

# Additive Manufacturing & 3D Printing



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# Module - 1



## Additive Manufacturing & 3D Printing



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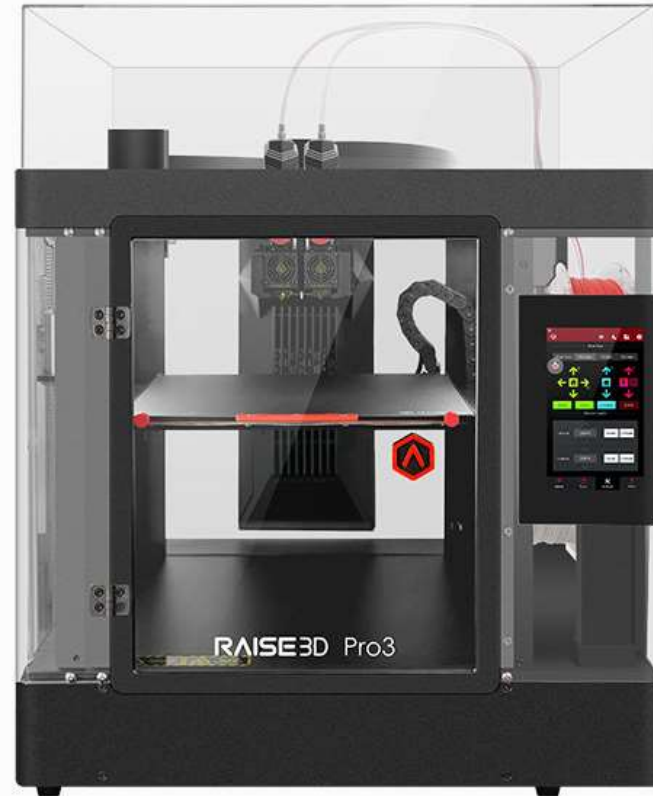
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# What is Additive Manufacturing?



# What is Additive Manufacturing?



1. Additive Manufacturing is a method in which the part is created by a layer upon another layer - additive process.
2. Using a specialized software, a 3-D CAD model is cut into very thin layers or cross-sections.
3. Then, depending on the specific method used (sintering, fused deposition, etc), the AM machine constructs the part layer by layer until a solid replica of the CAD model is generated.
4. The advantages of this process is clear: development of physical models can be accomplished in significantly less time as compared to the machining process.

# Commonly Used Terms for Additive Manufacturing



1. Rapid Prototyping (RP)
2. Direct CAD Manufacturing
3. Desktop Manufacturing
4. Instant Manufacturing
5. CAD Oriented Manufacturing
6. Layer Manufacturing
7. Material Deposit Manufacturing
8. Material Addition Manufacturing
9. Solid Freeforming

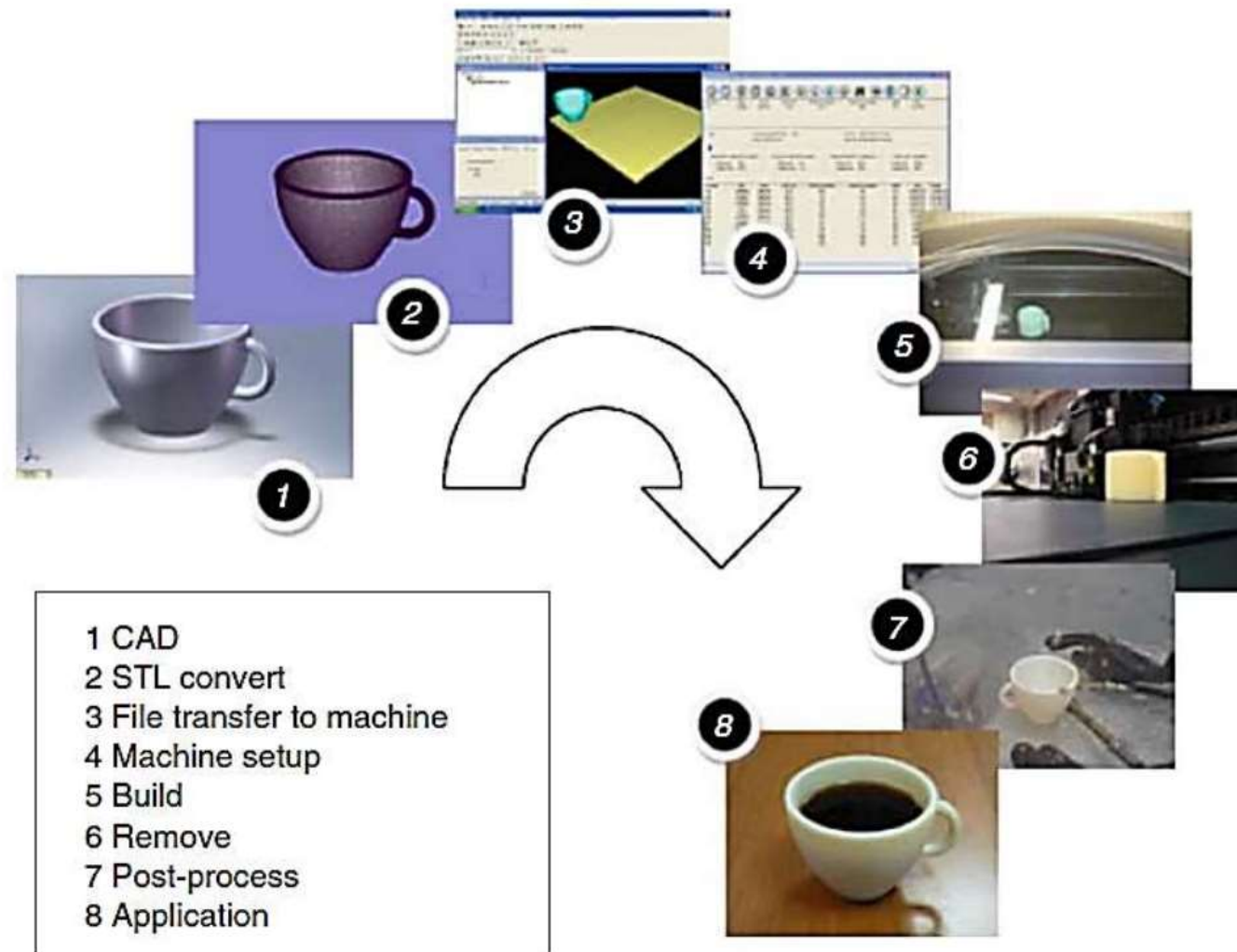
# Additive Manufacturing Process Chain



## The Eight Steps in Additive Manufacture

1. Conceptualization and CAD
2. Conversion to STL
3. Transfer and manipulation of STL file on AM machine
4. Machine setup
5. Build
6. Part removal and clean-up
7. Post-processing of Part
8. Application

# Additive Manufacturing Process Chain



# Additive Manufacturing Process Chain



## Step 1: Conceptualization and CAD

- The generic AM process start with 3D CAD information.
- There may be a many of ways as to how the 3D source data can be created.
- The model description could be generated by a computer.
- Most 3D CAD systems are solid modeling systems with some surface modeling components.



# Additive Manufacturing Process Chain



## Step 2: Conversion to STL

- The term STL was derived from **STereoLithography**.
- STL is a simple way of describing a **CAD** model in terms of its **geometry** alone.
- It **works by removing any construction data, modeling history, etc., and approximating the surfaces of the model with a series of triangular facets.**
- The minimum size of these triangles can be set within most CAD software and the **objective is to ensure the models created do not show any obvious triangles on the surface.**

# Additive Manufacturing Process Chain



## Step 2: Conversion to STL

- The process of converting to **STL** is automatic within most **CAD** systems.
- **STL file repair software** is used when there are problems with the file generated by the CAD system that may prevent the part from being built correctly.
- **With complex geometries**, it may be difficult to detect such problems while inspecting the CAD or the subsequently generated STL data.
- **If the errors are small then they may even go unnoticed** until after the part has been built.

# Additive Manufacturing Process Chain



## Step 2: Conversion to STL

- STL is essentially a surface description, the corresponding triangles in the files must be pointing in the correct direction; (in other words, the surface normal vector associated with the triangle must indicate which side of the triangle is outside vs. inside the part).
- While most errors can be detected and rectified automatically, there may also be a requirement for manual intervention.

# Additive Manufacturing Process Chain



## Step 3: Transfer to AM Machine and STL File Manipulation

- Once the STL file has been created, it can be sent directly to the target AM machine.
- Ideally, it should be possible to press a “print” button and the machine should build the part straight away.
- However there may be a number of actions required prior to building the part.
- The first task would be to verify that the part is correct.
- AM system software normally has a visualization tool that allows the user to view and manipulate the part.

# Additive Manufacturing Process Chain



## Step 3: Transfer to AM Machine and STL File Manipulation

- The user may wish to reposition the part or even change the orientation to allow it to be built at a specific location within the machine.
- It is quite common to build more than one part in an AM machine at a time.
- This may be multiples of the same part (thus requiring a copy function) or completely different STL files.

# Additive Manufacturing Process Chain



## Step 4: Machine Setup

- All AM machines will have at least some setup parameters that are specific to that machine or process.
- Some machines are only designed to run perhaps one or two different materials and with no variation in layer thickness or other build parameters.
- In the more complex cases to have default settings or save files from previously defined setups to help speed up the machine setup process and to prevent mistakes.
- Normally, an incorrect setup procedure will still result in a part being built.

# Additive Manufacturing Process Chain



## Step 5: Build Setup

- The first few stages of the AM process are semi-automated tasks that may require considerable manual control, interaction, and decision making.
- Once these steps are completed, the process switches to the computer controlled building phase.
- All AM machines will have a similar sequence of layer control, using a height adjustable platform, material deposition, and layer cross-section formation.
- All machines will repeat the process until either the build is complete or there is no source material remaining.

# Additive Manufacturing Process Chain



## Step 6: Removal and Cleanup

- The output from the AM machine should be ready for use.
- More often the parts still require a **significant amount of manual finishing** before they are ready for use.
- The part must be either **separated from a build platform** on which the part was produced or removed from excess build material surrounding the part.
- Some AM processes **use additional material** other than that used to make the part itself (secondary support materials).



# Additive Manufacturing Process Chain



## Step 7: Post Process

- Post-processing refers to the (usually manual) stages of finishing the parts for application purposes.
- This may involve abrasive finishing, like polishing and sandpapering, or application of coatings.

# Additive Manufacturing Process Chain



## Step 8: Application

- Following post-processing, parts are ready for use.
- Although parts may be made from similar materials to those available from other manufacturing processes (like molding and casting), parts may not behave according to standard material specifications.
- Some AM processes create parts with small voids or bubbles trapped inside them, which could be the source for part failure under mechanical stress.
- Some processes may cause the material to degrade during build or for materials not to bond, link, or crystallize in an optimum way.

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# Additive Manufacturing versus CNC Machining



- AM processes are very flexible and very capable
- However:
  - AM processes rely on specialized materials.
  - Limited accuracy in some cases.
- CNC Machining is:
  - *Subtractive* process
  - Accurate
  - Capable of using many common manufacturing materials.
- CNC Machining is NOT:
  - Automated
  - Easily usable except by highly skilled technicians
- CNC machining cannot create all parts.
  - No hollow parts.
  - No severely undercut features.
- The time consuming tasks of process and fixture planning are major factors which prohibit CNC machining from being used as a Additive Manufacturing Process.

# Classification of AM Processes



- There are various ways to classify the Additive Manufacturing techniques that have currently been developed
- The AM classification used here is based on the form of the starting material:

**1. Liquid-based**

**2. Solid-based**

**3. Powder-based**

# 1- Liquid-Based AM Processes

- Starting material is a liquid.
- About a dozen AM Processes are in this category.
- Includes the following processes:

**1.1 Stereolithography**

**1.2 Solid Ground Curing**

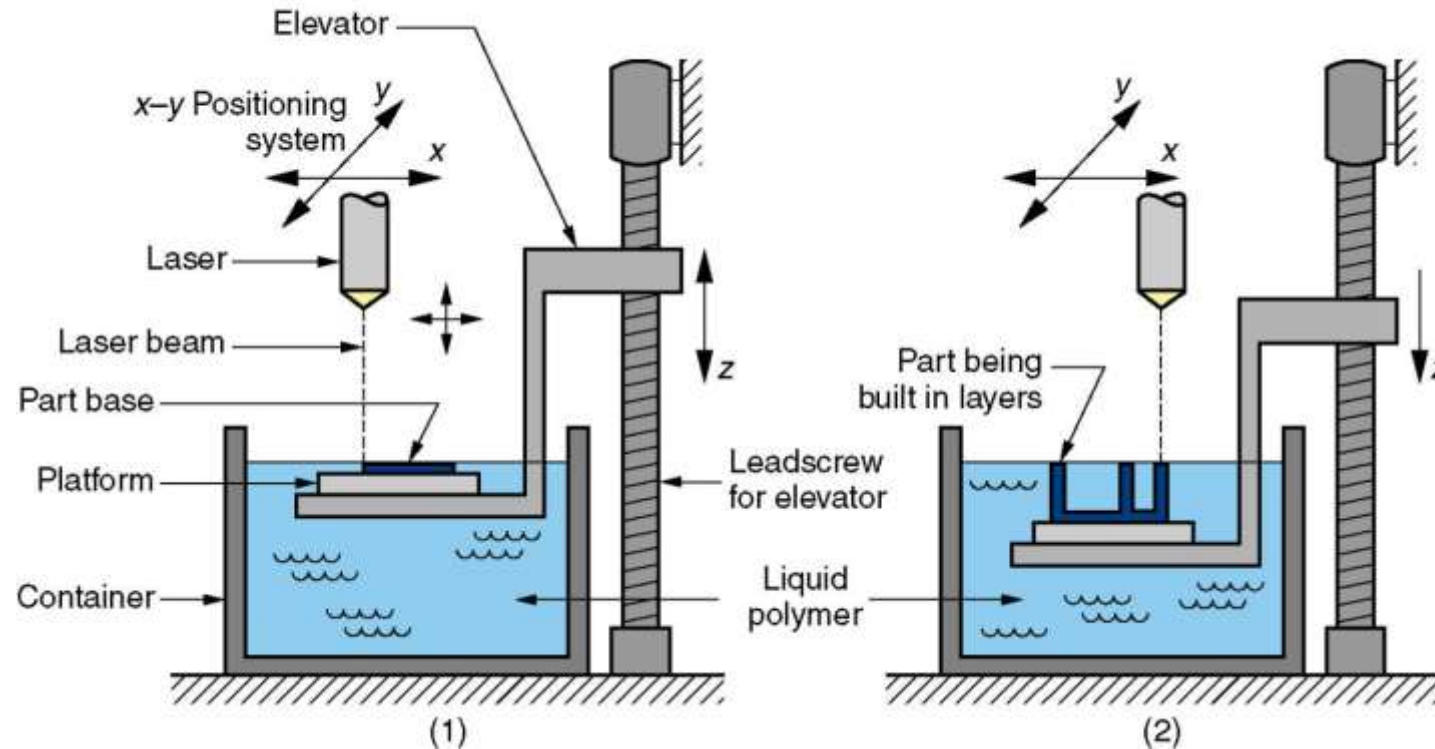
**1.3 Droplet Deposition Manufacturing**

# 1.1-Stereolithography (STL)

AM process for fabricating a solid plastic part out of a photosensitive liquid polymer using a directed laser beam to solidify the polymer.

- Part fabrication is accomplished as a series of layers - each layer is added onto the previous layer to gradually build the 3-D geometry
- The first addition RP/AM technology - introduced 1988 by 3D Systems Inc. based on the work of Charles Hull
- More installations than any other AM method

# Stereolithography



Stereolithography: (1) at the start of the process, in which the initial layer is added to the platform; and (2) after several layers have been added so that the part geometry gradually takes form.





A part produced by stereolithography

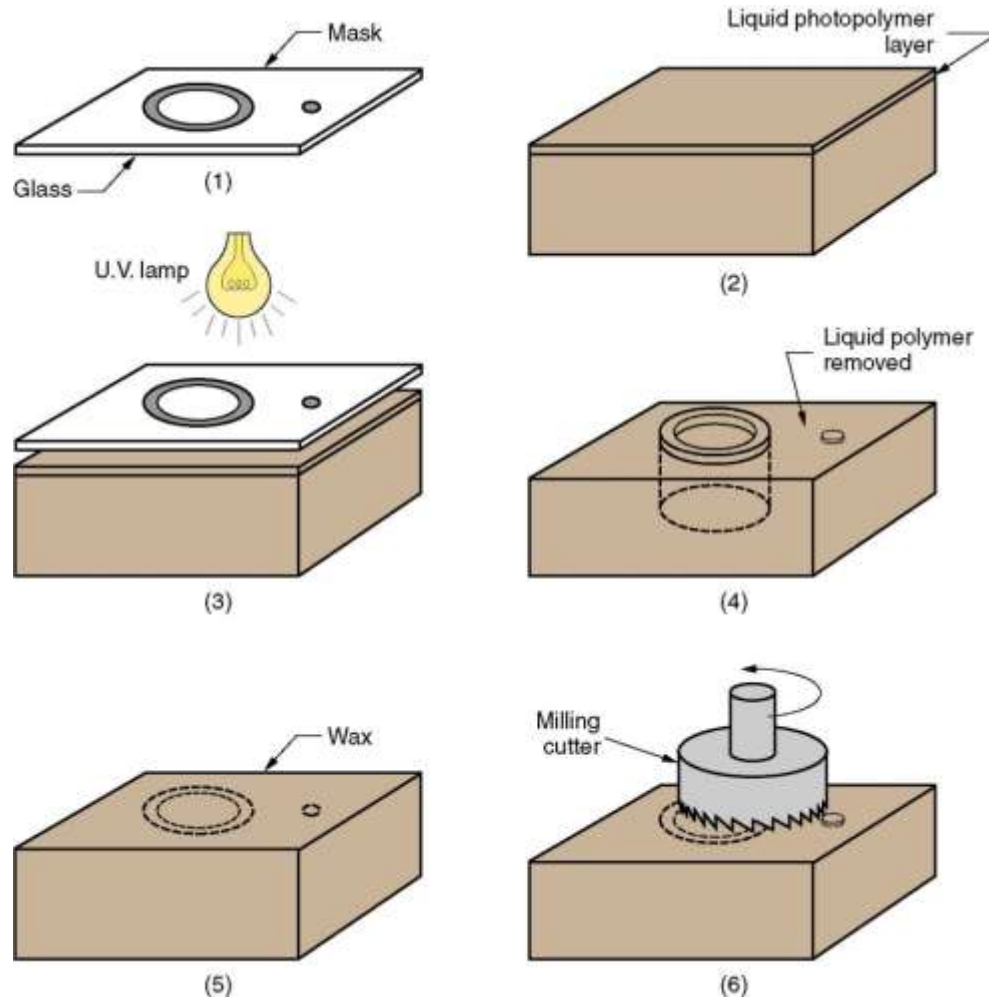
# 1.2- Solid Ground Curing (SGC)



Like stereolithography, SGC works by curing a photosensitive polymer layer by layer to create a solid model based on CAD geometric data.

- Instead of using a scanning laser beam to cure a given layer, the entire layer is exposed to a UV source through a mask above the liquid polymer
- Hardening takes 2 to 3 s for each layer

# Solid Ground Curing



## SGC steps for each layer:

- (1) mask preparation,
- (2) applying liquid photopolymer layer,
- (3) mask positioning and exposure of layer,
- (4) uncured polymer removed from surface,
- (5) wax filling,
- (6) milling for flatness and thickness.

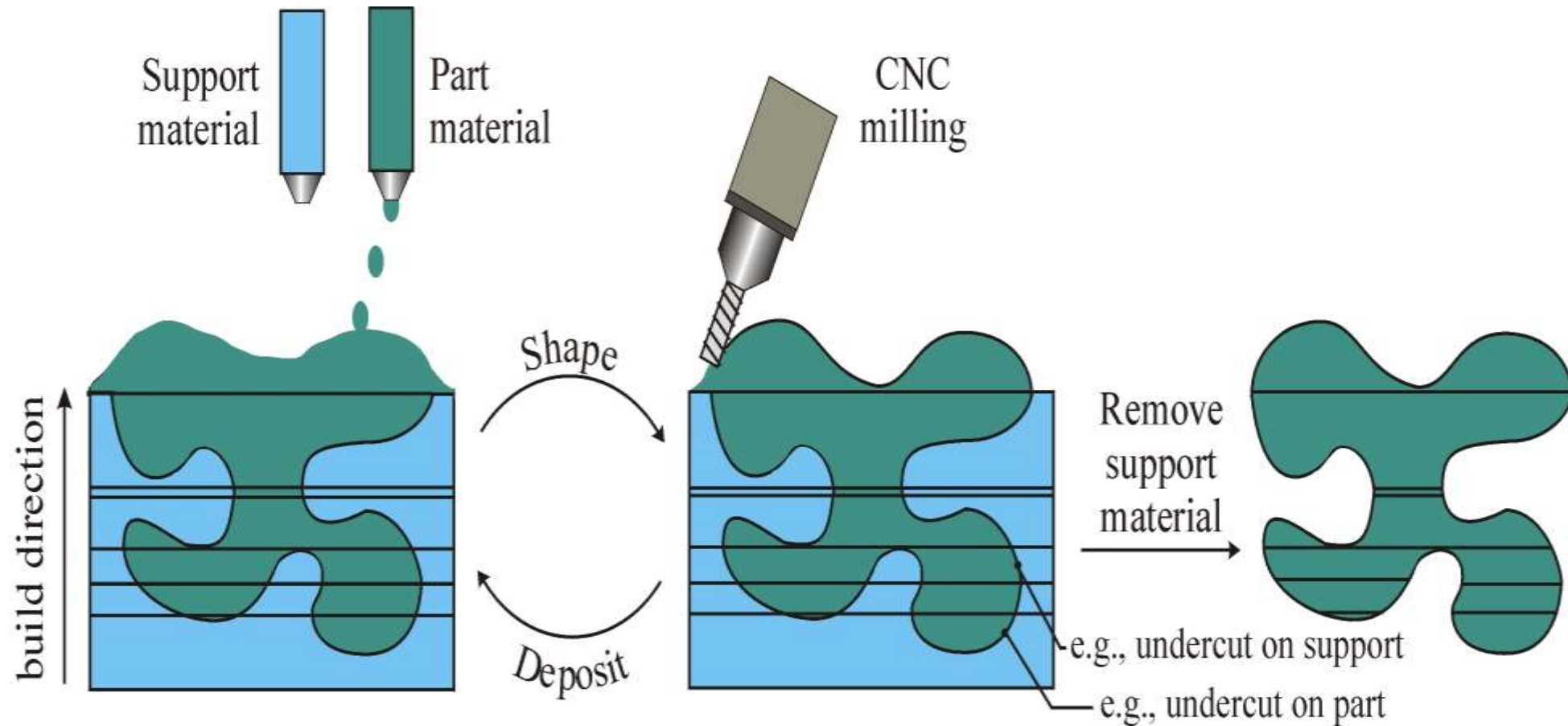
# 1.3- Droplet Deposition Manufacturing (DDM)



Starting material is melted and small droplets are shot by a nozzle onto previously formed layer.

- Droplets cold weld to surface to form a new layer
- Deposition for each layer controlled by a moving x-y nozzle whose path is based on a cross section of a CAD geometric model that is sliced into layers
- Work materials include wax and thermoplastics

# Droplet Deposition Manufacturing (DDM)



# 2- Solid-Based AM Processes



- Starting material is a solid
- Solid-based AM processes include the following processes:

**2.1- Laminated Object Manufacturing**

**2.2- Fused Deposition Modeling**

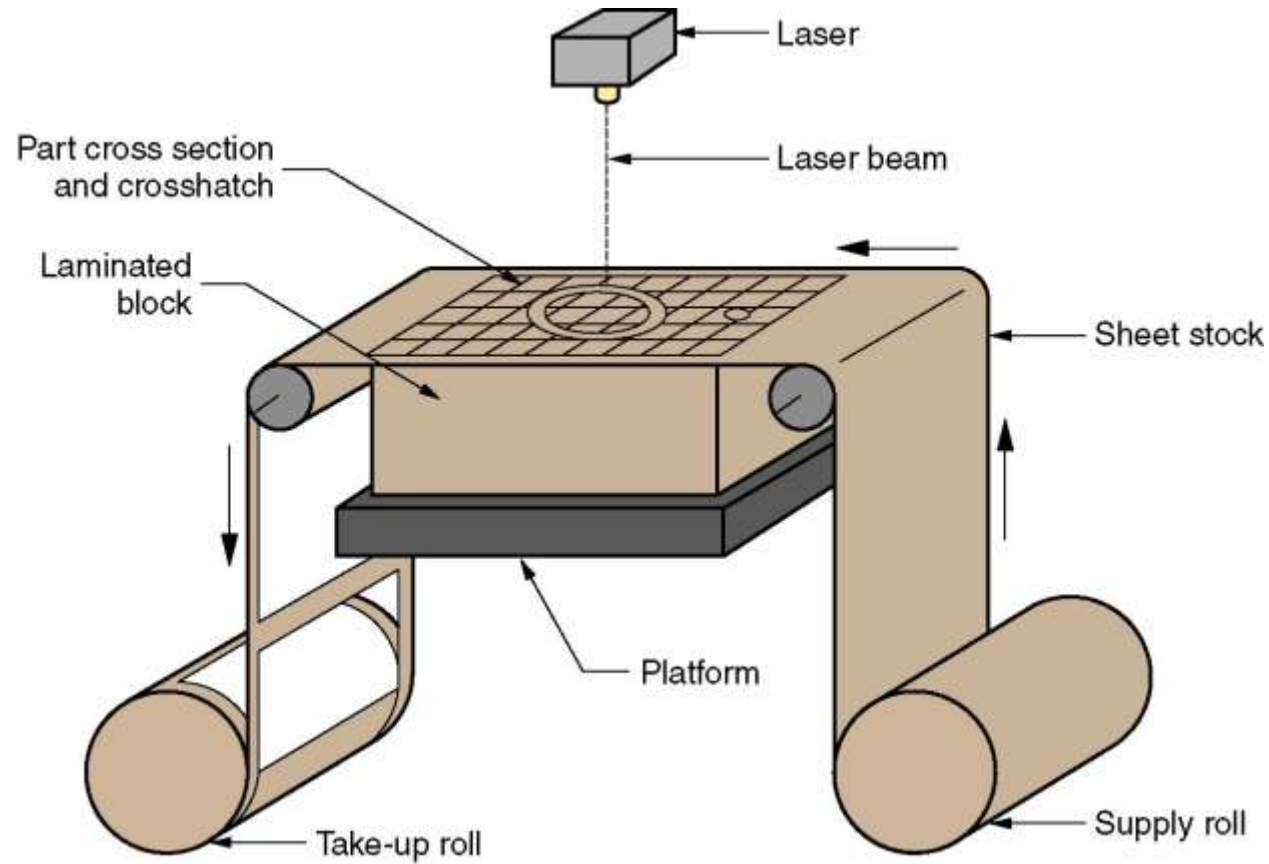
## 2.1- Laminated Object Manufacturing (LOM)



Solid physical model made by stacking layers of sheet stock, each an outline of the cross-sectional shape of a CAD model that is sliced into layers.

- Starting sheet stock includes paper, plastic, cellulose, metals, or fiber-reinforced materials
- The sheet is usually supplied with adhesive backing as rolls that are spooled between two reels
- After cutting, excess material in the layer remains in place to support the part during building

# Laminated Object Manufacturing



Laminated object manufacturing.



## 2.2- Fused Deposition Modeling (FDM)



AM process in which a long filament of wax or polymer is extruded onto existing part surface from a workhead to complete each new layer.

- Workhead is controlled in the  $x$ - $y$  plane during each layer and then moves up by a distance equal to one layer in the  $z$ -direction.
- Extrudate is solidified and cold welded to the cooler part surface in about 0.1 s.
- Part is fabricated from the base up, using a layer-by-layer procedure.

# 3- Powder-Based AM Processes



- Starting material is a powder
- Powder-based AM processes include the following:
  - 3.1- Selective Laser Sintering**
  - 3.2- Three Dimensional Printing**

## 3.1- Selective Laser Sintering (SLS)

Moving laser beam sinters heat-fusible powders in areas corresponding to the CAD geometry model one layer at a time to build the solid part.

- After each layer is completed, a new layer of loose powders is spread across the surface.
- Layer by layer, the powders are gradually bonded by the laser beam into a solid mass that forms the 3-D part geometry.
- In areas not sintered, the powders are loose and can be poured out of completed part.

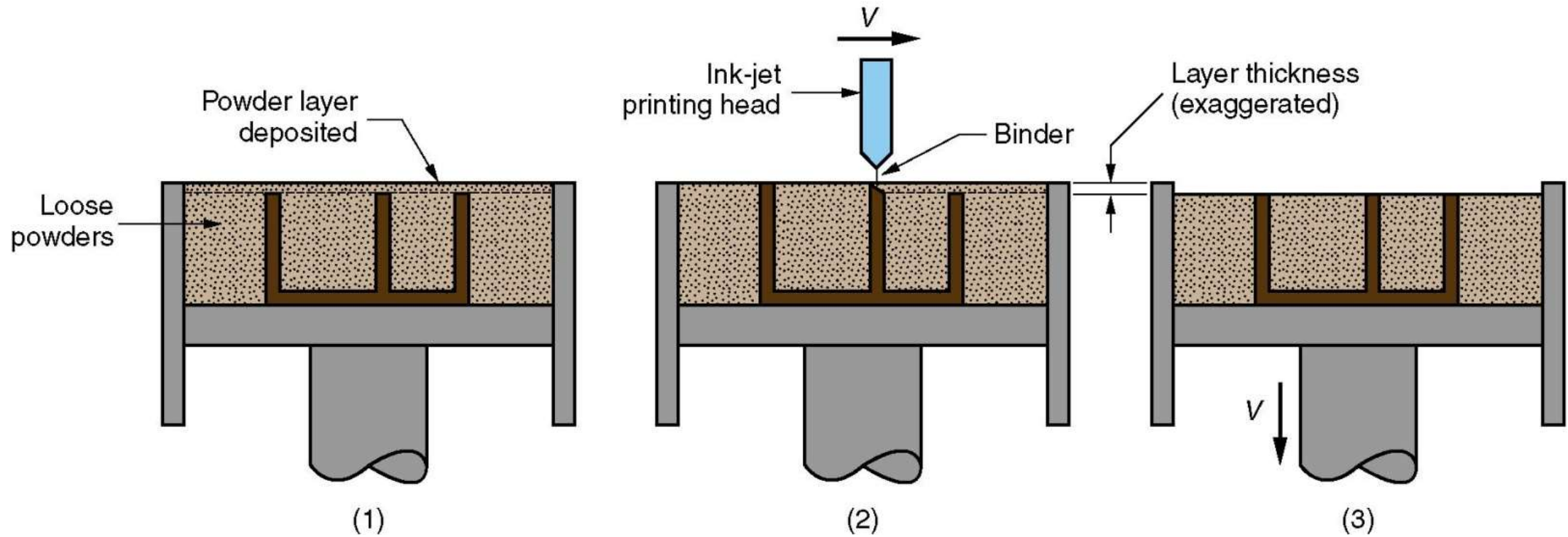
## 3.2- Three Dimensional Printing (3DP)



Part is built layer-by-layer using an ink-jet printer to eject adhesive bonding material onto successive layers of powders.

- Binder is deposited in areas corresponding to the cross sections of part, as determined by slicing the CAD geometric model into layers.
- The binder holds the powders together to form the solid part, while the unbonded powders remain loose to be removed later.
- To further strengthen the part, a sintering step can be applied to bond the individual powders.

# Three Dimensional Printing



Three dimensional printing: (1) powder layer is deposited, (2) ink-jet printing of areas that will become the part, and (3) piston is lowered for next layer (key:  $v$  = motion).

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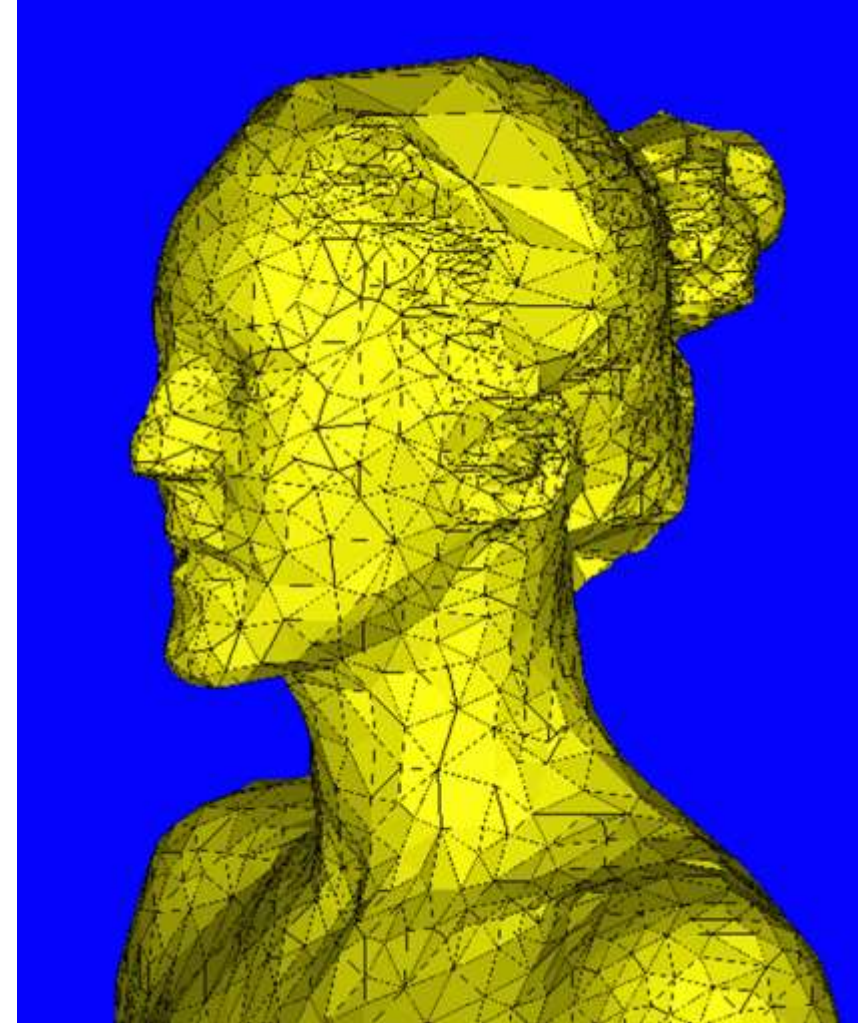
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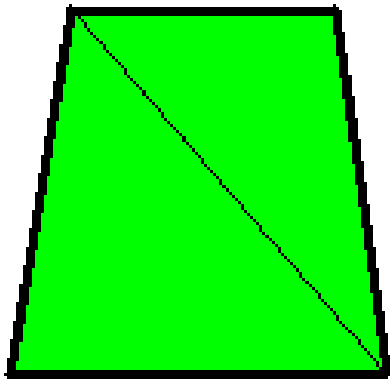
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# Triangulated Surfaces

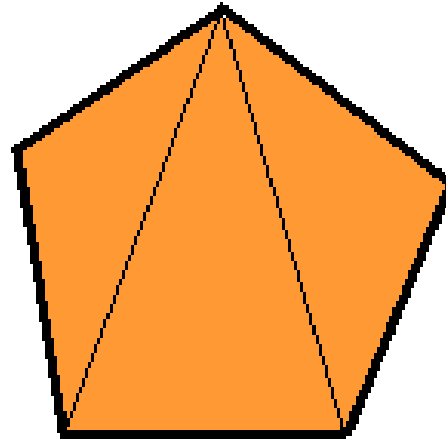
- Any 3D form (polyhedral or curved) can be approximated by a triangulated surface.
- Polygons of 4 or more sides can be divided into triangles.
- On a computer these are represented by listing the three corners for each triangle.
- A corner (a vertex) is described by XYZ coordinates.



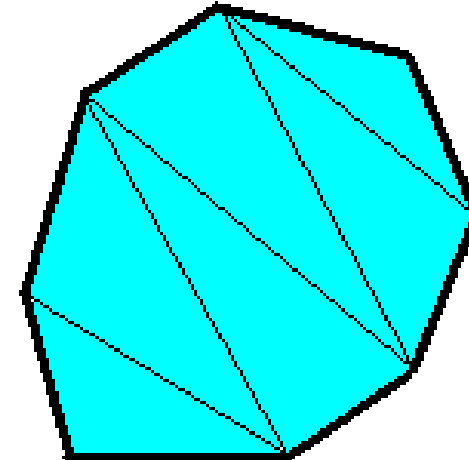
# Polygons Divide into Triangles



4 sides  $\rightarrow$  2



5 sides  $\rightarrow$  3



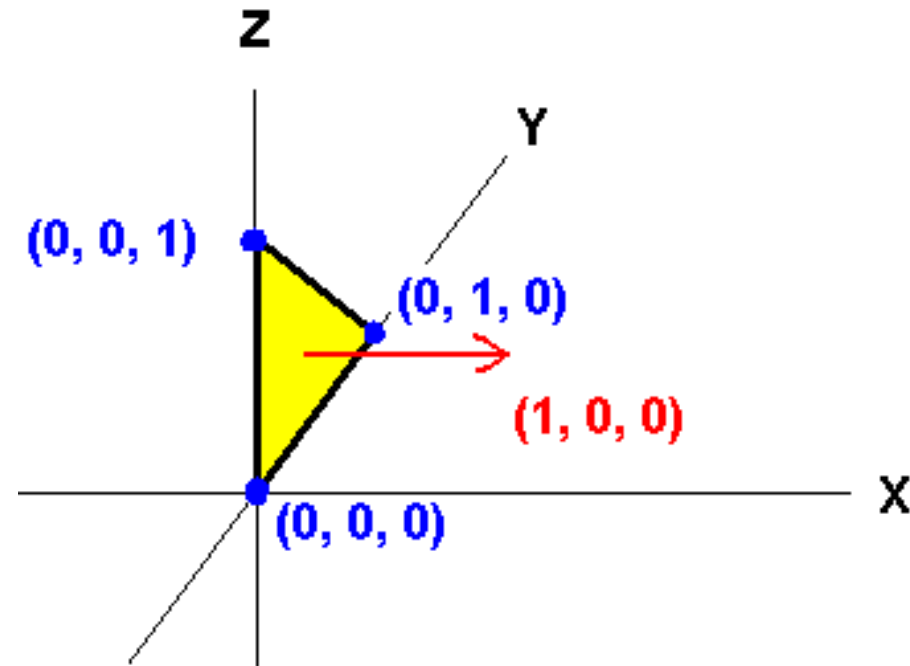
8 sides  $\rightarrow$  6

An  $n$ -gon is represented as  $n-2$  triangles



# Triangles in Space

- Each vertex has (X, Y, Z) coordinates
- List vertices starting with any of the three
- List counter-clockwise as seen from outside
- “Normal vector” points out from object
- Use “Right-handed” XYZ axes



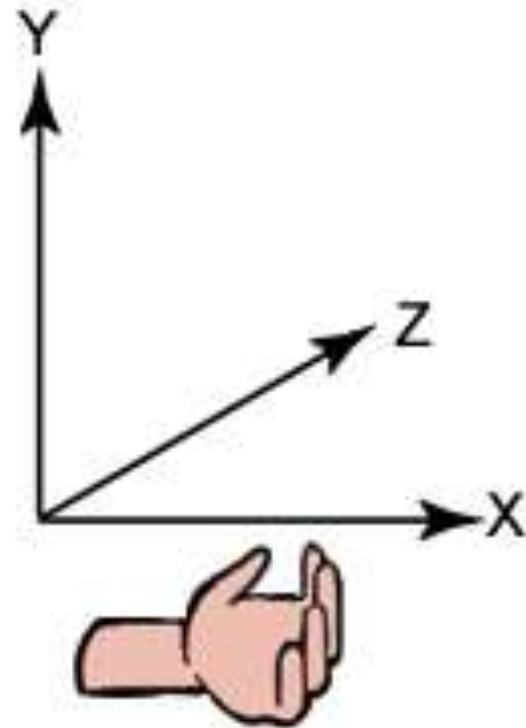
Triangle: (0,0,0) (0,1,0) (0,0,1)

Or: (0,1,0) (0,0,1) (0,0,0)

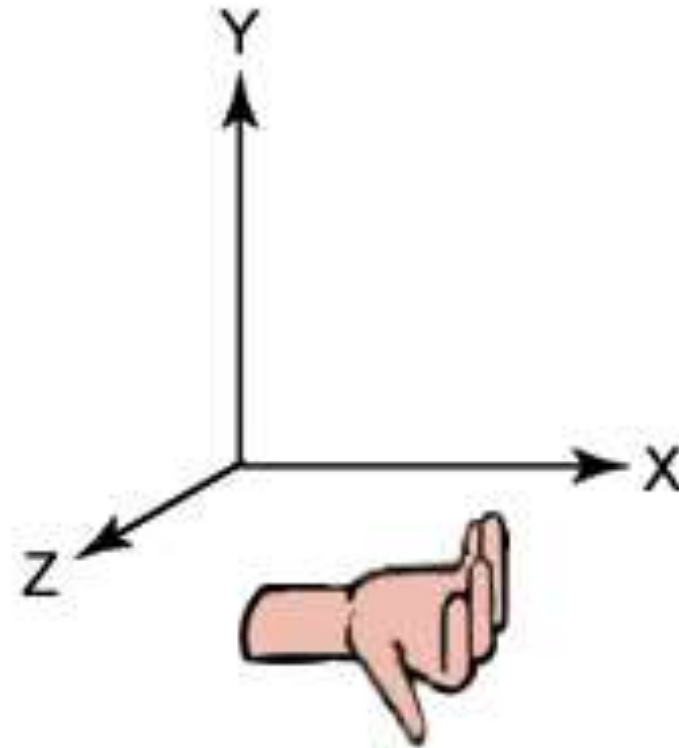
Or: (0,0,1) (0,0,0) (0,1,0)

# “Right-Handed” Coordinate System

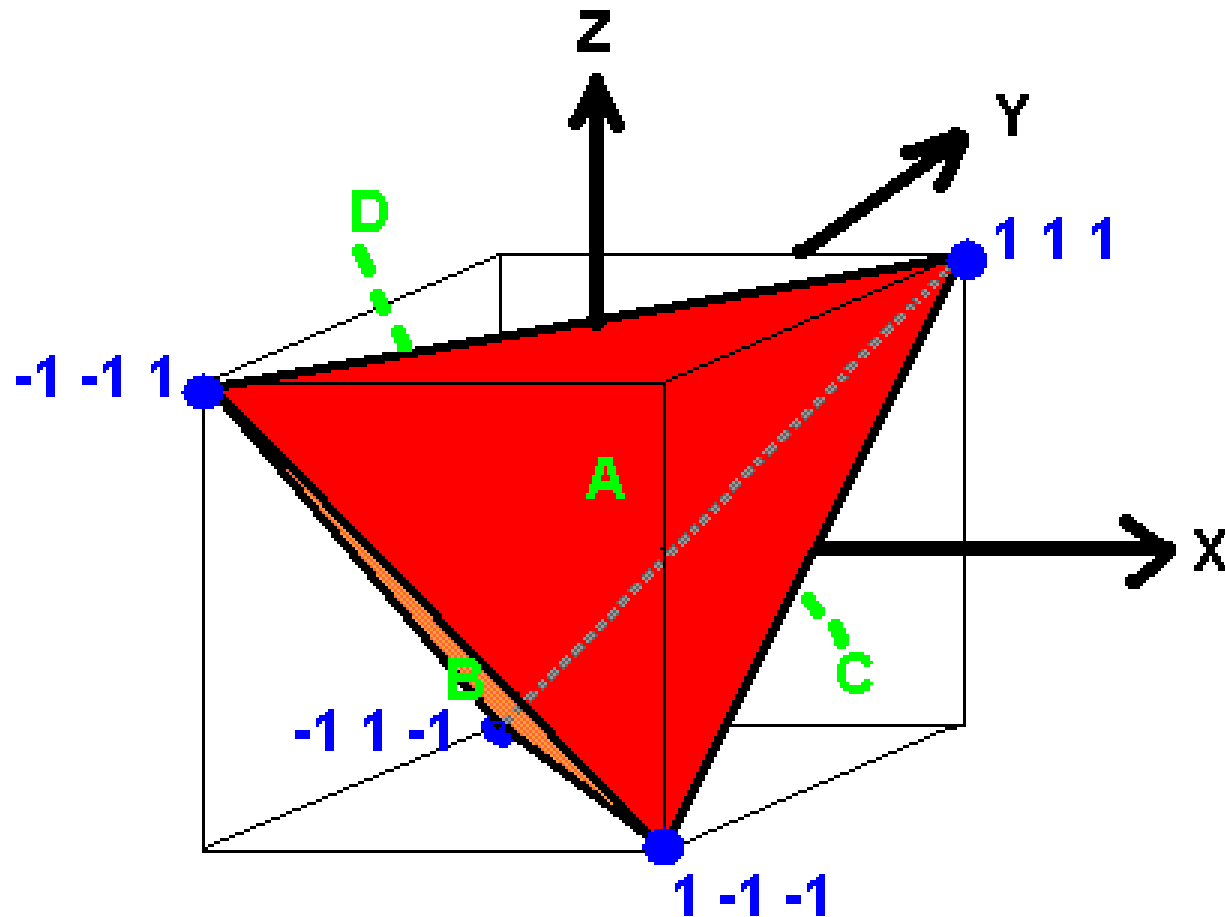
Left-handed  
Cartesian Coordinates



Right-handed  
Cartesian Coordinates



# Example Tetrahedron



- A:  $(1\ 1\ 1)\ (-1\ -1\ 1)\ (1\ -1\ -1)$   
 B:  $(-1\ -1\ 1)\ (-1\ 1\ -1)\ (1\ -1\ -1)$   
 C:  $(1\ 1\ 1)\ (1\ -1\ -1)\ (-1\ 1\ -1)$   
 D:  $(1\ 1\ 1)\ (-1\ 1\ -1)\ (-1\ -1\ 1)$

# *stl* File Format

- You can create an ASCII *stl* file in any text editor, e.g., *word* or *wordpad*
- Then view it in any 3D viewing program.
- Usually a 3D design program (e.g., *Maya*) is used to create/modify/view the file, but we will make files with a text editor as an exercise to understand the process.
- The *stl* file can then be given to a solid freeform fabrication machine to have your form physically created.

# *stl* File Format

- Create file in any text editor
- Write a start line, an end line, and a group of 7 lines for each triangle.
- Triangles can be listed in any order.

```
solid <name>  
  <triangle 1 (7 lines)>  
  <triangle 2 (7 lines)>  
  <triangle 3 (7 lines)>  
  ...  
endsolid <name>
```

# *stl* File Format

- For each triangle give 7 lines:

facet normal 0 0 0

outer loop

vertex X Y Z

vertex X Y Z

vertex X Y Z

endloop

endfacet

- Only the X Y Z parts need to change for each triangle
- (Some programs need the “normal”)
- Easy to “copy” and “paste” in editor

# Example *stl* File Format (ASCII)

solid tetrahedron

facet normal 0 0 0

outer loop

vertex 1 1 1

vertex 1 -1 -1

vertex -1 1 -1

endloop

endfacet

facet normal 0 0 0

outer loop

vertex 1 1 1

vertex -1 1 -1

vertex -1 -1 1

endloop

endfacet

facet normal 0 0 0

outer loop

vertex 1 1 1

vertex -1 -1 1

vertex 1 -1 -1

endloop

endfacet

facet normal 0 0 0

outer loop

vertex -1 1 -1

vertex 1 -1 -1

vertex -1 -1 1

endloop

endfacet

endsolid tetrahedron

# Demonstration



- Design an object (a pyramid)
  - determine coordinates of vertices
  - determine triangles
- Create *.stl* file in editor
- Save it with new name, e.g., *pyramid.stl*
- Paste in start line, group of 7 lines, and end line
- Edit it to have enough groups of 7 lines
- Edit each group to have the three XYZs for one triangle
- View it in 3D viewing program
- Find any problems and edit file to fix them.



# Slicing Techniques

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- STL-based Slicing
  - Direct Slicing
  - Slicing Software
-

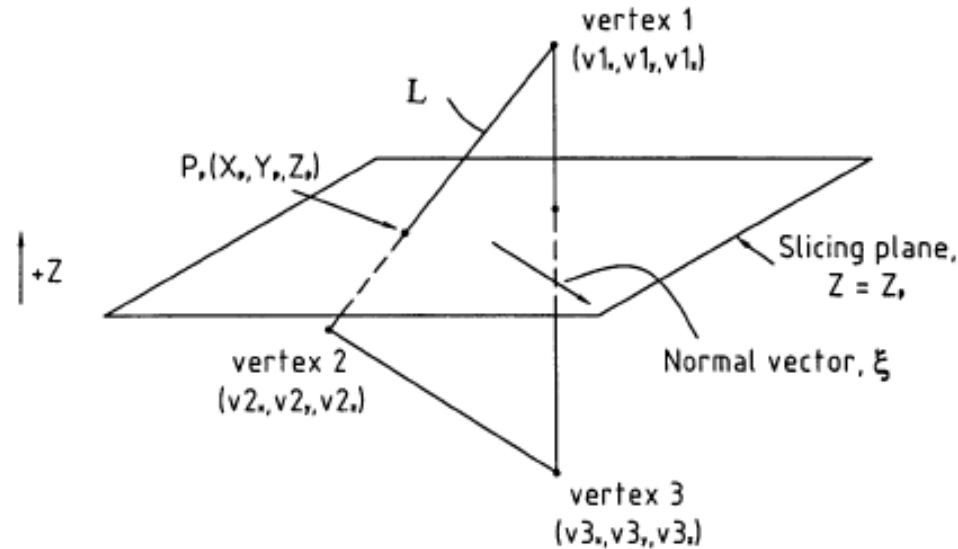
# Model Slicing

An STL model is sliced by intersecting it with horizontal slicing plane, each of which gives piecewise linear contours of a layer.

A slice of a complex object may have groups of contours and each group may have multiple internal and external complex contours.

The contours of a slice are distributed in a random manner without any known topological hierarchy relationship.

# Model Slicing



$$\frac{X_p - v1_x}{v2_x - v1_x} = \frac{Y_p - v1_y}{v2_y - v1_y} = \frac{Z_p - v1_z}{v2_z - v1_z} = t$$

$$(0 \leq t \leq 1)$$

Liao, YS and Chiu, YY, A New Slicing Procedure for Rapid Prototyping Systems, The International Journal of Advanced Manufacturing Technology, (2001).

# Model Slicing

## Slicing Strategies

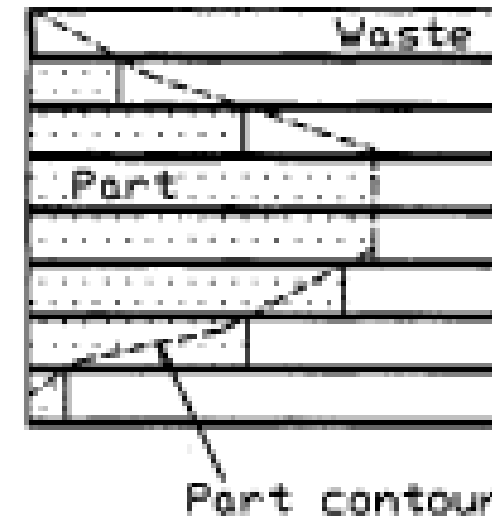
### Top-down slicing

The intersection point between the facet and the slicing plane is calculated and extended down to the thickness of the layer.

$$X_p = \frac{(Z_p - v1_z)(v2_x - v1_x)}{(v2_z - v1_z)} + v1_x$$

$$Y_p = \frac{(Z_p - v1_z)(v2_y - v1_y)}{(v2_z - v1_z)} + v1_y$$

$Z_p$ : the slicing height



Liao, YS and Chiu, YY, A New Slicing Procedure for Rapid Prototyping Systems, The International Journal of Advanced Manufacturing Technology, (2001).

# Model Slicing

## Bottom up slicing

The intersection point between the facet and the slicing plane is calculated and extended up to the thickness of the layer

## Slicing Strategies

If

$$Z_p \geq v2_z$$

$$X_p = \frac{(Z_p - v1_z)(v2_x - v1_x)}{(v2_z - v1_z)} + v1_x$$

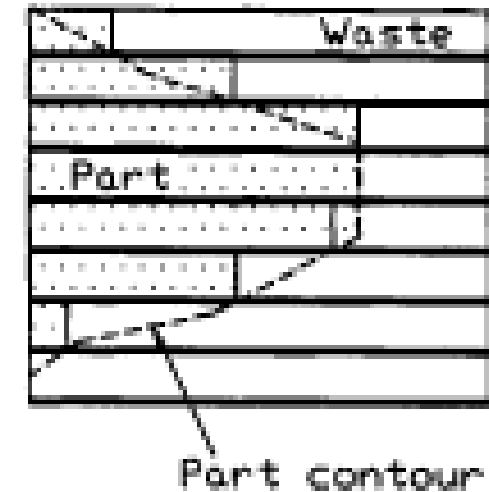
$$Y_p = \frac{(Z_p - v1_z)(v2_y - v1_y)}{(v2_z - v1_z)} + v1_y$$

If

$$Z_p < v2_z$$

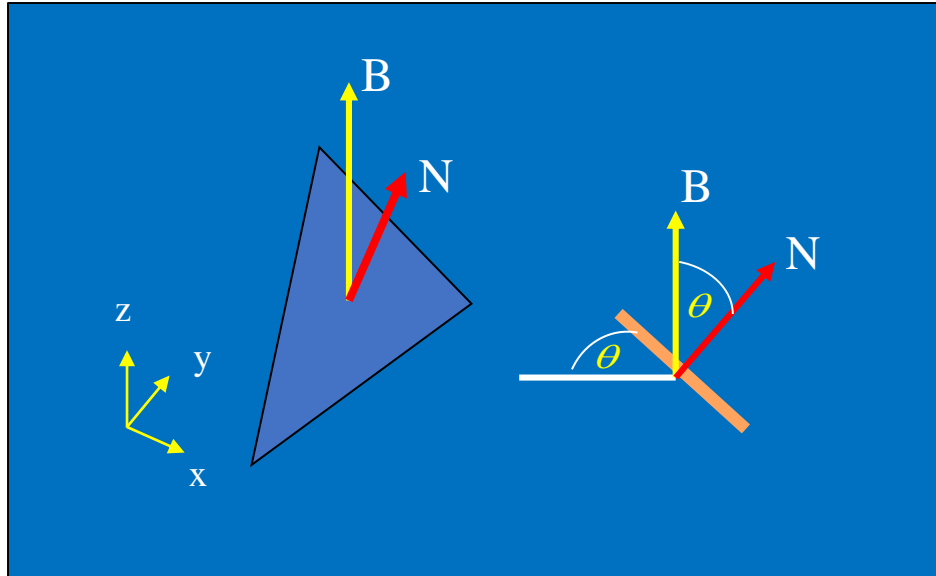
$$X_p = \frac{(Z_p - v2_z)(v3_x - v2_x)}{(v3_z - v2_z)} + v2_x$$

$$Y_p = \frac{(Z_p - v2_z)(v3_y - v2_y)}{(v3_z - v2_z)} + v2_y$$



$Z_p$ : Slicing height of the previous layer

# Model Slicing



B: Unit building direction  
N: Unit normal direction  
 $\theta$ : Angle between the facet  
and the horizontal plane

$$D = B \bullet N$$

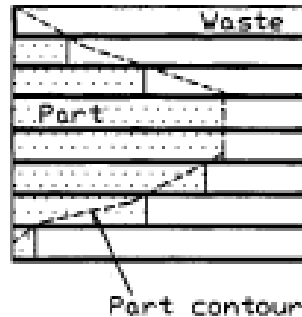
If  $D=0$ , the intersection point is at the exact contour

If  $D<0$ , the intersection point is the positive tolerance

If  $D>0$ , the intersection point is the negative tolerance

# Model Slicing

The two slicing strategies can create both oversize and undersize problems depending on the slopes

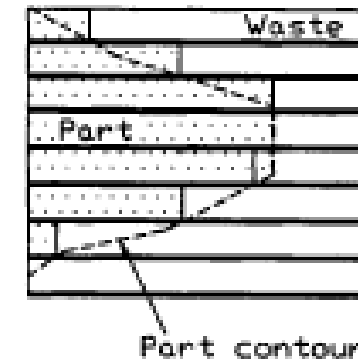


For Top down

- Negative slope results in undersize
- Positive slope results in oversize

For Bottom up

- Negative slope results in oversize
- Positive slope results in undersize

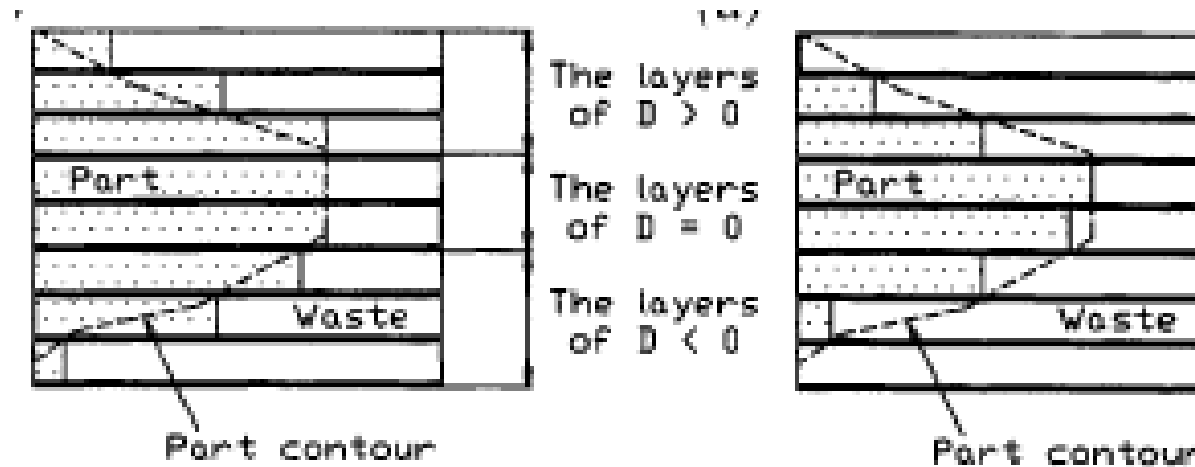


# Model Slicing

## Positive Tolerance Slicing

- If slope is negative, use bottom up method
- If slope is positive, use top down method

## Alternative Slicing Strategies

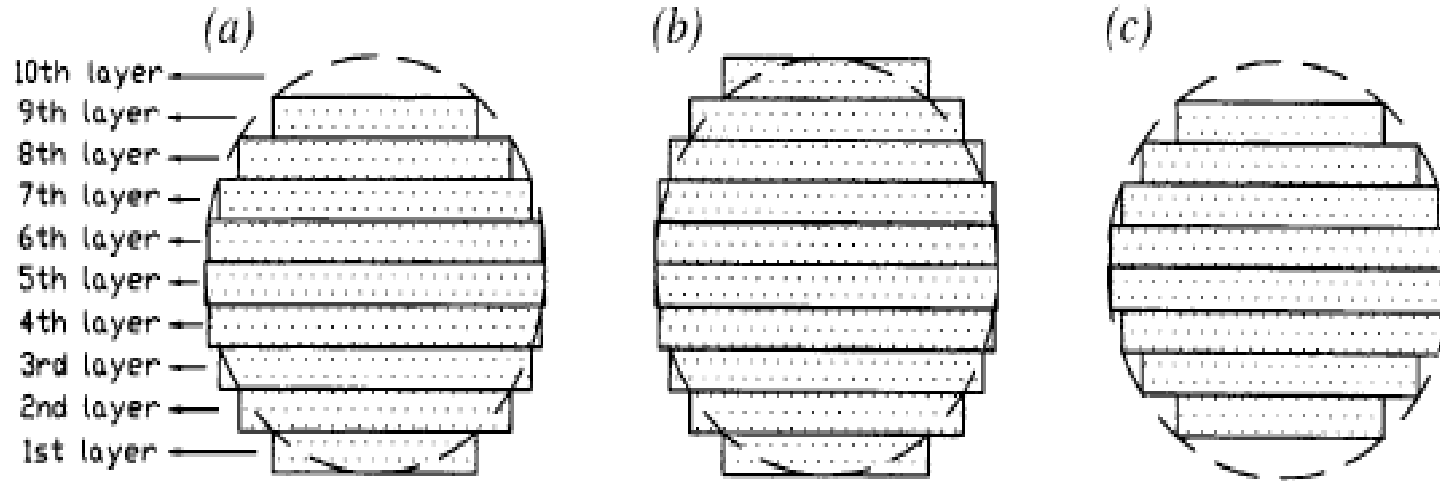


## Negative Tolerance Slicing

- If slope is negative, use top down method
- If slope is positive, use bottom up method



# Model Slicing

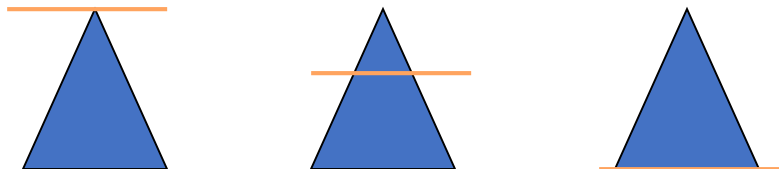


Layer	Dot value (D)	Slicing methods: top down (T) or bottom up (B)		
		Ordinary slicing method	Positive tolerance	Negative tolerance
1	-0.9	T	T	B
2	-0.7	T	T	B
3	-0.5	T	T	B
4	-0.3	T	T	B
5	-0.1	T	T	B
6	0.1	T	B	T
7	0.3	T	B	T
8	0.5	T	B	T
9	0.7	T	B	T
10	0.9	T	B	T

# Model Slicing

To minimize memory usage, a pick-and drop approach that reads one facet at a time has been applied.

- The z coordinates of the three vertices are compared with the current cutting plane.
- If the facet does not intersect with the plane, it will be ignored.
- If the intersection exists, its line segment will be kept in a linked list.



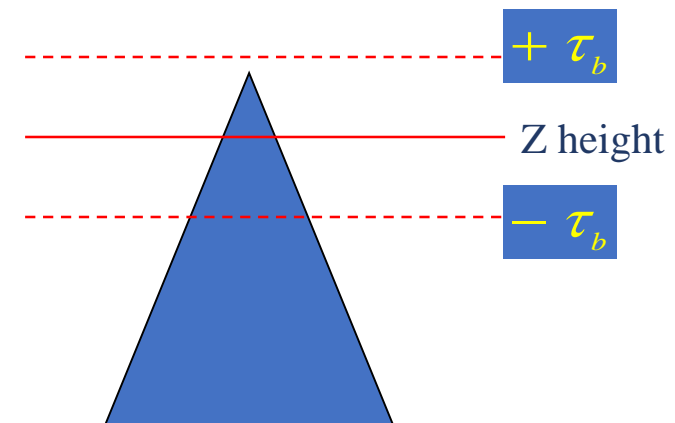
# Model Slicing

The critical factor in the slicing process is the choice of degree of vicinity that is a numerical difference between an absolute original and absolute represented value.

The degree of vicinity specifies how close two values are.

Since rounding-off error is bound to occur during operations on floating data, a bound tolerance,  $\tau_b$ , is set.

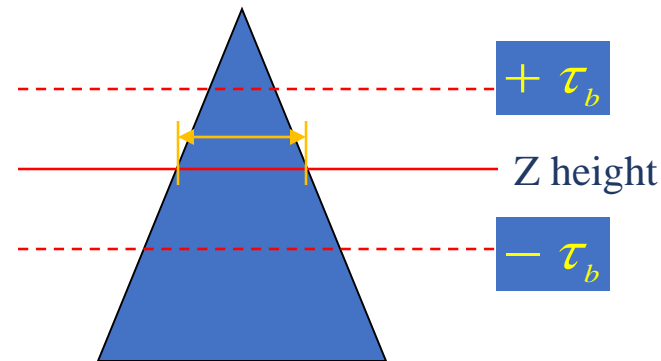
The difference is regarded equal if it is within a tolerance range.



# Model Slicing

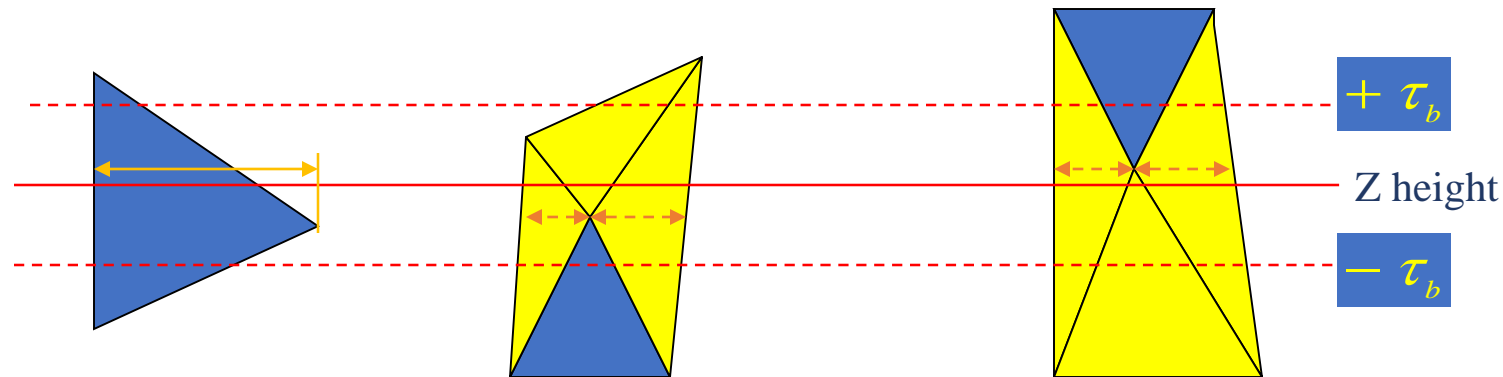
The possible cases of intersection of a facet and the cutting plane can be categorized into four groups

Group 1: This is a normal case where the intersection is away from the three vertices. The line segment is calculated directly from the two end points of the intersection.



# Model Slicing

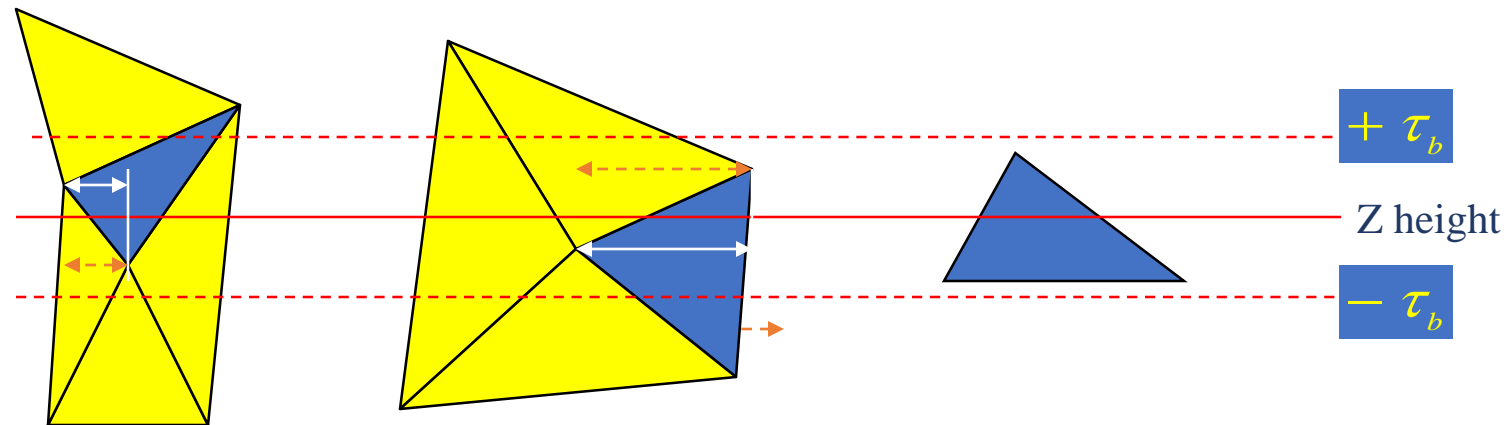
Group 2: One vertex lies in the cutting plane. This can be subdivided into three regions. If the remaining two vertices lie in the different regions, the segment is valid. If they are in the same region, it is ignored as the line segment will be identified from its neighboring facets.



# Model Slicing

Group 3: Two vertices lie in the cutting plane. This is a concurrent case that results in duplicated line segment and one of them should be ignored.

Group 4: All vertices lie in the cutting plane. This is a rare case and is covered by other cases.

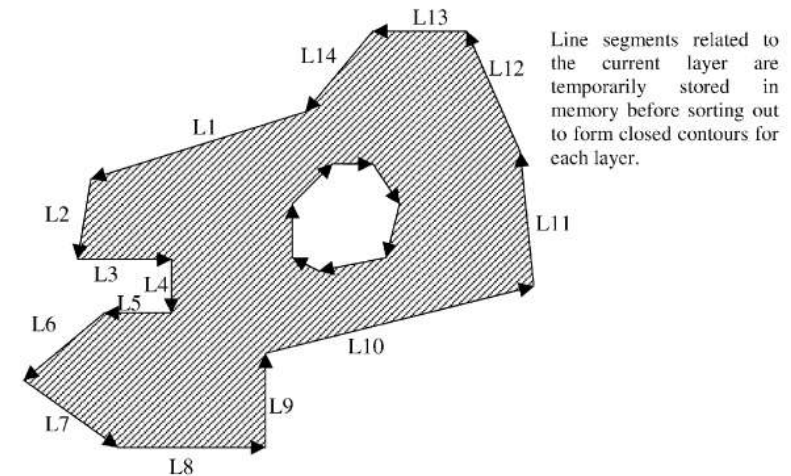


# Model Slicing

## Contour Construction by head-to-tail- search

All line segments in the linked list are used to construct contours. The facet normals determine the pointing directions of the line segments by the head-to-tail search.

The start and the end vertices of the line segments are called the head and the tail. The search repeatedly connects the line segments by checking the vicinity of its head with the tail of the neighbor using bound tolerance.

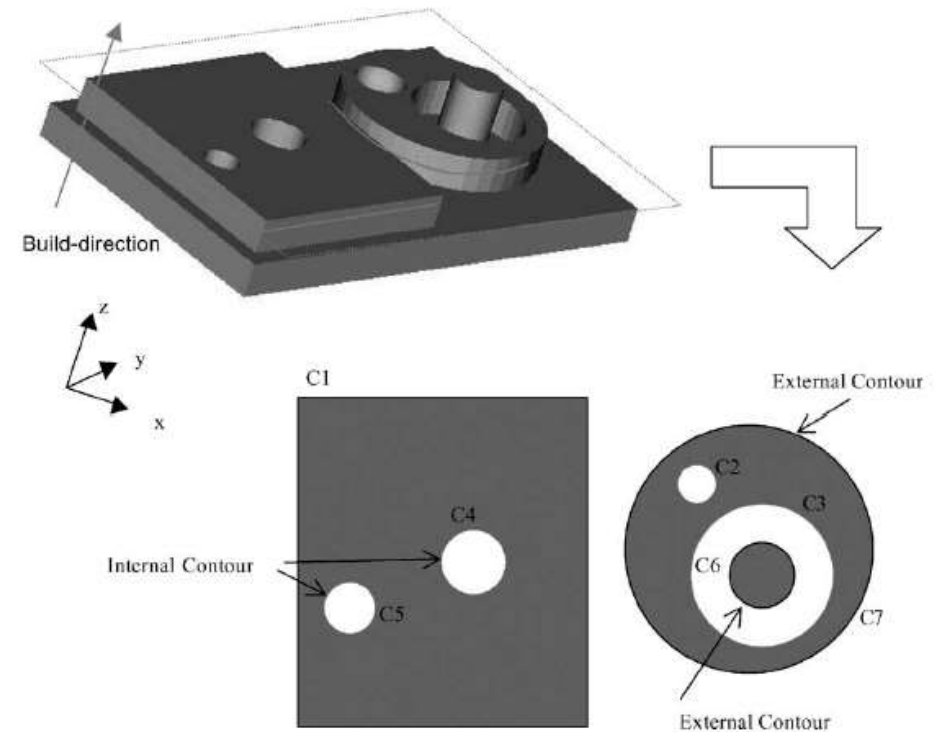


# Model Slicing

A slice may contain groups of contours, and each group may have multiple internal and external contours. These contours do not intersect with each other.

The basic idea is to sort and subsequently to group layers in a parent-and-son relationship by using:

- Hierarchy sorting: build a parent-and-son containment relationship of contours.
- Contour sequencing: arrange the contours in a sequence easing subsequent operations.





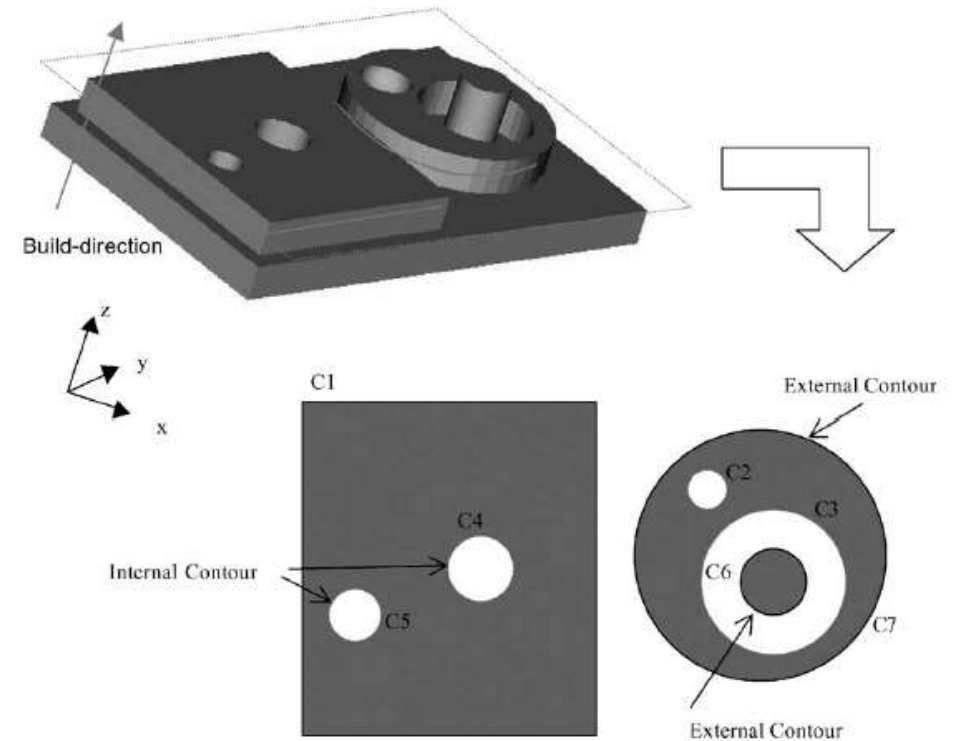
# Model Slicing

## Hierarchy sorting

Ray shooting technique for finding intersection points of a line and a model is applied to identify the containment.

The hierarchy relationships of any two contours within a slice can be:

- External and external (C1 & C7)
- External and internal (C1 & C4)
- Internal and internal (C4 & C5)



# Model Slicing

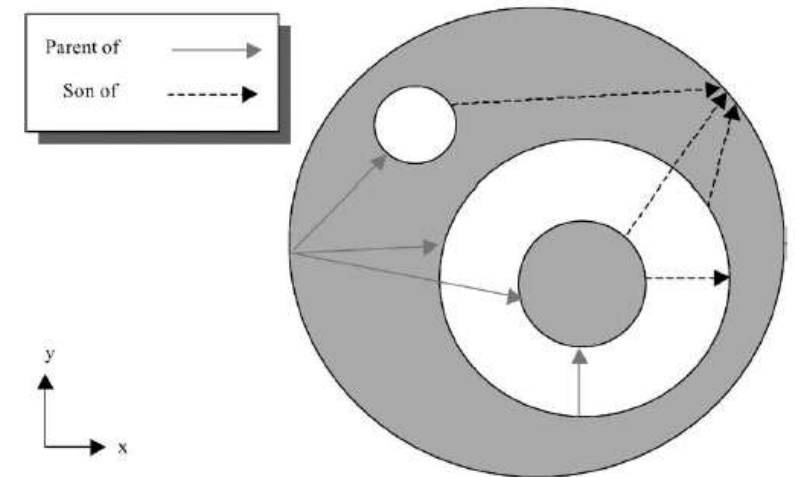
Let an unorganized collection of bound contour  $C$ , in 2D space,  $R^2$ , be given as

$$C = \{(C_x)\} \in R^2 \quad x = 0, 1, 2, \dots, i$$

List of Points for each contour  $C_x$  be given as

$$P = \{(x_j, y_j)\} \in R^2 \quad j = 0, 1, 2, \dots, n \quad \text{and} \quad P_n = P_0$$

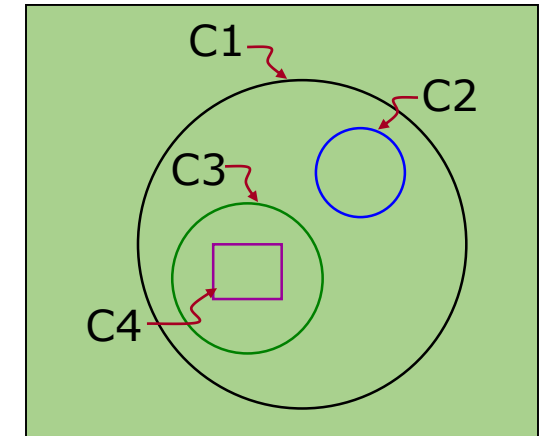
For any two contours,  $C_x$  is said to be contained in  $C_y$  if any arbitrary point in  $C_x$  is contained in  $C_y$ .  
 $C_y$  is then put in the parent list of  $C_x$ .



# Model Slicing

There are three possibilities for the relationship between any two contours:

- $C_x$  is contained in  $C_y$
- $C_y$  is contained in  $C_x$
- They are independent



The maximum number of investigation is  ${}^nP_2$

After performing the above procedure, all contours will carry their own parent list, and each contour will be assigned a level number that indicate its number of parents.

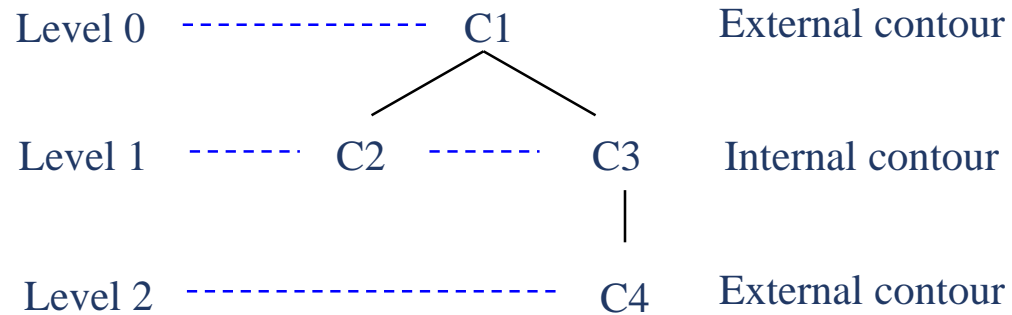
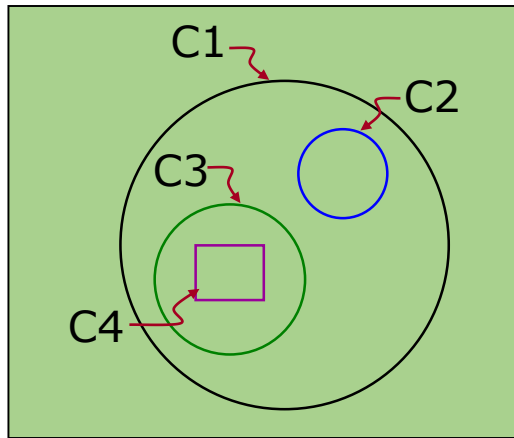
Parent list of C2: C1

Level of C2: 1

# Model Slicing

The parent list and the level numbers are then used for generating hierarchy sequencing

- All contours are grouped according to their level numbers

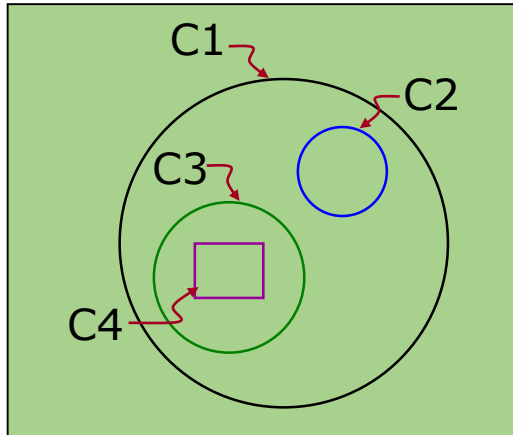


Level 0: C1  
Level 1: C2, C3  
Level 2: C4

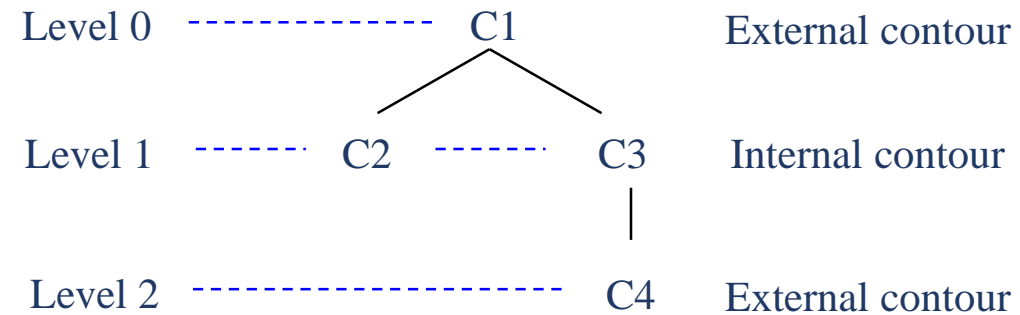
# Model Slicing

- Start forming the sequence by selecting one member from group 0 and put in the final sequence
- Find its son from member of level 1. If a son is found, it is attached in the final sequence, and the level number is increased by one and
  - If there exists any contour in the new level, the search continues for its son
  - If there are no contour in the new level or if no son is found, the search step back to previous level and repeat the process until the final sequence is completed.

# Model Slicing

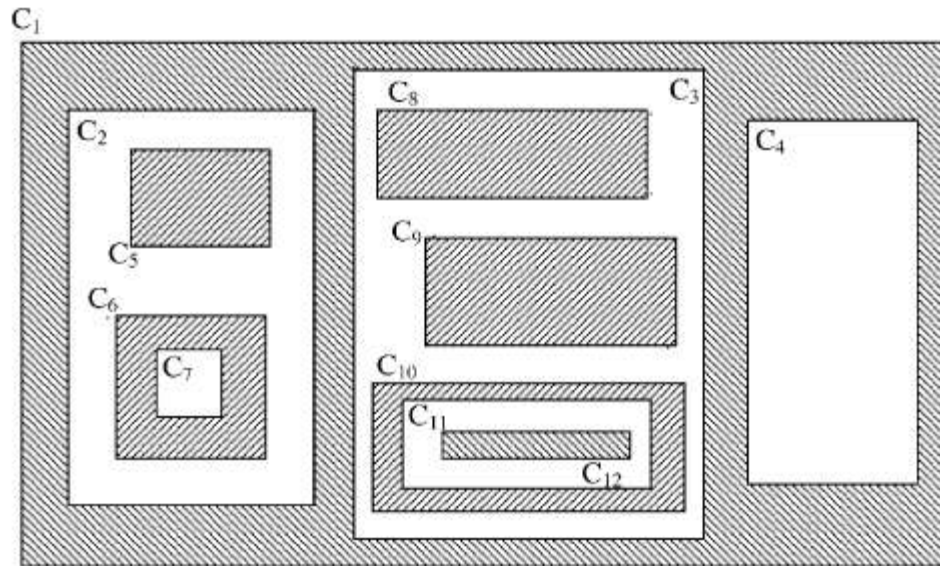


	Parent	Level
C1	-	0
C2	C1	1
C3	C1	1
C4	C1,C3	2



Final sequence before sequencing: C1-C2-C3-C4

# Model Slicing



	Parent	Level
C1	-	0
C2	C1	1
C3	C1	1
C4	C1	1
C5	C1,C2	2
C6	C1,C2	2
C7	C1,C2,C6	3
C8	C1,C3	2
C9	C1,C3	2
C10	C1,C3,	2
C11	C1,C3,C10	3
C12	C1,C3,C10,C11	4

Final sequence : C1-C2-C5-C6-C7-C3-C8-C9-C10-C11-C12-C4

# Model Slicing

## Contour sequencing

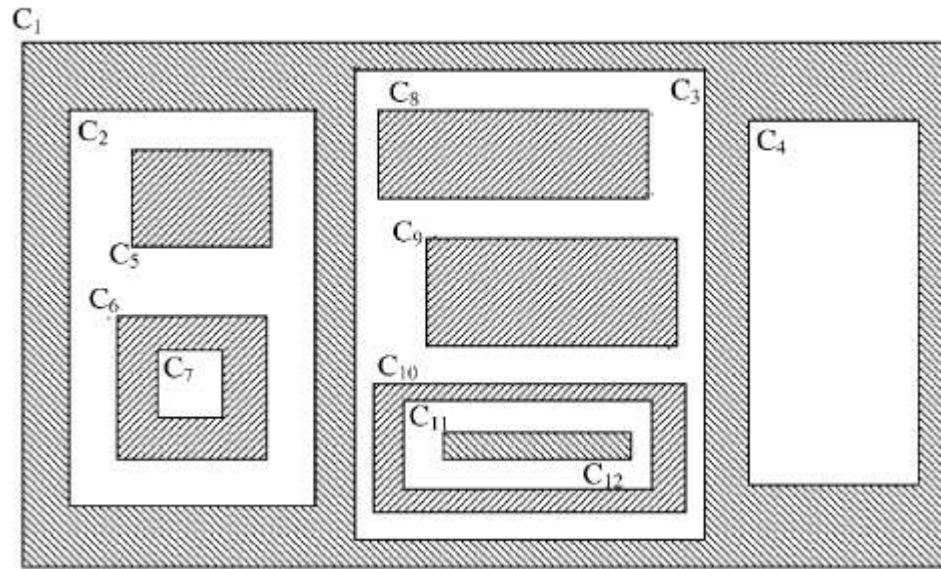
The hierarchy sorting has arranged the multiple-level contours in an appropriate sequence for the layer.

Next step is to arrange the contours at the same level that may still be random.

Contours with the same level are arranged according to their minimum and maximum x and y values. If the two or more contours bounding boxes overlap, the original sequence will be used.



# Model Slicing

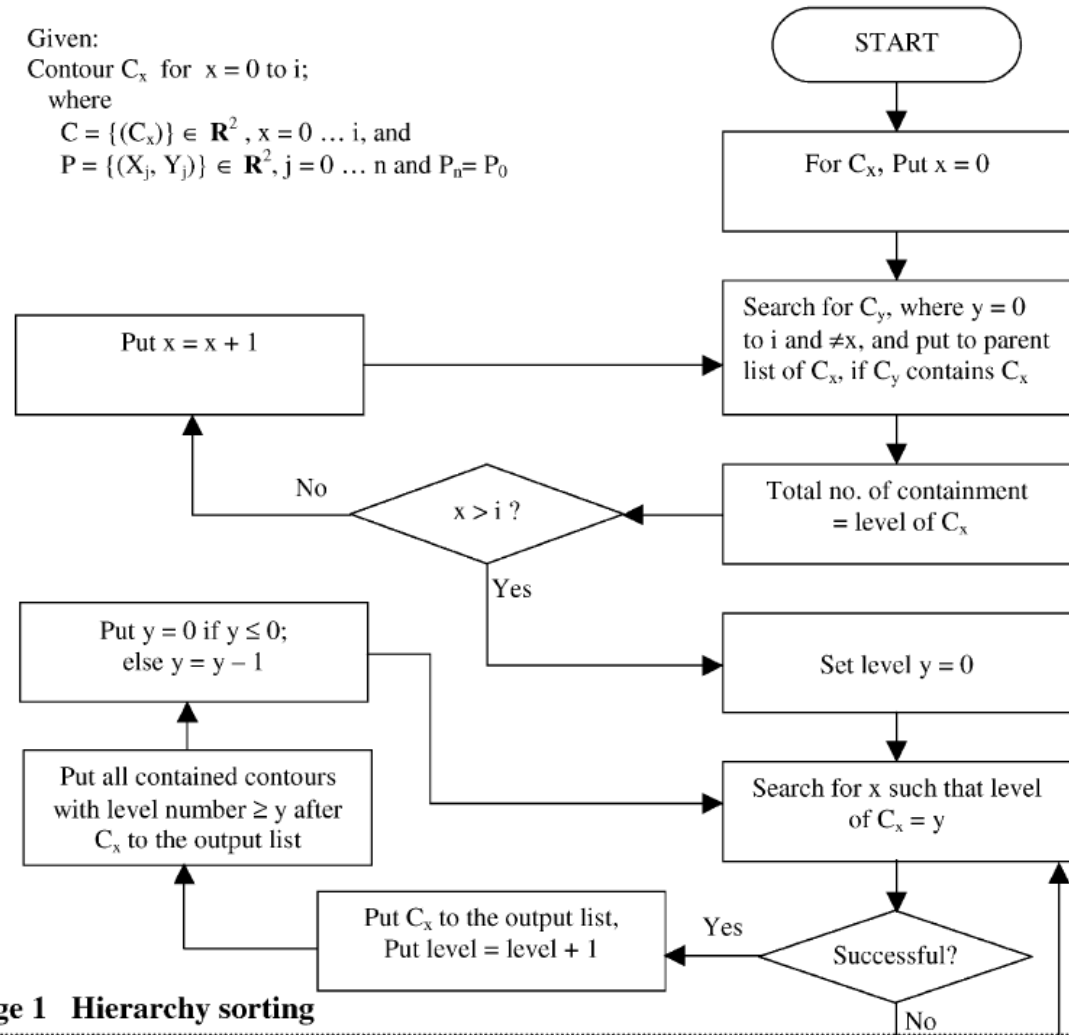


	Parent	Level
C1	-	0
C2	C1	1
C3	C1	1
C4	C1	1
C5	C1,C2	2
C6	C1,C2	2
C7	C1,C2,C6	3
C8	C1,C3	2
C9	C1,C3	2
C10	C1,C3,	2
C11	C1,C3,C10	3
C12	C1,C3,C10,C11	4

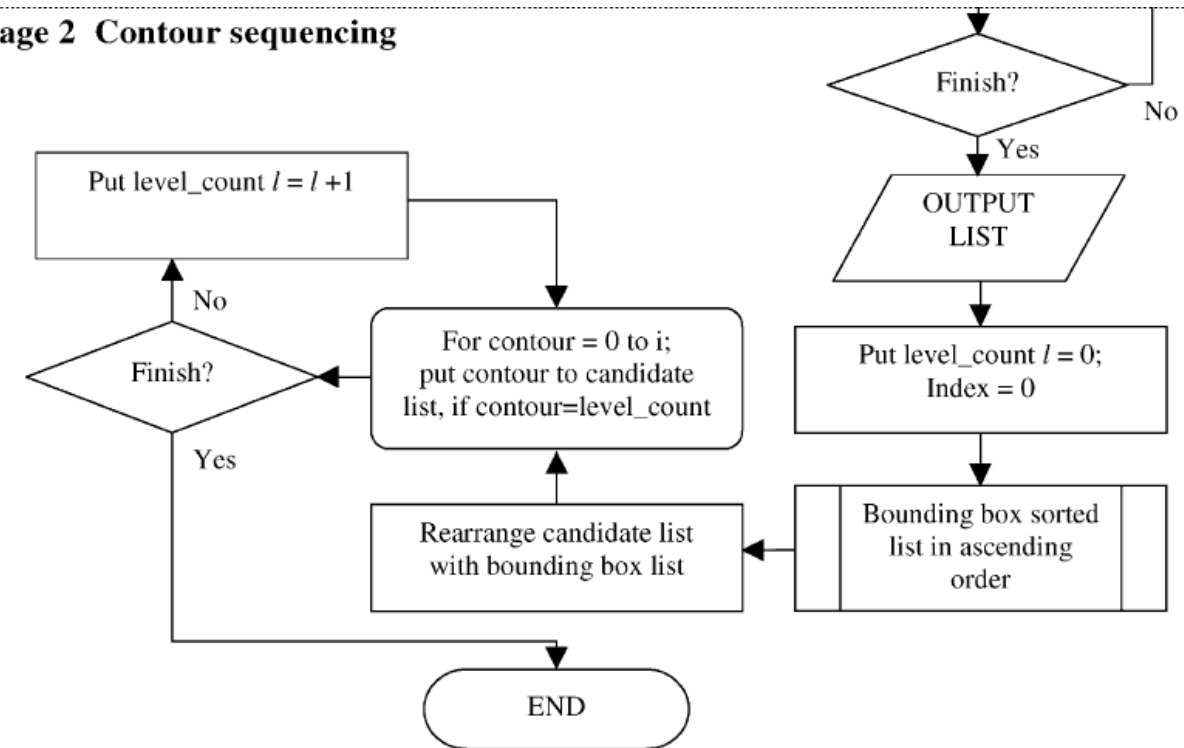
Final sequence before sequencing: C1-C2-C5-C6-C7-C3-C8-C9-C10-C11-C12-C4

Final sequence after sequencing: C1-C2-C5-C6-C7-C3-C8-C9-C10-C11-C12-C4

Given:  
Contour  $C_x$  for  $x = 0$  to  $i$ ;  
where  
 $C = \{(C_x)\} \in \mathbf{R}^2, x = 0 \dots i$ , and  
 $P = \{(X_j, Y_j)\} \in \mathbf{R}^2, j = 0 \dots n$  and  $P_n = P_0$



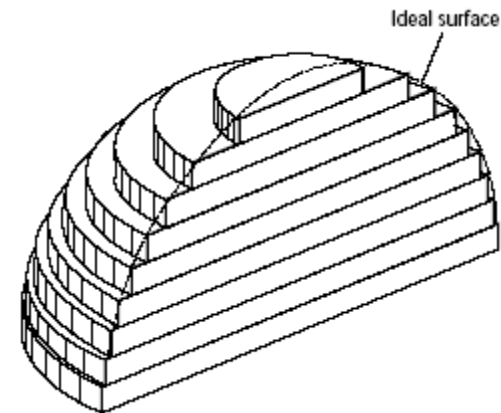
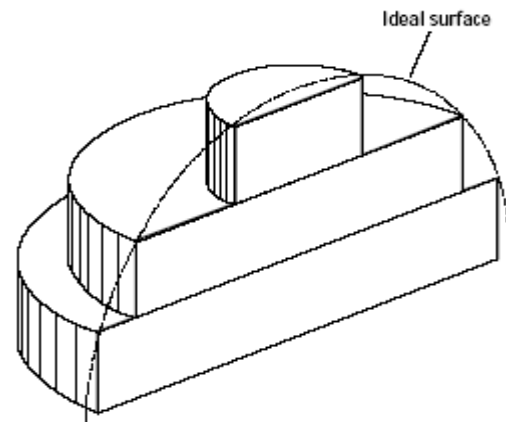
## Stage 2 Contour sequencing



# Adaptive Slicing

Accuracy and time are two critical contradictory factors that need to be balanced.

Typically solution is to find an appropriate thickness and apply it through out the part.



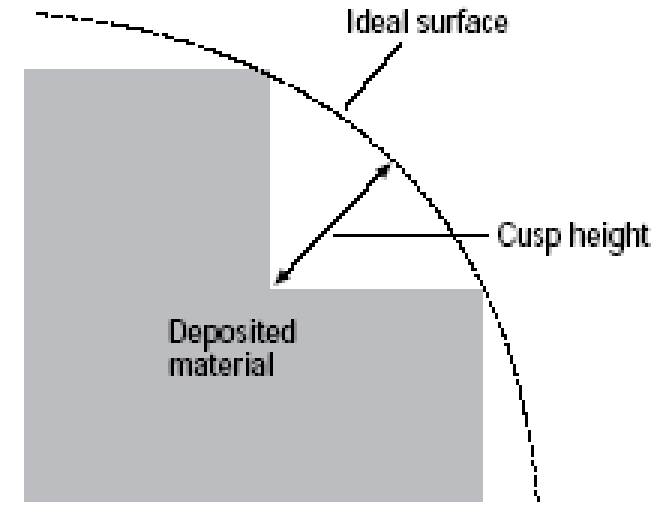
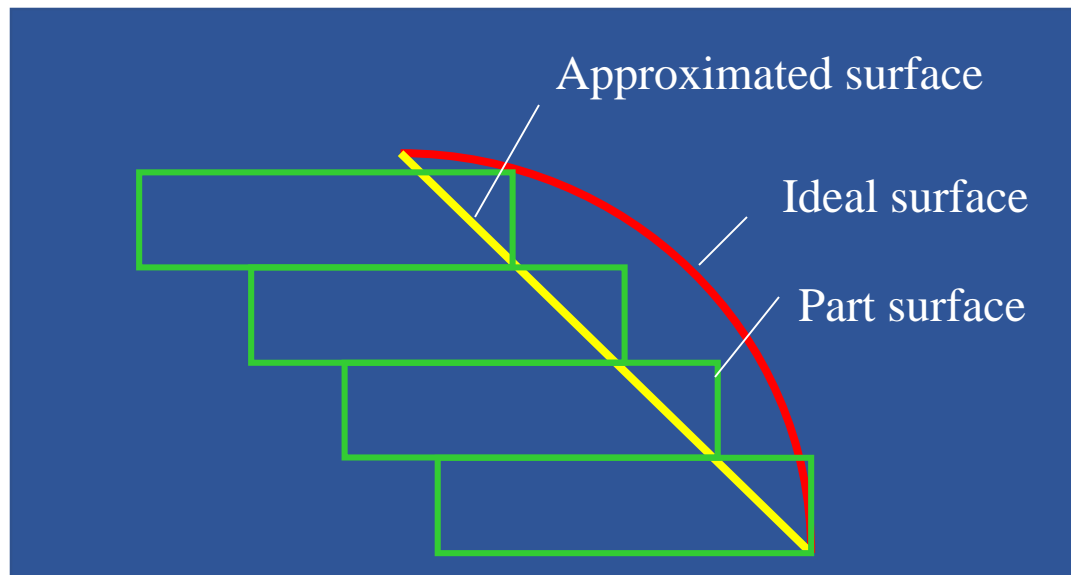
# Adaptive Slicing

Constant thickness slicing is widely used due to its simplicity. However, there are some disadvantages which cannot be easily eliminated.

- There exists the possibility of missing features because we can't guarantee that all the dimensions are multiples of a fixed thickness.
- When dealing with curved parts, an inconsistent surface finish is likely to occur
- Constant thickness slicing tends to increase the building time.

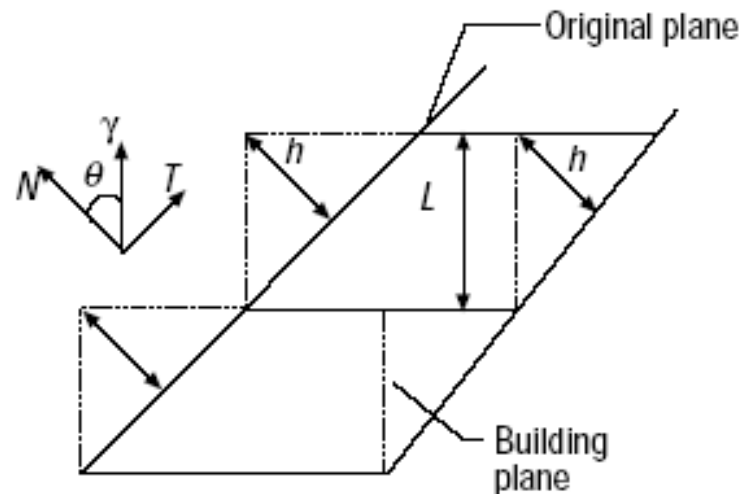
# Adaptive Slicing

The basic principle of adaptive slicing is to evaluate locally the surface characteristics to select layer thickness that restrict the maximum surface error, usually measure by cusp height.



# Adaptive Slicing

For a planar surface, like the facet, the layer thickness can be determined from a given cusp height, and the angle between the surface normal and building direction



$$L = \frac{\delta}{\cos \theta}$$

$$\delta = h$$

# Adaptive Slicing

The layer thickness at point P is calculated from the cusp height within the user specified cusp height tolerance,  $\delta_{\max}$

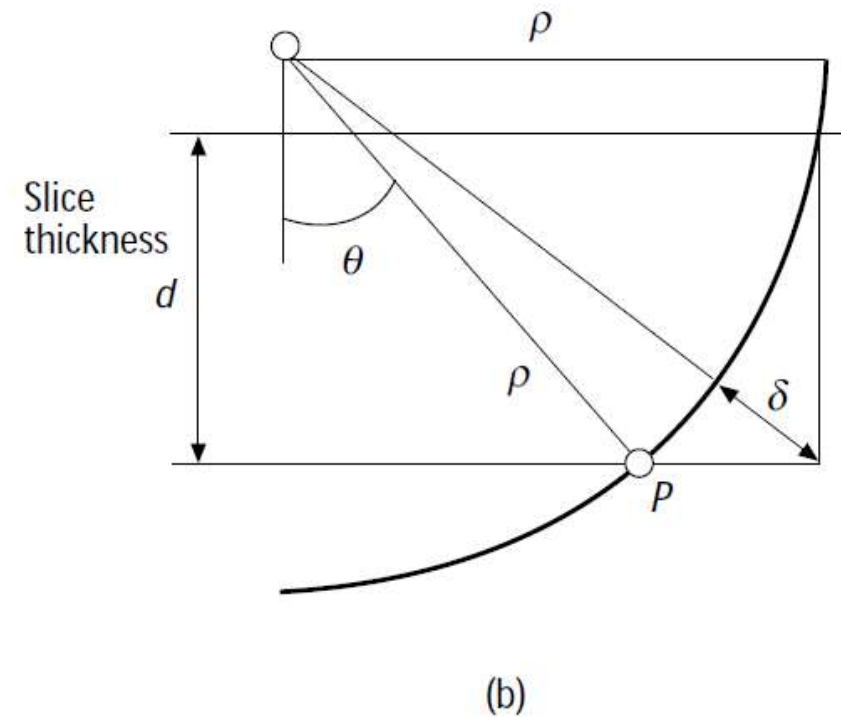
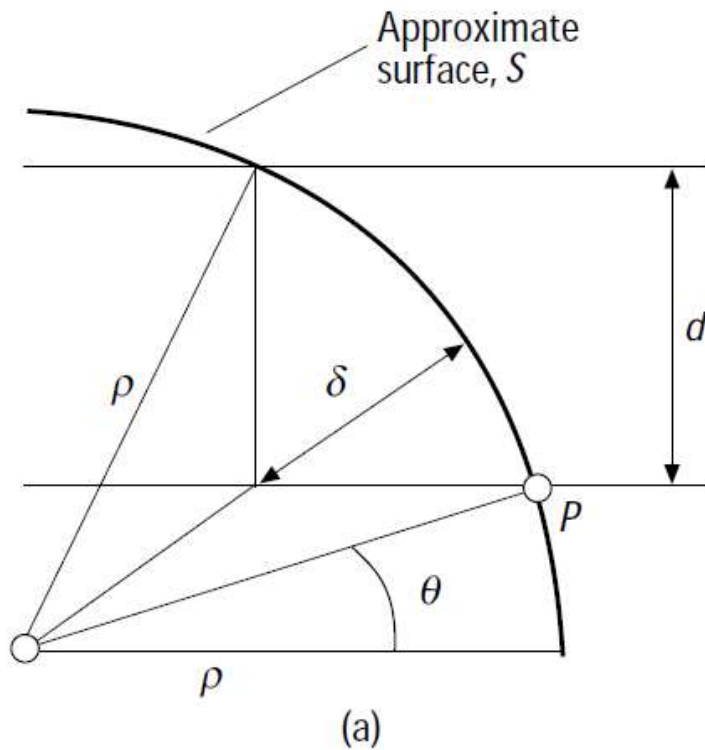
$$\begin{aligned}\bar{\delta} &= \delta \bar{n} \\ \|\bar{\delta}\|_2 &= \delta \leq \delta_{\max}\end{aligned}$$

Where  $\bar{n} = [n_x, n_y, n_z]$  is unit vector at point P

$$\begin{aligned}L_P &= \min\left\{L_{\max}, \frac{\delta_{\max}}{n_z}\right\} \\ L_{\text{slice}} &= \max\left\{L_{\min}, \min\{L_{P_i}\}\right\}\end{aligned}$$

# Adaptive Slicing

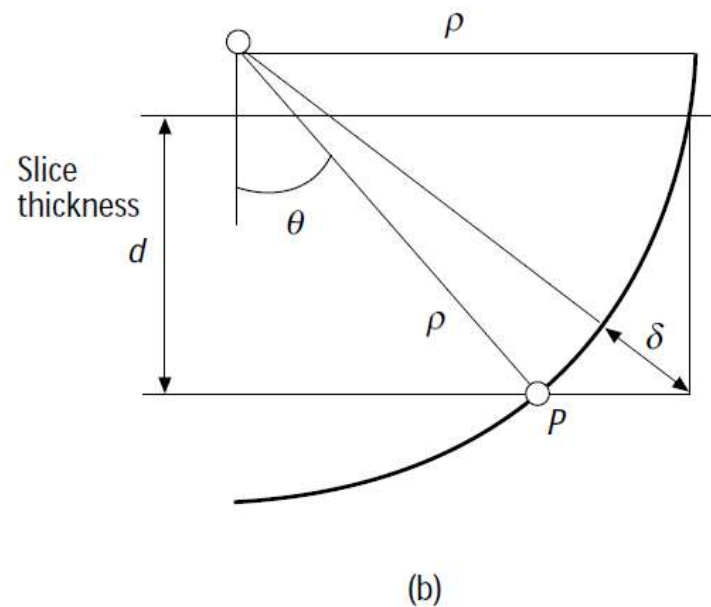
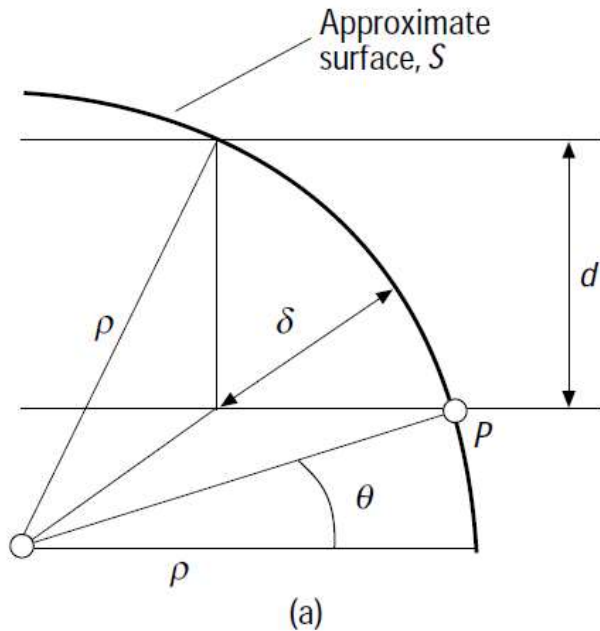
Approximating the local geometry with a sphere





# Adaptive Slicing

Approximating the local geometry with a sphere



The method of extrapolation of the local surface upward in the vertical direction depends on the surface geometry used to model the part. In the case of sculptured surfaces, the part surface can be approximated locally by a sphere  $S$  with a radius equal to the part's local surface curvature  $\rho$  in the vertical direction. The maximum acceptable layer thickness  $d$  at a given point  $P$  can then be found as a function of  $\rho$ , the maximum acceptable cusp height  $\delta$ , and the angle  $\theta$  between the centre of  $S$  and  $P$ [2]. Specifically, for the case where the centre of  $S$  is above  $P$ , such as in Figure 4(a),

$$d = -\rho \sin \theta + \sqrt{\rho^2 \cos^2 \theta - 2\delta\rho - \rho^2}, \quad (1)$$

otherwise, as shown in Figure 4(b),

$$d = -\rho \cos \theta - \sqrt{\rho^2 \cos^2 \theta - 2\delta\rho - \rho^2}. \quad (2)$$

# Adaptive Slicing

## Stepwise Uniform Technique

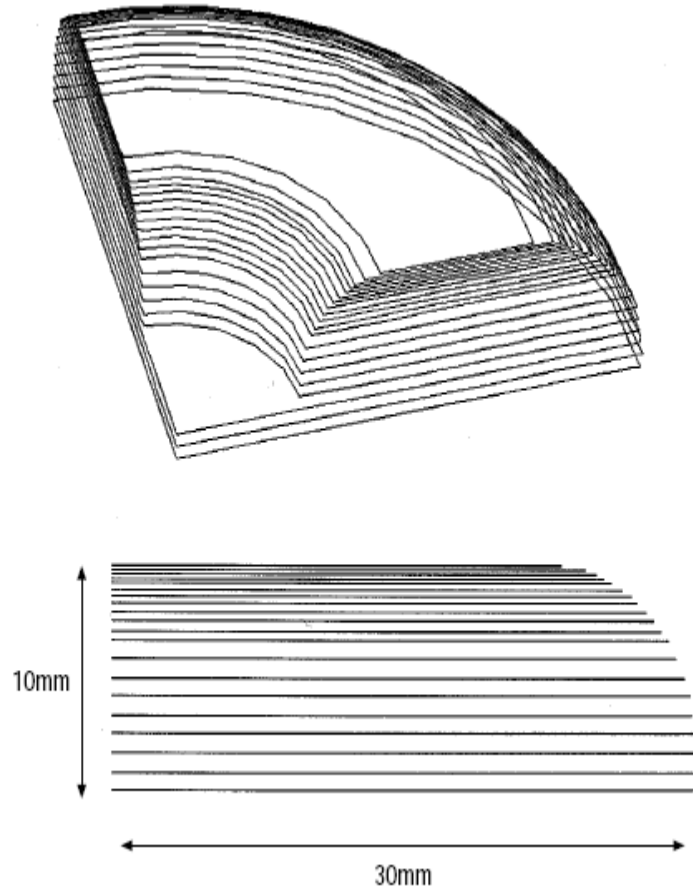
The model is first subdivided into uniform, horizontal slabs of maximum thickness,  $L_{\max}$ . These slabs are subdivided individually as needed to satisfy the maximum cusp height.

Each slab is examined from both top down and bottom up Directions.

Number of layers

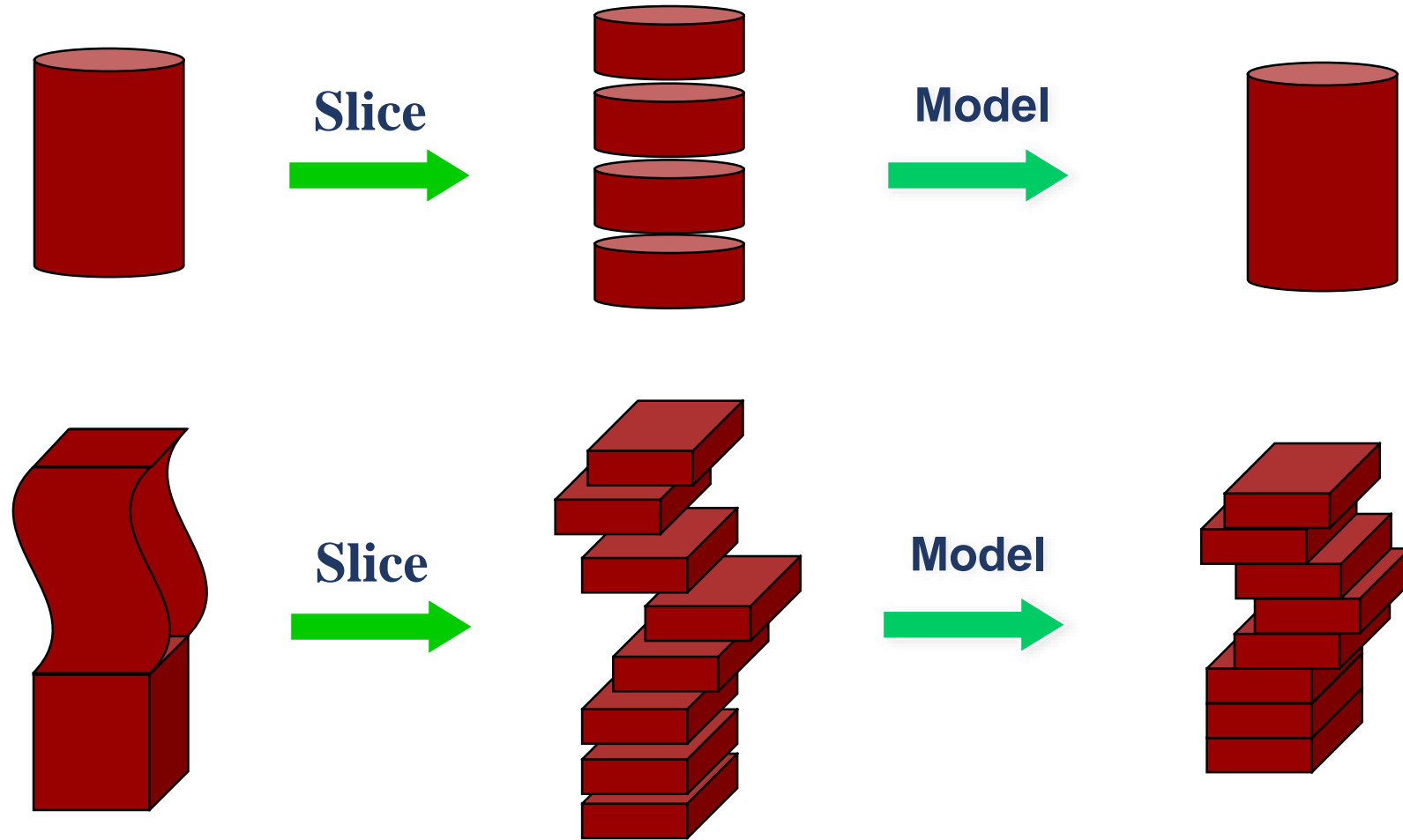
$$L_{\text{slice}} = \frac{L_{\max}}{\alpha_{\text{slab}}}$$
$$\alpha_{\text{slab}} = \text{int} \left( \frac{L_{\max}}{\delta_{\max}} \max \{ n_{z_{\text{bottom}}}, n_{z_{\text{top}}} \} \right)$$
$$\alpha_{\text{slab}} \in [1, \alpha_{\max}]$$
$$\alpha_{\max} = \text{int} \left( \frac{L_{\max}}{L_{\min}} \right)$$

# Adaptive Slicing

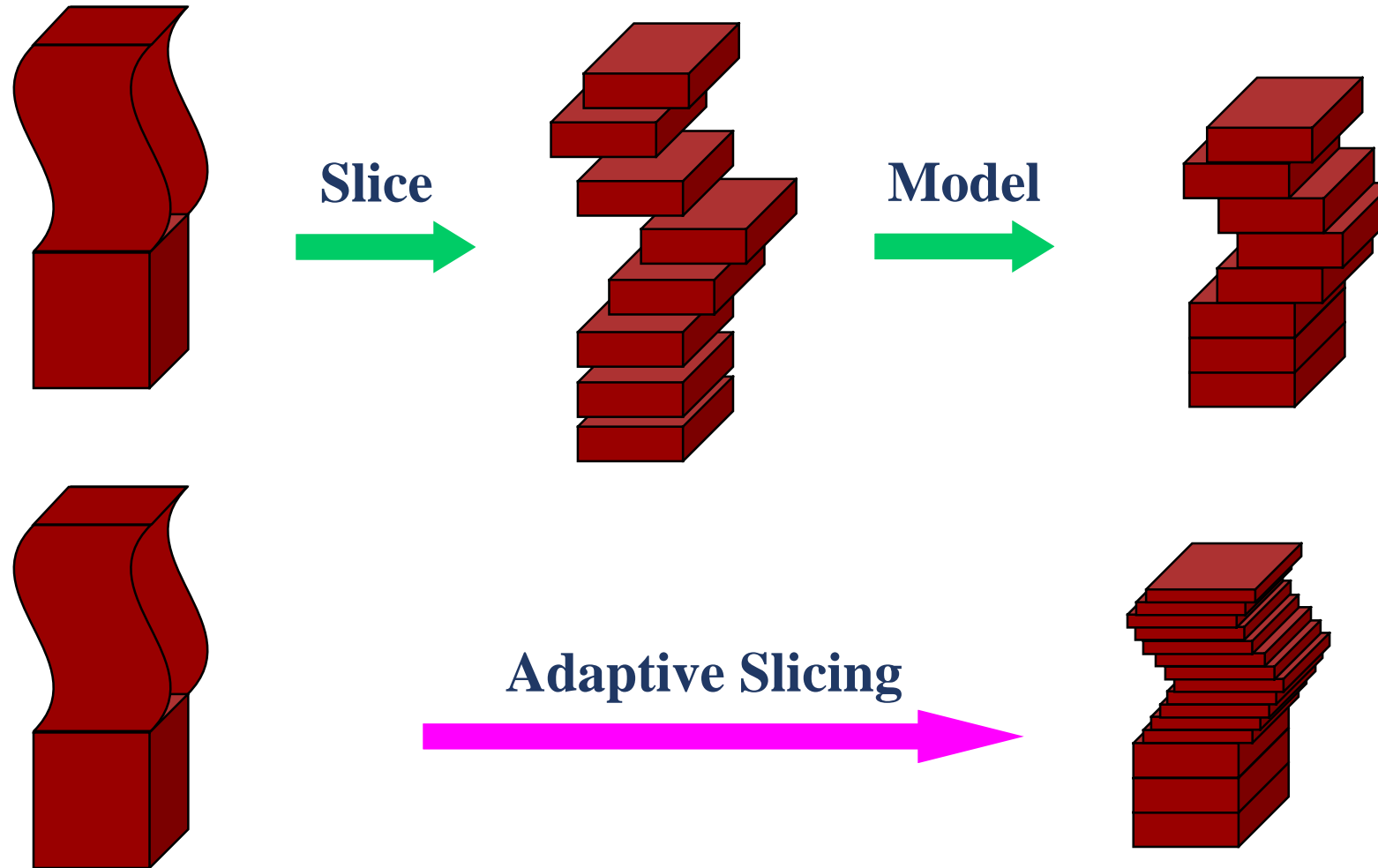


Method	Layer thickness		Number of layers	Recorded build time	
	(Inches)	(mm)		Actual (hours)	Relative (%)
Uniform thick layers	0.0150	0.38	26	0.51	33
Uniform thin layers	0.0050	0.13	79	1.52	100
New adaptive slicing	0.0050	0.13	41	0.73	48
	0.0075	0.19			
	0.0150	0.38			

# Direct Slicing Process



# Direct Slicing Process



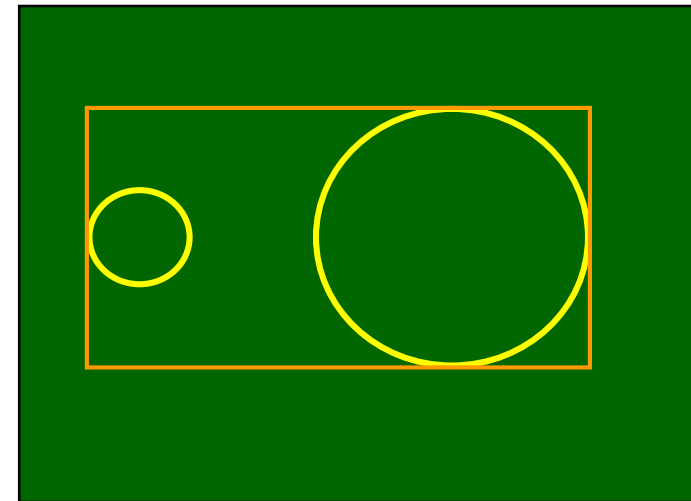
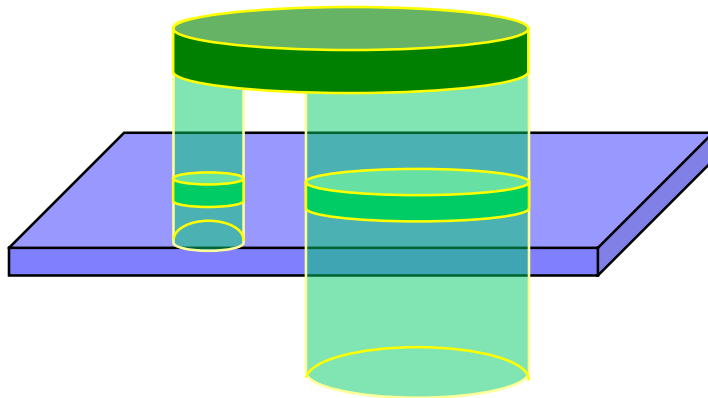
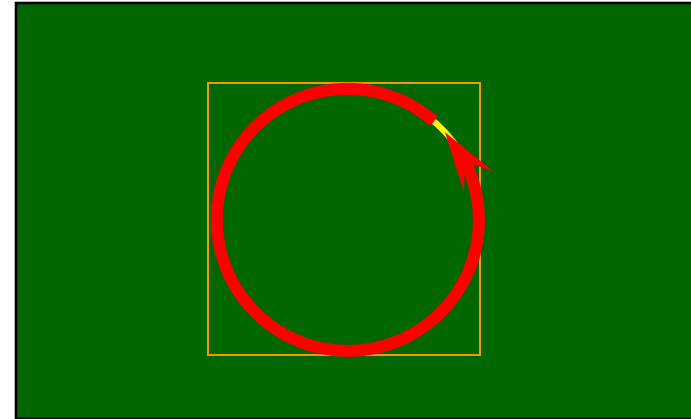
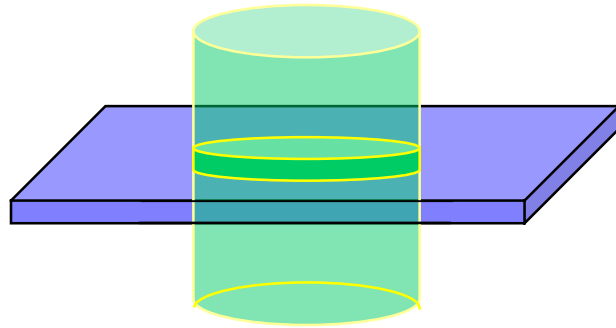
# Adaptive Slicing



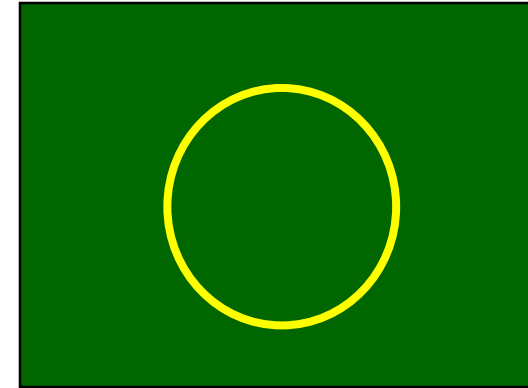
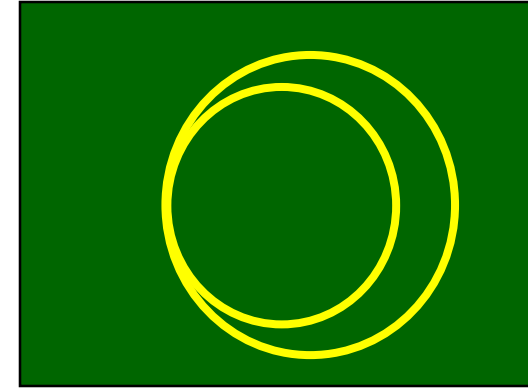
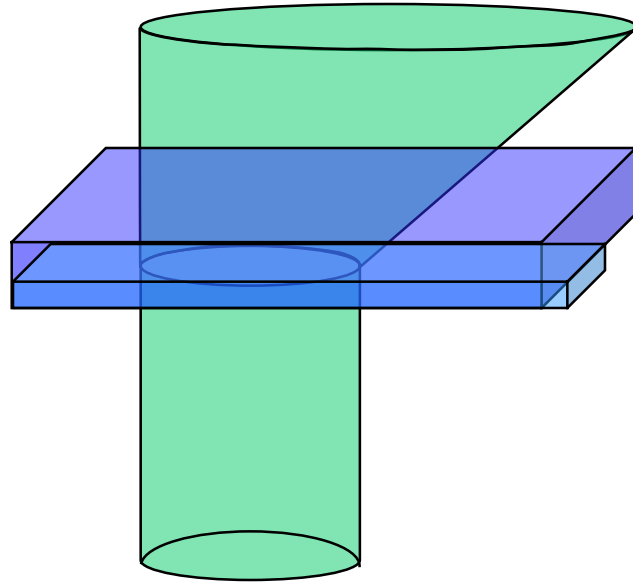
## Contour identicalness

The model is sliced with a standard layer thickness and its top and bottom contours are compared to see whether the thickness can be increased. If the two contours are equal to within tolerance, the thickest possible layer thickness that does not exceed the tolerance is identified.

# Direct Slicing Process

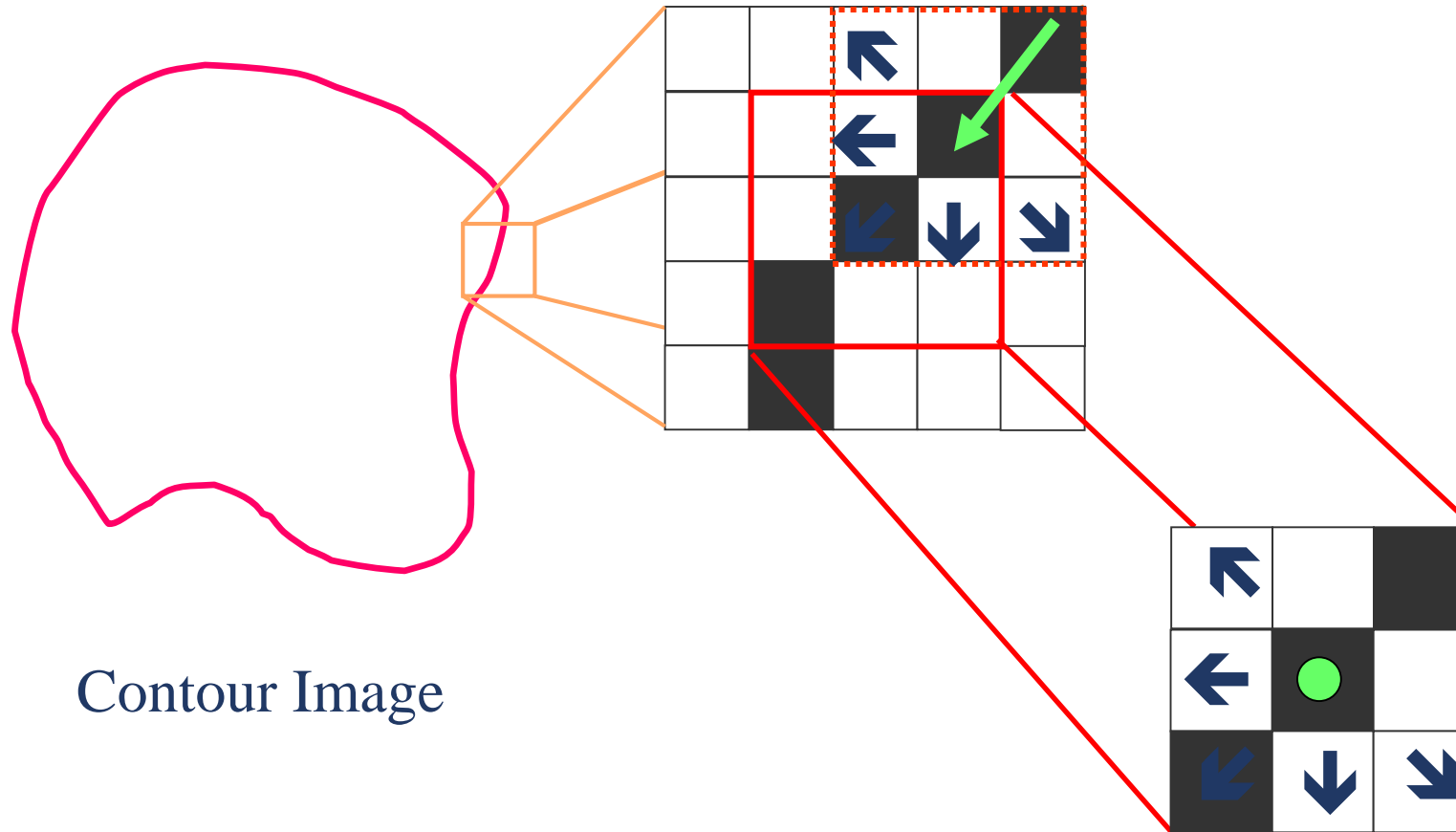


# Direct Slicing Process

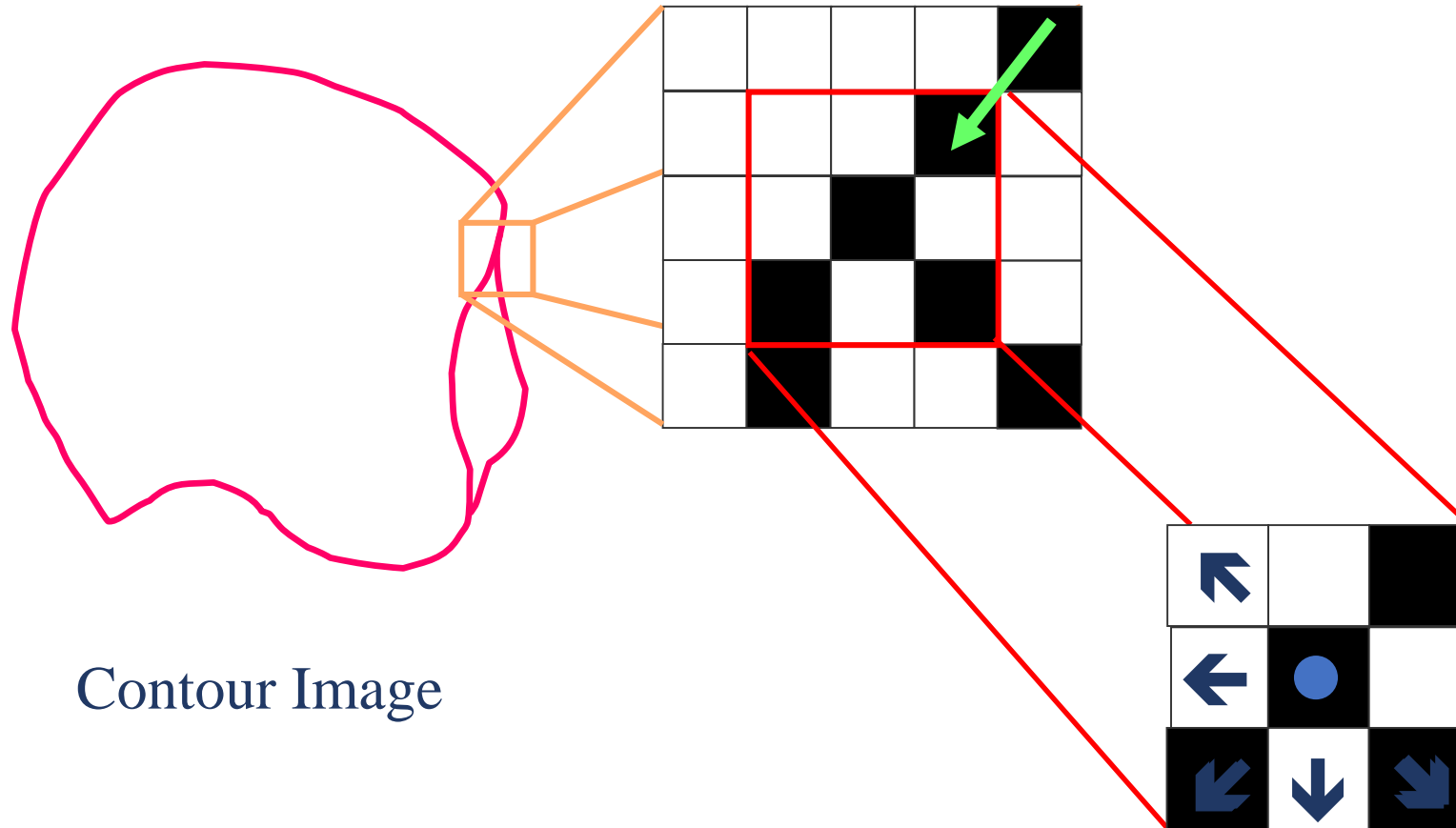




# Contour Search Algorithm













# Contour Search Algorithm



Contour Image

# Adaptive Direct Slicing

Front view	Side view	
		<b>Step 1:</b> Two images of a curvature lamp drawing were taken at two vertical orthographic views: front and side views.
		<b>Step 2:</b> Identifying the image boundary that contains the entire part to minimize processing time of subsequent steps. A simple algorithm was applied to seek for the first pixels in four directions. They were used to create the boundary of the part.
		<b>Step 3:</b> Applying Canny edge detection algorithm to determine the edge of front and side images of sample CAD drawing.
		<b>Step 4:</b> Locally analyzing the images layer by layer. Two criteria were applied on the edge images for identifying the surface complexity: contours deviation and feature on surface layer. The recommendations on slicing positions were sent to a commercial program to slice and extract contour data. <i>Note: The maximum thickness was 3 mm. The minimum thickness was 1 mm.</i>
		<b>Step 5:</b> Slicing the sample model using commercial CAD software according to the recommended positions. The slicing contours can be generated layer by layer. This step is called layer-based virtual prototype fabrication.

# Comparison Among Four Slicing Methods

Fig. 8 Layer-based virtual prototypes of the curvature lamp. a Uniformly sliced model with 1 mm. b Uniformly sliced model with 3 mm. c Uniform cusp height model. d Adaptively sliced model

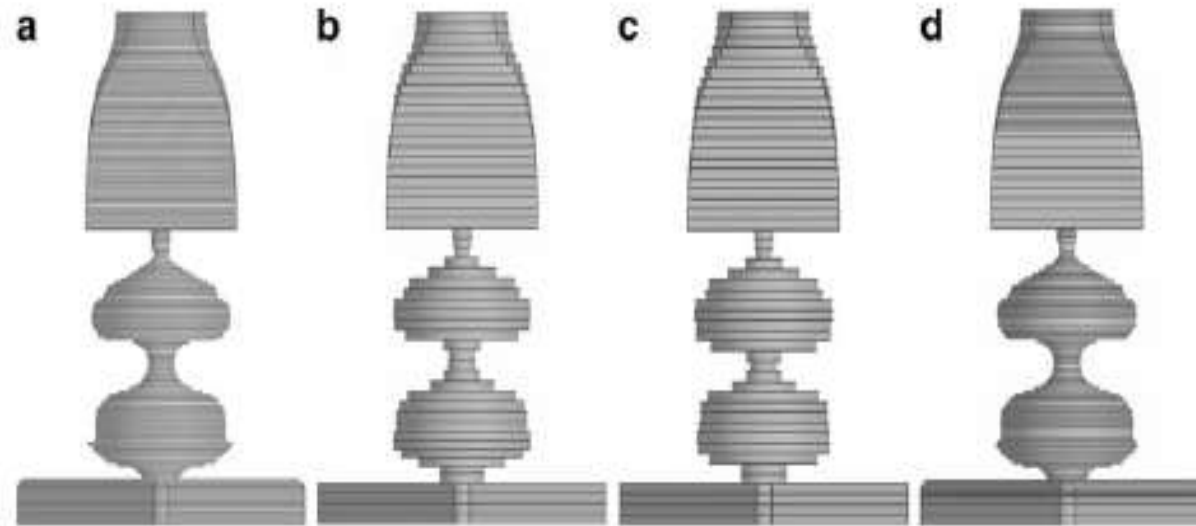
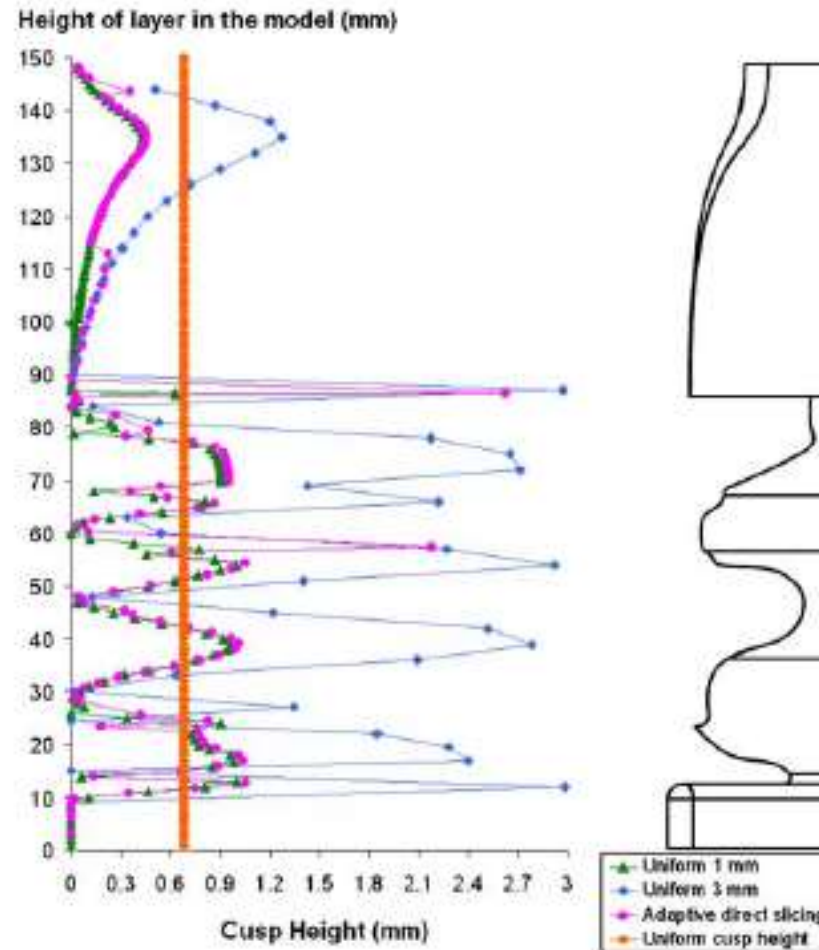


Table 2 The number of layers resulted from slicing curvature lamp model with four slicing methods

Methods	Cusp height (mm)	$E_{\max}$ (mm)	Layer thickness (mm)	Number of layers
Uniform direct slicing (min.)	0 ~ 0.983	0.7	1	150
Uniform direct slicing (max.)	0 ~ 2.922	0.7	3	50
Uniform cusp height	0.68	0.7	1.525 ~ 3	51
New adaptive direct slicing	0 ~ 1.055	0.7	1.056	93
			1.5	3
			2.363	2
			2.694	1
			3	13
			112	

# Comparison of Cusp Height Among Four Slicing Methods



**Fig. 9** The comparison of the cusp height resulting from adaptive direct slicing method and uniform slicing with maximum and minimum thickness

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# Thanks

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