Additive Manufacturing Technology and Trends
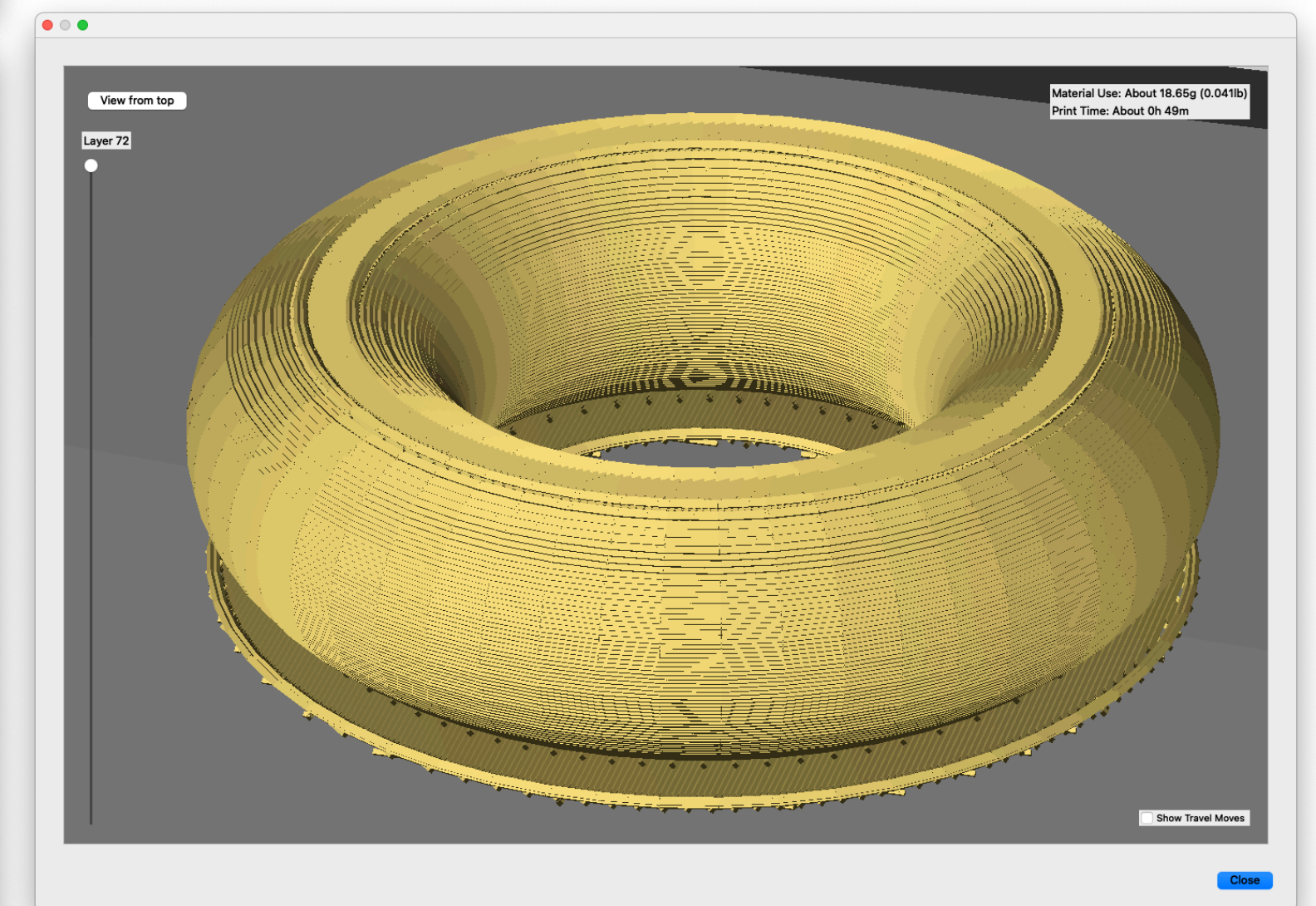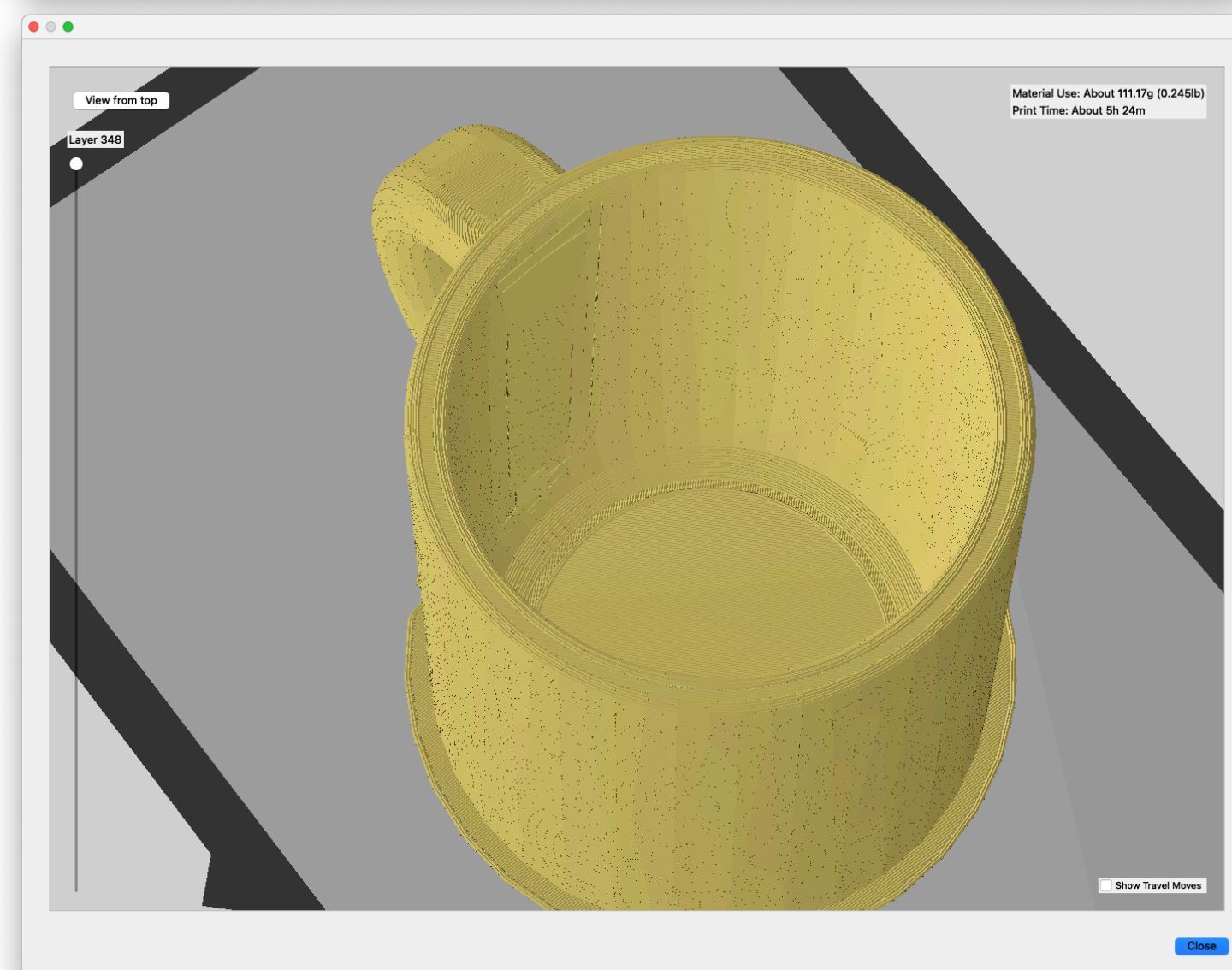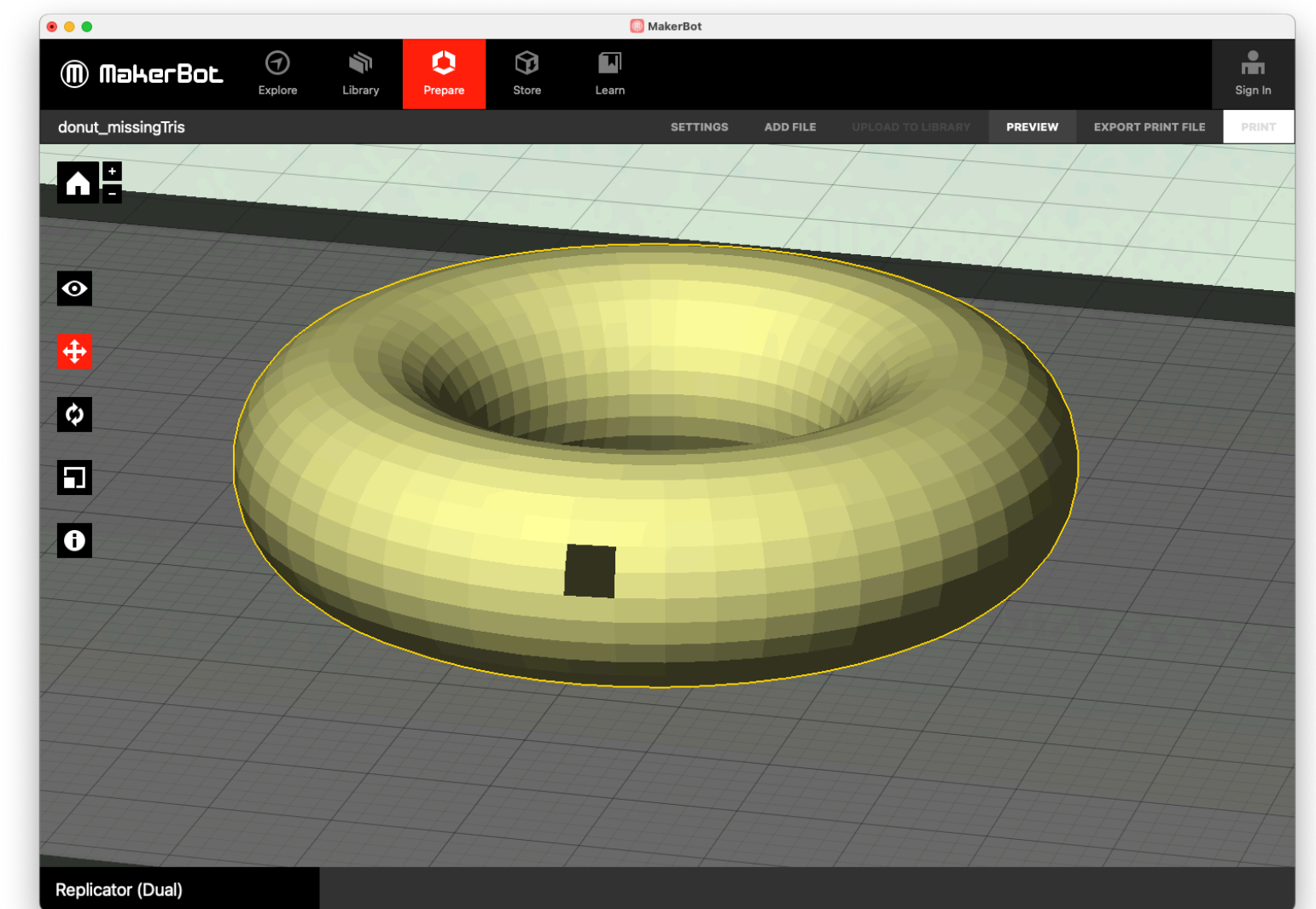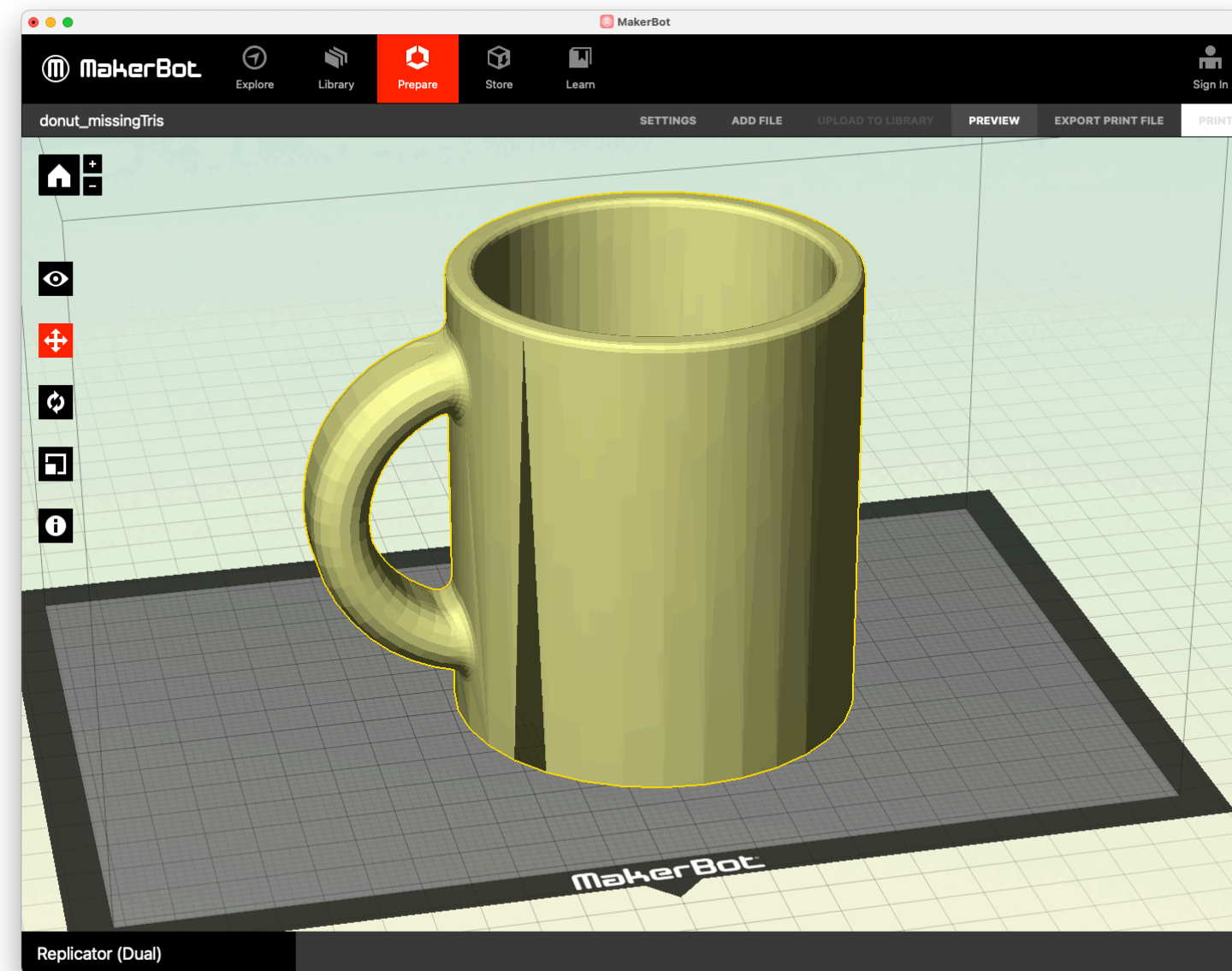
MCA Session Topic: CAD to CAM

6/26/22

Instructors:
1. Alex Raymond Renner: arenner@iastate.edu
2. Michael Holm: mdholm@iastate.edu

Session 1 In-Class Activity Discussion

- Open the mug or donut in PrusaSlicer or Cura (if you haven't already done so)

- Did we get the same result in all software applications?

- Why does the missing face cause issues?

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

Legend:

| CAD	Machine	Post Process(es)
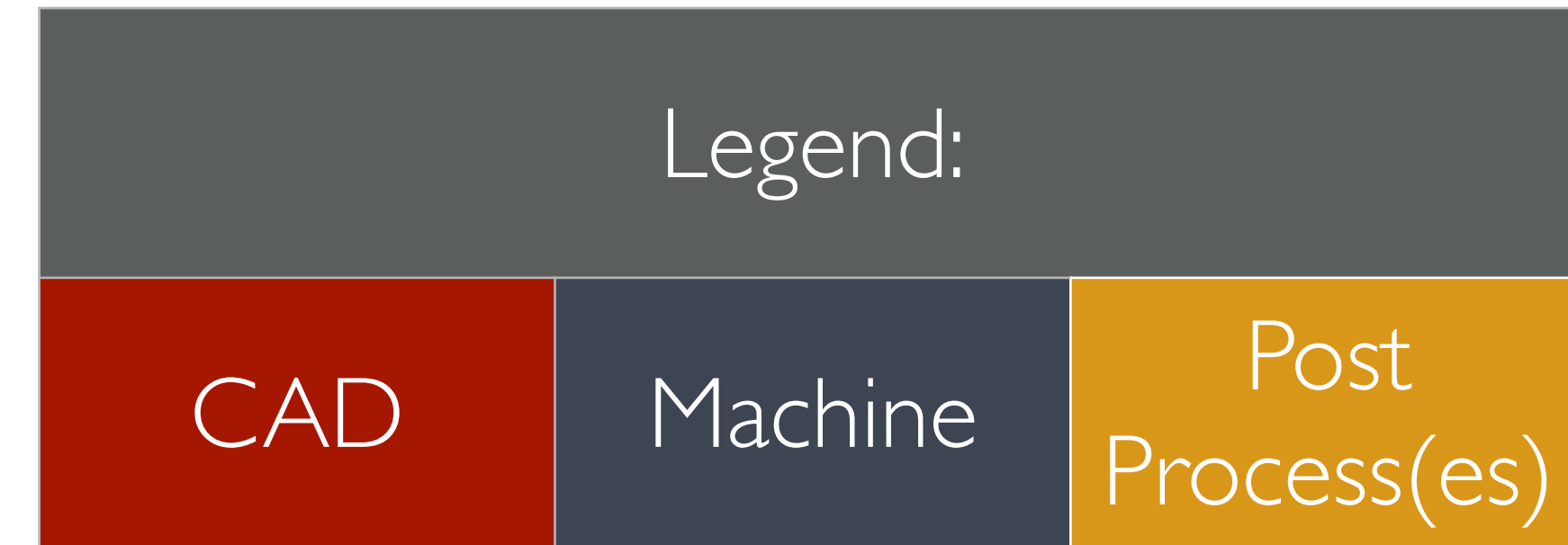
- The **rapid** part of the process
- Users **assume** Additive Manufacturing is the **best** solution.
- Expenses and potential cost savings are **high**.

IOWA STATE UNIVERSITY
Virtual Reality Applications Center

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

Transition from CAD to Machine

- Often involves two people, causing potential issues:

  - Designer's intent may conflict with Additive Manufacturing (AM) requirements

  - AM Machine operator often does not know designer intent

- *"AM language"* barriers

  - Lack of verbal communication between two people quality is not a function of quantity

  - Digital data elements, transfer method(s), and unique accept/reject criteria

CAD to CAM

- Iterative Process

- Consult 3D printer operator as early as possible

- Not just designing to meet customer requirements

  - Non-manifold geometry

  - 3D Printer considerations (how good can the machine make it)

  -
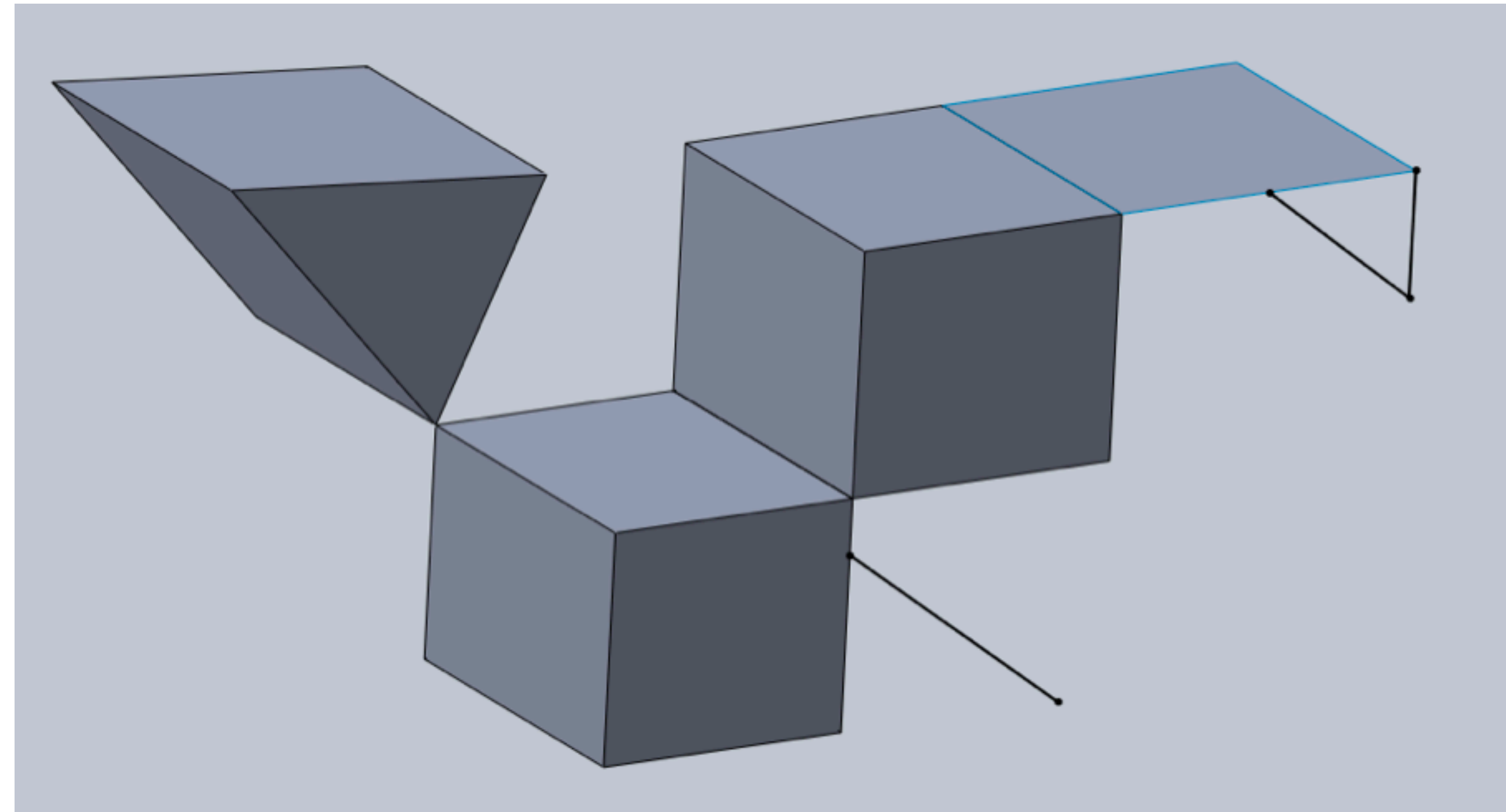
Designer to AM User Discussion

Designer	AM User
"Is my STL ok?"	"I'm sure your design is great!"
"No, I mean is it going to print?"	"That's hard to say"
"WHAT! I was told you were the expert?"	"Well I have lots of experience, just not with your design."
"AHAH, so you DON'T like my design, I knew it!!!"	"[*mumbling*] apparently I need a PhD in Engineering and be a magician"

MCA Session 1 Activity Review

- Good converters use <u>BREP</u> surface connections when converting to STL.

- Once exported to STL can you go back to "perfect CAD"?

- Michael: "explain why STL to CAD is not possible in a blog post - and you'll be asked to help on doing the impossible conversion anyway".
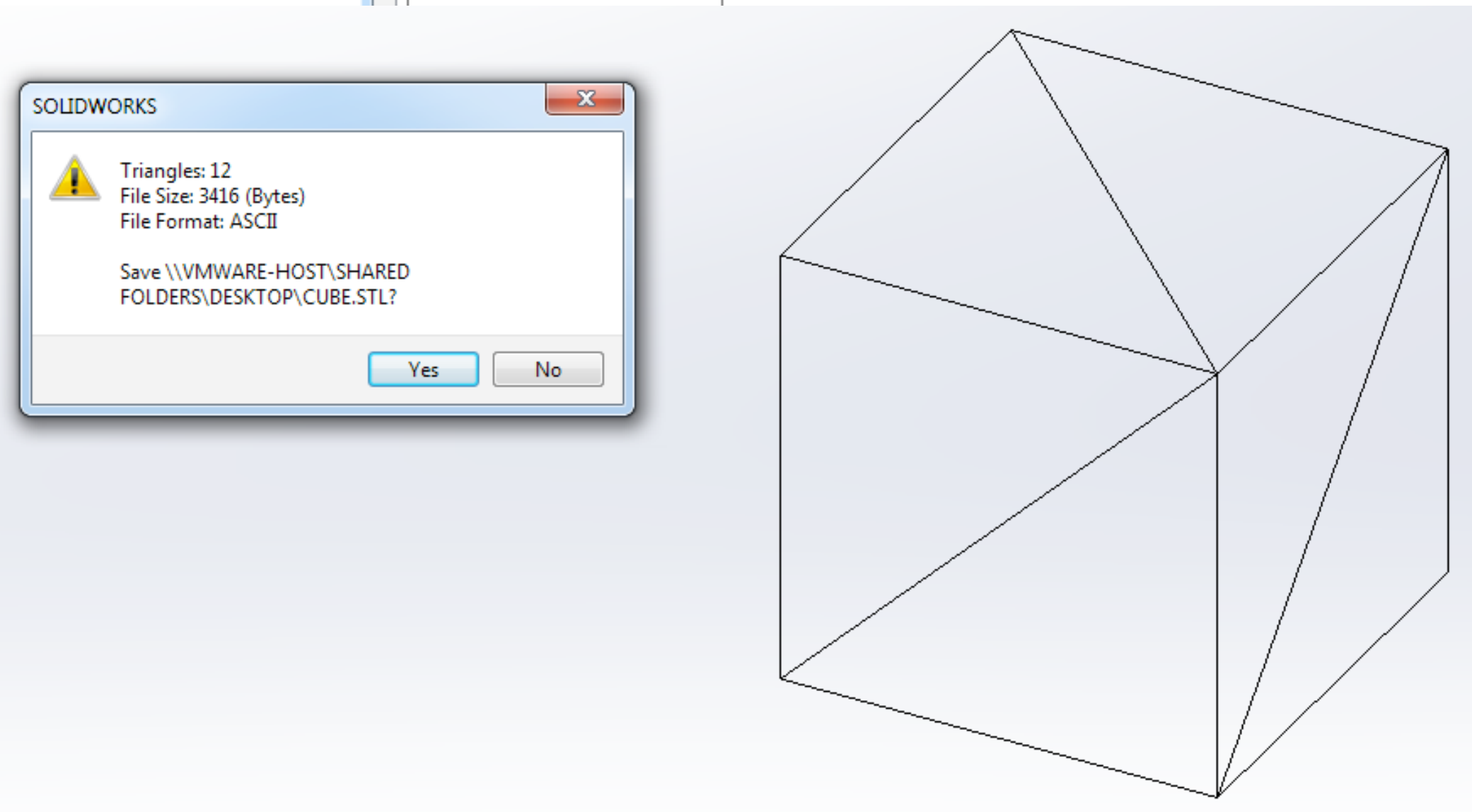
CAD → BREP Converter → STL

??? (STL → CAD)
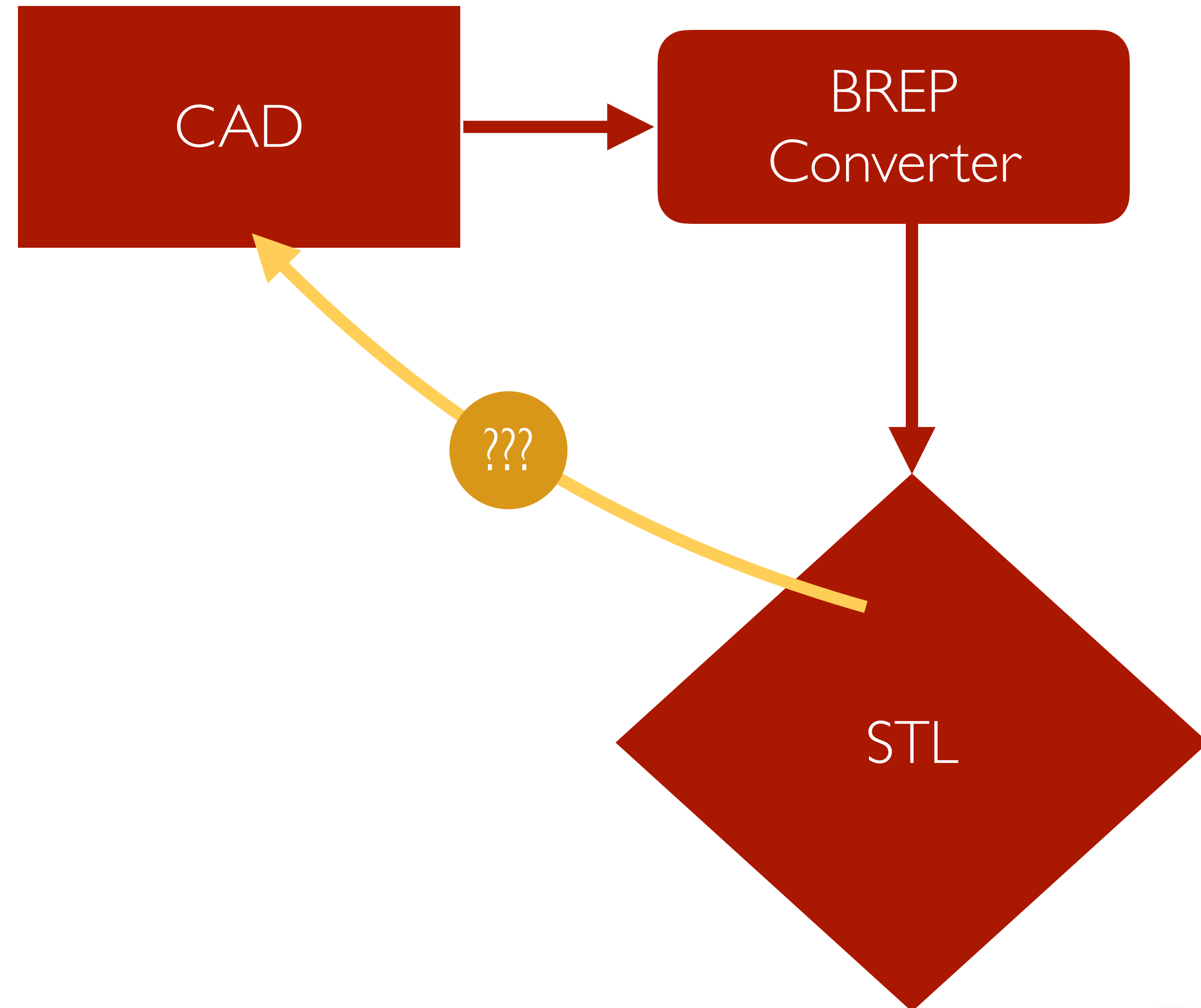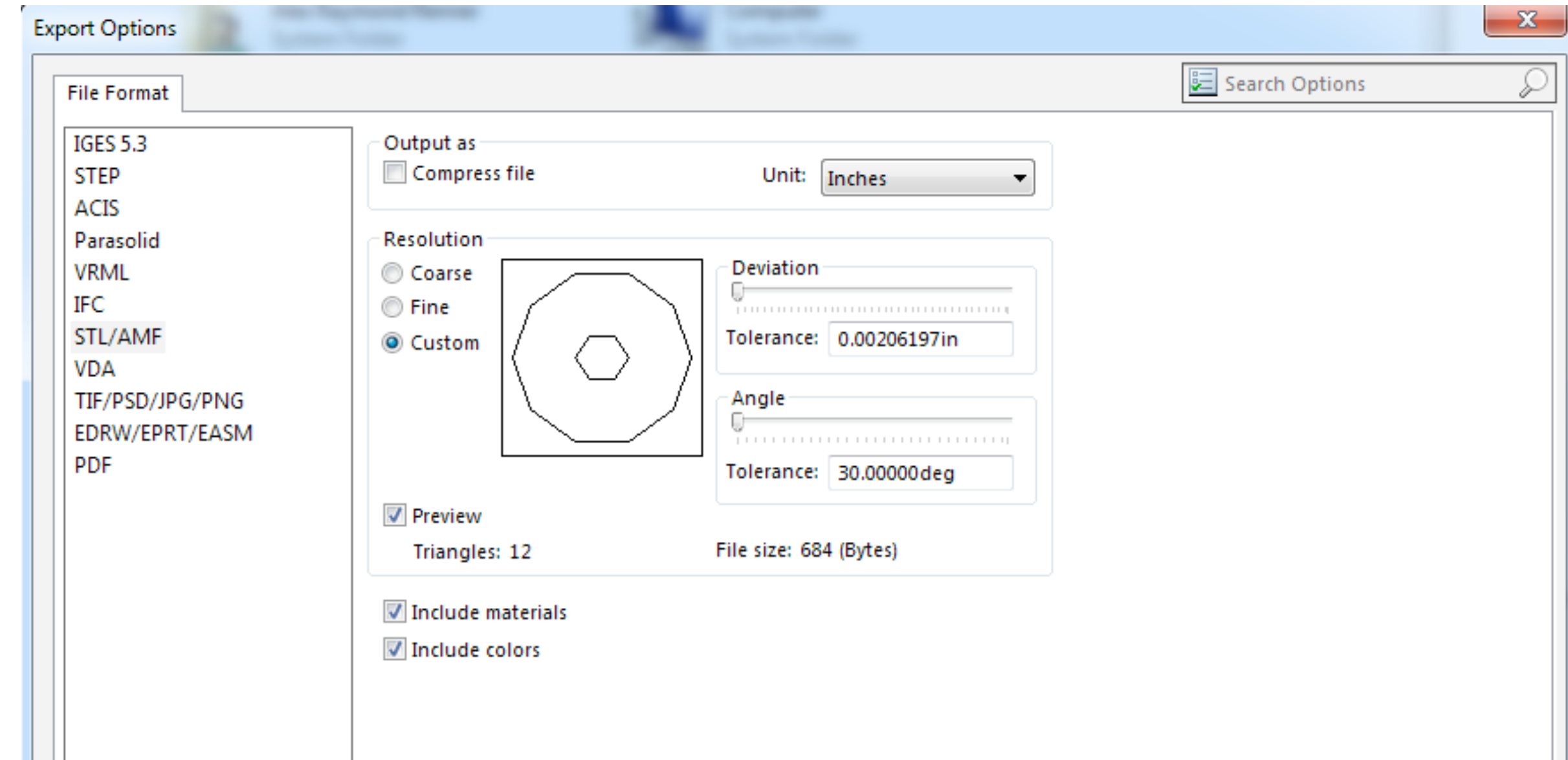
CAD Export Options

- STL/AMF

  - Mesh 3D model format ISO/ASTM 52900

  - What's do they have in common?

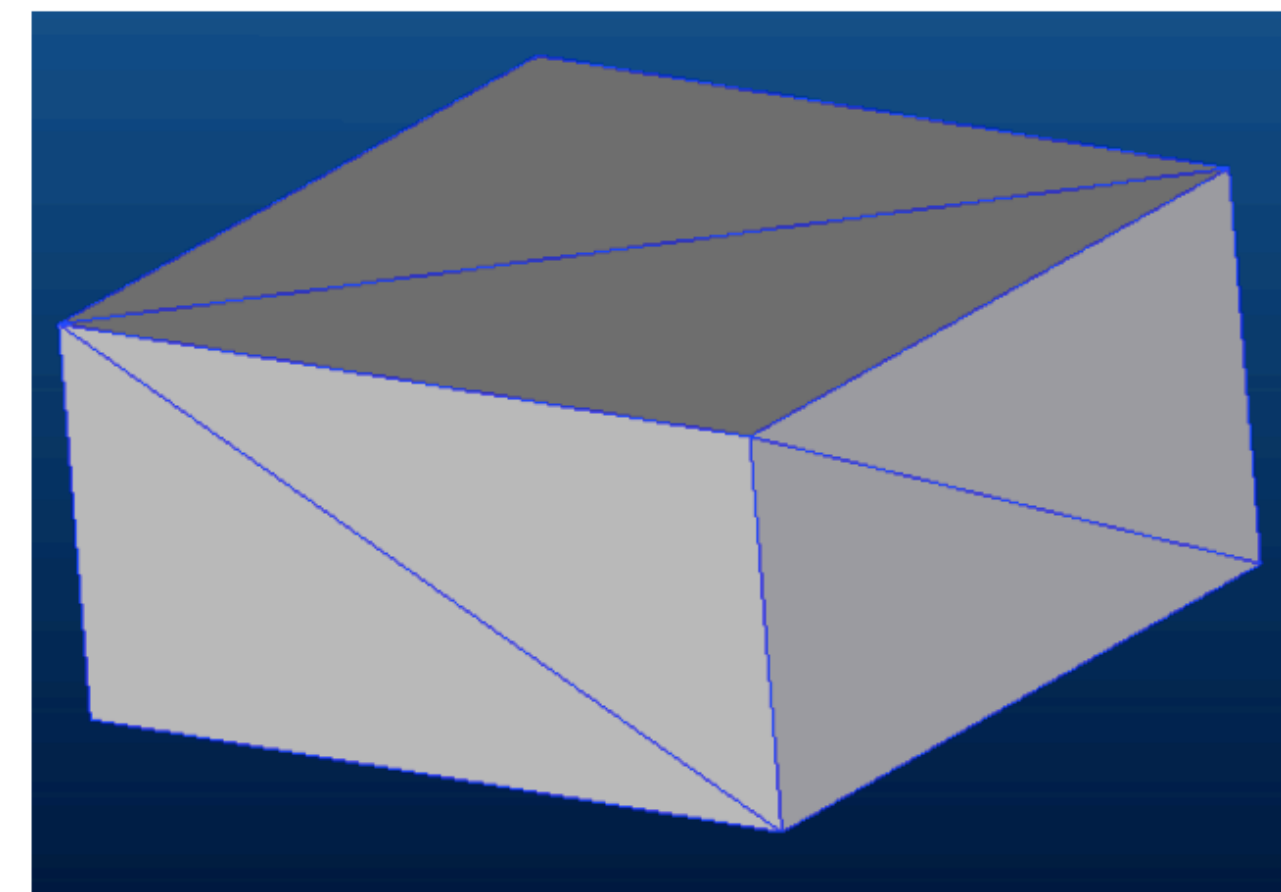- Export Resolution = CAD Approximation Tolerance

  - Chordal Deviation?
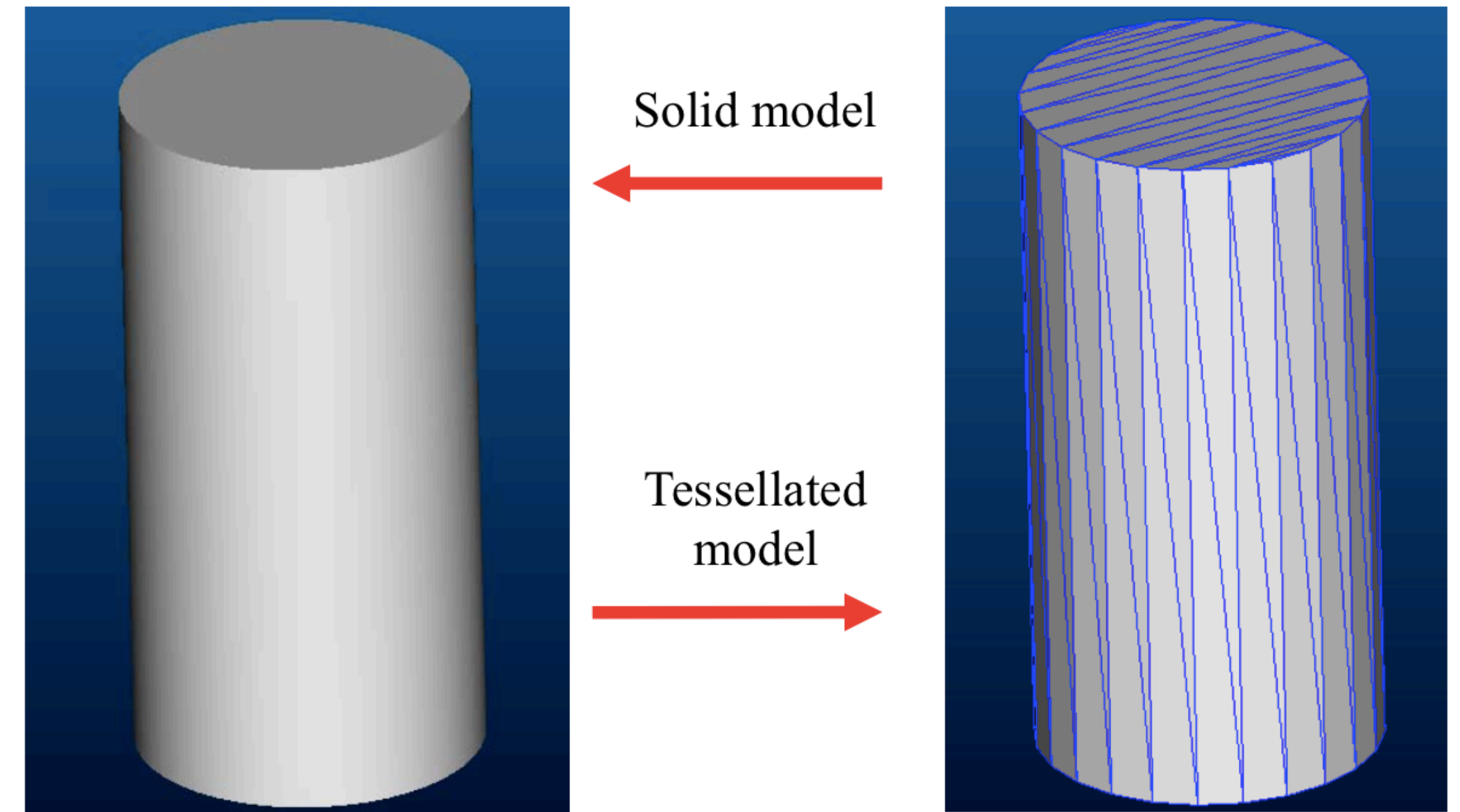
  - Angle Tolerance?

IOWA STATE UNIVERSITY
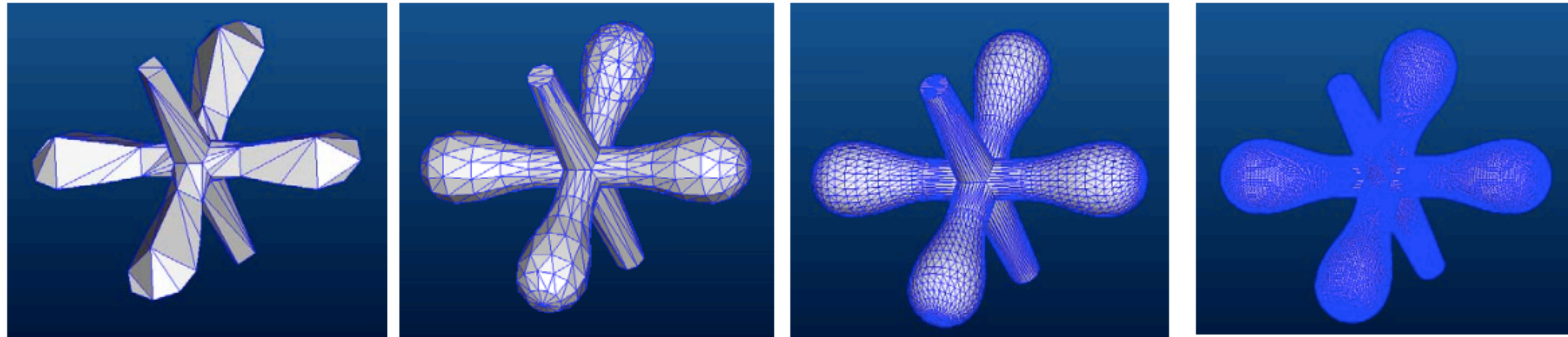Virtual Reality Applications Center

Tessellation

- OBJ, VRML, STL?

- Engineering CAD Settings

- Exporting an approximation

  - Coarse or Fine?

  - Binary or ASCII?

  - Chordal Deviation?

  - Angle Tolerance?

Solid model

Tessellated model

*What is the error for a prismatic part?

Approximation Error
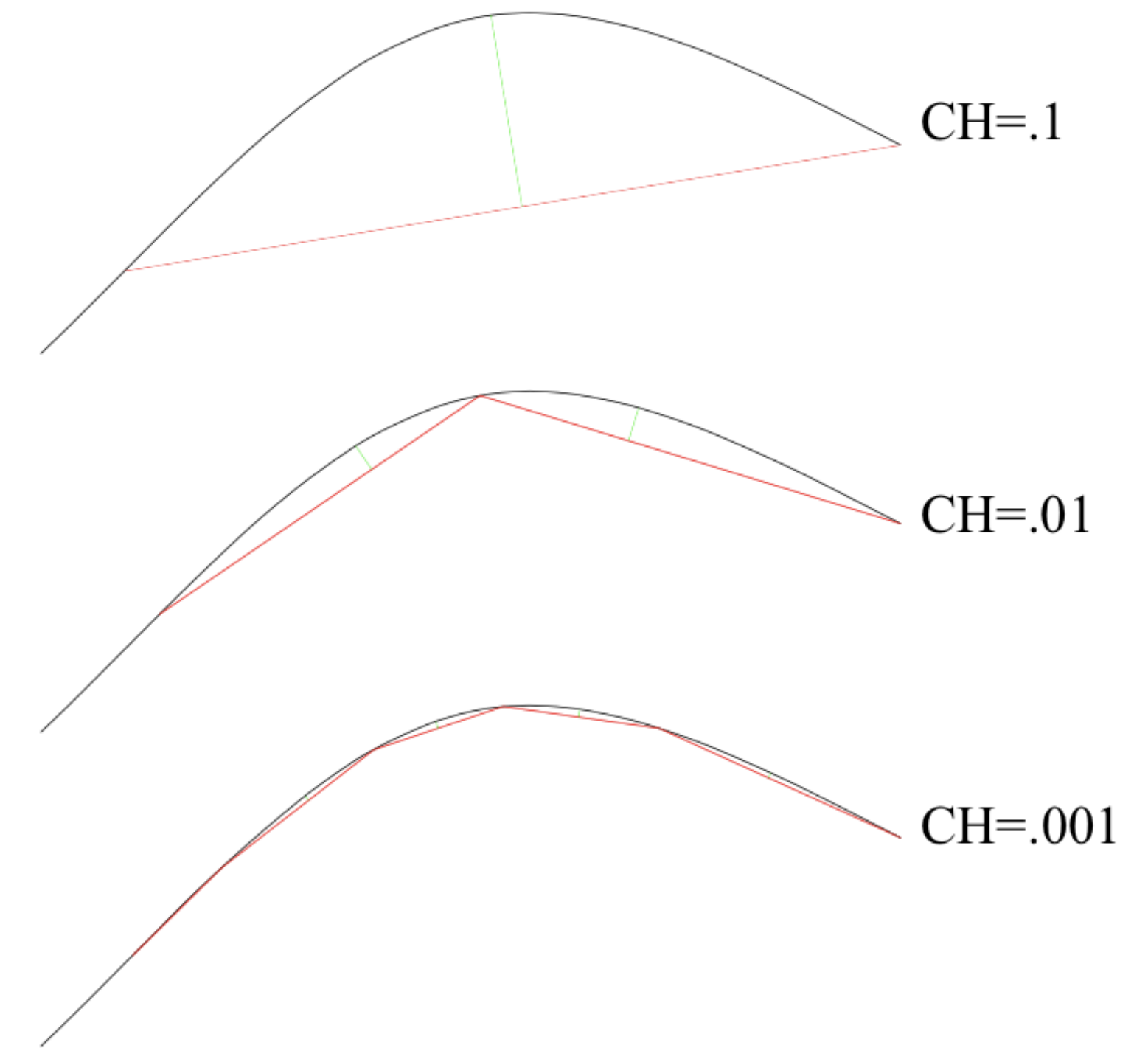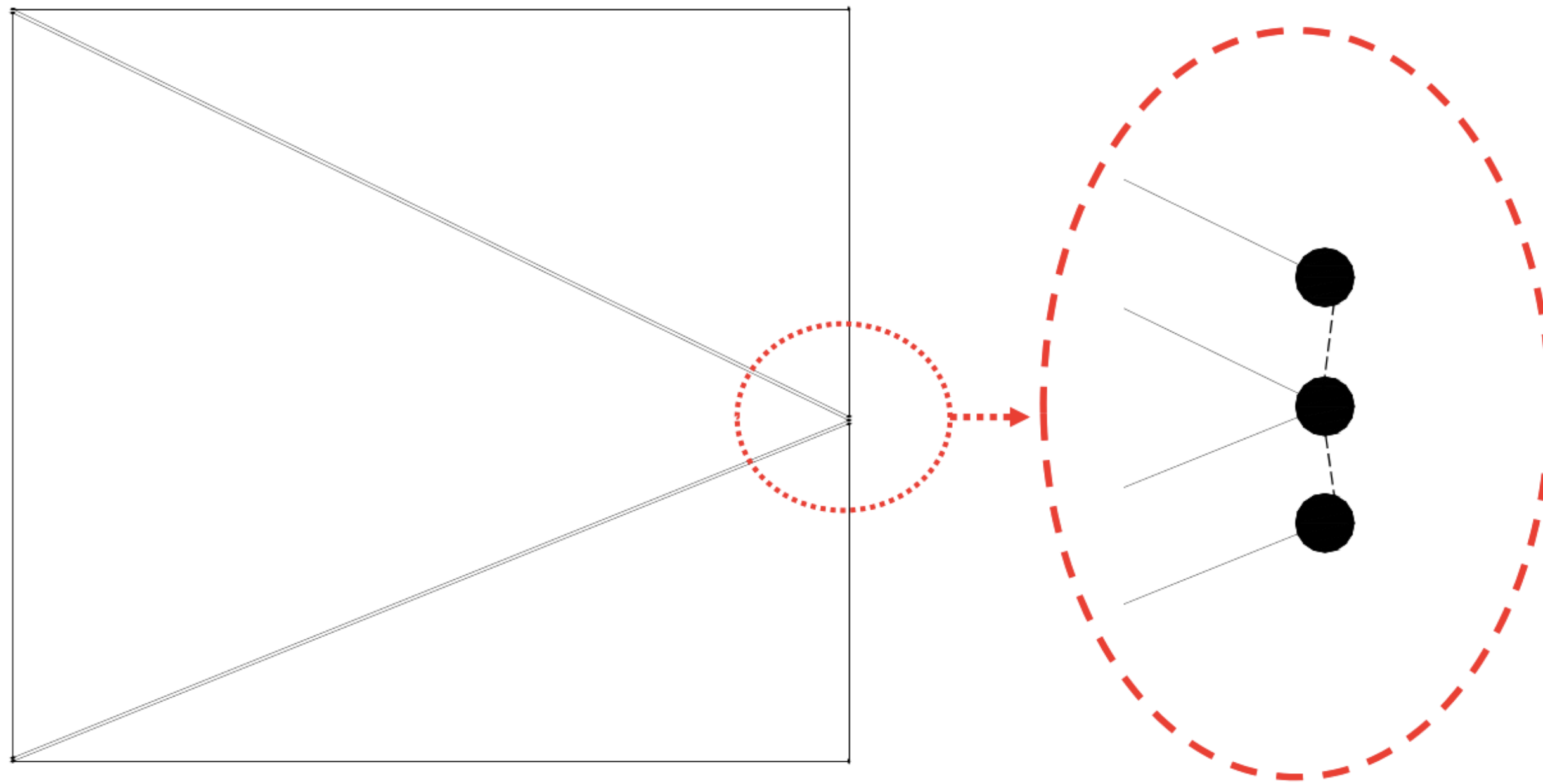

188 facets | 728 facets | 4,232 facets | 35,804 facets

← Error

File size (#of facets) →

Trade off of error versus file size (number of facets)

Chordal Deviation and Angle Tolerance

CH=.1

CH=.01

CH=.001

STL vs. STL 2.0 (AMF)

- Additive Manufacturing Format (AMF) has been called STL 2.0

- May contain additional information such as color, volume, units that some AM machines need

- Fundamental concepts of the STL format are incorporated

- Still under development, could but does not need to replace the STL format

```xml
<?xml version="1.0" encoding="UTF-8"?>
<amf unit="millimeter" version="1.1" xml:lang="en"><constellation id="0">
    <instance objectid="2922"/></constellation><object id="2922" type="model">
        <mesh>
            <vertices>
                <vertex><coordinates><x>-12.7</x><y>-12.7</y><z>-12.7</z></coordinates></vertex>
                <vertex><coordinates><x>12.7</x><y>-12.7</y><z>-12.7</z></coordinates></vertex>
                <vertex><coordinates><x>-12.7</x><y>-12.7</y><z>12.7</z></coordinates></vertex>
                <vertex><coordinates><x>12.7</x><y>-12.7</y><z>12.7</z></coordinates></vertex>
                <vertex><coordinates><x>-12.7</x><y>12.7</y><z>-12.7</z></coordinates></vertex>
                <vertex><coordinates><x>12.7</x><y>12.7</y><z>-12.7</z></coordinates></vertex>
                <vertex><coordinates><x>-12.7</x><y>12.7</y><z>12.7</z></coordinates></vertex>
                <vertex><coordinates><x>12.7</x><y>12.7</y><z>12.7</z></coordinates></vertex>
            </vertices>

            <volume>
                <triangle><v1>2</v1><v2>6</v2><v3>0</v3></triangle>
                <triangle><v1>6</v1><v2>4</v2><v3>0</v3></triangle>
                <triangle><v1>1</v1><v2>2</v2><v3>0</v3></triangle>
                <triangle><v1>4</v1><v2>1</v2><v3>0</v3></triangle>
                <triangle><v1>5</v1><v2>3</v2><v3>1</v3></triangle>
                <triangle><v1>3</v1><v2>2</v2><v3>1</v3></triangle>
                <triangle><v1>4</v1><v2>5</v2><v3>1</v3></triangle>
                <triangle><v1>7</v1><v2>6</v2><v3>2</v3></triangle>
                <triangle><v1>3</v1><v2>7</v2><v3>2</v3></triangle>
                <triangle><v1>5</v1><v2>7</v2><v3>3</v3></triangle>
                <triangle><v1>6</v1><v2>7</v2><v3>4</v3></triangle>
                <triangle><v1>7</v1><v2>5</v2><v3>4</v3></triangle>
            </volume>
        </mesh>
    </object>
</amf>
```

```
solid cube
    facet normal 1.000000e+000 1.365924e-016 0.000000e+000
        outer loop
            vertex 1.000000e+000 1.000000e+000 1.000000e+000
            vertex 1.000000e+000 0.000000e+000 1.000000e+000
            vertex 1.000000e+000 1.000000e+000 0.000000e+000
        endloop
    endfacet
    facet normal 1.000000e+000 1.365924e-016 0.000000e+000
        outer loop
            vertex 1.000000e+000 1.000000e+000 0.000000e+000
            vertex 1.000000e+000 0.000000e+000 1.000000e+000
            vertex 1.000000e+000 0.000000e+000 0.000000e+000
        endloop
    endfacet
    facet normal 0.000000e+000 1.000000e+000 0.000000e+000
        outer loop
            vertex 0.000000e+000 1.000000e+000 1.000000e+000
            vertex 1.000000e+000 1.000000e+000 1.000000e+000
            vertex 0.000000e+000 1.000000e+000 0.000000e+000
        endloop
    endfacet
```

STL Files: Made for 3D printing

- De-Facto" standard file for RP

- A faceted representation of the boundary of a part, where each facet is a triangle

- Process of creating this representation is called "Tessellation"

- The STL file is an approximation of the surfaces of the part

MCA Session 2, Activity #1

- Sketch the cylinder and triangular extruder shape

- Sketch hyperrectangle shapes inside the cylinder and extruded triangle shapes
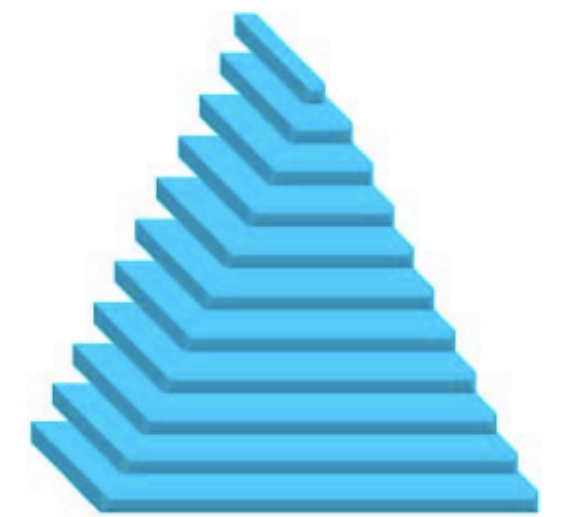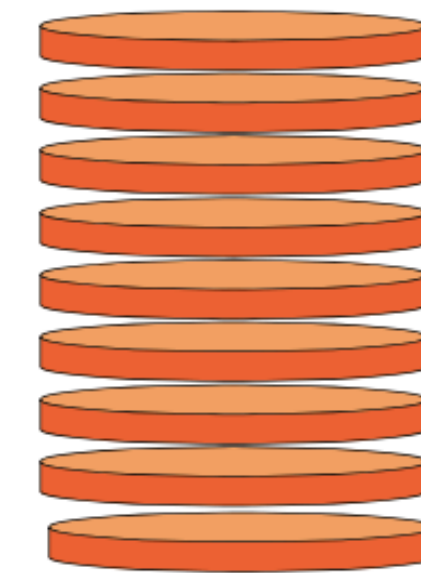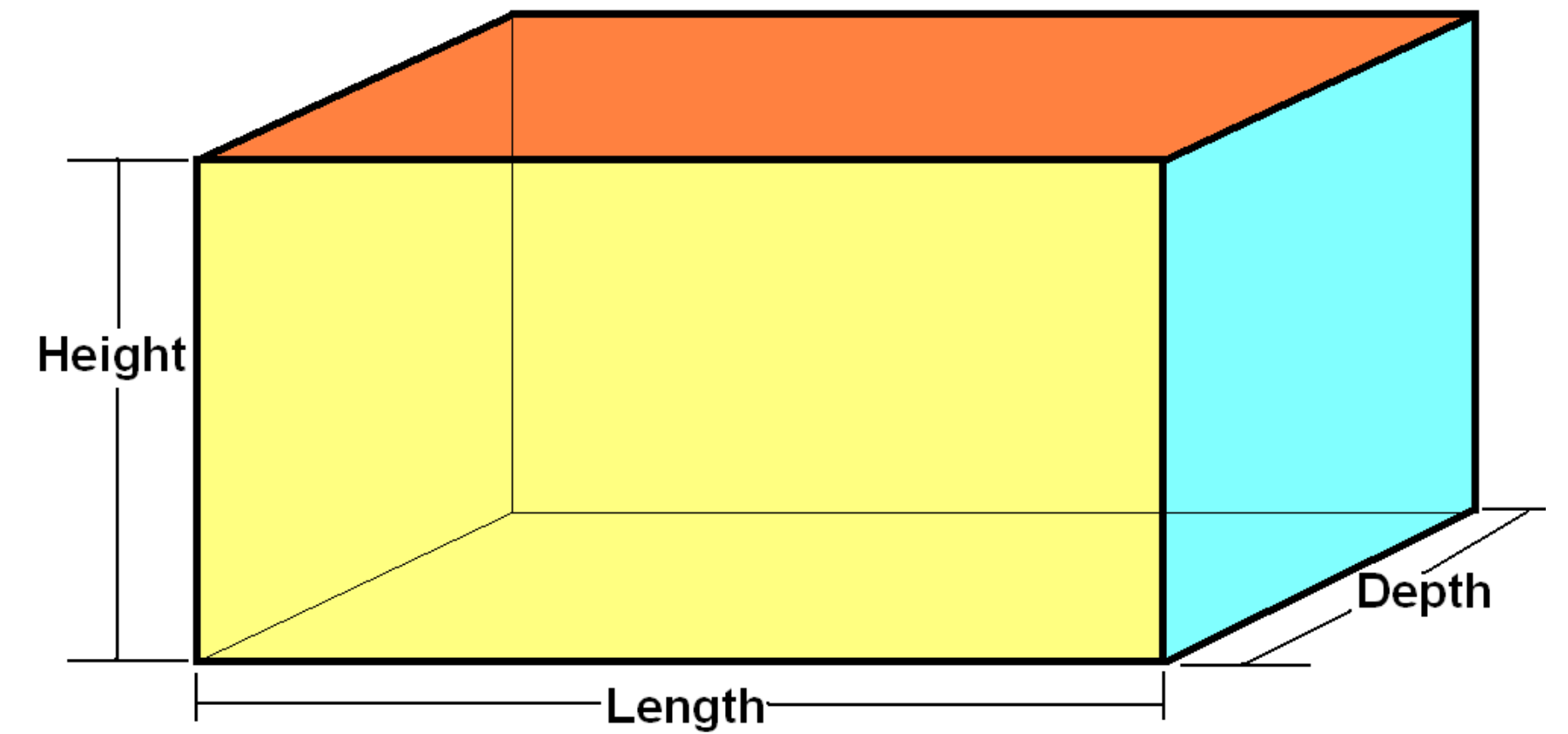
Near-CAD Model Analyses

- 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…?
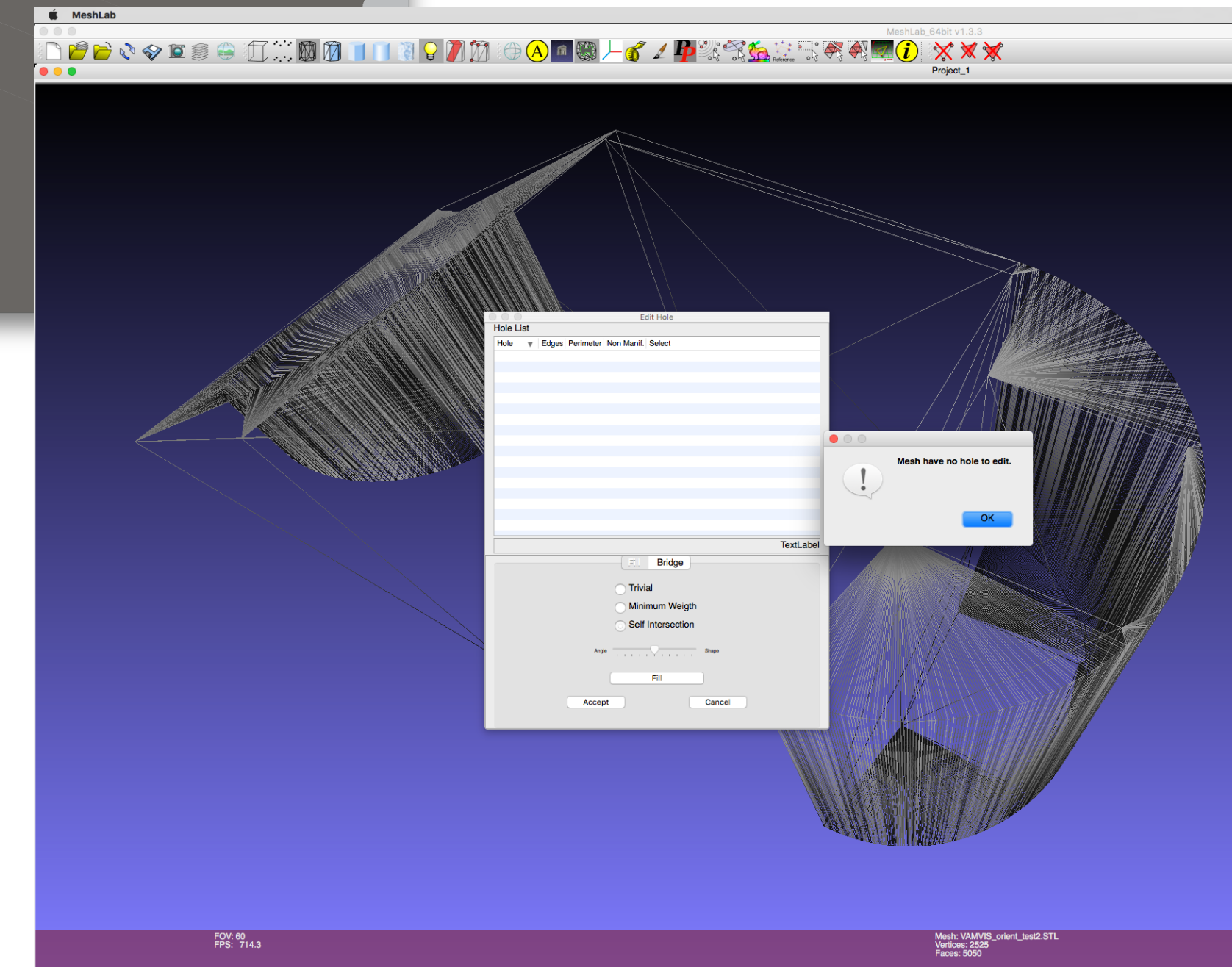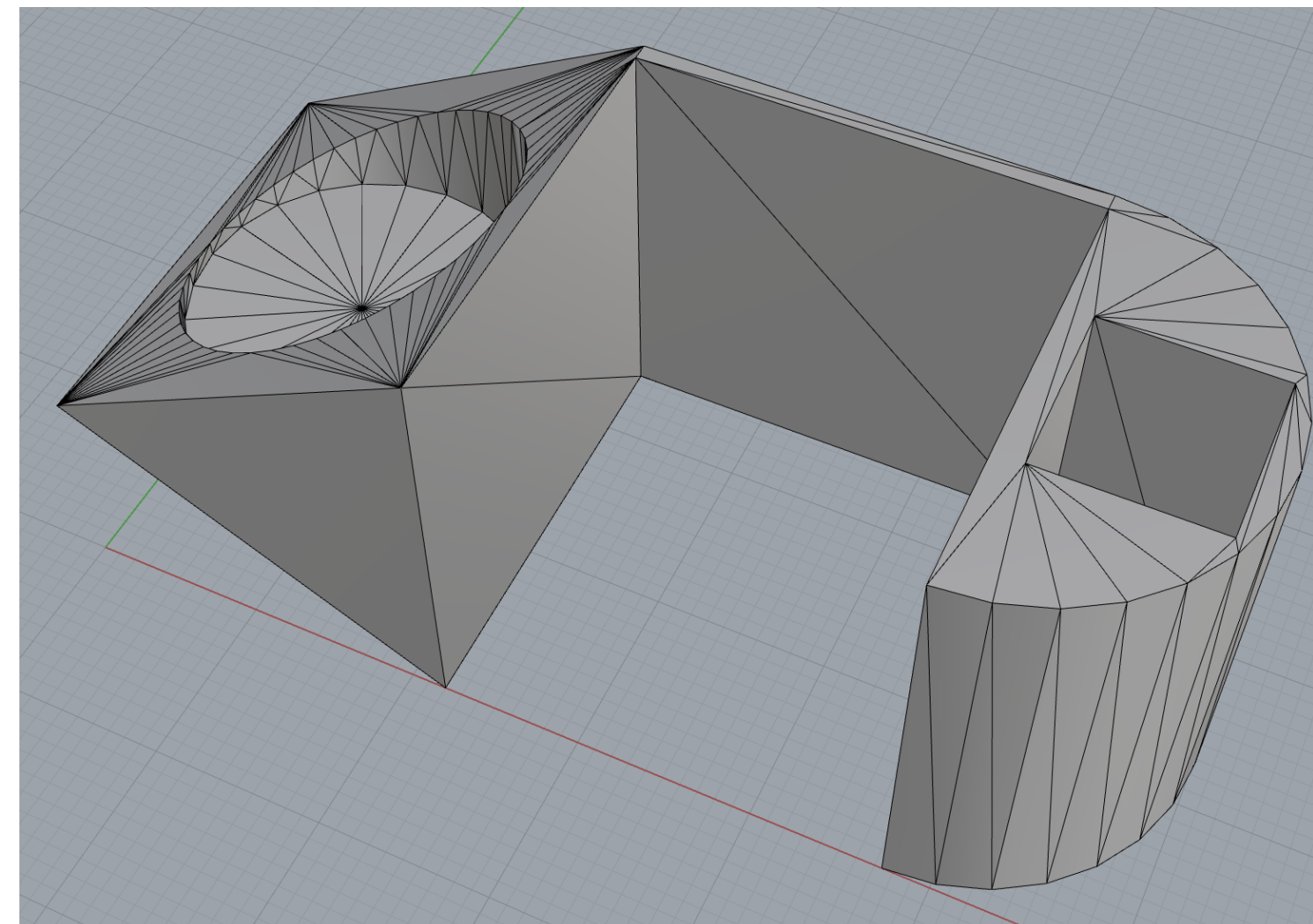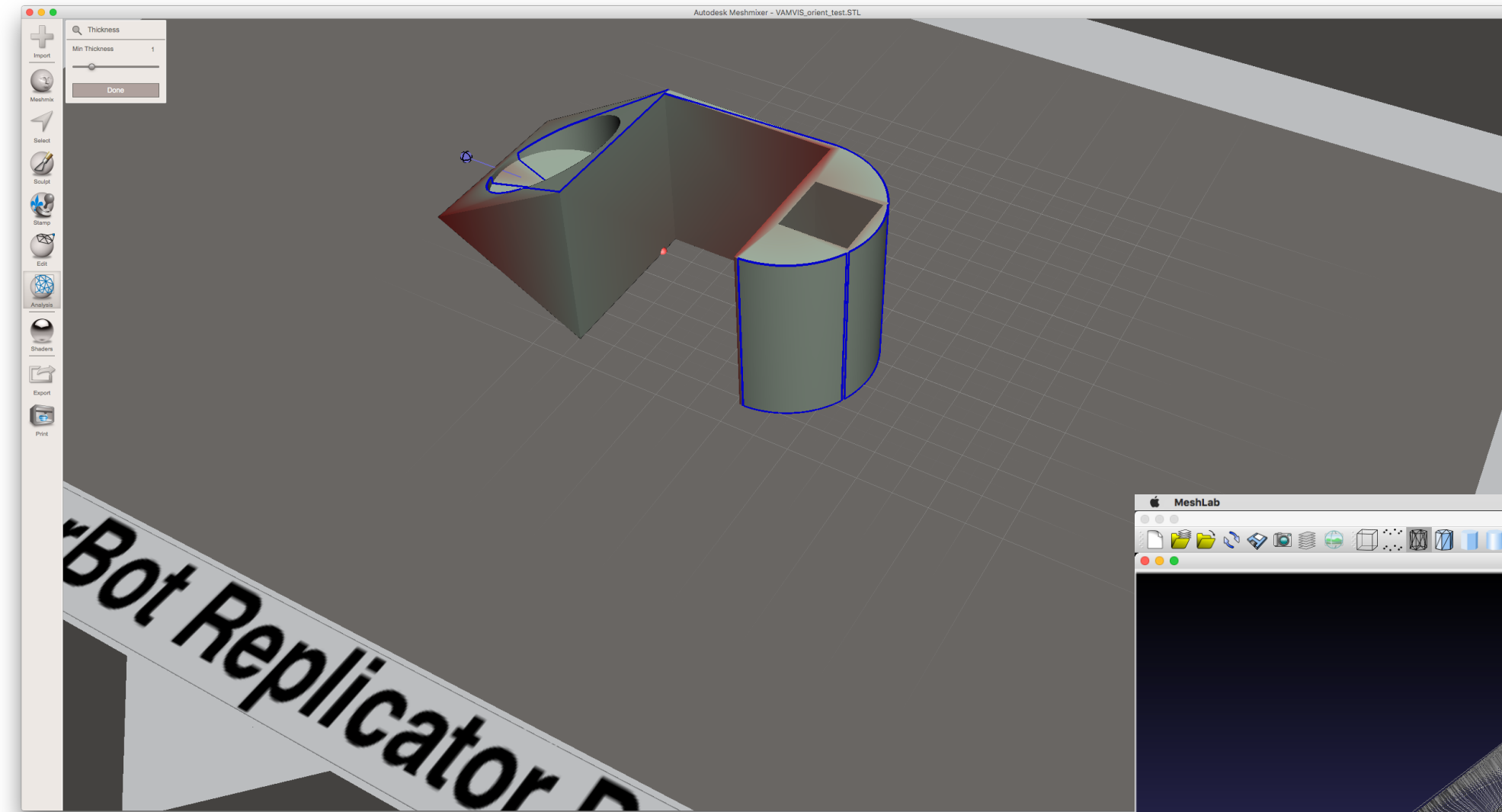
Rules Make STL Files Good

○ 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
endfacet
```
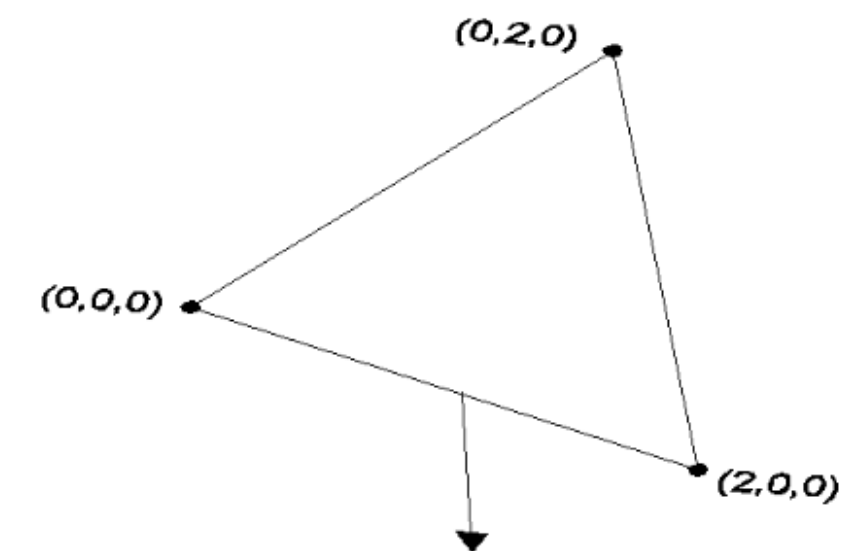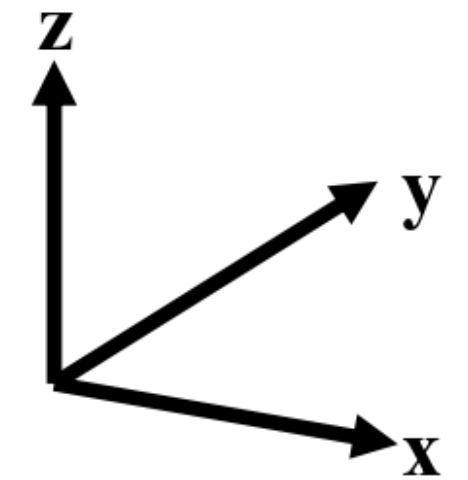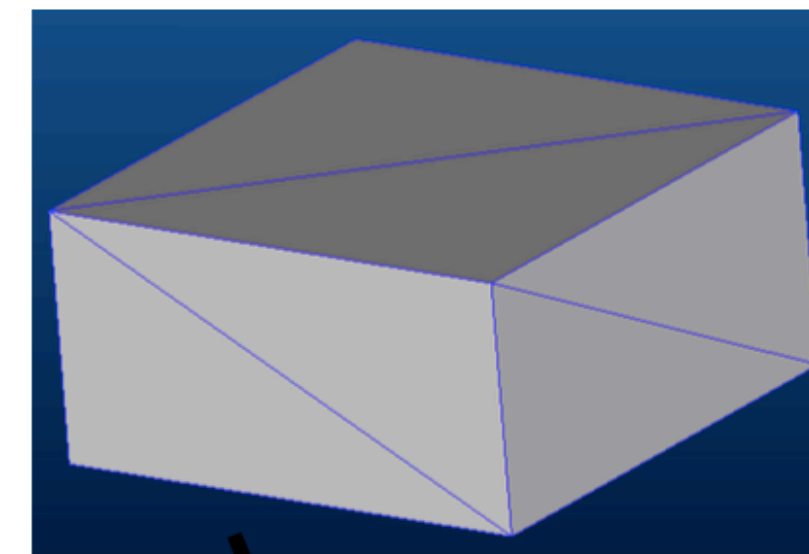
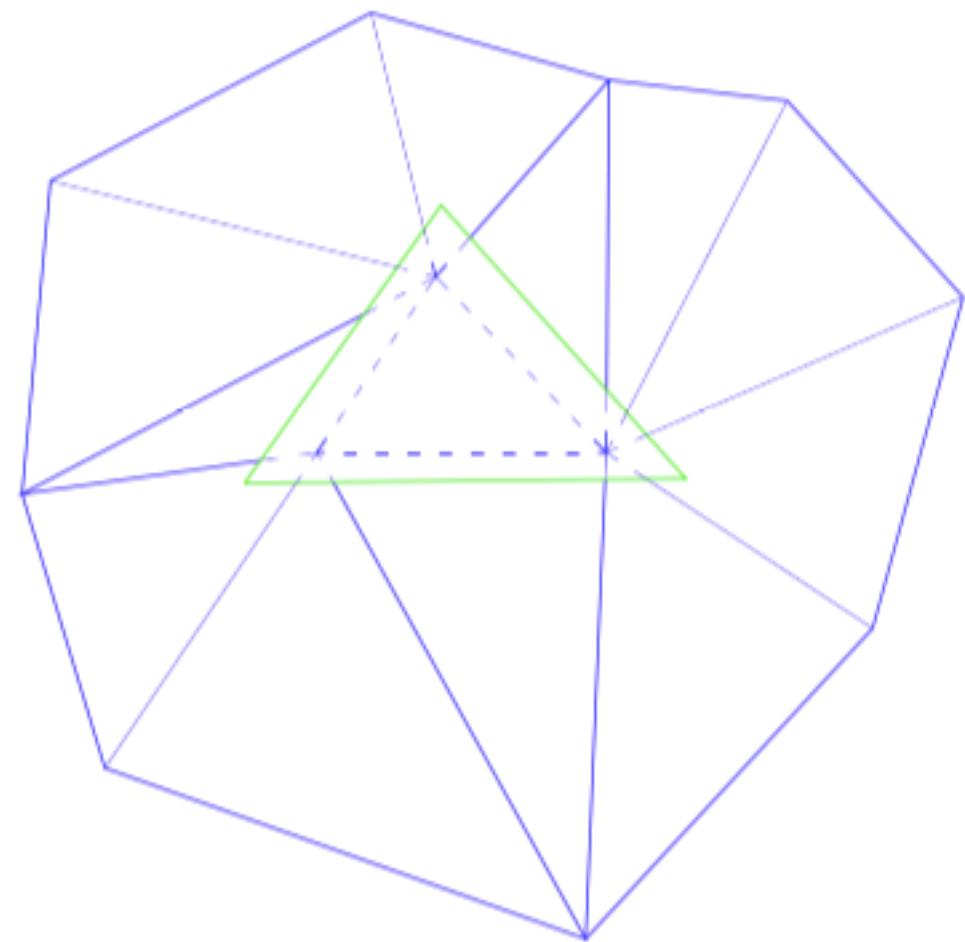*The facet normal always points to the "outside"
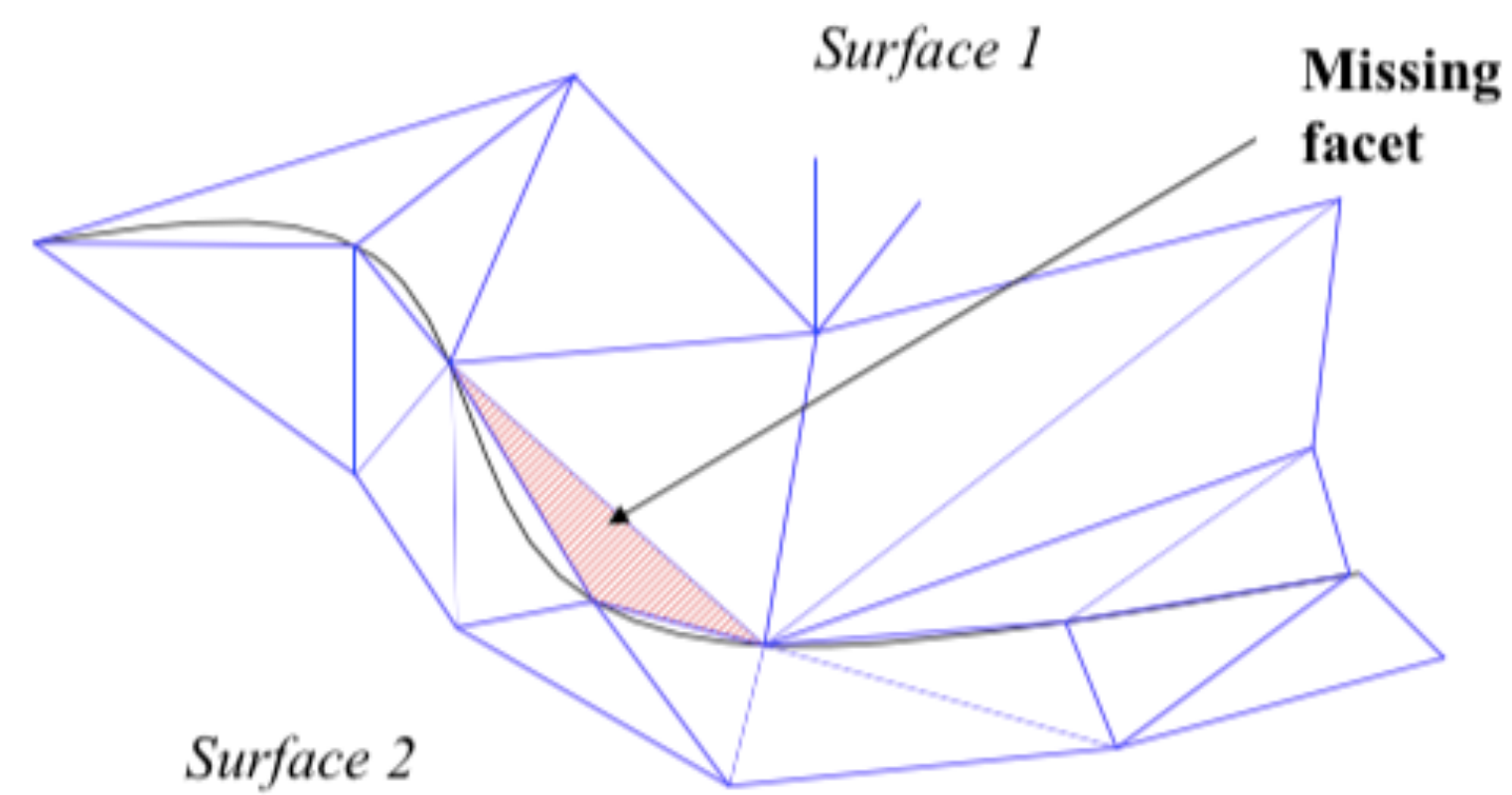
(0,2,0)

(0,0,0)

(2,0,0)
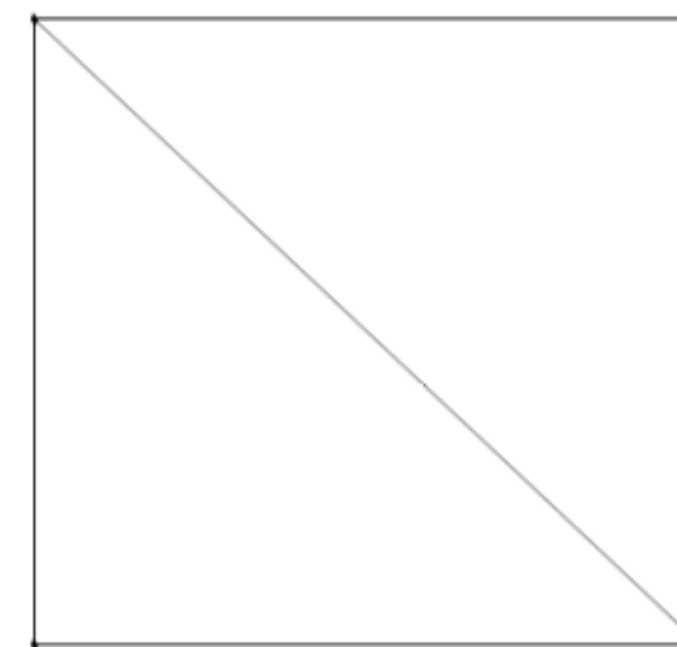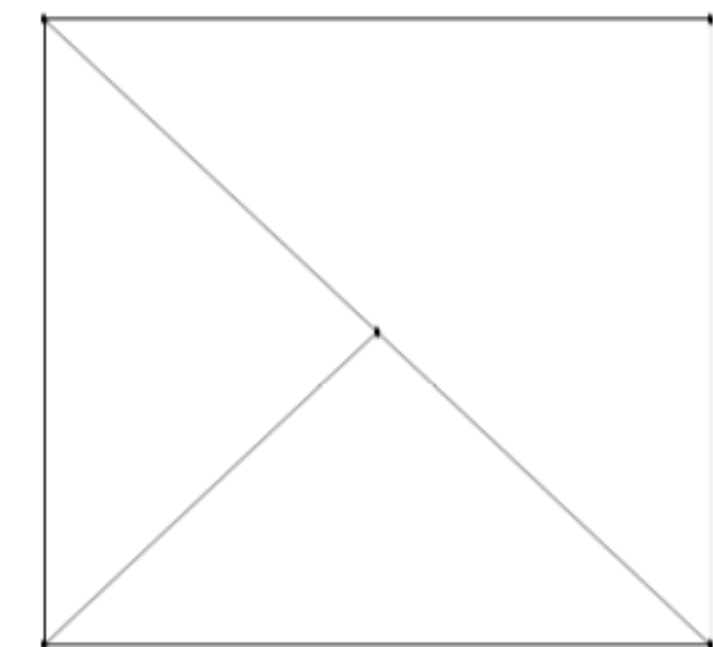
VALID

INVALID

STL Tessellation Errors
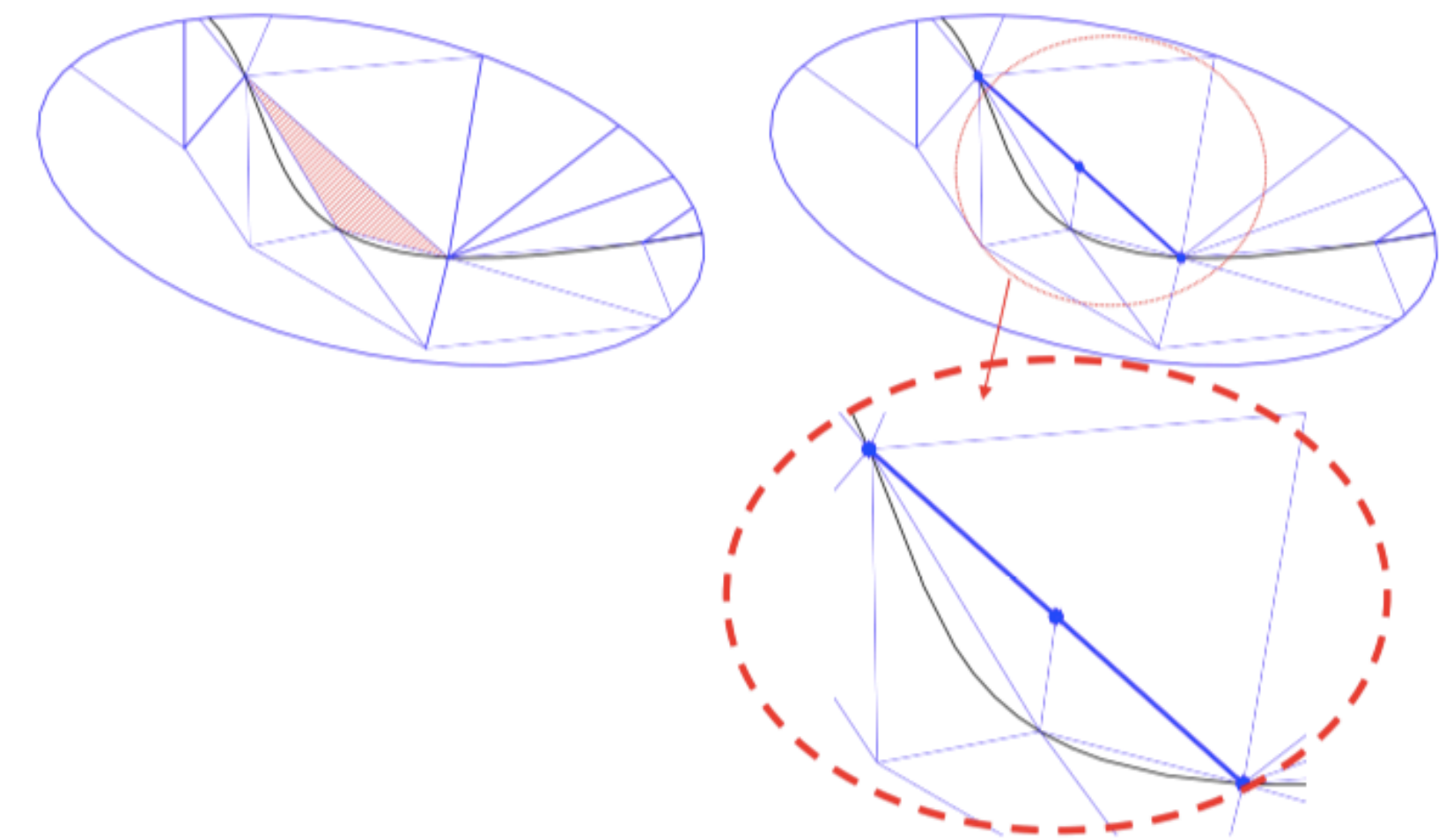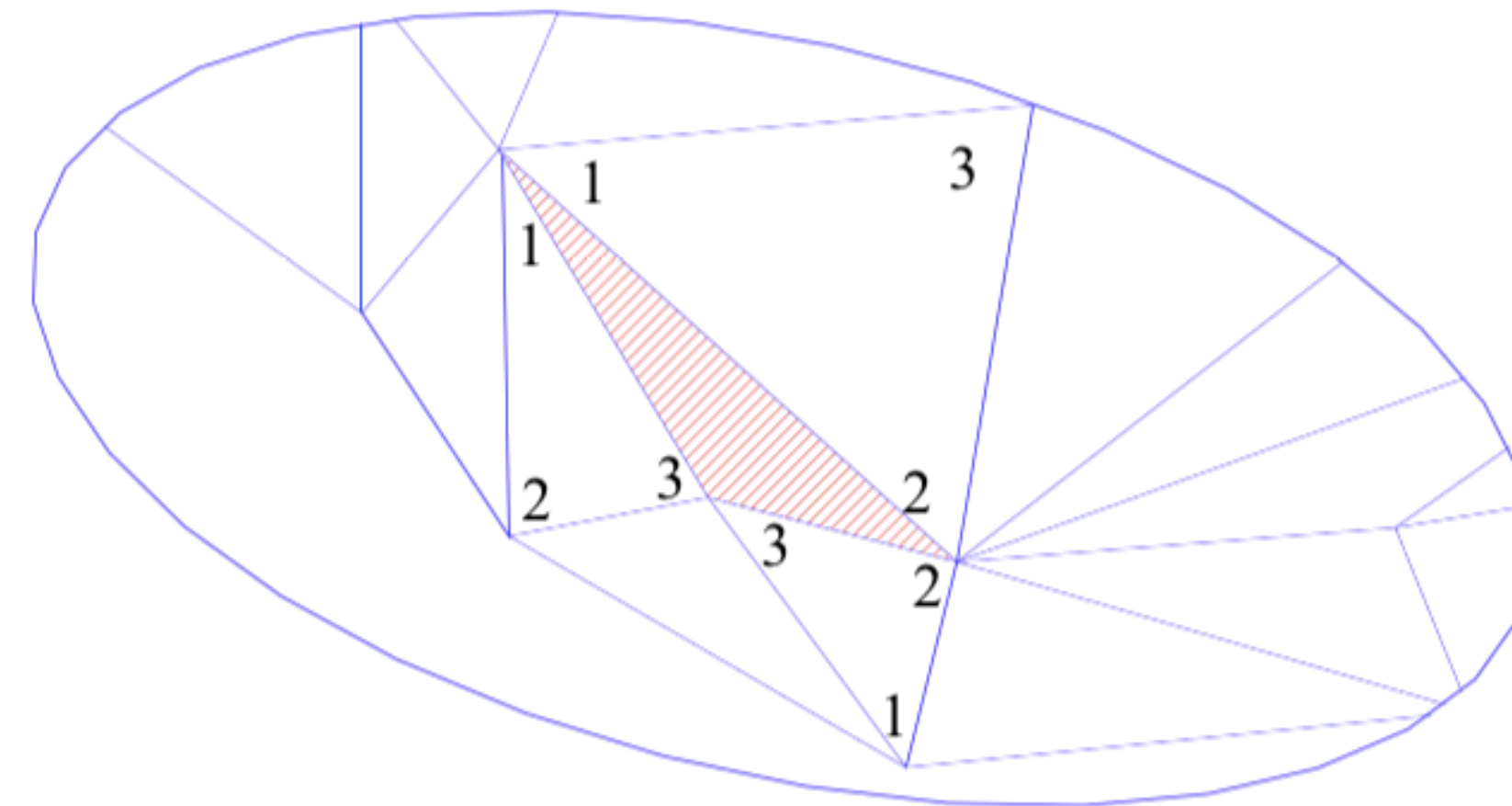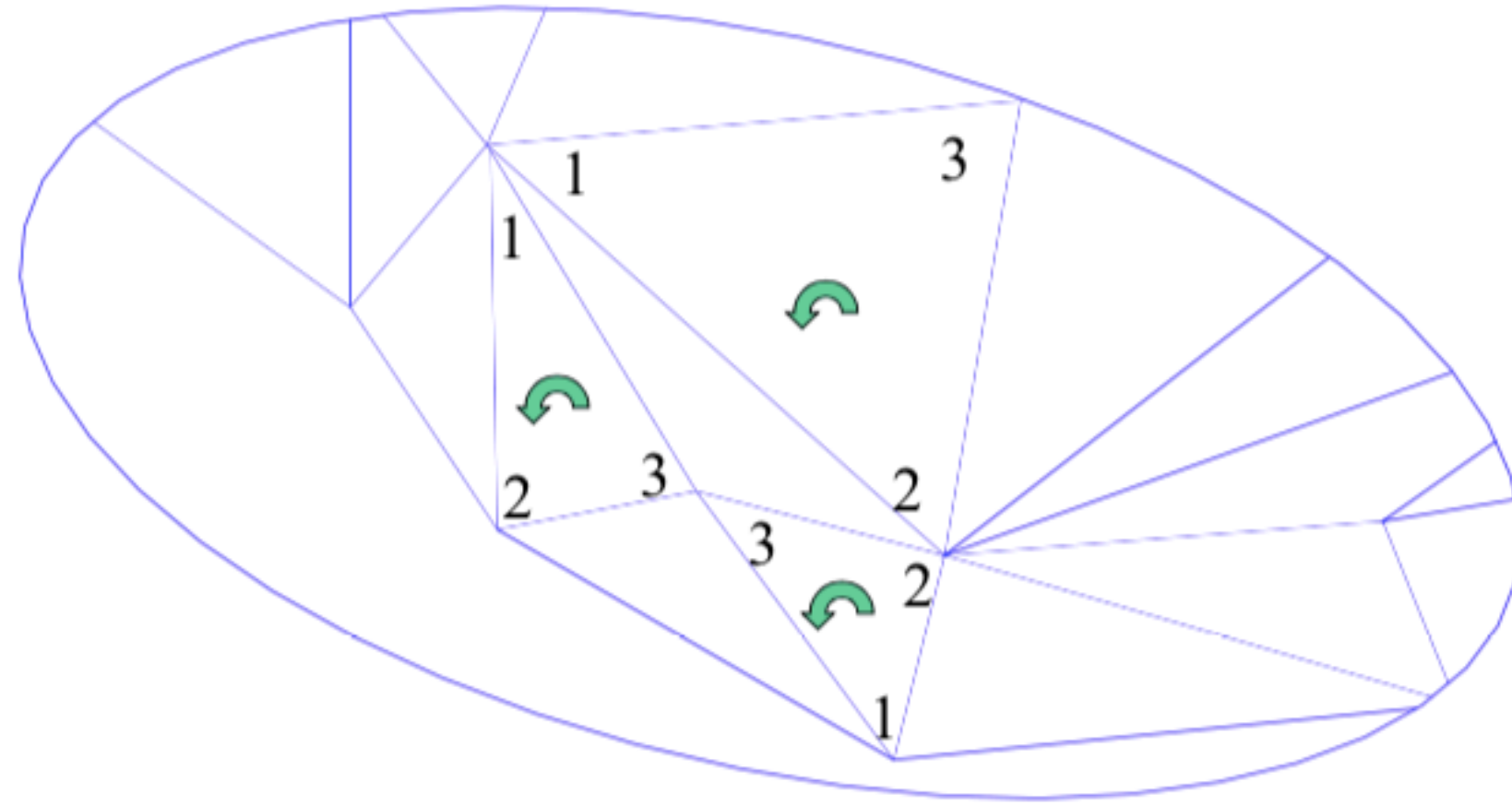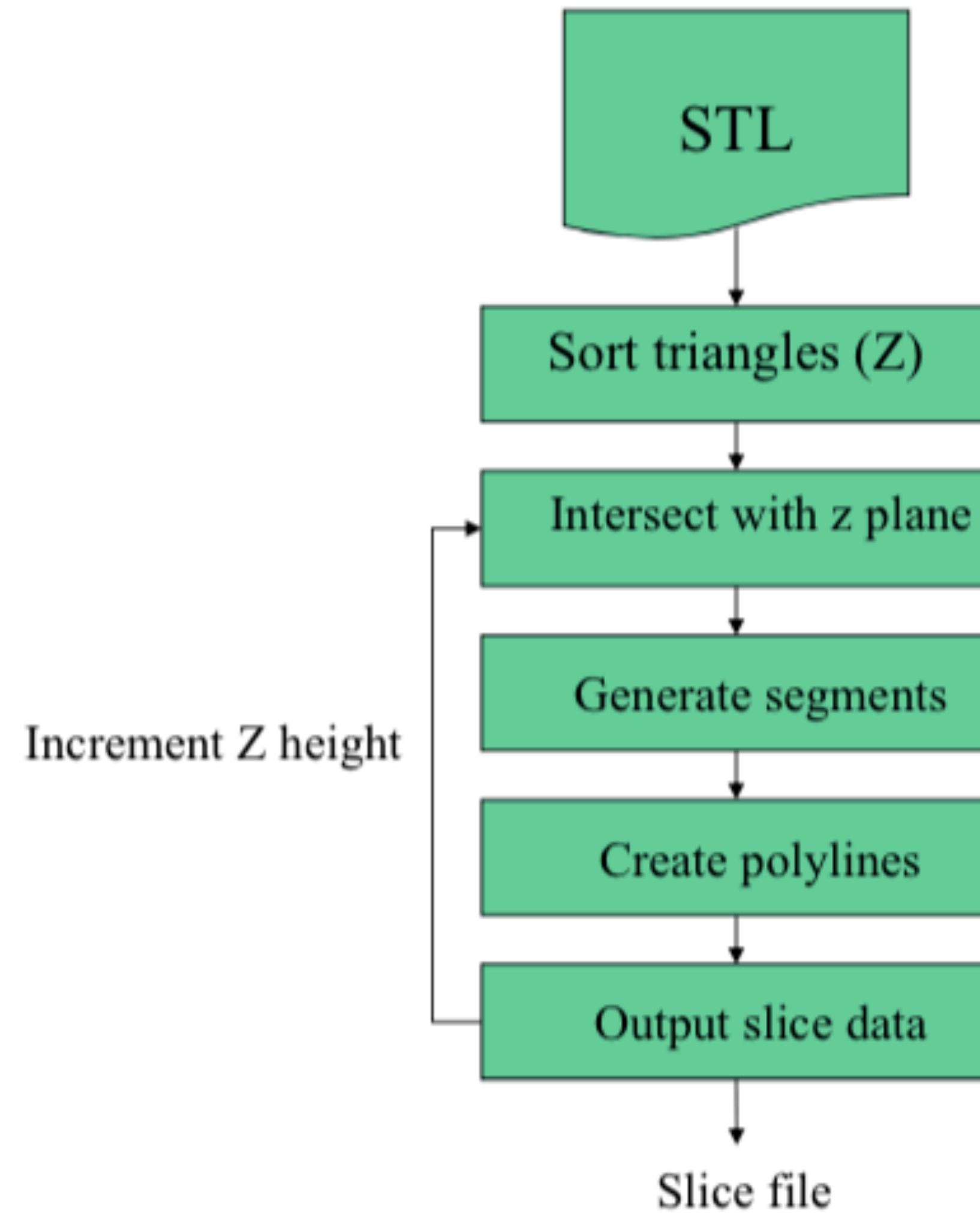

Overlapping Facets

Missing Facets

Degenerate Facets

Surface 1

Missing facet

Surface 2

IOWA STATE UNIVERSITY
Virtual Reality Applications Center

Cannot Slice if not Watertight

10 Minute Break

Slicing an STL File

Intersect With Z-Plane

STL

Sort triangles (Z)

Intersect with z plane

Increment Z height

Generate segments

Create polylines

Output slice data

Slice file
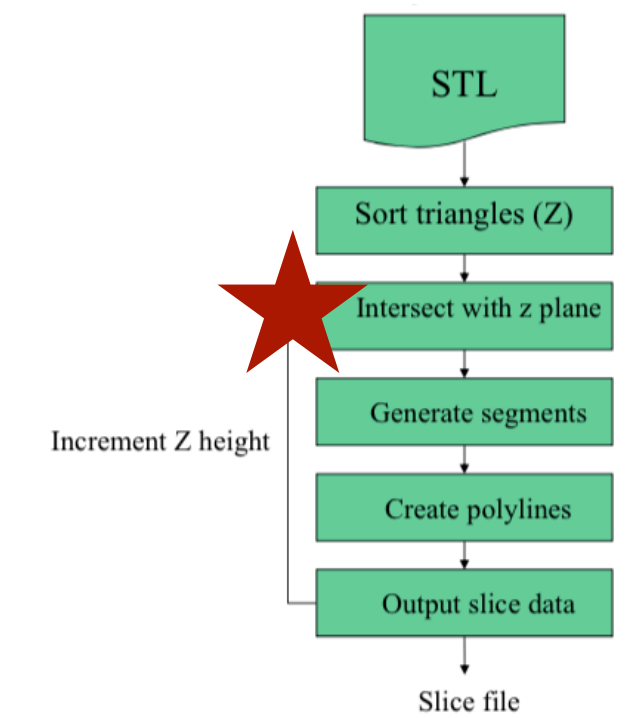
◉ Every segment belongs to exactly two triangles (vertex to vertex rule)

◉ 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
```
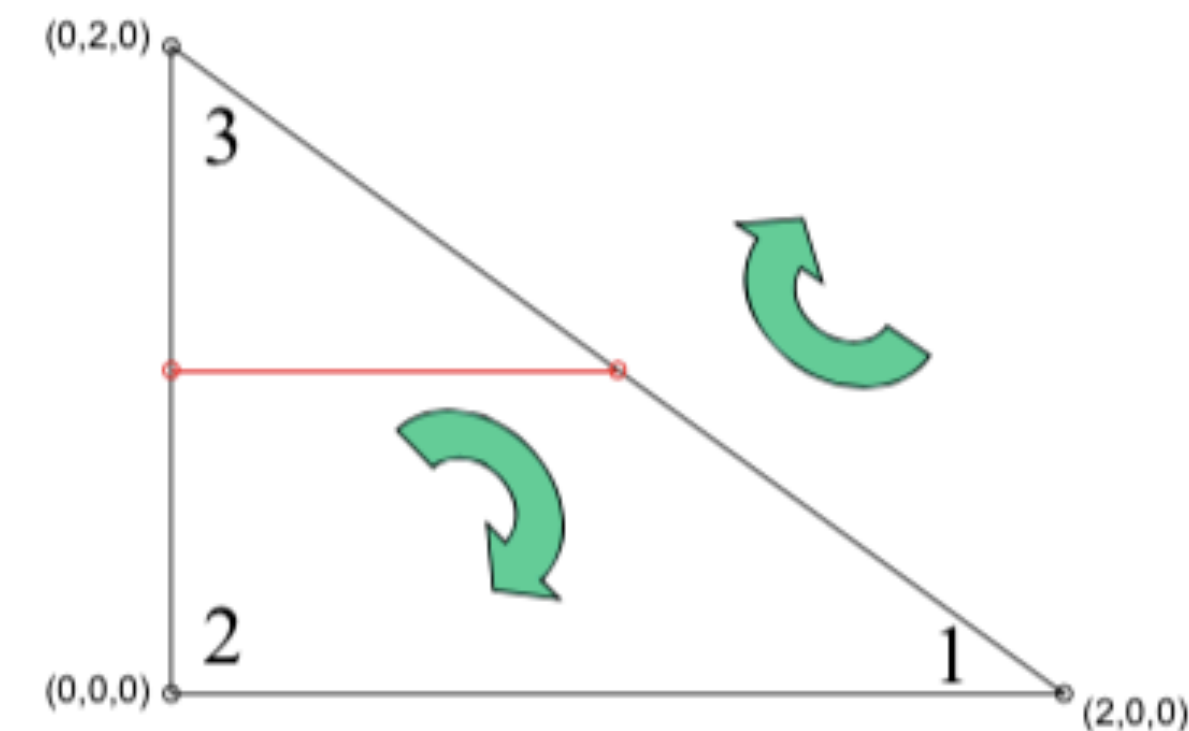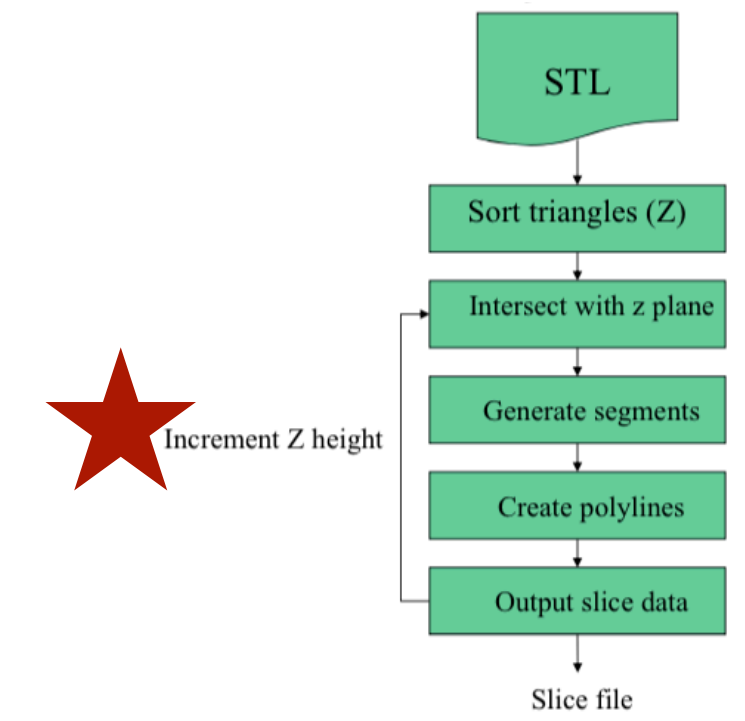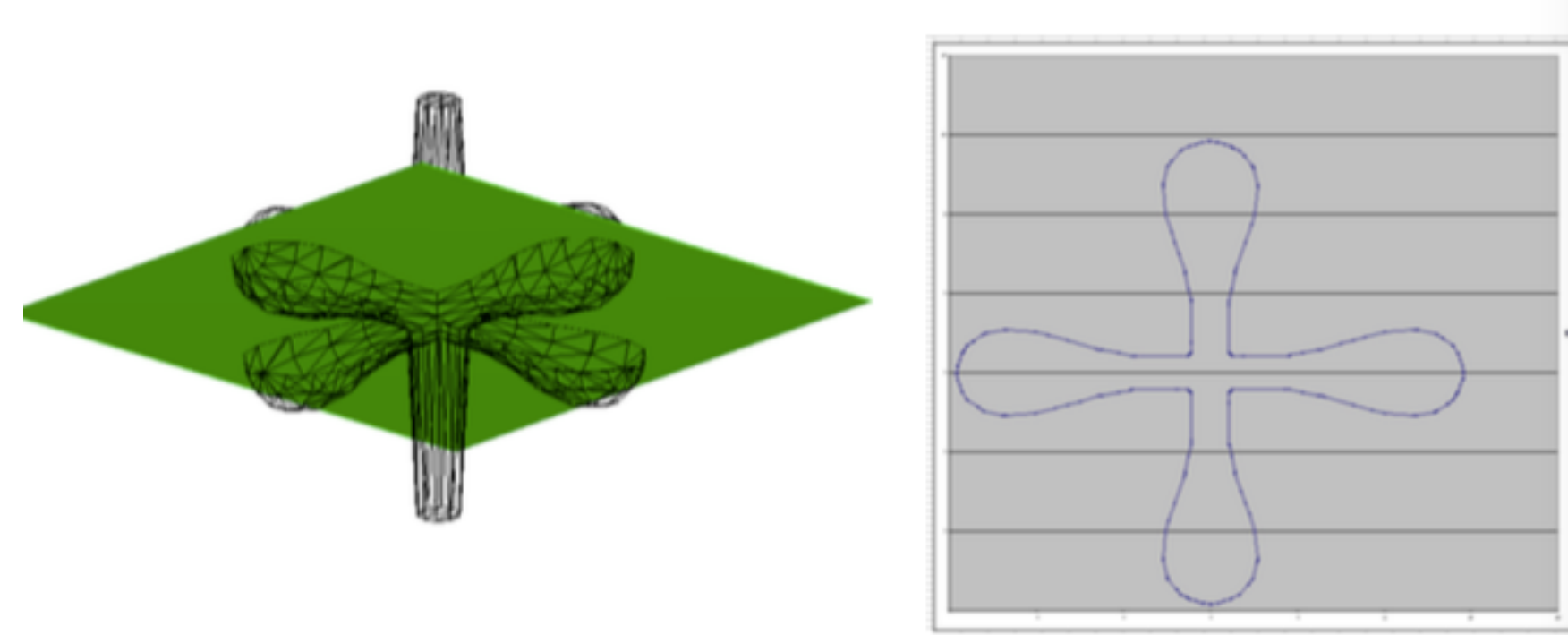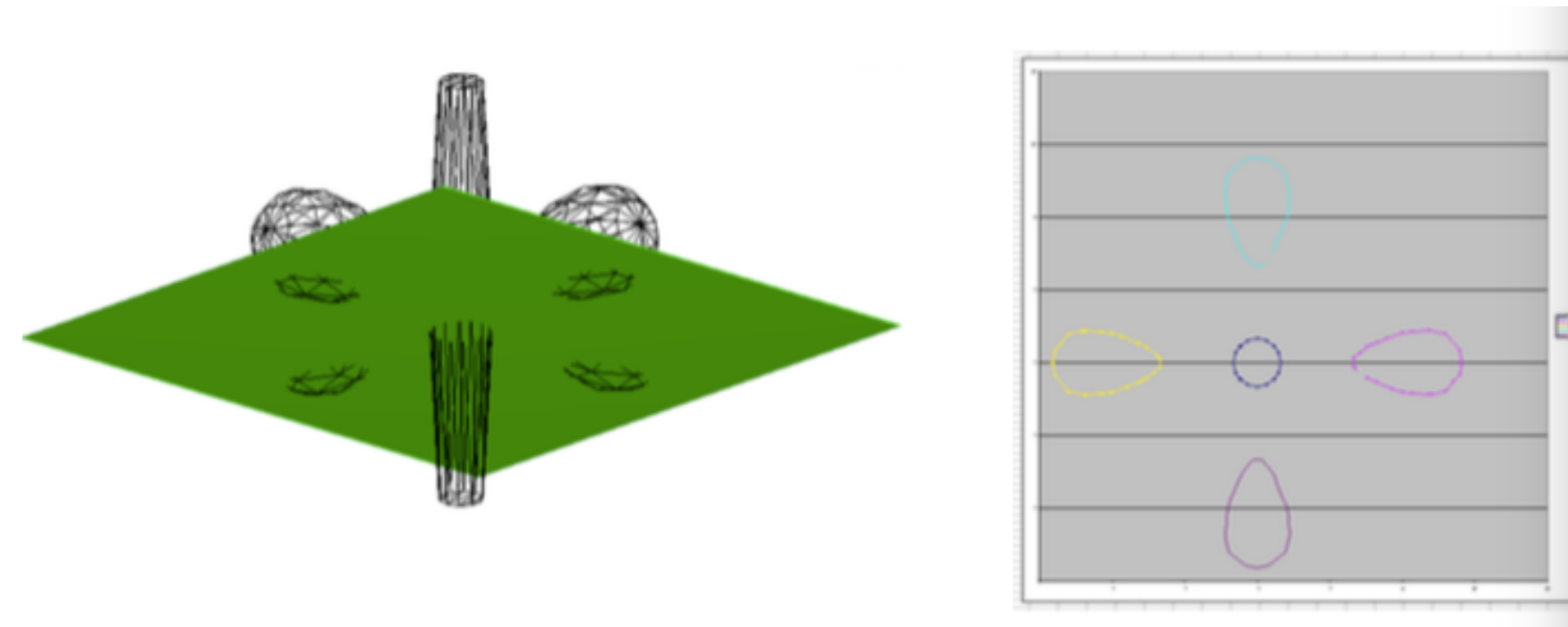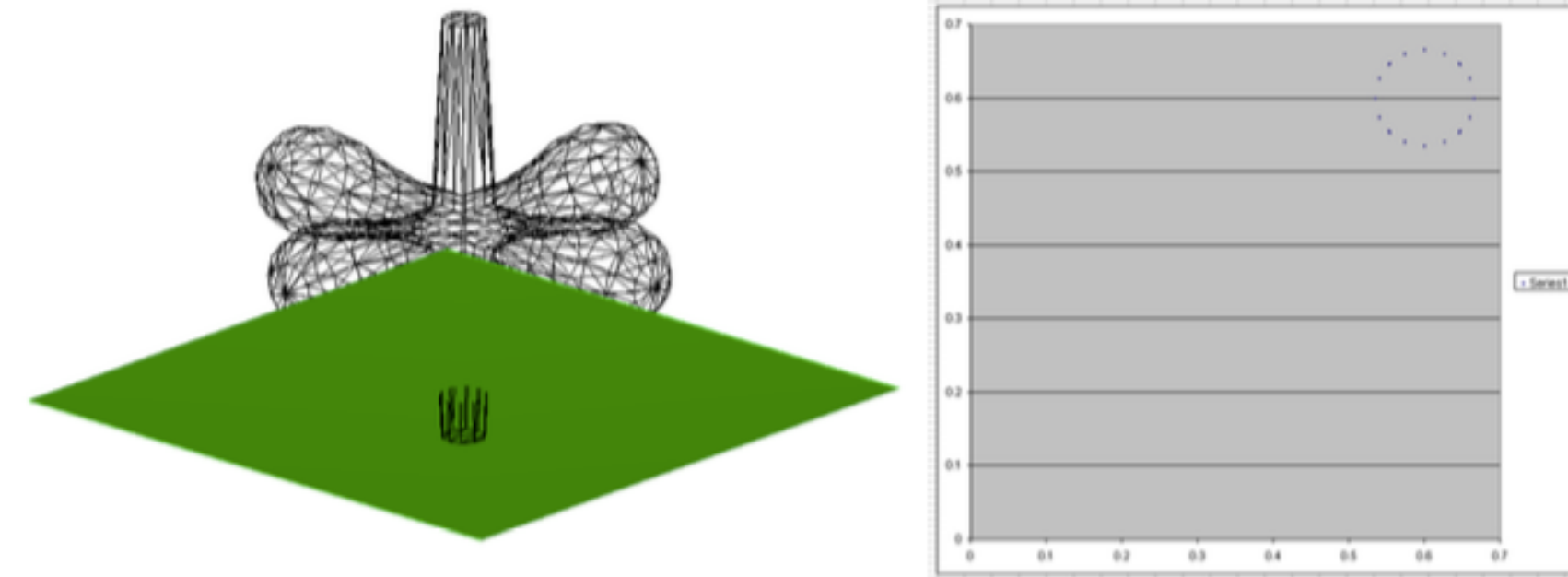
If Segment 3-1 exists, then segment 1-3 must also exist…else?
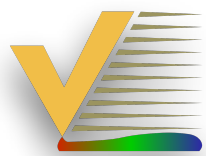
Increment Z height

1. Green plane slices through STL

2. Resulting 2D contour Plotted

3. Change Z position

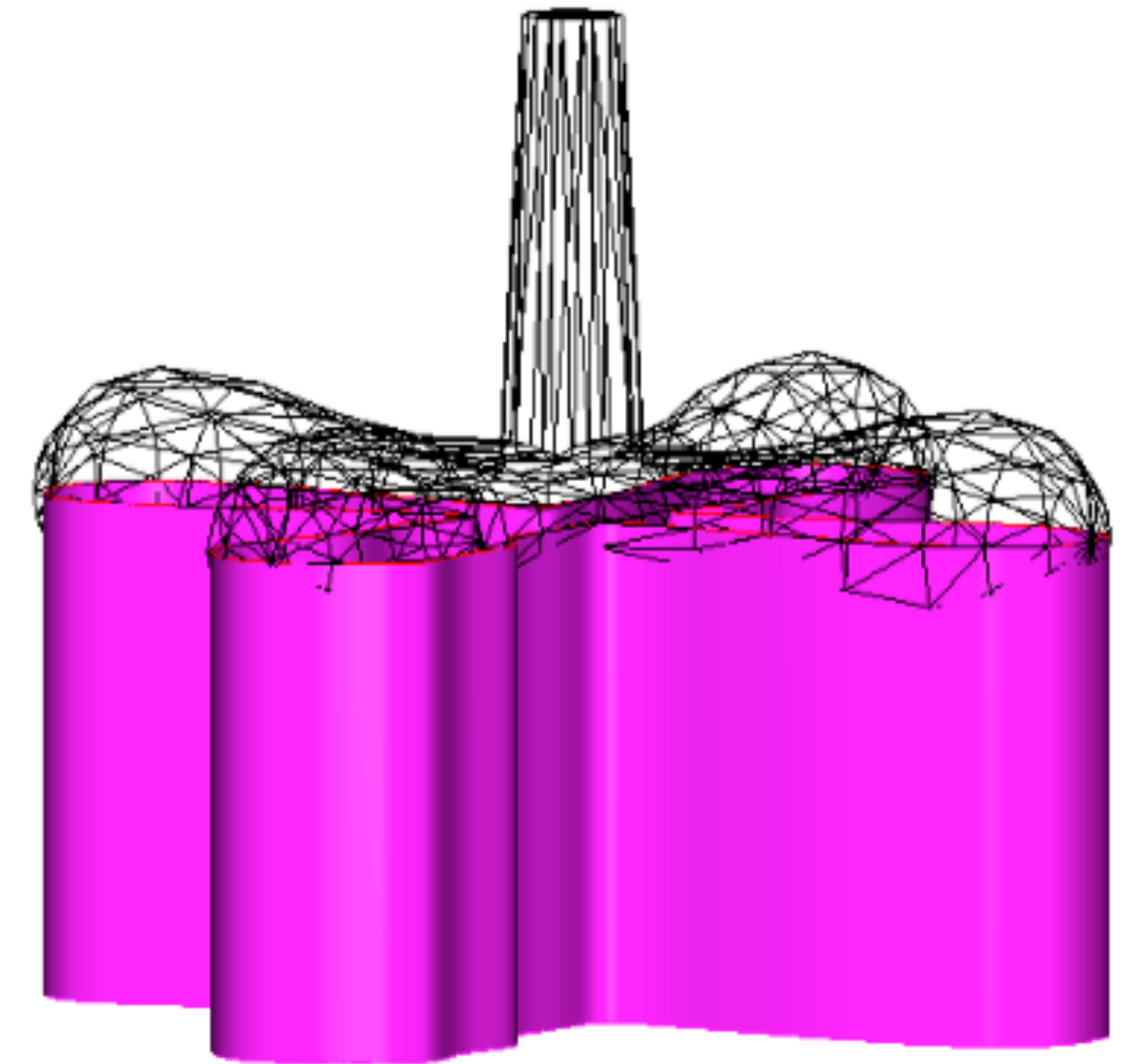4. Repeat

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
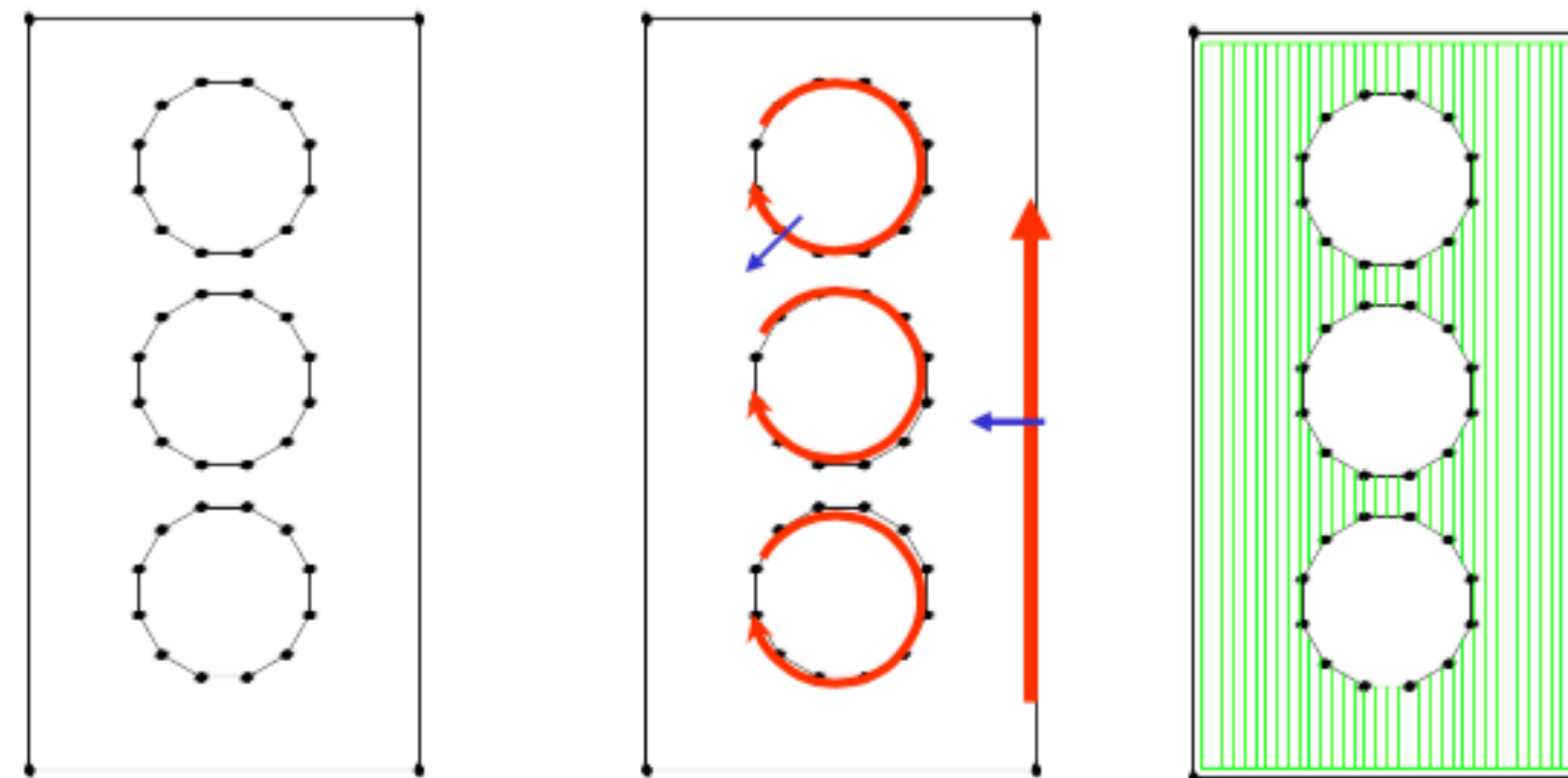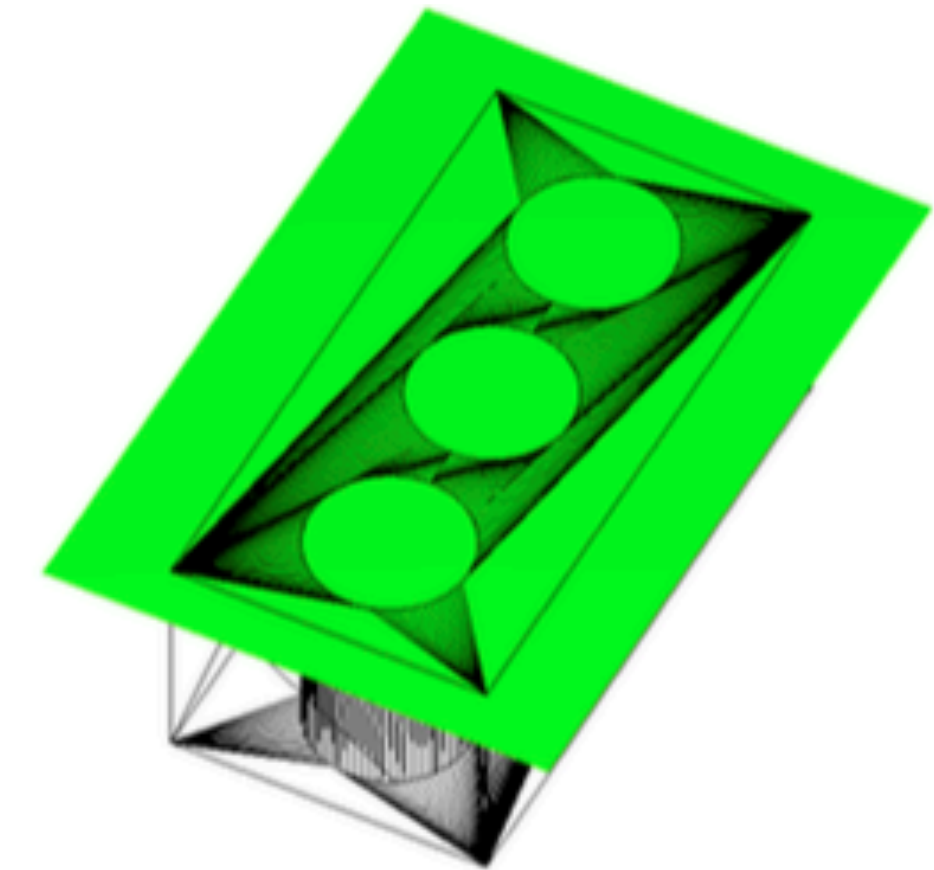
What's Up?

- 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


```
solid BoxS
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
...
```

# MCA Session 1 Activity Discussion

- 3D Printer Hardware

  - What type of info might be sent to the machine?

  - What components in the schematic on the right can be removed and why?

  - What's the difference between firmware and software?

  - If you never saw the CAD file, but had the slice files, could you print the part?

  - What type of info might be sent from the machine to the STL file in the software?
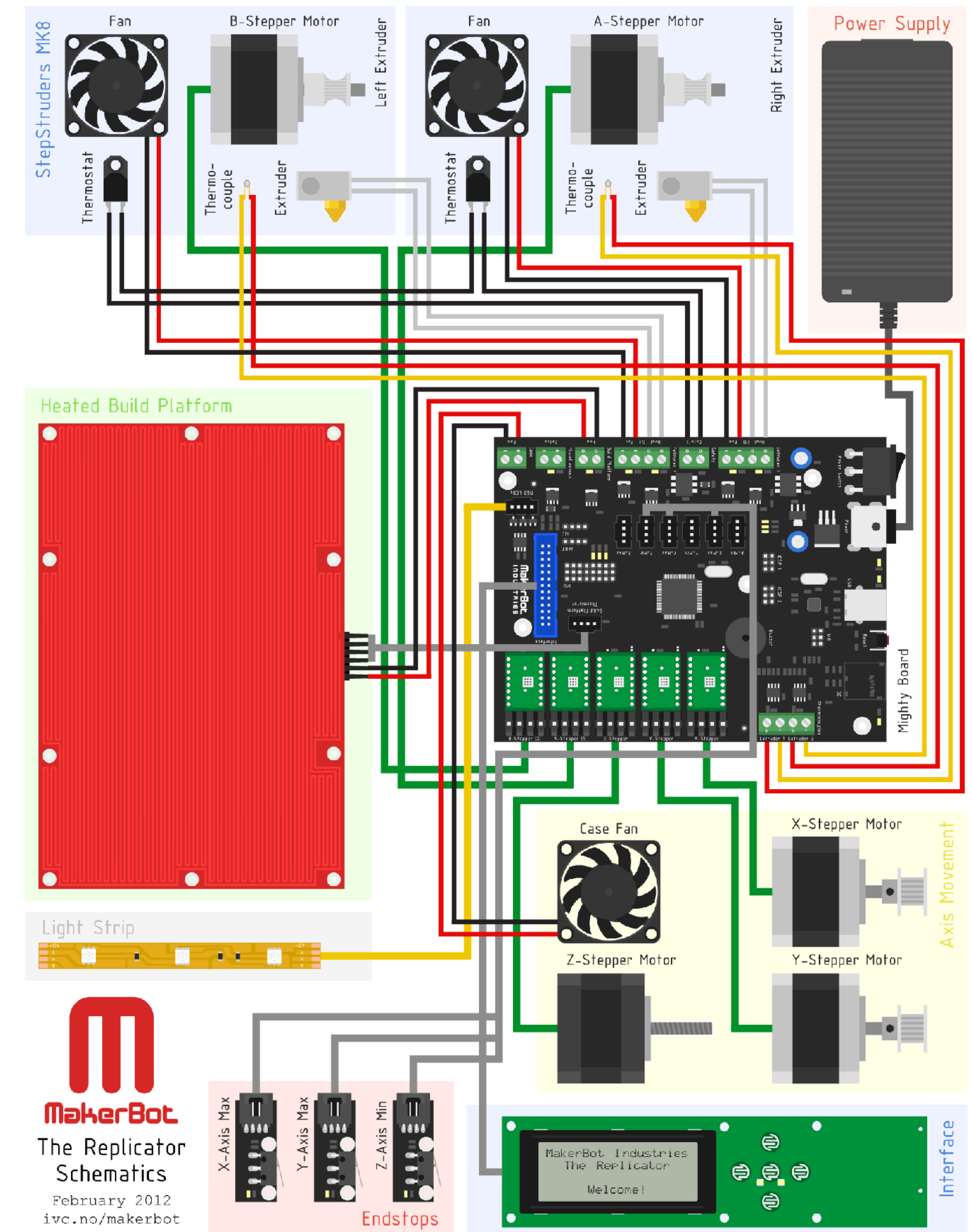
From Slices to Layers

- 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
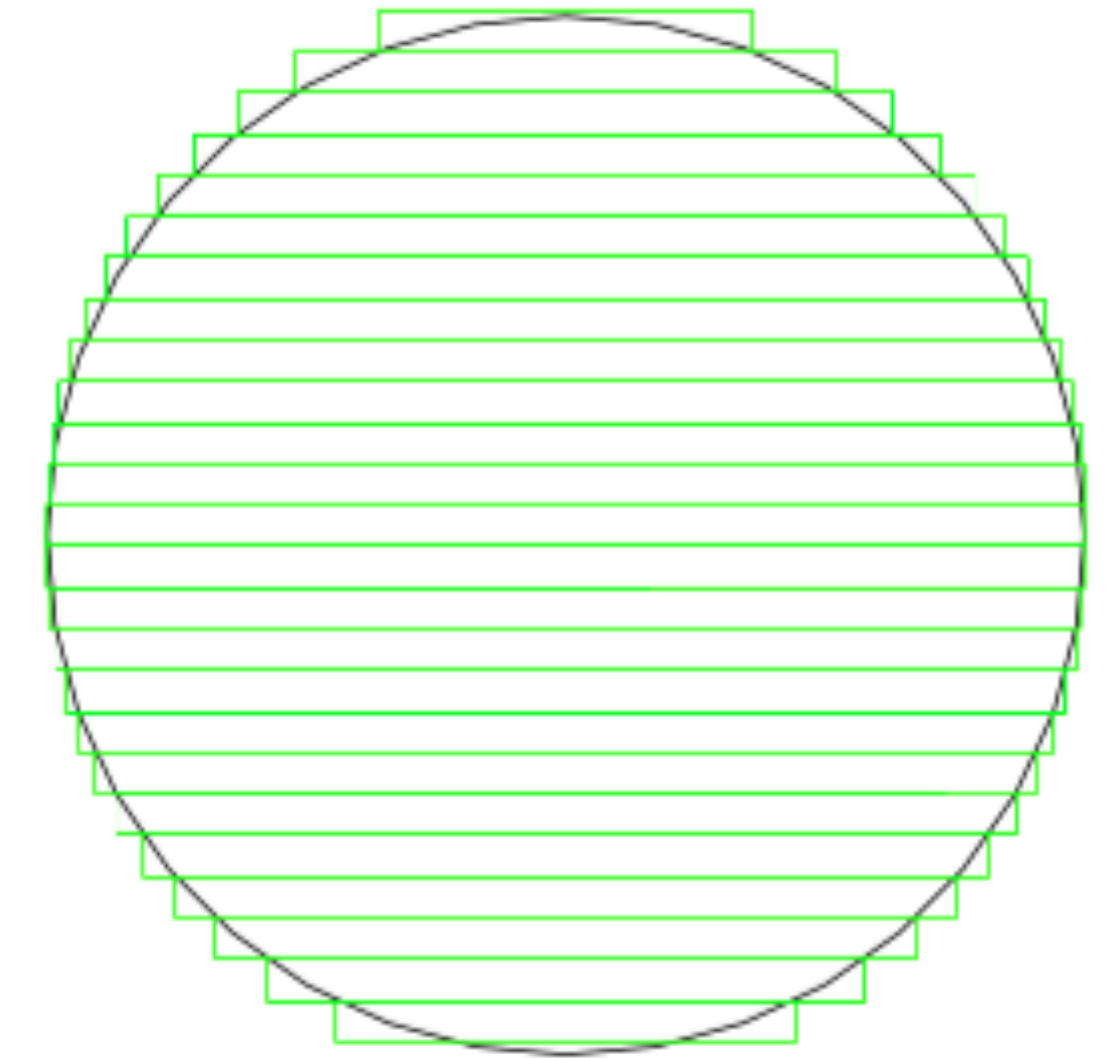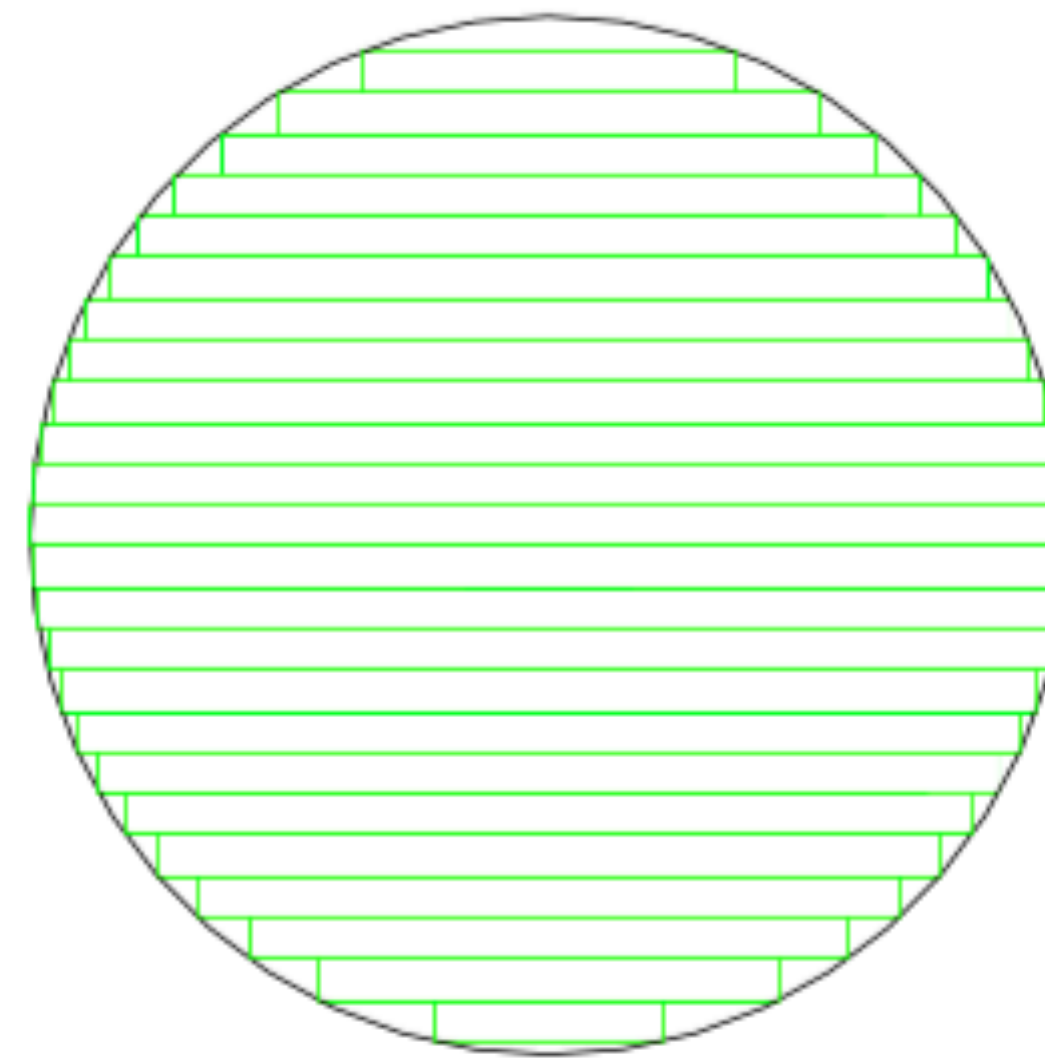
Over and Under Approximation Error
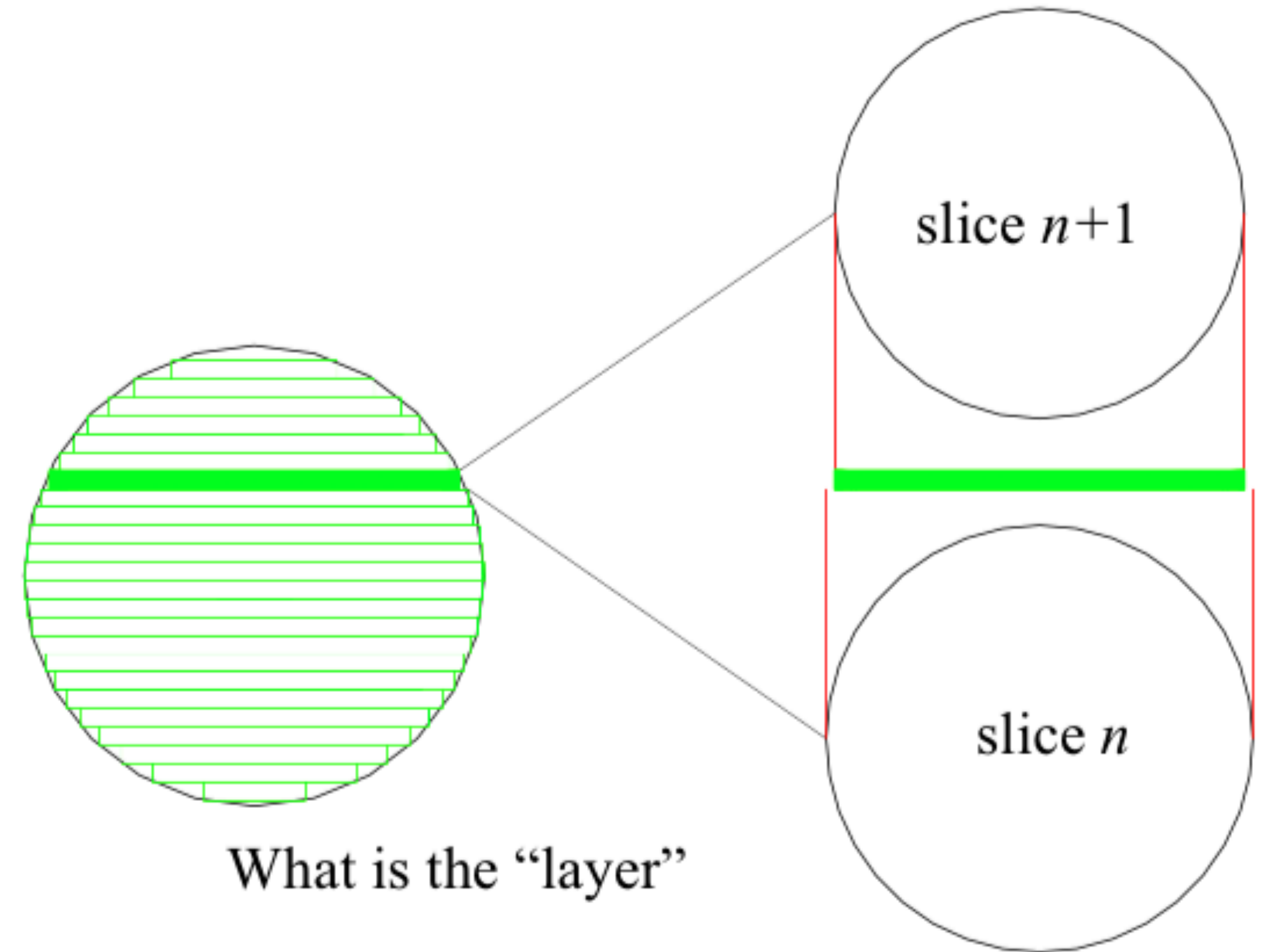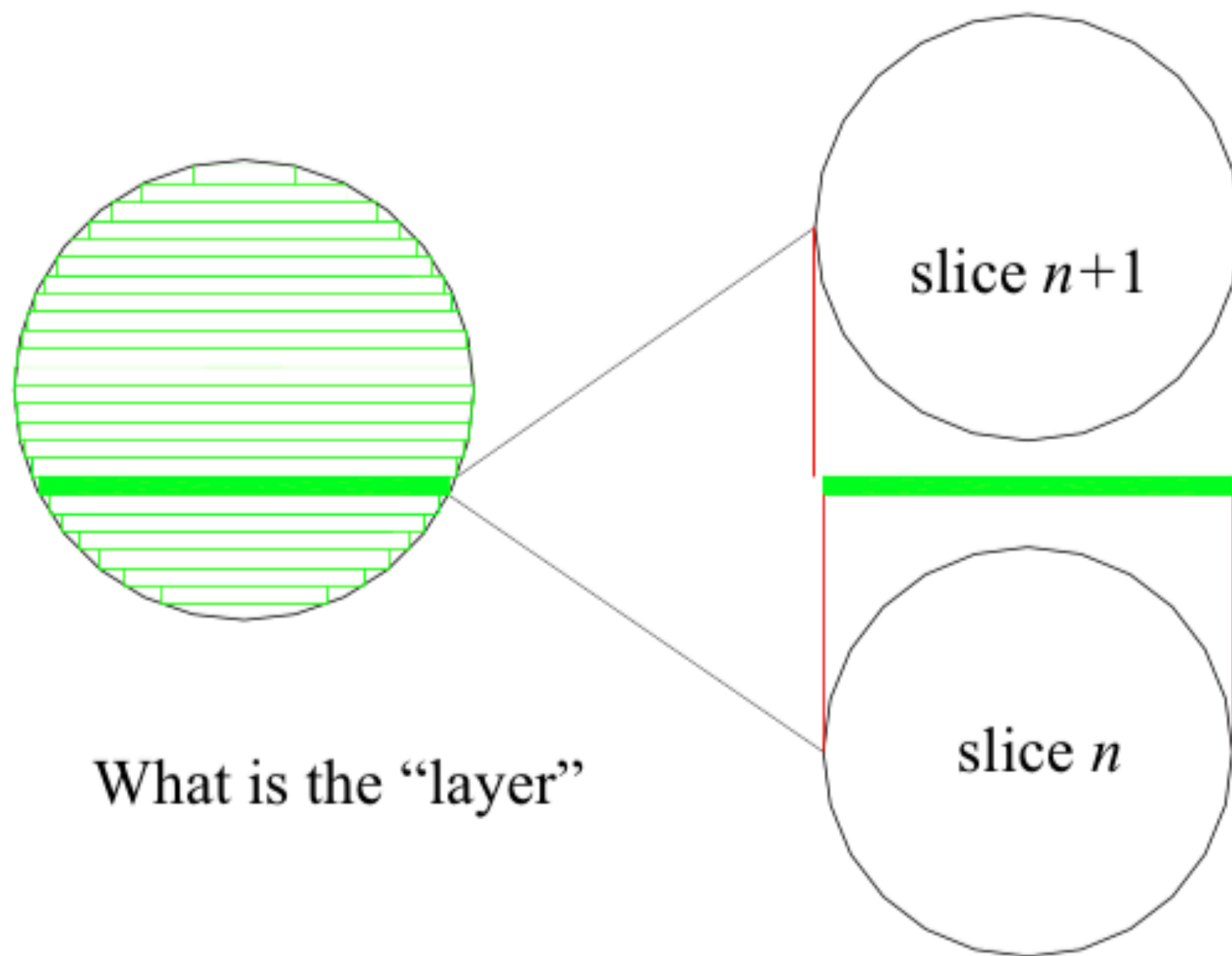
Different Geometry, Similar Slice/Layer Problems


slice $n+1$

slice n
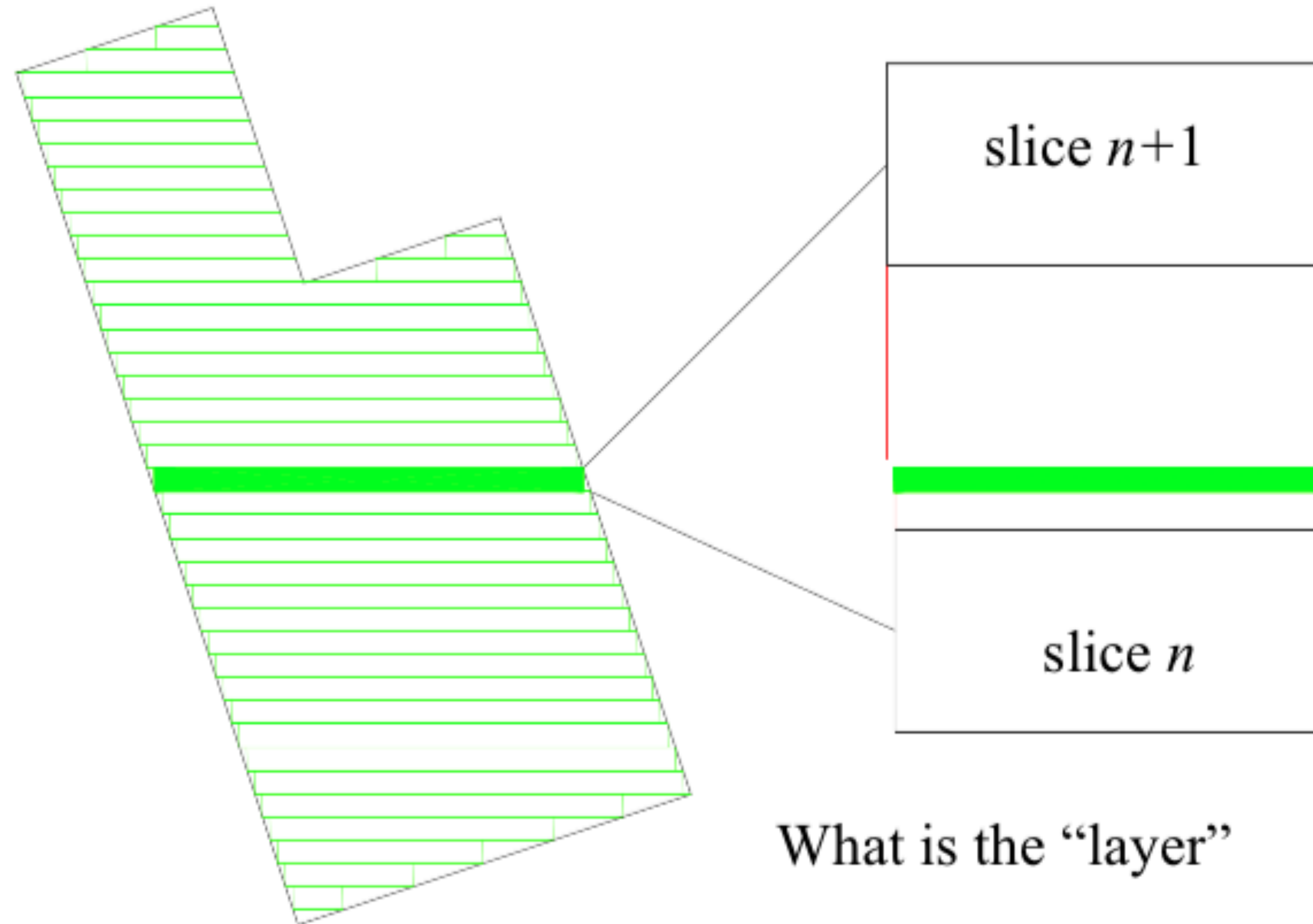
What is the "layer"

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
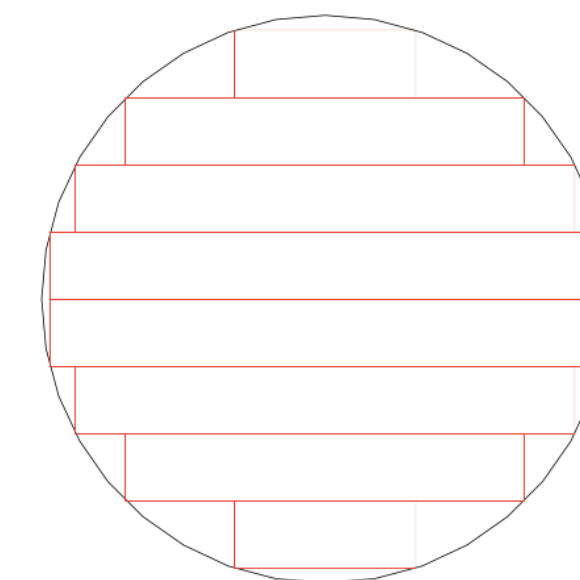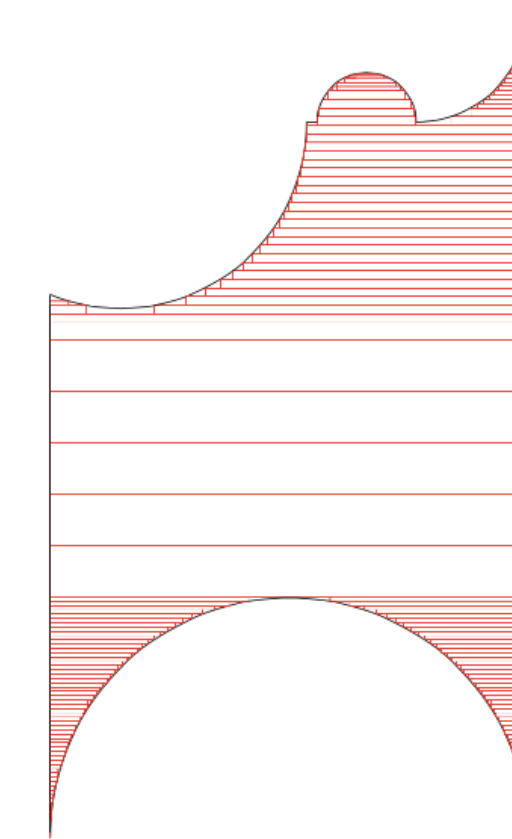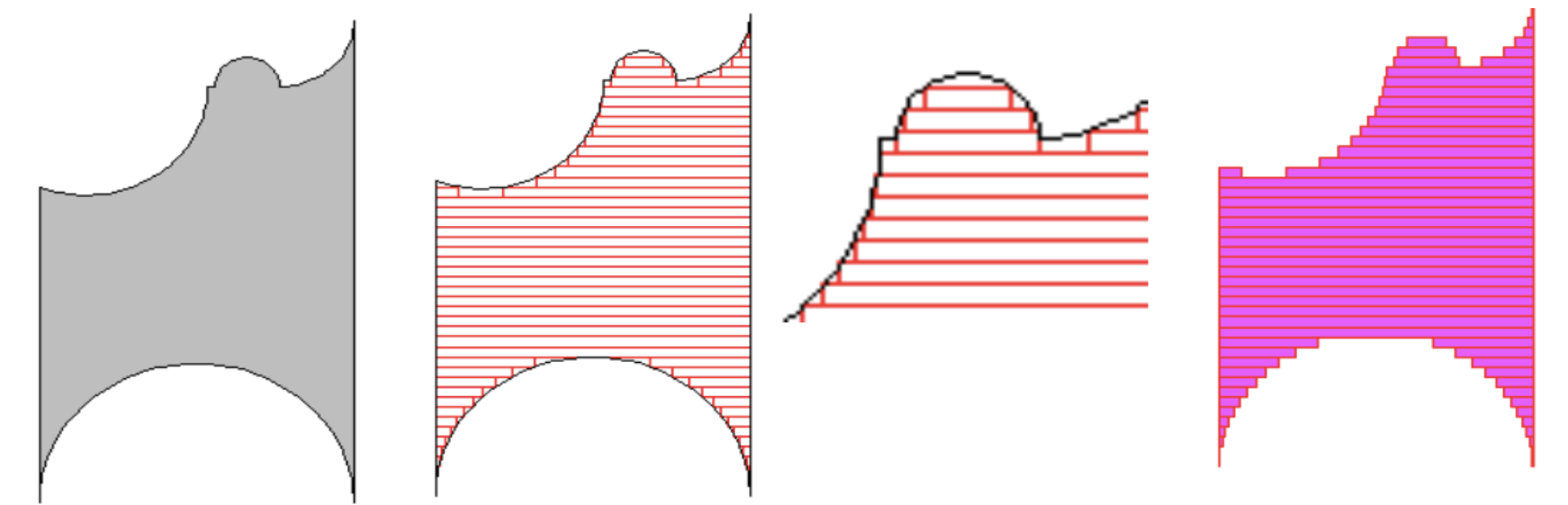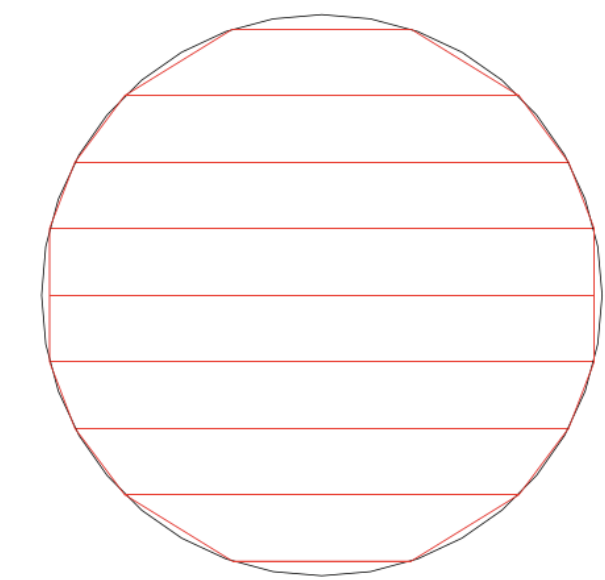
Zeroth-order   First-order

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"?

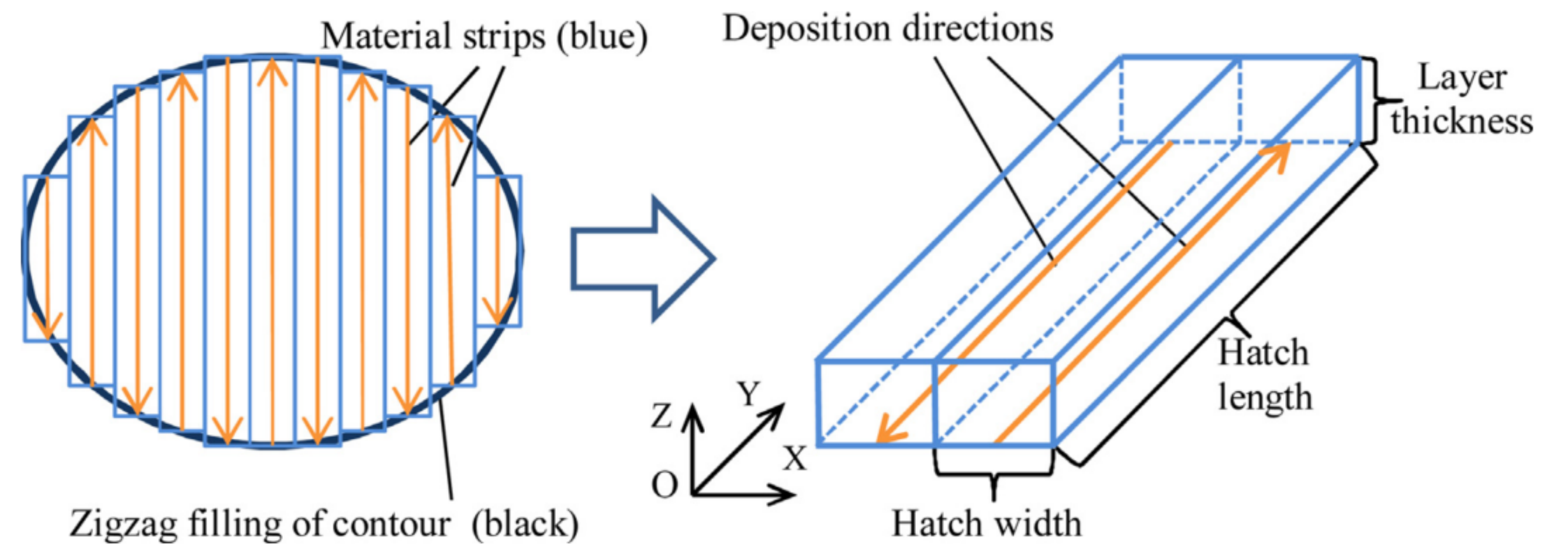- (Hint: layer thickness is almost always larger than X-Y positional tolerance)

Material strips (blue)

Deposition directions

Layer thickness

Hatch length

Zigzag filling of contour (black)

Hatch width

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

MCA Session 1, In-Class Activity #2

- Theme: Hands-On machine component investigation

- Use the provided explanation and hands-on investigation of machine components to answer these questions:

1. For a machine component that is heated and a second that moves, where/when in the G-code do the components get the info they need?

2. What type of data conversion occurs for the motor(s) used in the following G-code commands:

   - G1 X9.202 Y15.578 Z0.600 F9000; Travel Move

   - G1 X8.962 Y15.888 Z0.600 F5400 A47.05344; Inset

3. If you never saw the CAD file, but had the slice files, could you print the part?