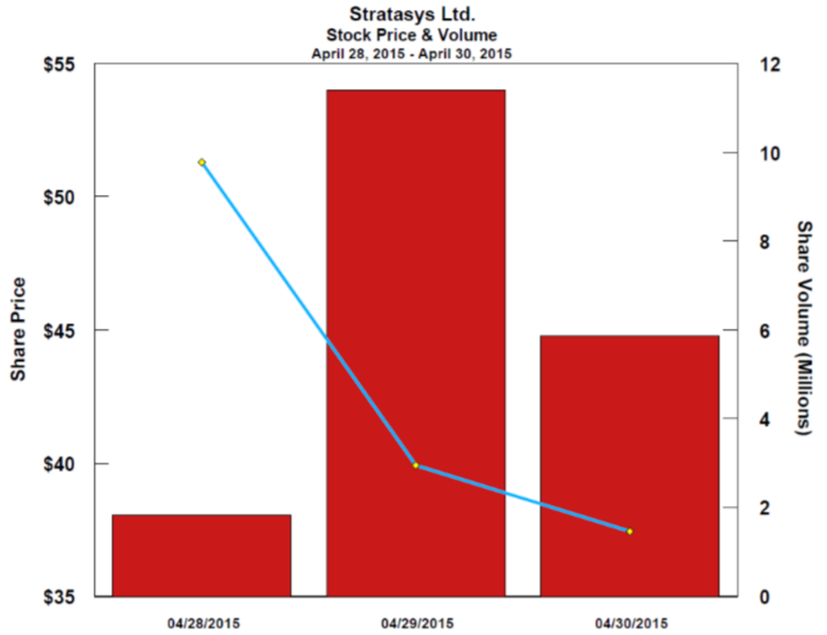
222. The decline in the Company's stock price by approximately 27% on April 29 and April 30, 2015, was the direct result of the nature and extent of the revelations made to the market regarding the severity of the financial and operational issues facing Stratasys and its MakerBot unit that had been concealed or misrepresented by Defendants.

Old School Ideas vs. New School Challenges





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The Next Industrial Revolution?

3D printing has the potential to revolutionize the way we make almost everything. The next industrial revolution in manufacturing will happen in America. We can get that done.

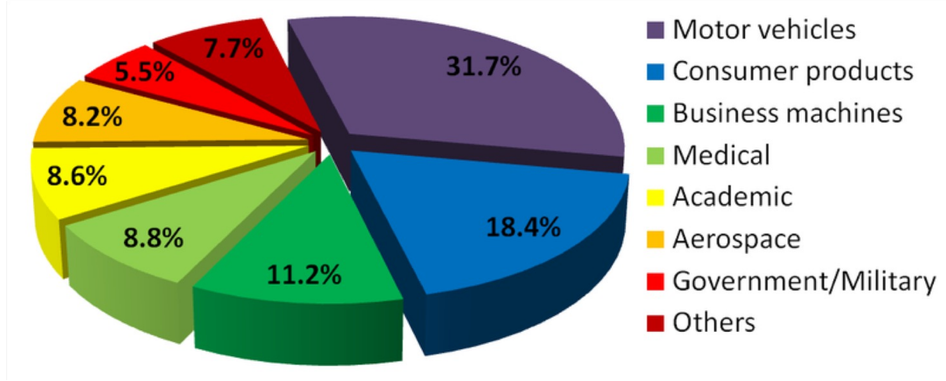
BARACK OBAMA

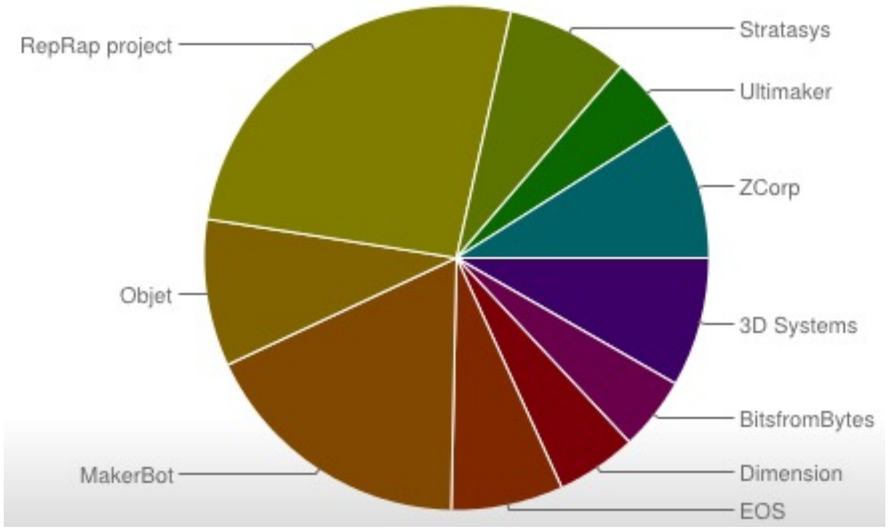
STEM EDUCATION COALITION

Science Technology Engineering Mathematics

3 Create an Innovative 3D Printing Curriculum

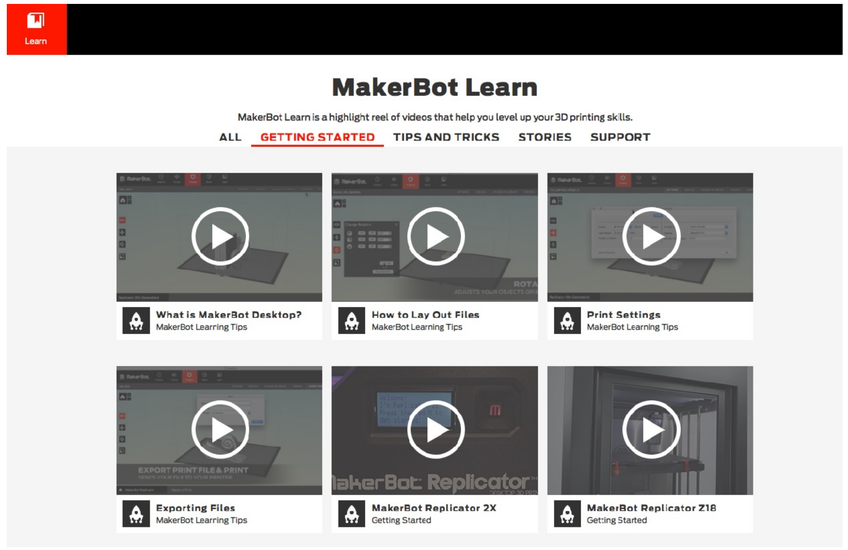
MakerBot Academy is working on a curriculum to help American teachers and schools integrate 3D printing into their lesson plans. We'll be sure to have more initiatives and Thingiverse design challenges in the future and can hardly wait to share them with you.





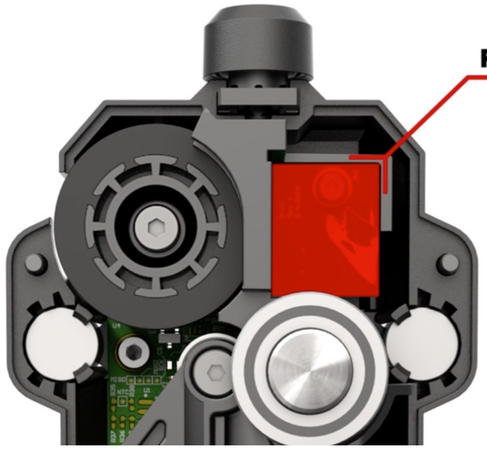
3D Printer Training

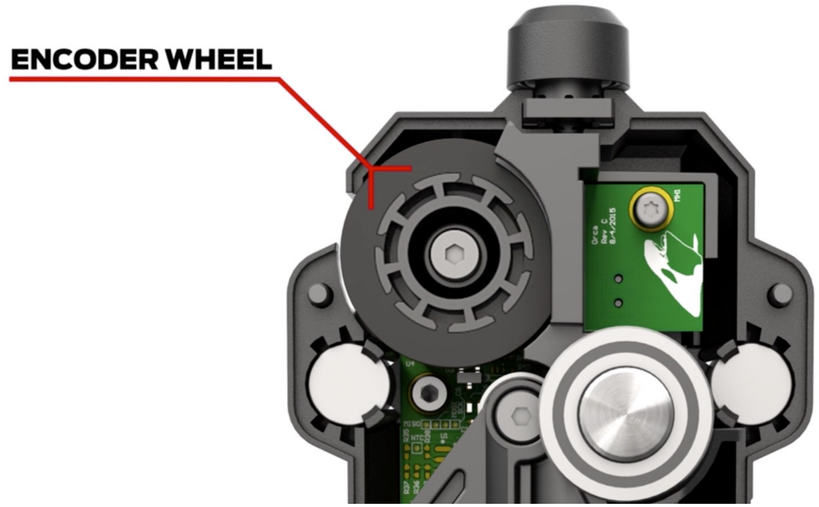
- Training Modes (Example: MakerBot)
  - Innovation Center
  - Webinars
  - Video Tutorials
- Which part is the best one to use for Training in any Mode?
- Which material is the best one to use for Training in any Mode?

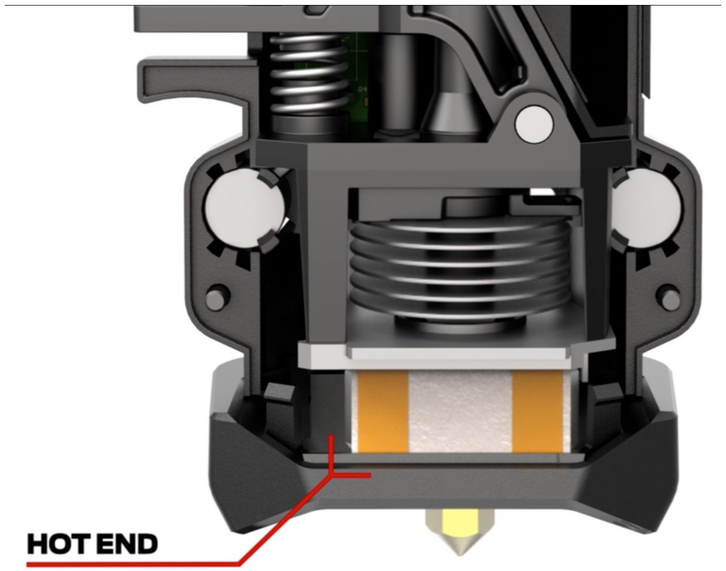


Who’s Smarter? You or the Extruder?

- How can you test if there’s filament present in an extruder?
- Can an encoder test if filament is going through the nozzle?
- What temperature(s) do you want the hot end of a FFF machine to be exposed to?







Prototype Testing, Production, or Quality Assurance?

- Prototype of a Rapid Prototyping machine
- Actual Engineering of a machine component that makes things
- Lots of very controlled testing of 3D printing
- #hours * #prints = 3D printer or “3D copier”?