3D Printing Oriented Design: Geometry and Optimization

Siggraph Asia 2014 Course

Dec. 5, 2014 , Shenzhen

SIGGRAPH ASIA 2014 SHENZHEN

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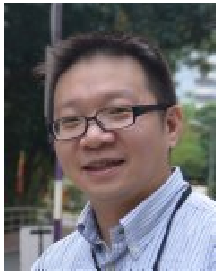
Web: http://staff.ustc.edu.cn/~lgliu/Courses/SigAsia_2014_course_3Dprinting/index.html

Part 2: Fabrication Principles



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- The Chinese University of Hong Kong
- http://www2.mae.cuhk.edu.hk/~cwang

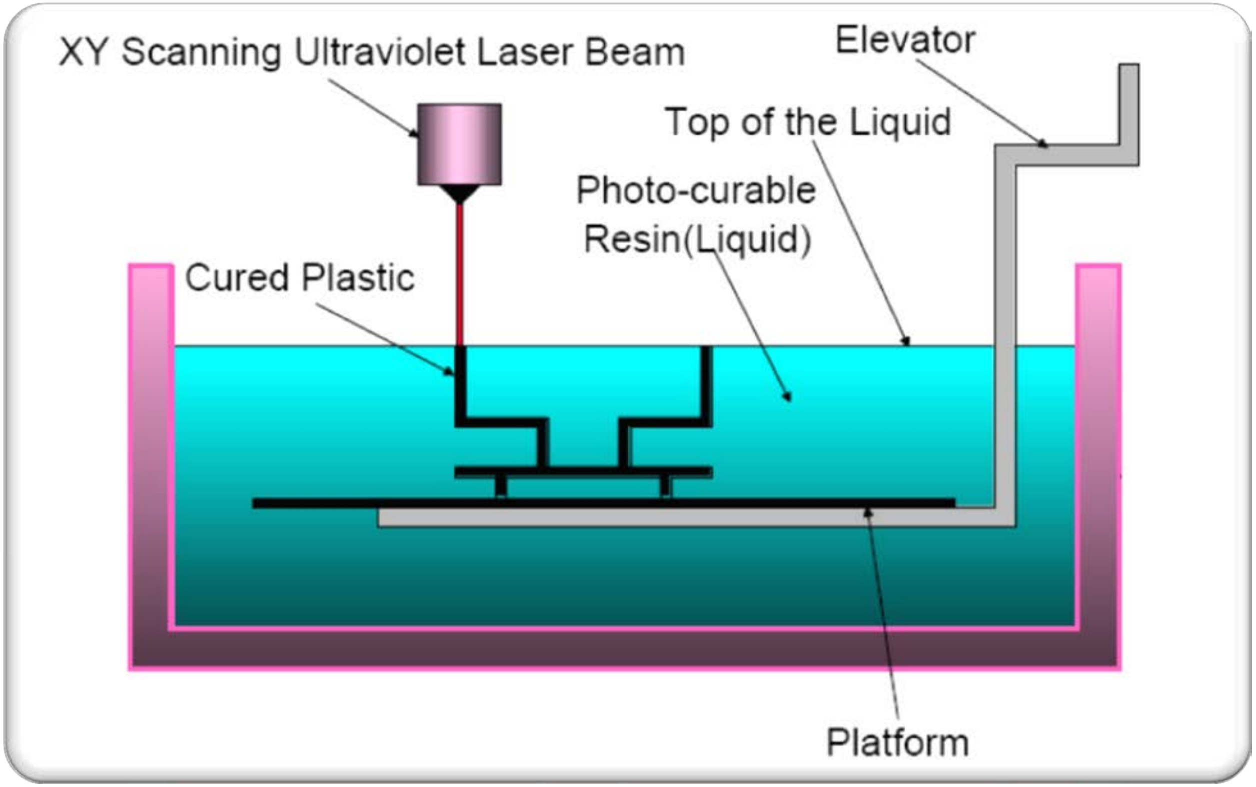
Outline

- Different Types of Additive Manufacturing
  - Six different types
- Numerical Robustness
  - Problem of B-rep in approximate arithmetic
  - Computation in image space
- Basic Computing for Fabrication
  - Slicing
  - Support structures

Six Types of AM – Different Principles

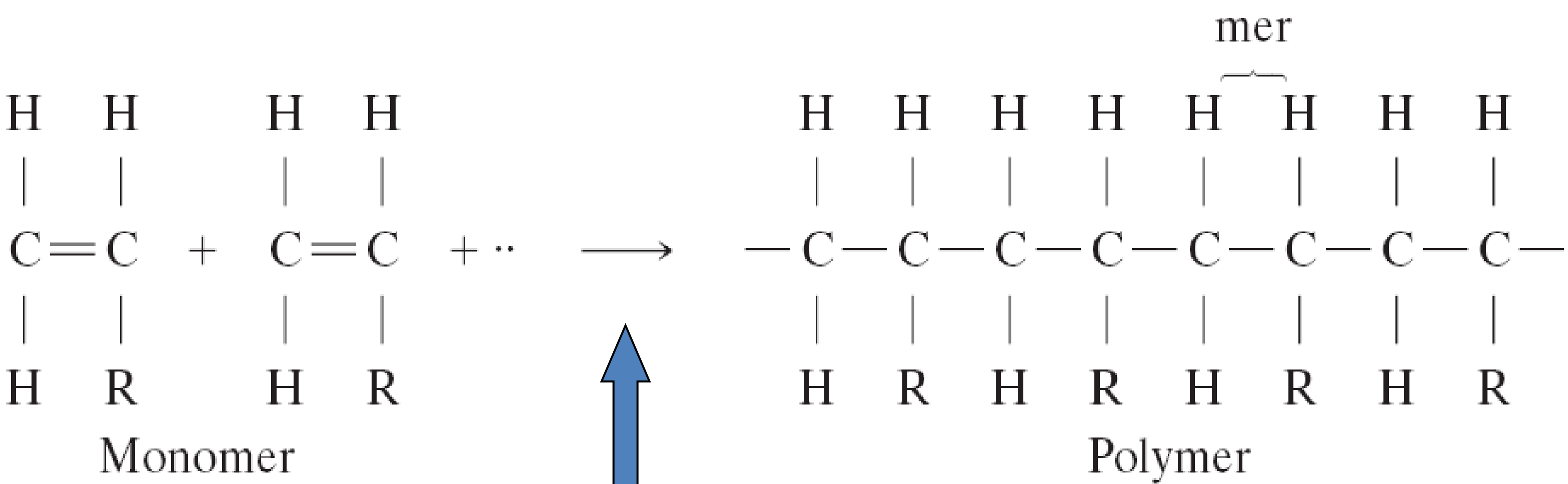
- Lasers:
  - Stereolithography Apparatus (SLA)
  - Selective Laser Sintering (SLS)
- Nozzles:
  - Fused Deposition Modeling (FDM)
- Printheads:
  - Multi-jet Modeling (MJM)
  - Binder-jet Printing (3DP)
- Cutters:
  - Laminated Object Modeling (LOM)

Stereo Lithography Apparatus (SLA)



- Introduced in 1984 by *Charles Hull* who founded 3D Systems Inc.
- The first commercial Solid Freeform Manufacturing process;
- Based upon the use of an ultraviolet laser which is used to solidify a photocurable liquid polymer.

Monomer and Polymer



Liquid

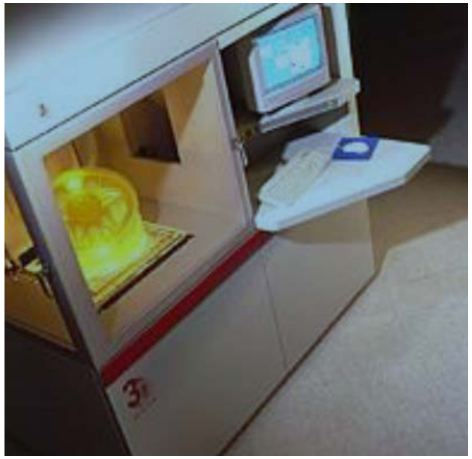
Solid

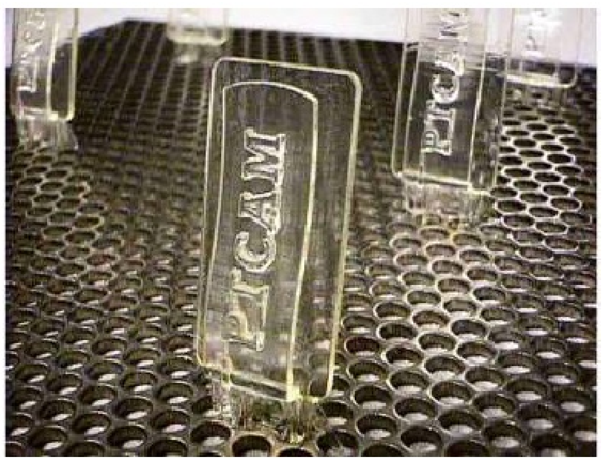
Heat / UV light

Polymer injection molding

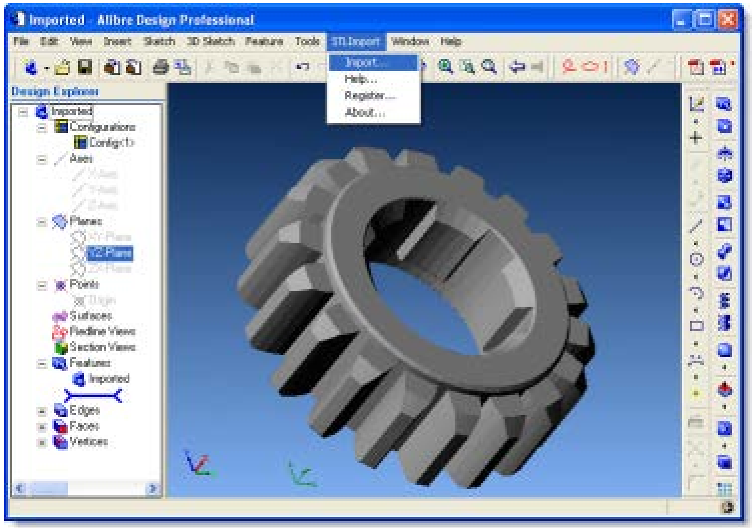
Stereolithography

Example Parts



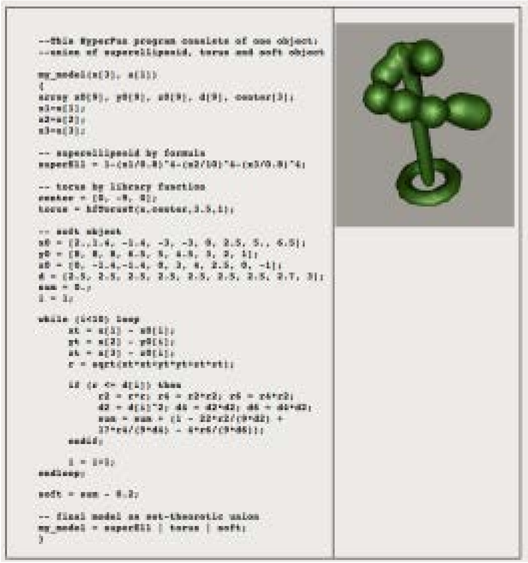


3D Models for Fabrication



CAD Systems

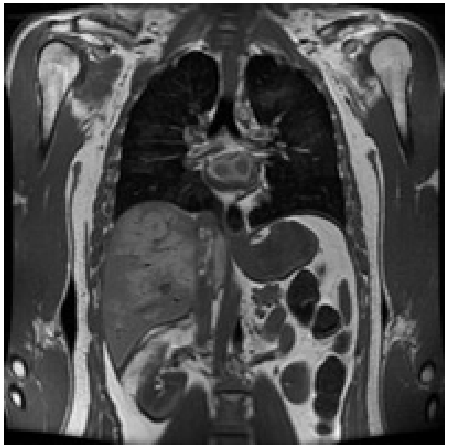
Implicit representations



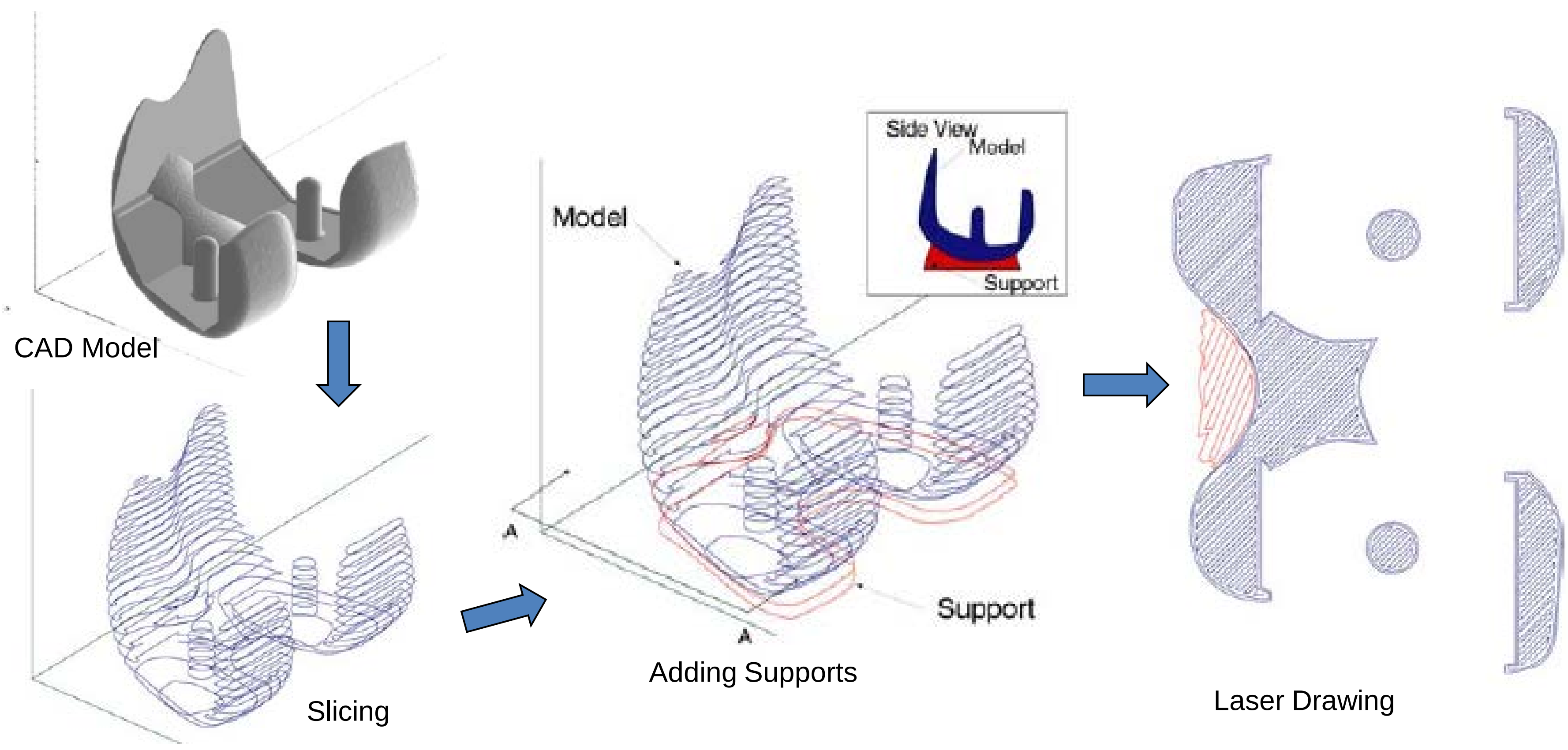
STL (STereoLithography)

3D Scanners

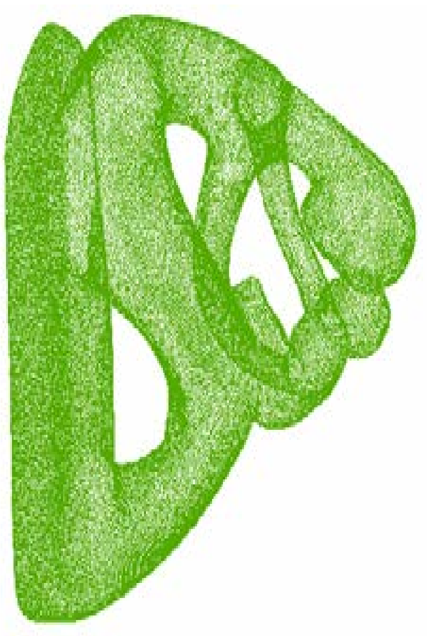
CT/MRI



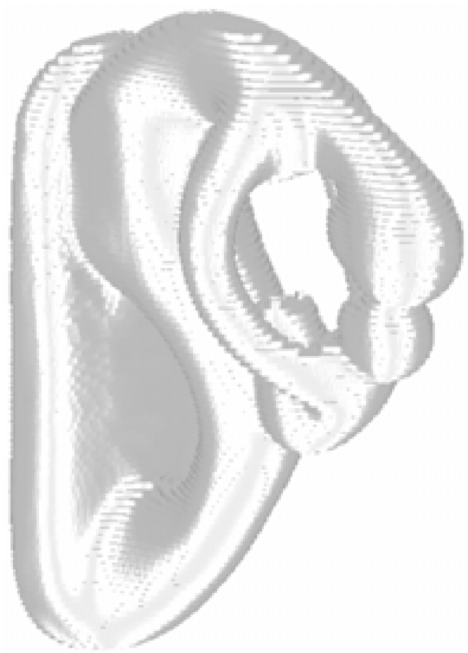
Main Computation Steps in SLA



Support Generation Example



Point cloud

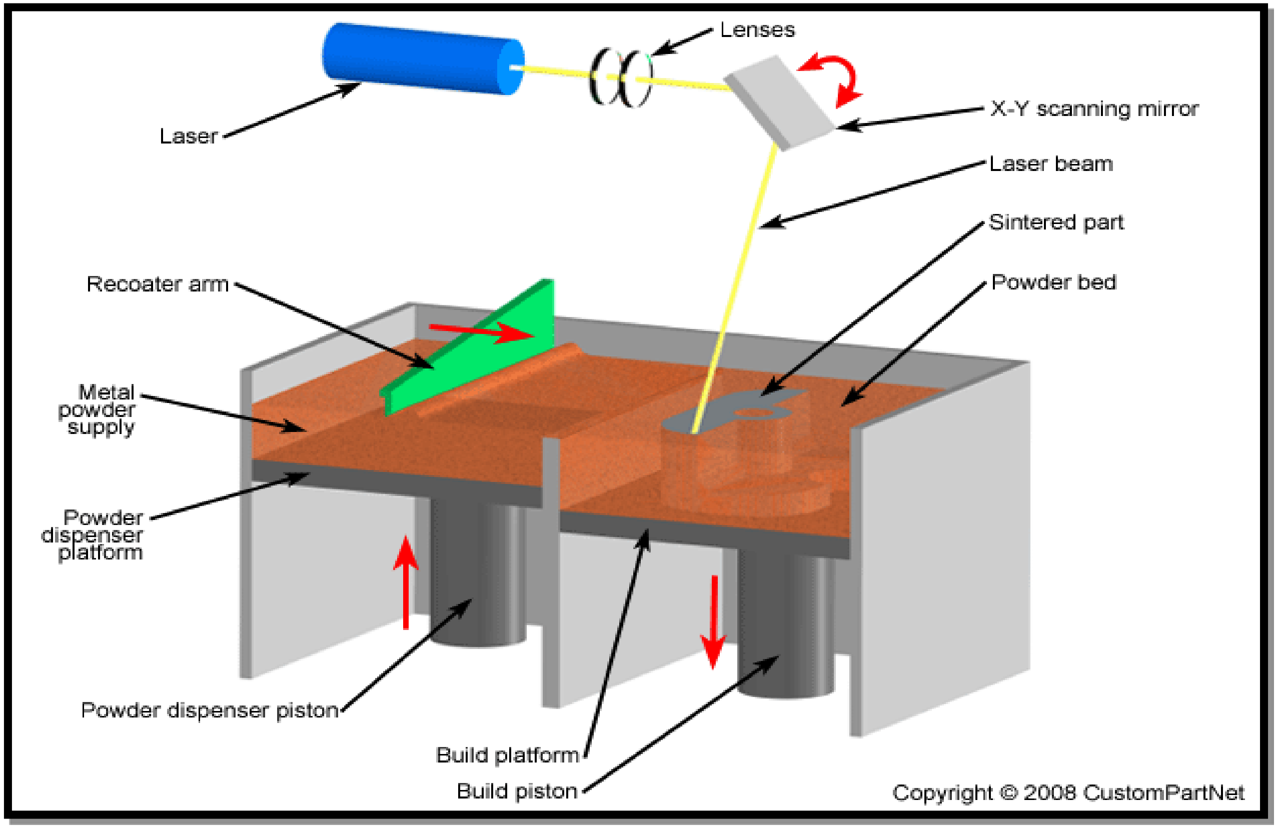


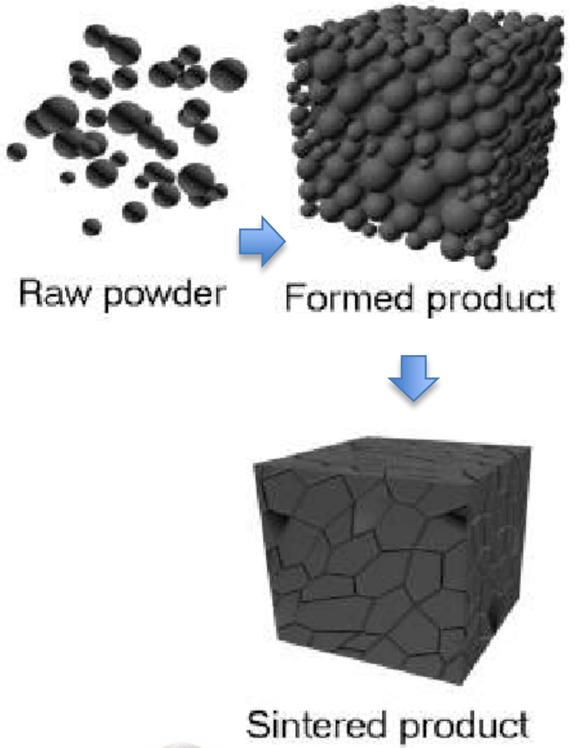
Sliced model

Fabricated Object

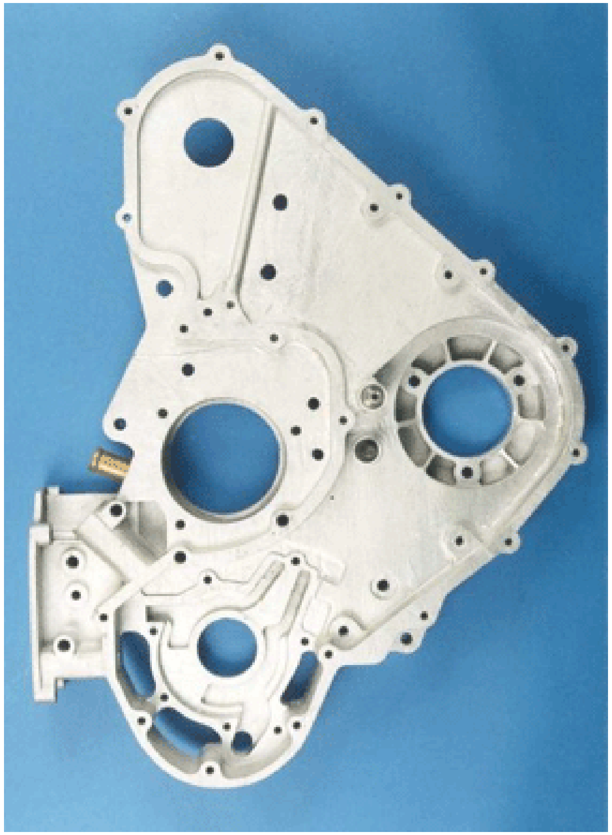
By Yong Chen (University of Southern California)

Selective Laser Sintering/Melting





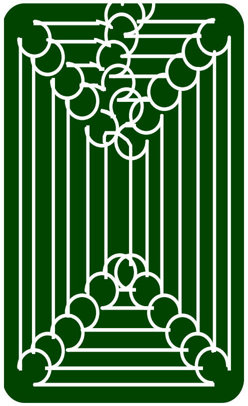
Models Fabricated by SLS

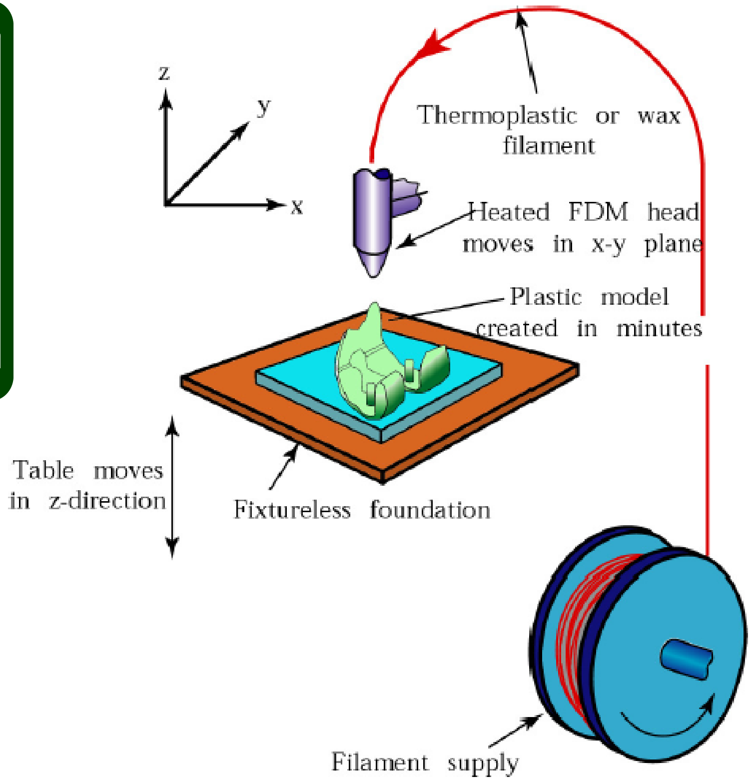


Metal Part by SLS

Polymer Part by SLS

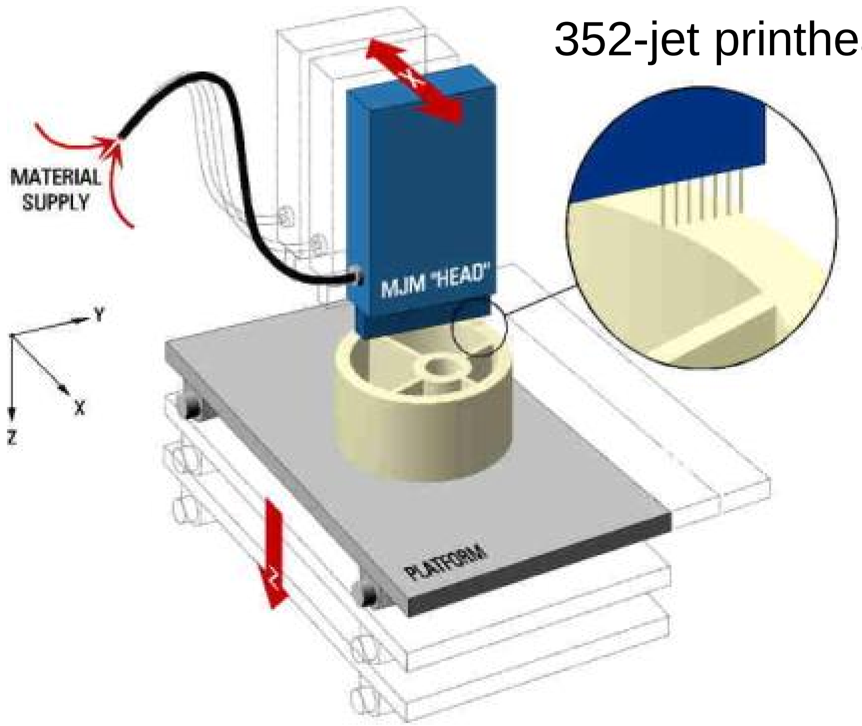
Fused Deposition Modeling





- Introduced in 1988 by *Scott Crump* who founded *Stratasys*
- The best-selling Rapid Prototyping technology in terms of installation number

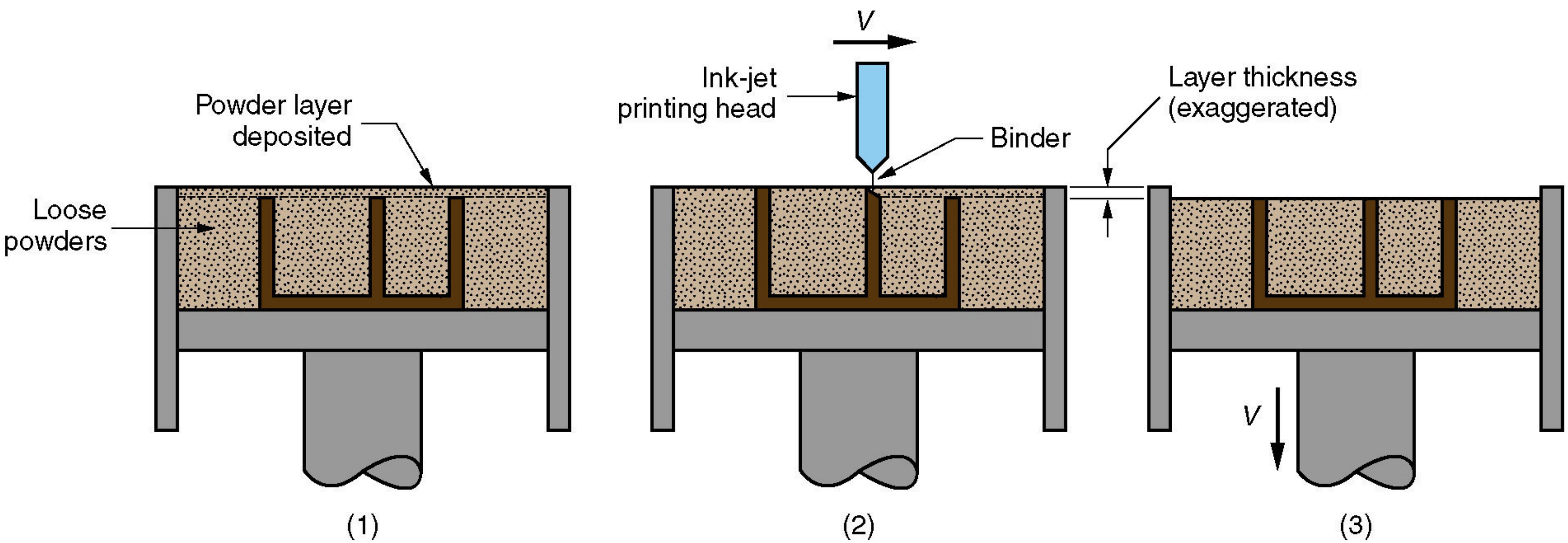
Multi-Jet Modeling



Jetting of photopolymer in desired space, which is then cured by a flash of UV light

Material Deposition

Binder-Jet Printing (3DP)

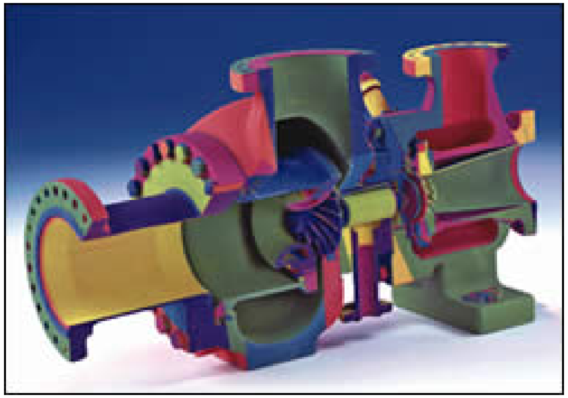


(1) powder layer is deposited
(2) ink-jet printing of areas that will become the part
(3) piston is lowered for next layer

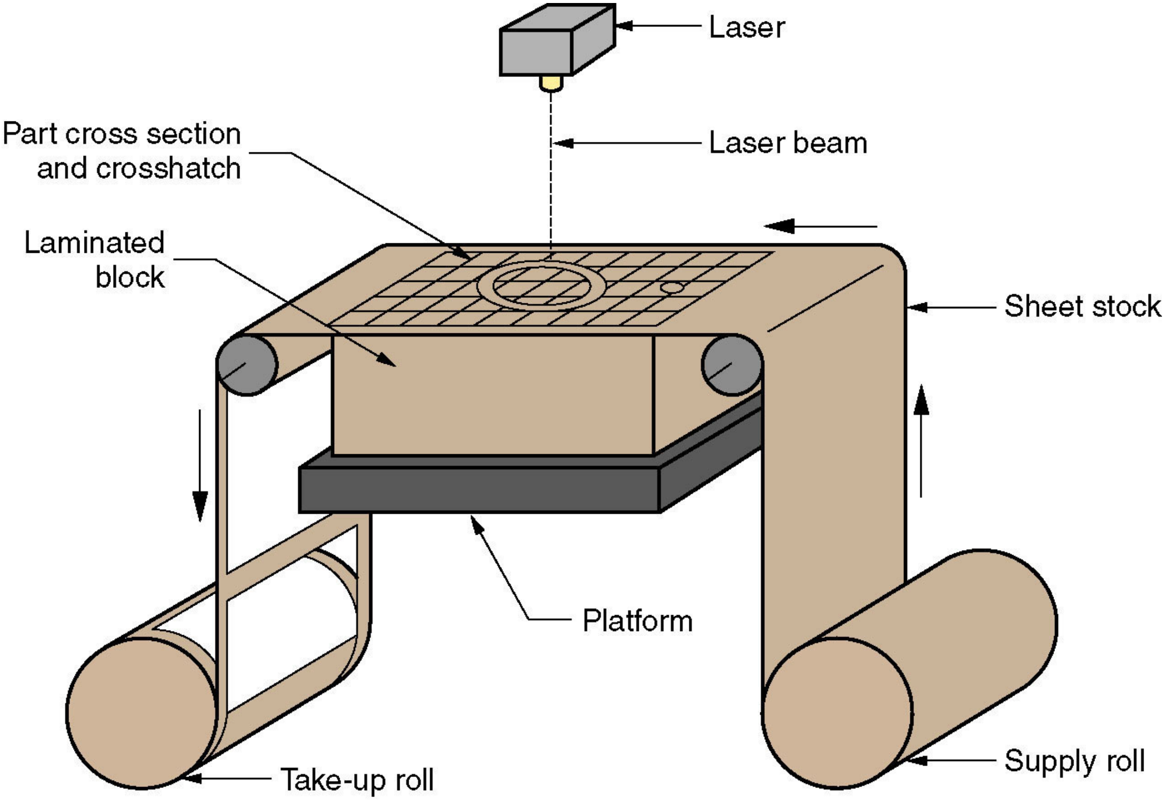
Part strength is low if compared to SLS (binding instead of sintering)

ZPrinter – Z Corporation

An example of machine using 3DP technique



Laminated Object Manufacturing



Stacking layers of sheet stock, each an outline of the cross-sectional shape of a CAD model.

Starting material is sheet stock, such as paper, plastic, cellulose, metals, or fiber-reinforced materials.

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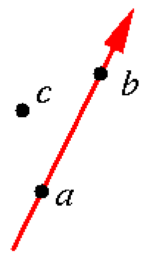
Numerical Robustness

- Computation in IEEE arithmetic
  - Limited precision of floating-point arithmetic
- Geometry becomes inexact after intersection
- Geometric predicates
  - Correct?
  - Self-intersected models?

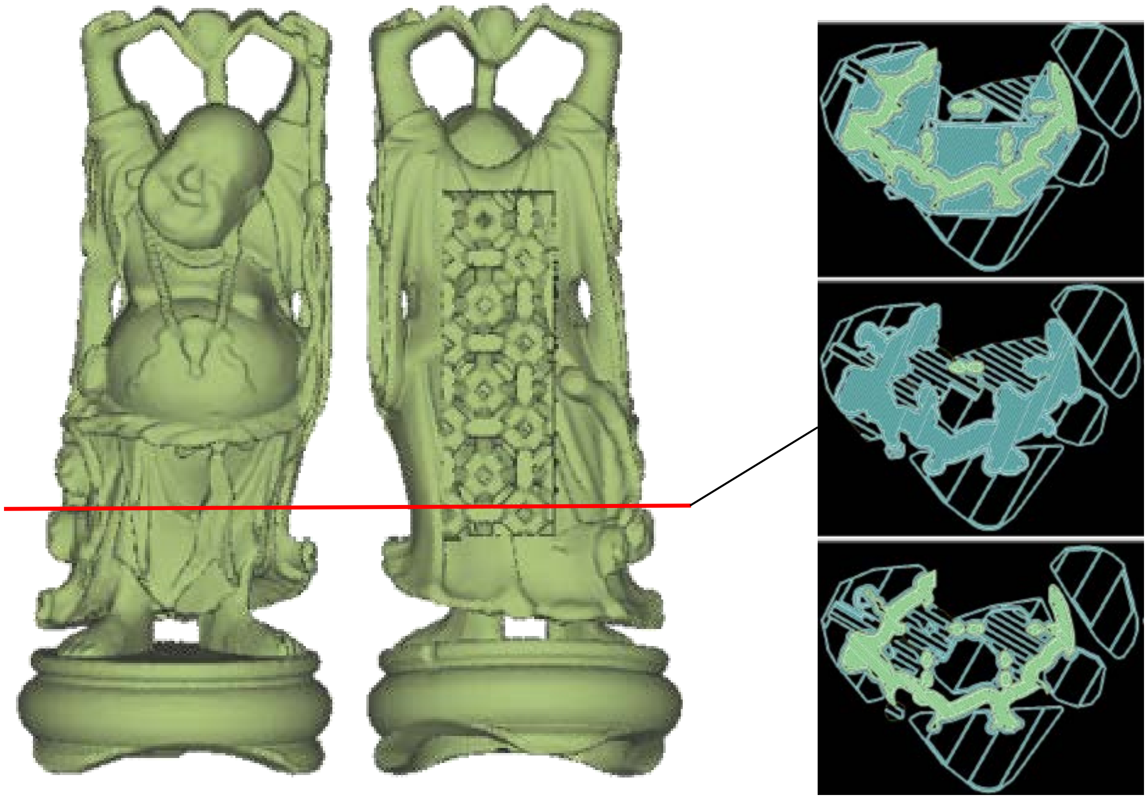
Orientation

Does c lie on, to the left of, or to the right of $\overrightarrow{ab}$?

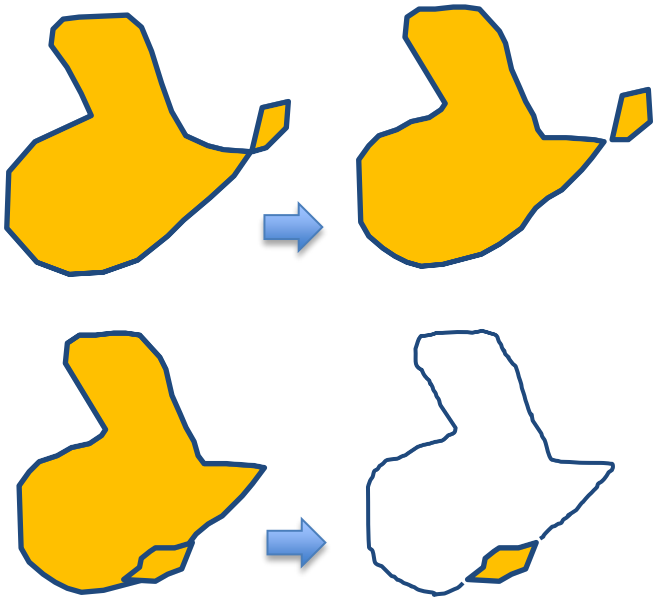


$$\begin{vmatrix} a_x & a_y & 1 \\ b_x & b_y & 1 \\ c_x & c_y & 1 \end{vmatrix} = \begin{vmatrix} a_x - c_x & a_y - c_y \\ b_x - c_x & b_y - c_y \end{vmatrix}$$

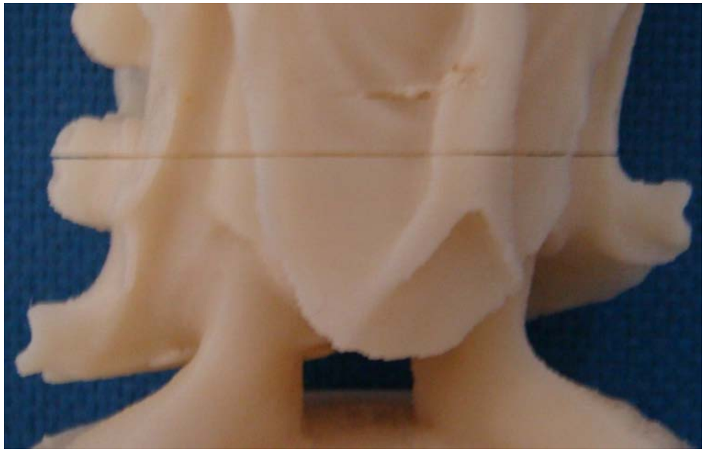
Problem of Inexact B-rep

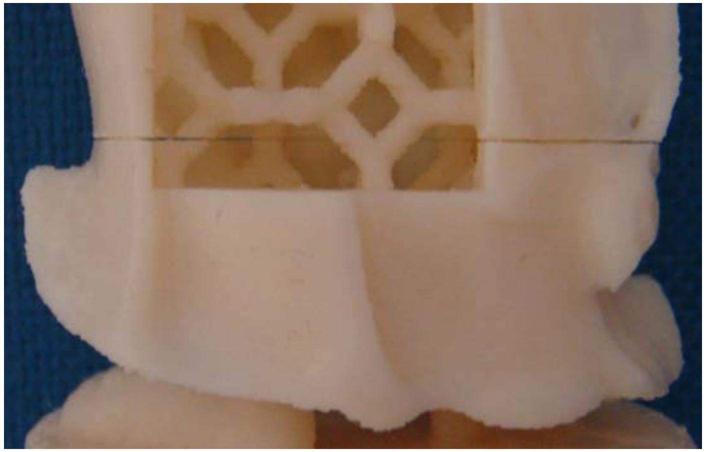


Can it be easily repaired?

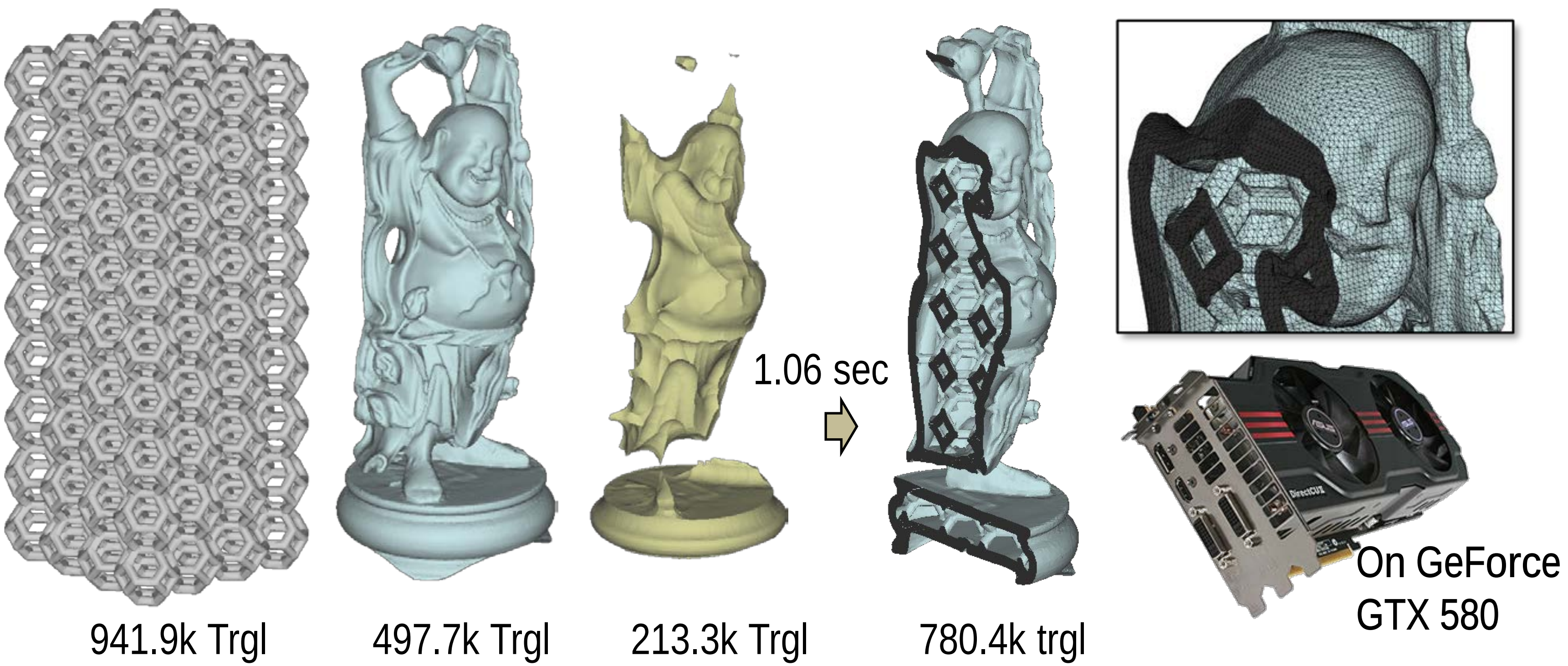


Problem of Inexact B-rep (cont.)





Robust Computation in Image Space



Using Ray-rep by Layered Depth-Normal Images (LDNI) on GPUs

Charlie C.L. Wang, Yuen-Shan Leung, and Yong Chen, "Solid modeling of polyhedral objects by Layered Depth-Normal Images on the GPU", Computer-Aided Design, vol.42, no.6, pp.535-544, June 2010.

Semi-Implicit Representation

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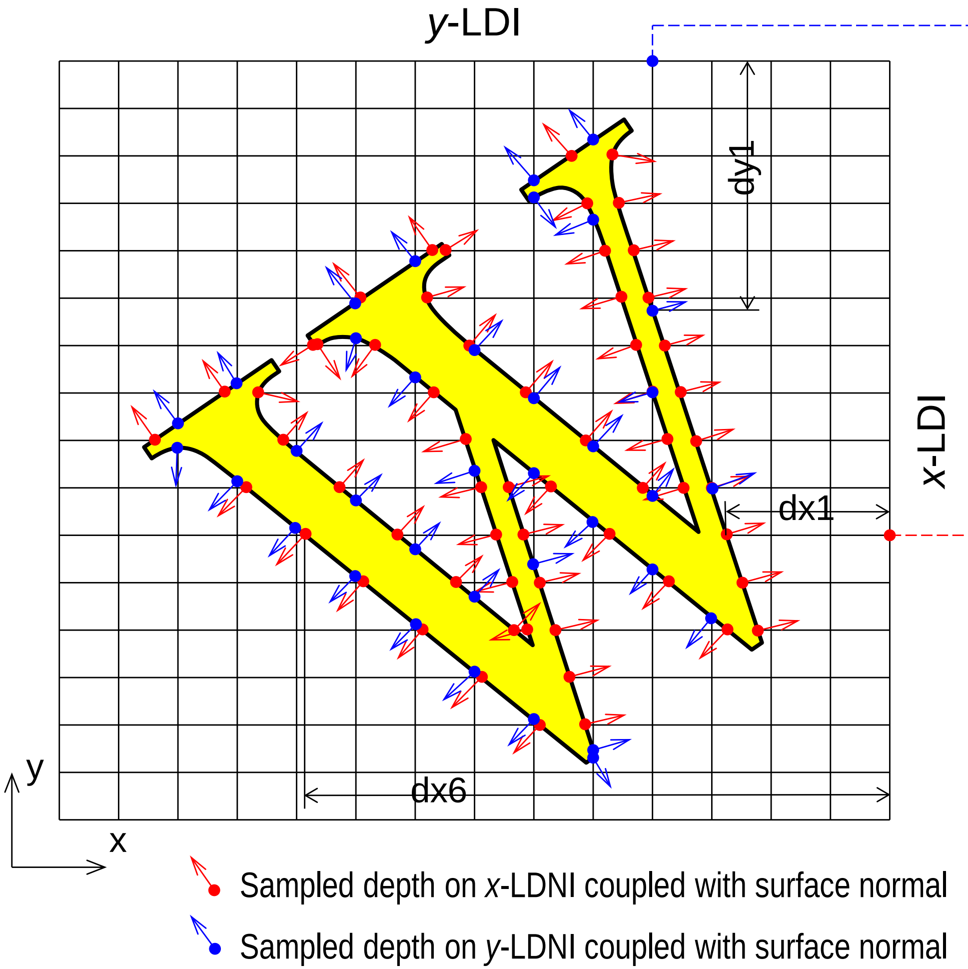
1D Solids on Rays

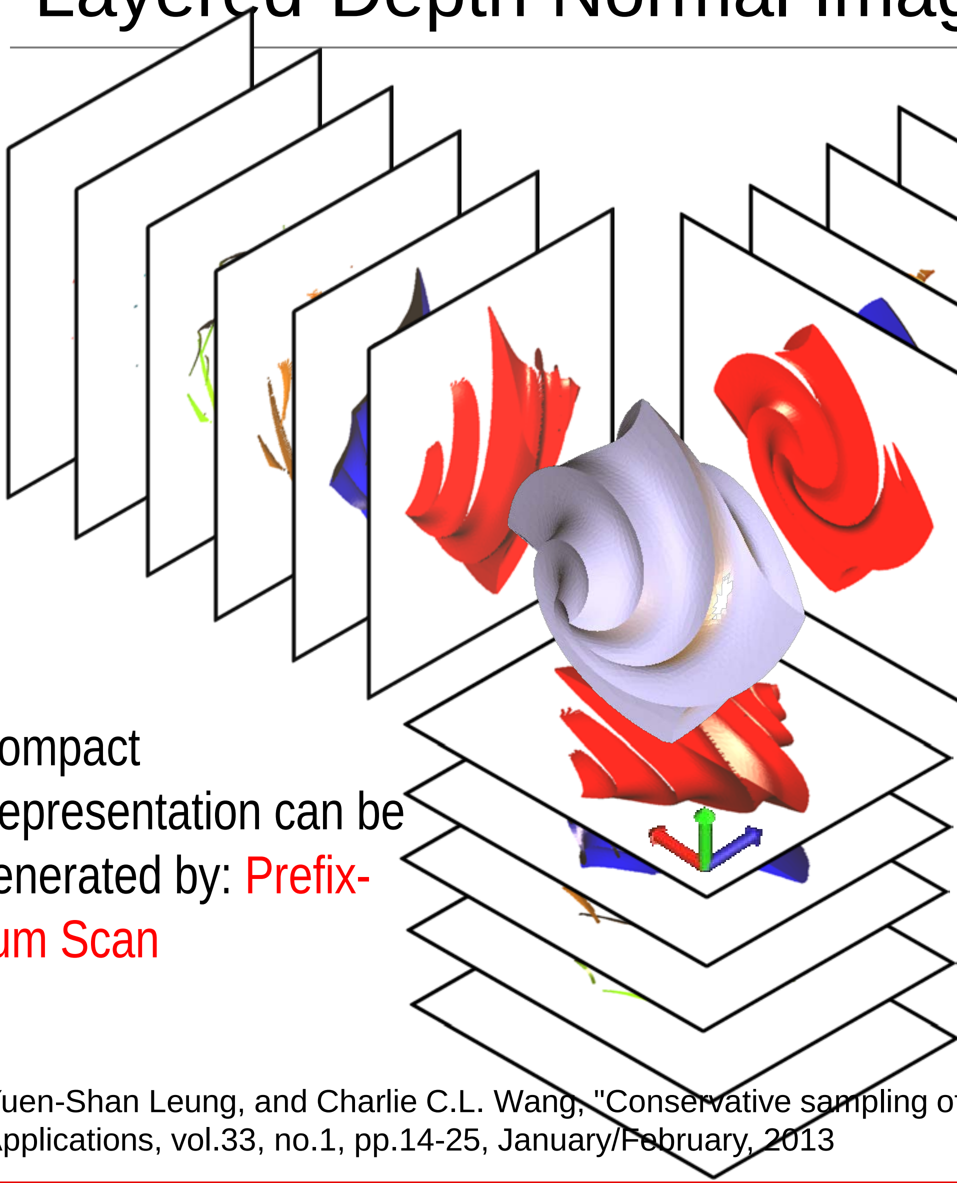


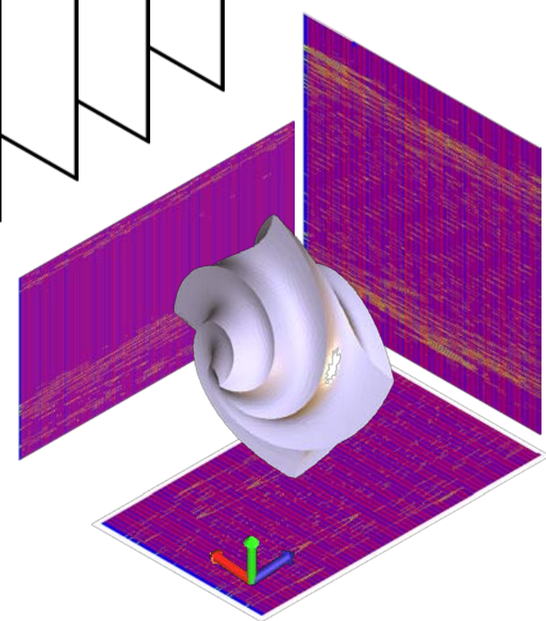
4				
	dy1	$n1_x$	$n1_y$	$n1_z$
	dy2	$n2_x$	$n2_y$	$n2_z$
	dy3	$n3_x$	$n3_y$	$n3_z$
	dy4	$n4_x$	$n4_y$	$n4_z$

6				
	dx1	$n1_x$	$n1_y$	$n1_z$
	dx2	$n2_x$	$n2_y$	$n2_z$
	dx3	$n3_x$	$n3_y$	$n3_z$
	dx4	$n4_x$	$n4_y$	$n4_z$
	dx5	$n5_x$	$n5_y$	$n5_z$
	dx6	$n6_x$	$n6_y$	$n6_z$

Layered-Depth Normal Images (LDNI)

Two Arrays:
1) 2D Index Array
2) 1D Data Array



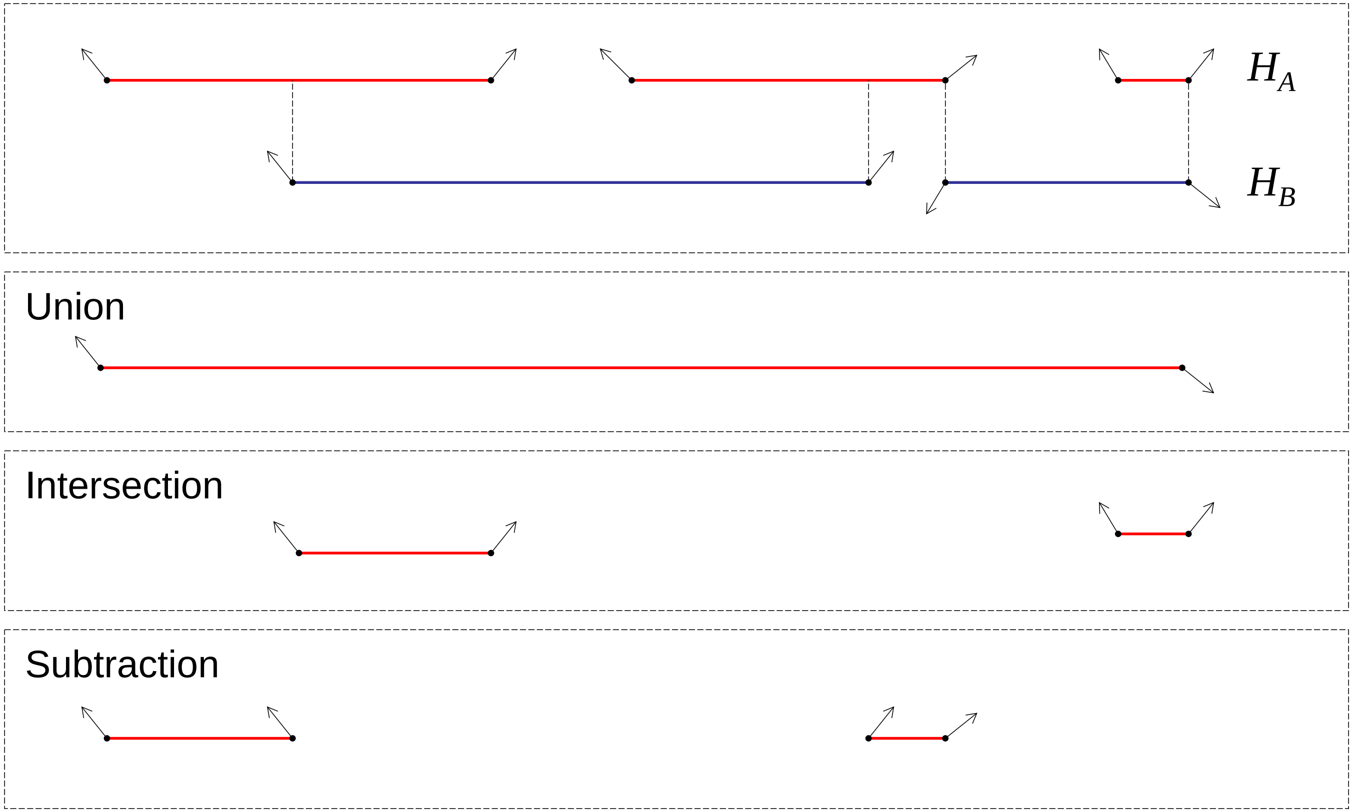


Compact Representation can be generated by: Prefix-sum Scan

Yuen-Shan Leung, and Charlie C.L. Wang, "Conservative sampling of solids in image space", IEEE Computer Graphics and Applications, vol.33, no.1, pp.14-25, January/February, 2013

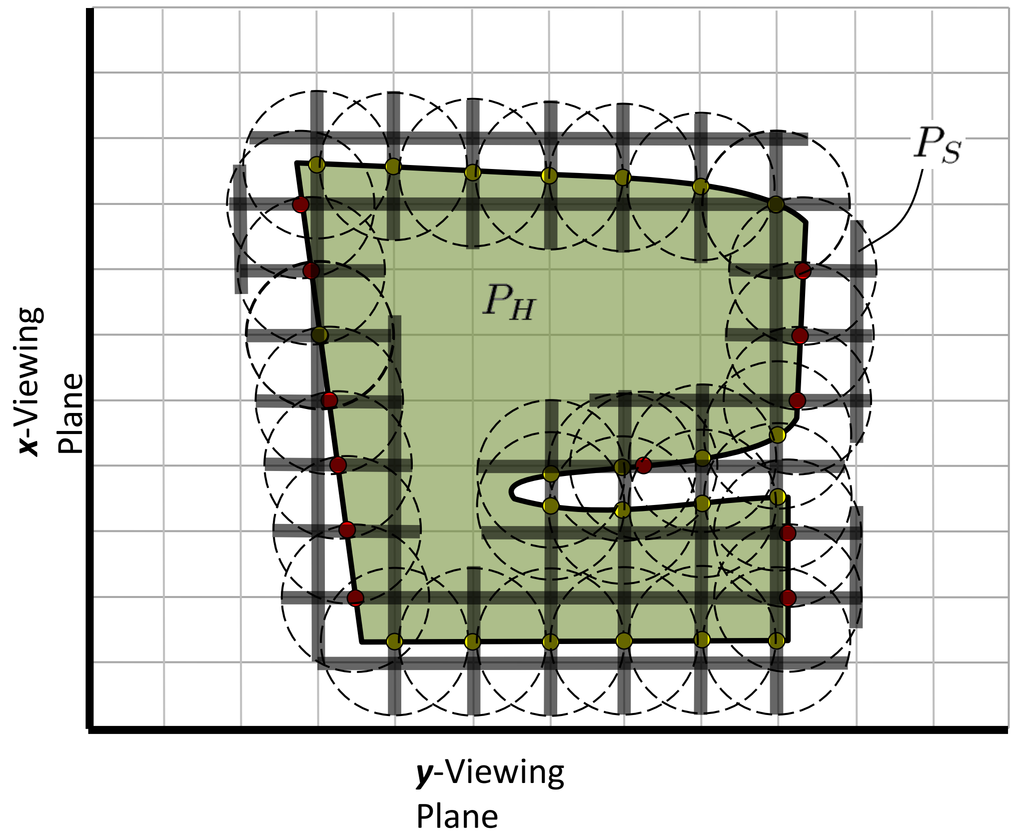
Boolean Operations on Rays

- Inherit the simplicity of Boolean on ray-rep – Robust
- Highly parallel – computing on rays of LDNI



Hanli Zhao, Charlie C.L. Wang, Yong Chen, and Xiaogang Jin, "Parallel and efficient Boolean on polygonal solids", The Visual Computer, 2011.

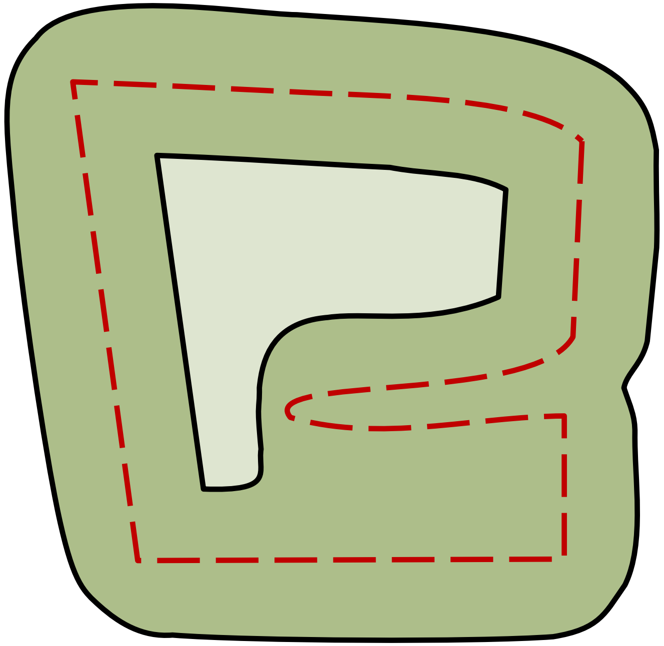
Hollowing by Offsetting



Offsetting Result:

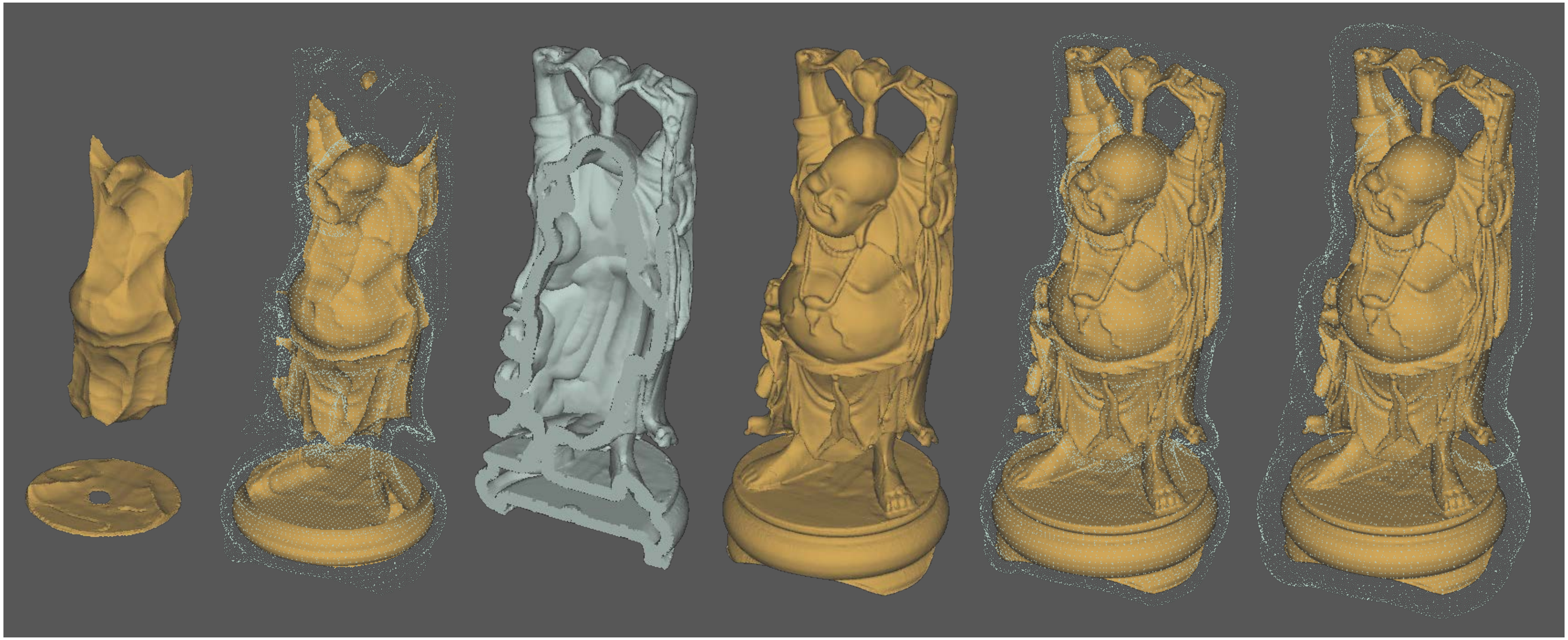
Exterior Offset = P_H U P_S

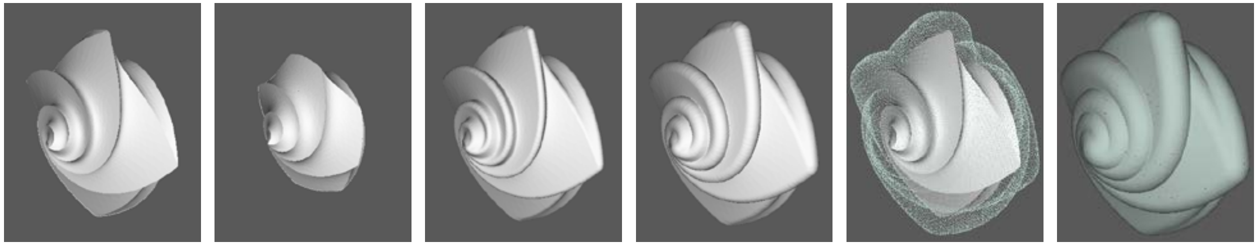
Interior Offset = P_H - P_S



Offsetting by Super-Union of Spheres

GPU-Based Offsetting





Interactive Modeling on GPUs (res.:1024x1024)

(Wang & Manocha, 2012)

Charlie C.L. Wang, and Dinesh Manocha, "GPU-based offset surface computation using point samples", Computer-Aided Design, ACM SPM 2012, October 29-31, 2012, Dijon, France, vol.45, no.2, pp.321-330.

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Robust Slicing Algorithm

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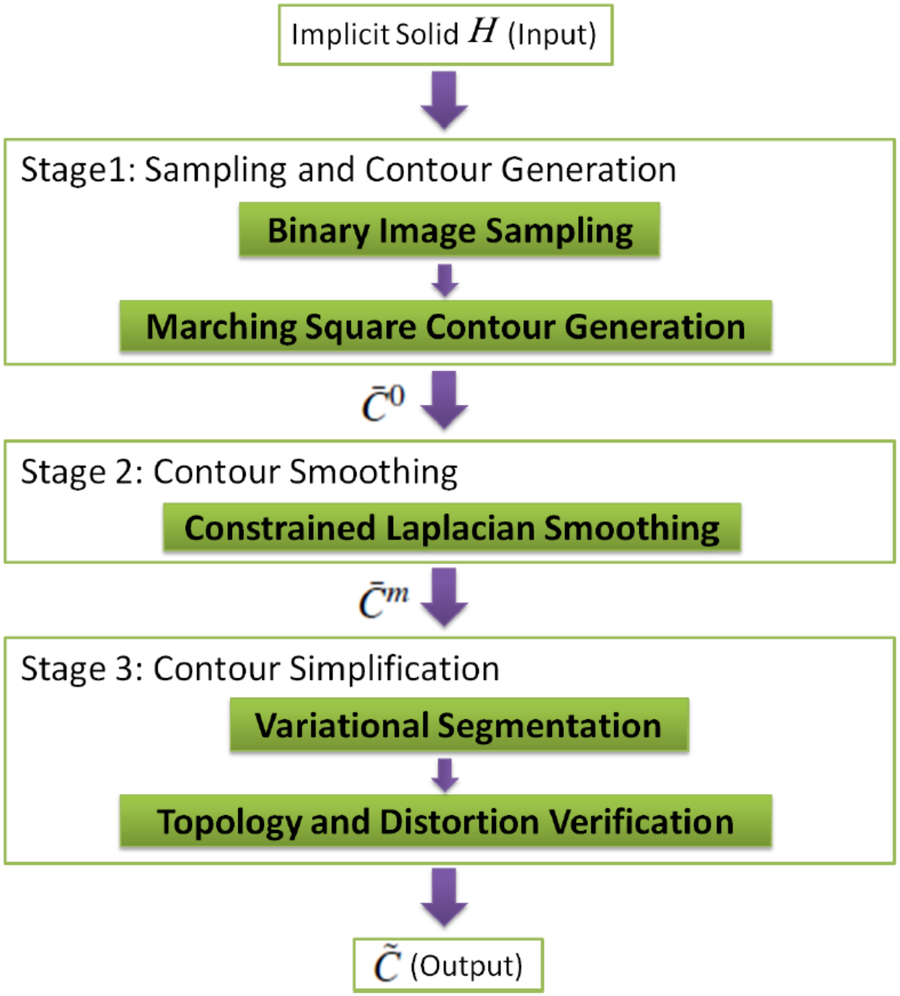
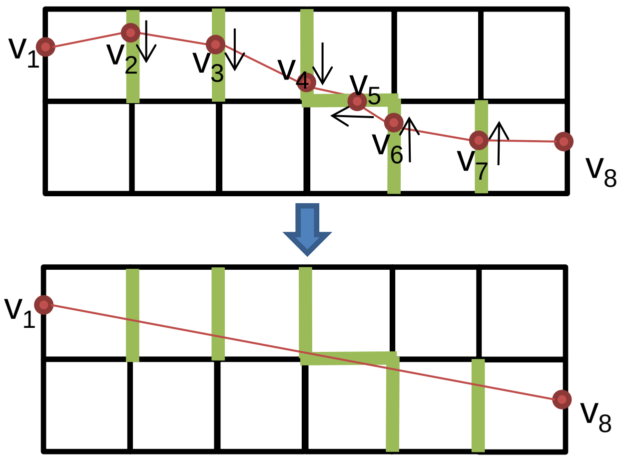


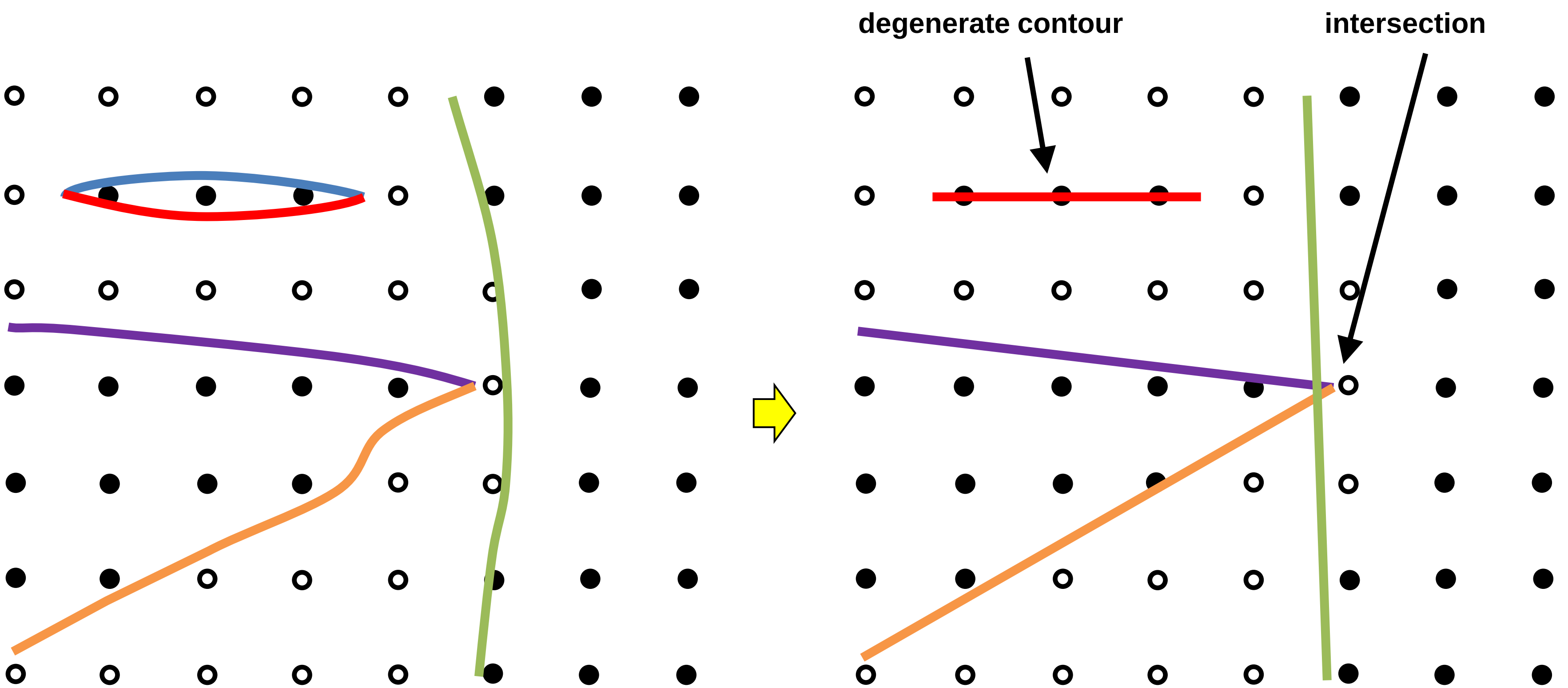
Binary Image Sampling by using the concept of r-regular to guarantee the topological faithful

In the Stages 2 and 3, the self-intersection must be prevented by the stick-concept when sliding on the edges



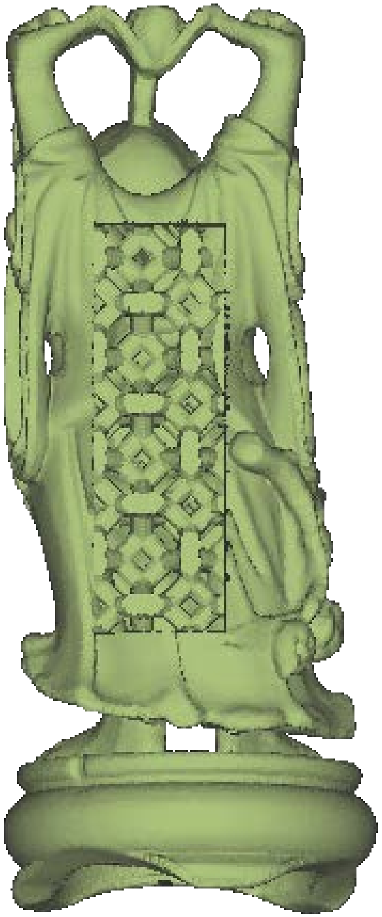
Pu Huang, Charlie C.L. Wang, and Yong Chen, "Intersection-free and topologically faithful slicing of implicit solid", ASME Transactions - Journal of Computing and Information Science in Engineering, vol.13, no.2, 021009 (13 pages), June 2013.

Self-Intersection-Free Contours

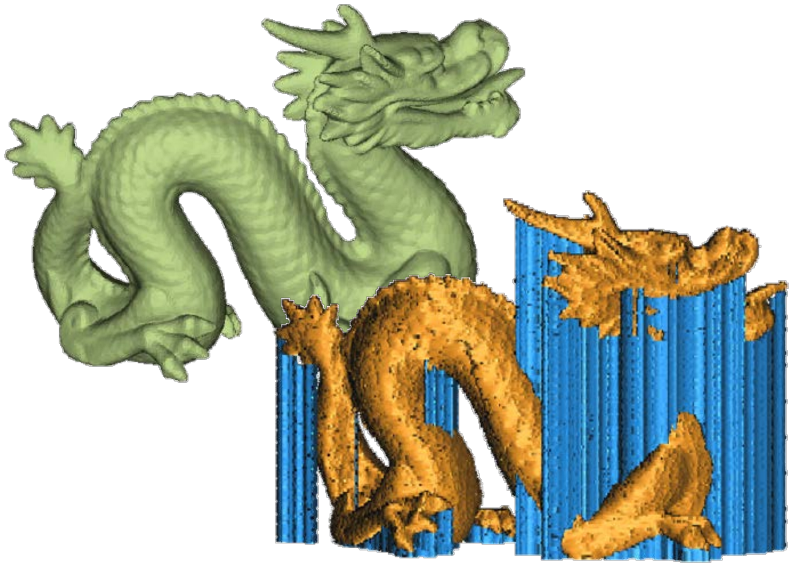


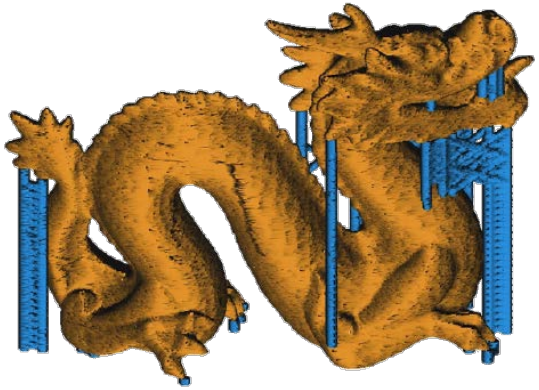
Without snapping the contours on the edge-sticks, self-intersection happens

Results of Contouring and Printing

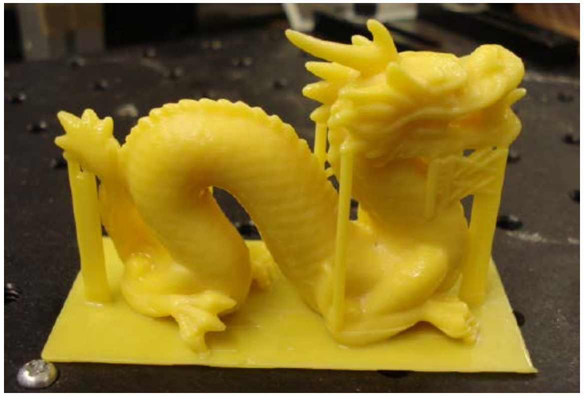


Supporting Structure?





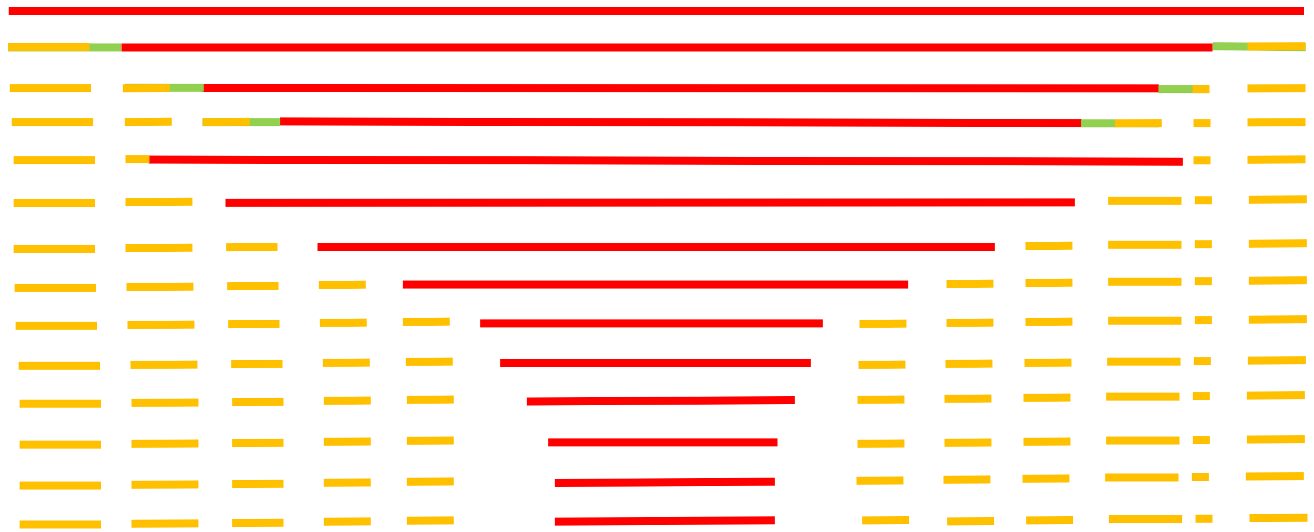
Multi-Materials: Resolvable materials for supporting structure



Single Material: Using structures to support

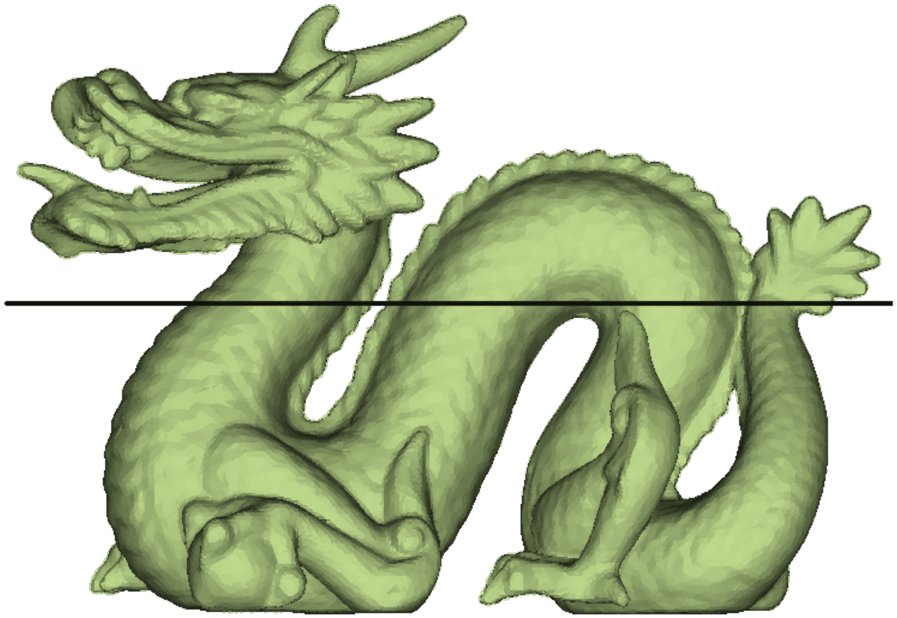
Region Subtraction Algorithm

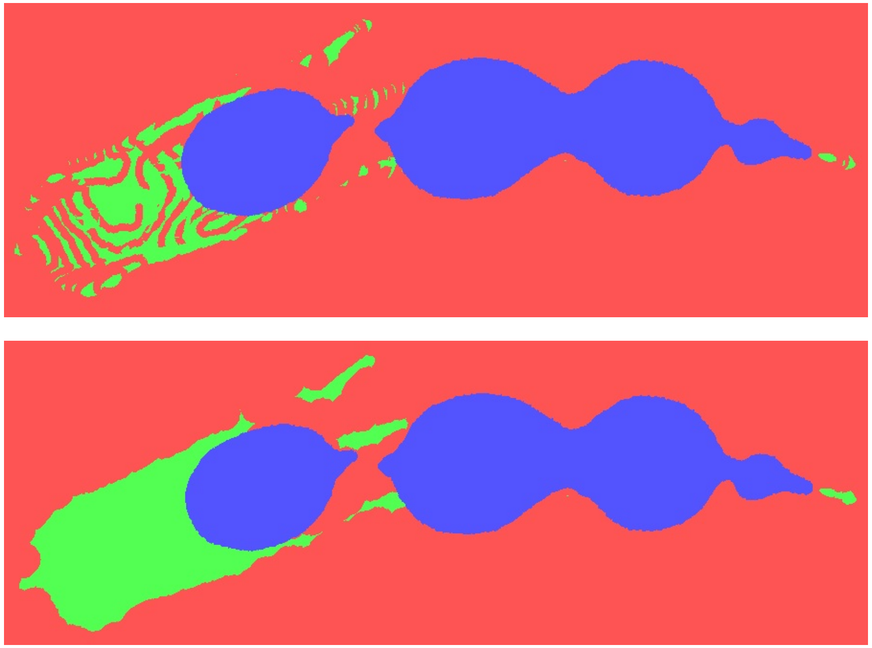
- **Top-down Order:**
  - Step 1: calculate the shadow
  - Step 2: exclude the self-support region with growing-swallow
  - Step 3: project the support region from above layer down to current layer



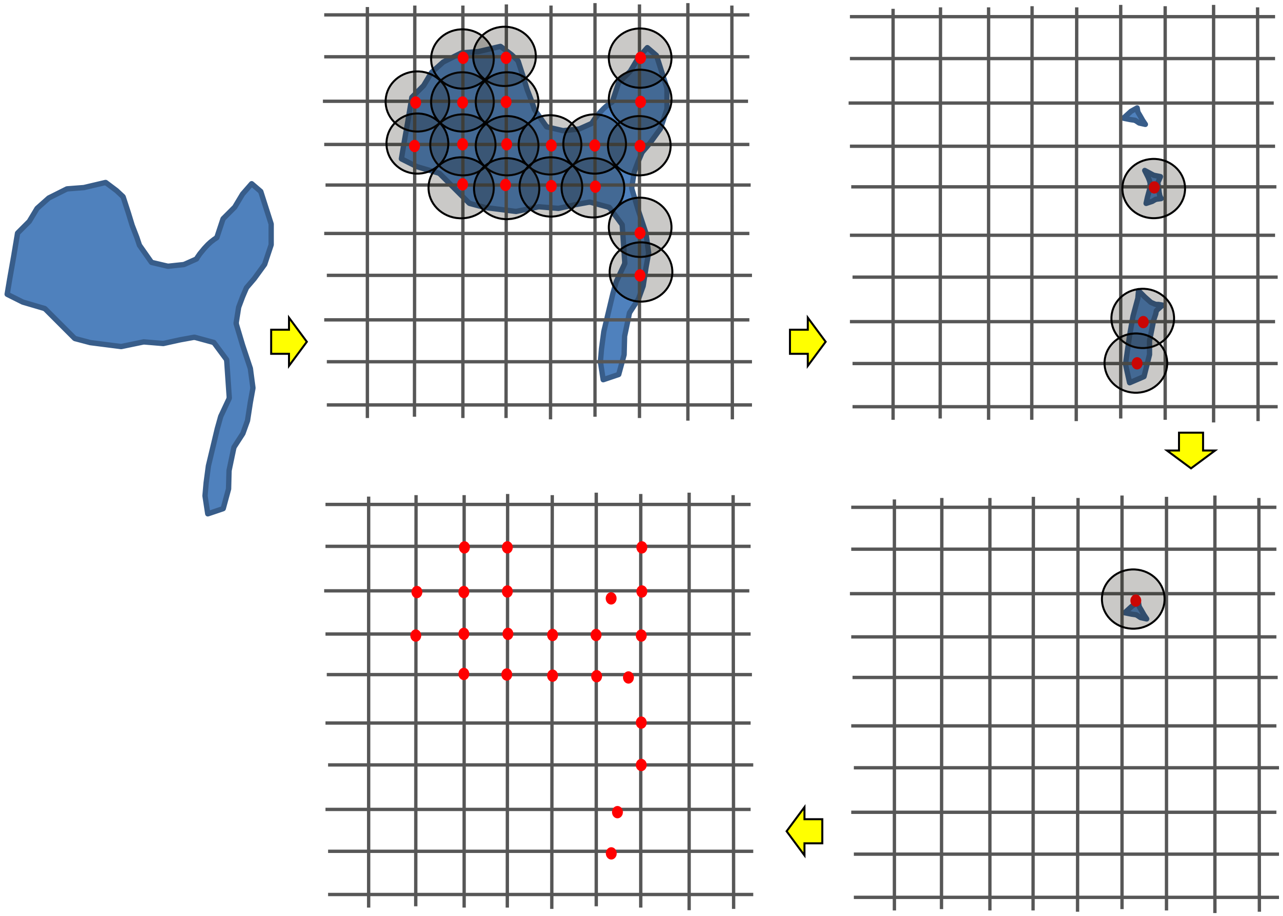
Robust Region Subtraction (Multi-Material)

- Robustly computed in image space
- Dilation and erosion must be applied to remove those self-supported regions





Subtraction on Anchors (Single Material)

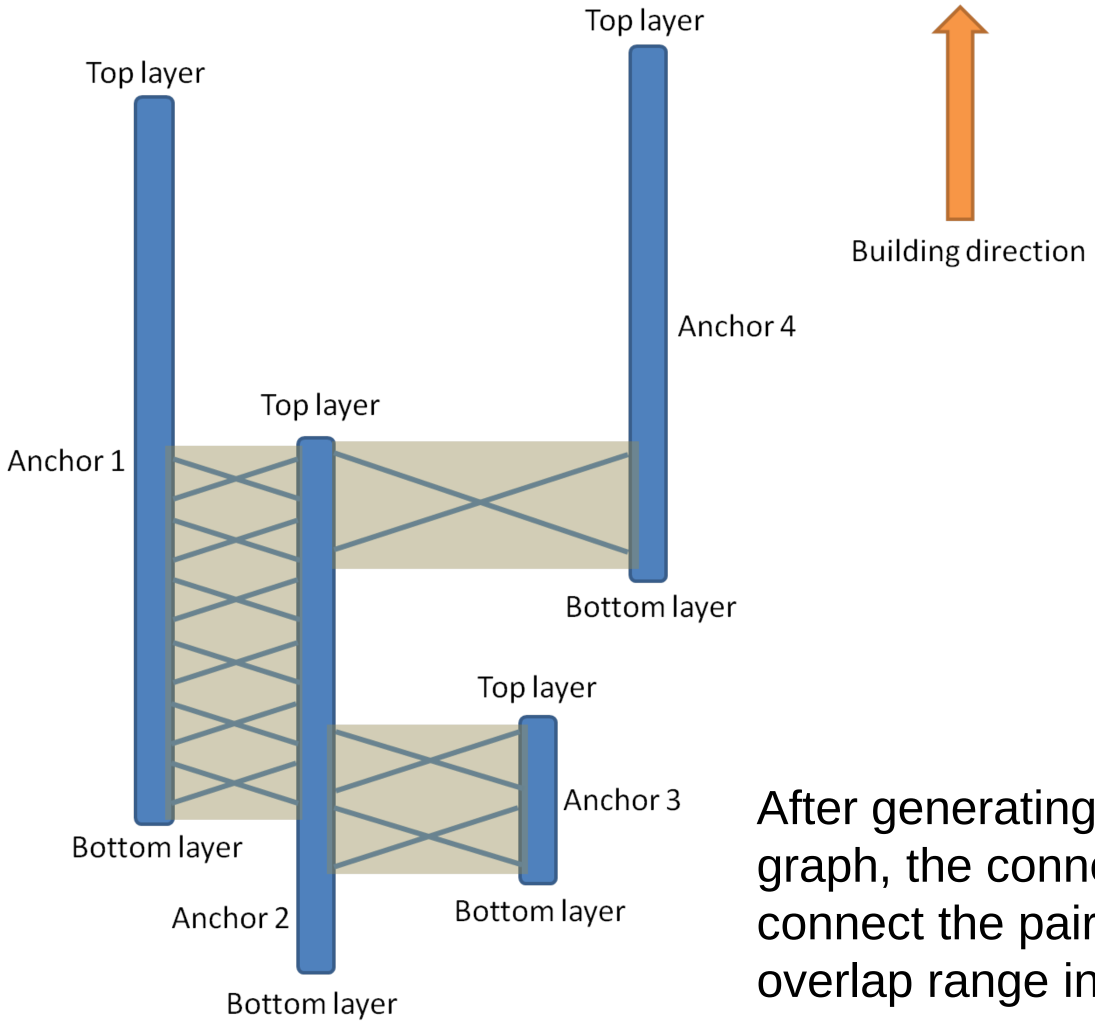


First scan: use a uniform grid to intersect the region to be support with the grid nodes

Second scan: Use the orthogonal rays forming the uniform grid to scan the remaining region

Third scan: perform pixel-wise scan for remaining region

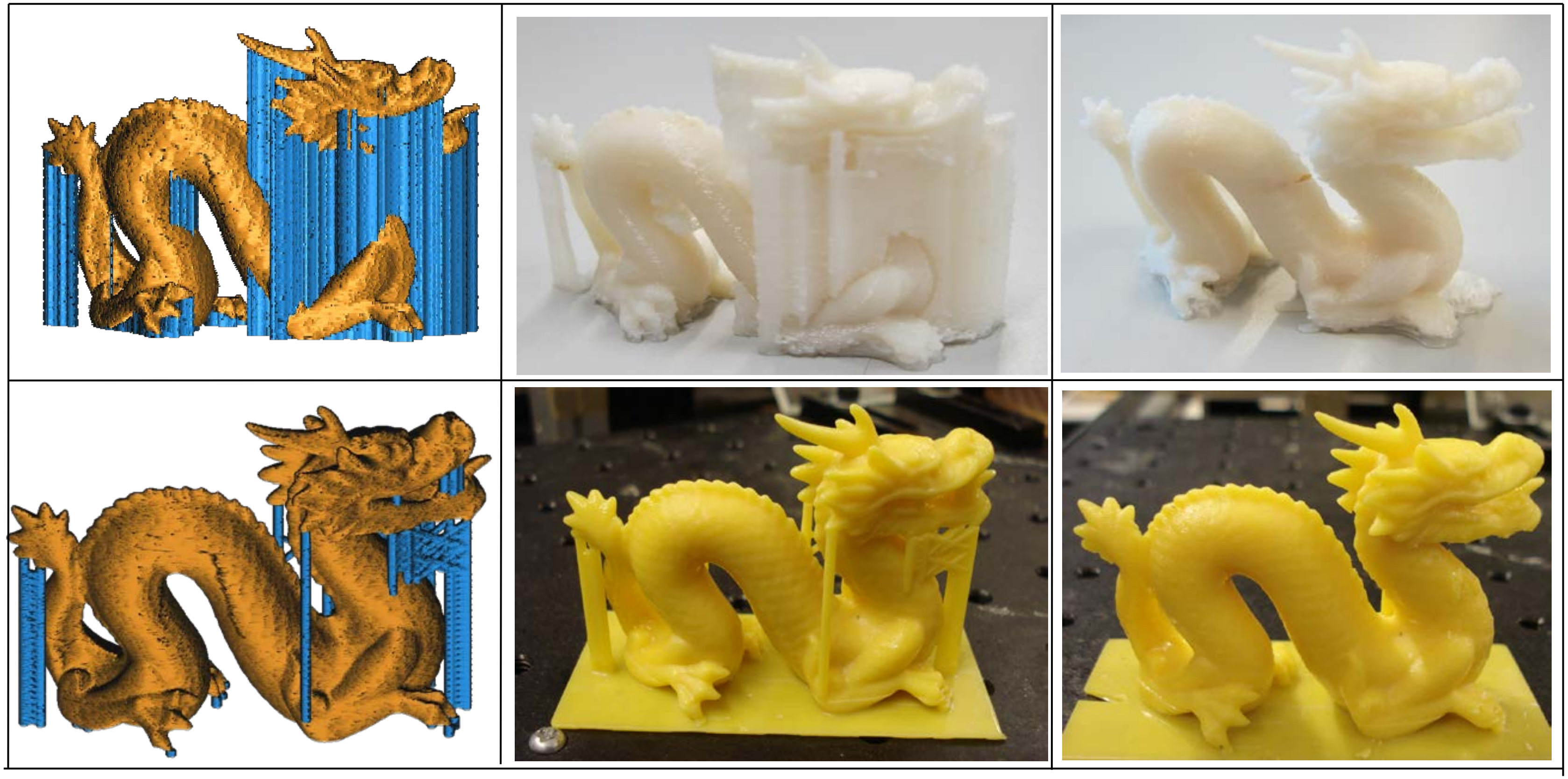
Linking Supporting Bars



After generating the anchor connection graph, the connection operation is applied to connect the pairs of anchors which have overlap range in building direction.

Pu Huang, Charlie C.L. Wang, and Yong Chen, "Algorithms for layered manufacturing in image space", Book Chapter, ASME Advances in Computers and Information in Engineering Research, 2014.

Support Structure Generation



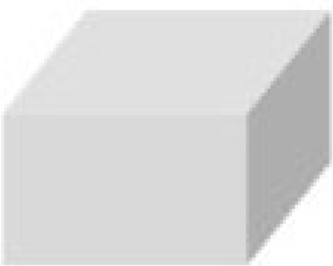
Direct slicing and support generation resultant contour	Fabricated part with support	Fabricated part after removing support

Video

Benefits of Additive Manufacturing

- Very flexible: direction fabrication from CAD model
- Minimal material waste (Additive but not subtractive)
- Manufacturing is responsible for 33% of the world's carbon footprint

Subtractive Machining:



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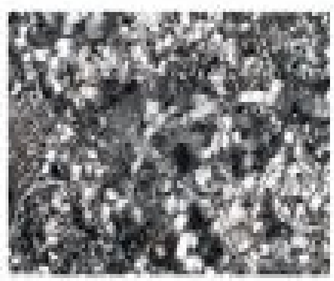

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20 : 1
Buy to fly

5000 lb. forged billet

4750 lb. chips

250 lb. finish machined part

Limitations / Challenges

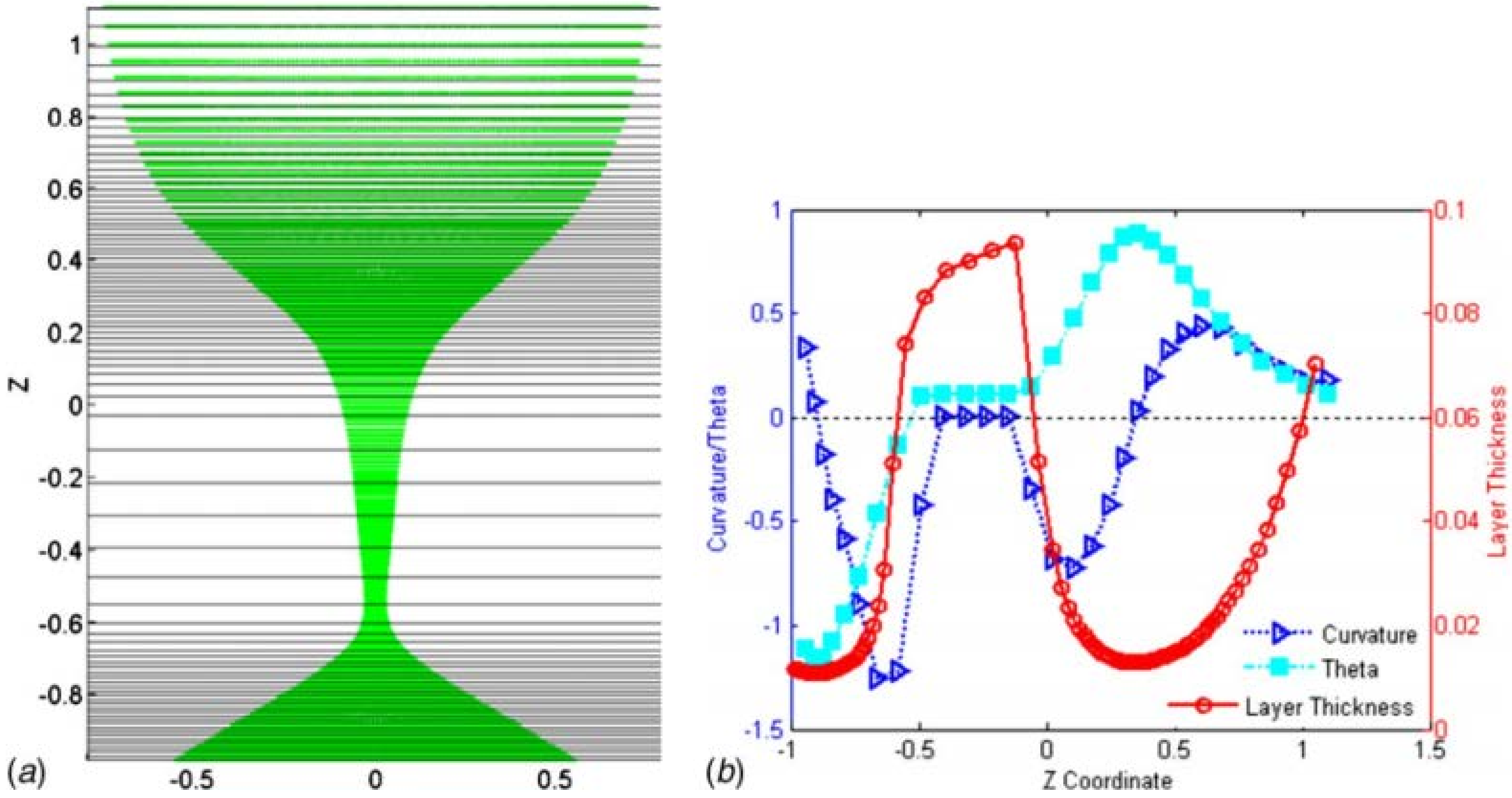
- High time cost (pre- and post-processing, etc.)
- Limited part sizes
- Limited fabrication speed
- Limited materials (20k vs. 200 materials)
- Poor surface finish
- Low dimensional accuracy and resolution
- Inconsistent part quality

Summary of Additive Manufacturing

- Direct way of fabricating products from digital models
- Provide tremendous freedoms in designing product shapes and material properties
- Has a lot of challenges by evolving quickly

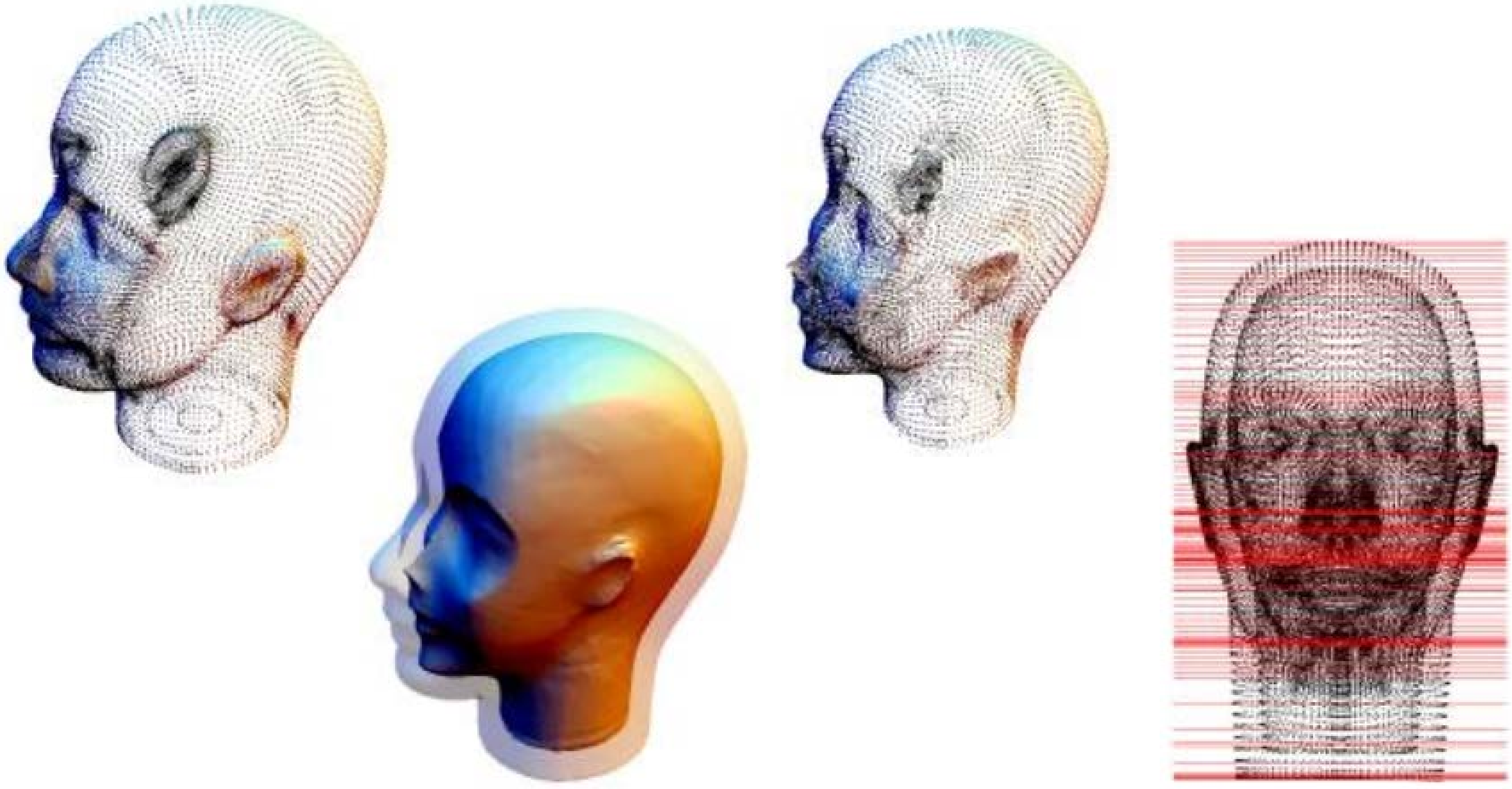
- Recent development:
  - 1) adaptive slicing to reduce the time of fabrication
  - 2) hollowing to reduce both the material and time cost
  - 3) optimization for generating support structures

Adaptive Slicing



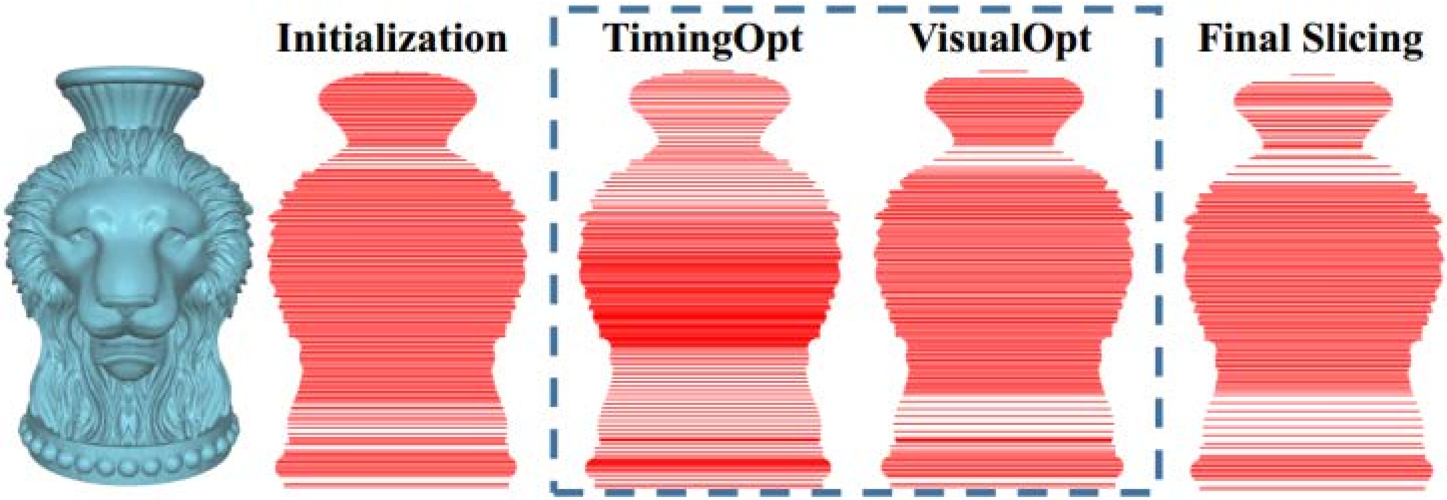
Yang, P. and Qian, X., "Adaptive Slicing of Moving Least Squares Surfaces: Toward Direct Manufacturing from Point Cloud Data," ASME Journal of Computing and Information Science in Engineering, Vol. 8, No. 3, Sep 2008.

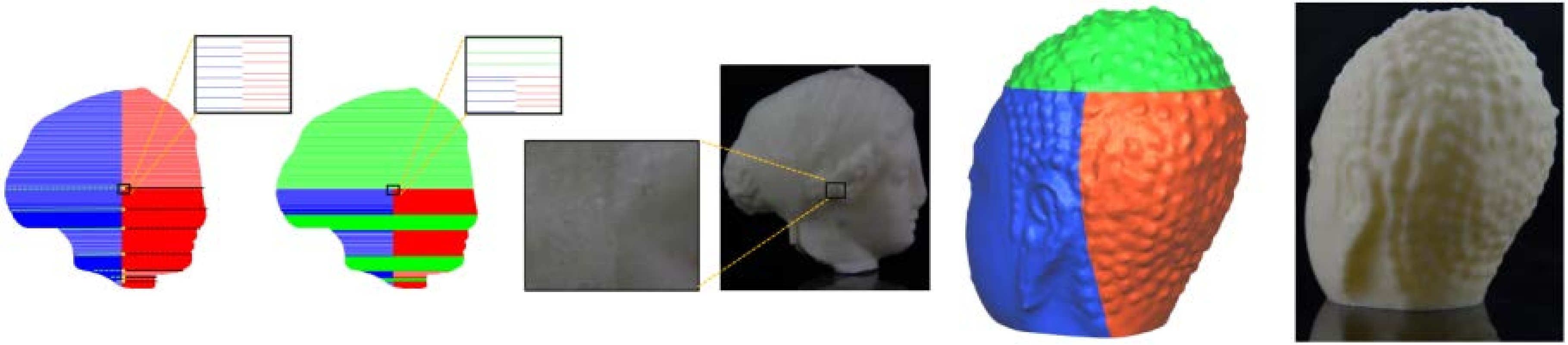
Adaptive Slicing



Shengjun Liu, and Charlie C.L. Wang, "Duplex fitting of zero-level and offset surfaces", Computer-Aided Design, vol.41, no.4, pp.268-281, April 2009.

Adaptive Slicing





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Optimizing Supporting Structures

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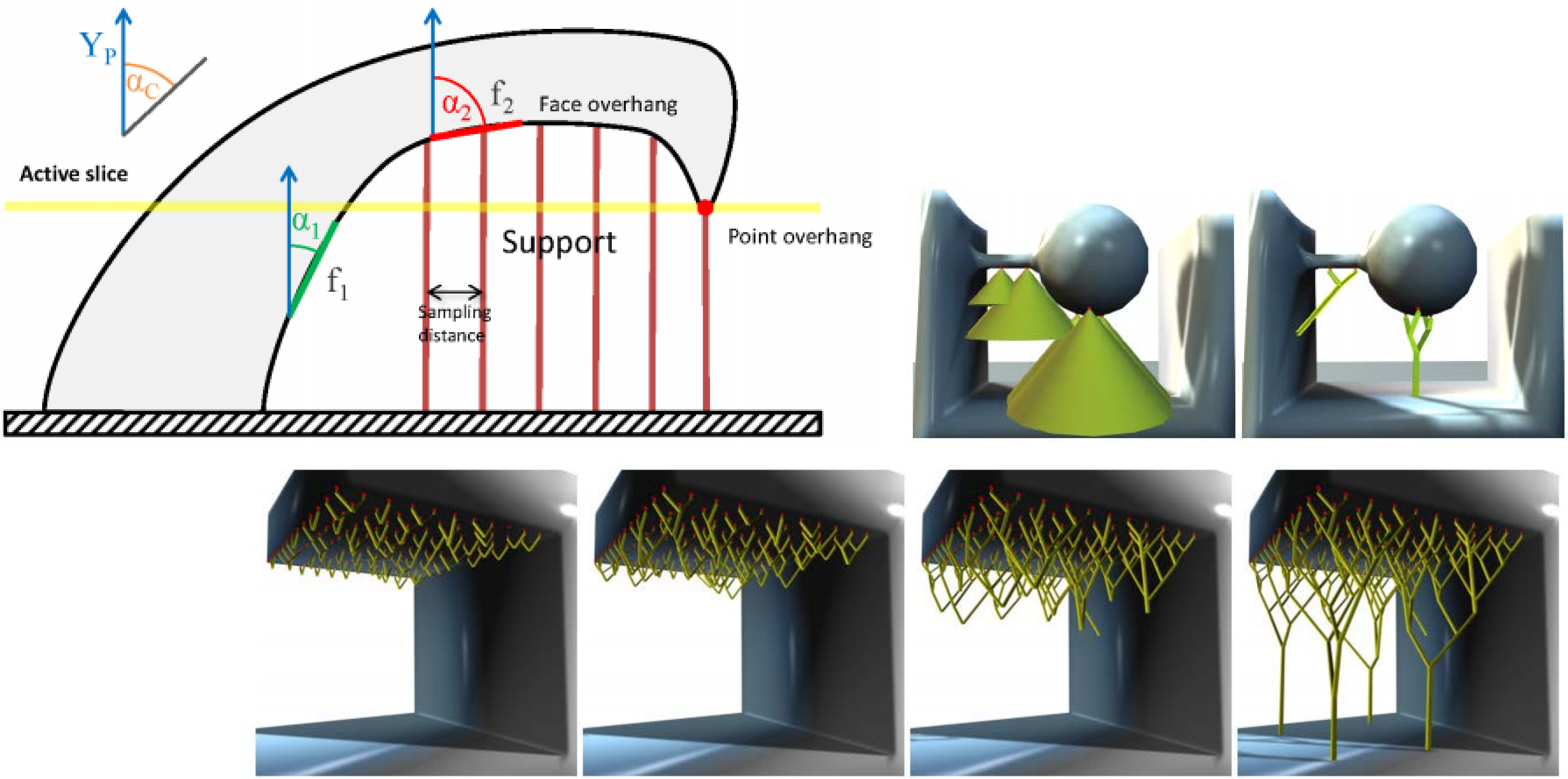
Optimizing Supporting Structures



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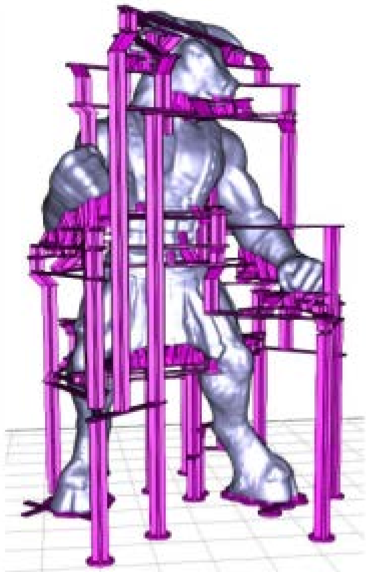
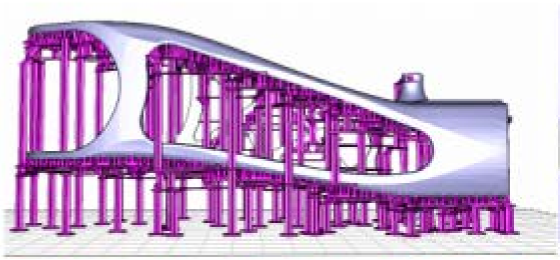
Optimizing Supporting Structures

MeshMixer



Bridging the Gap



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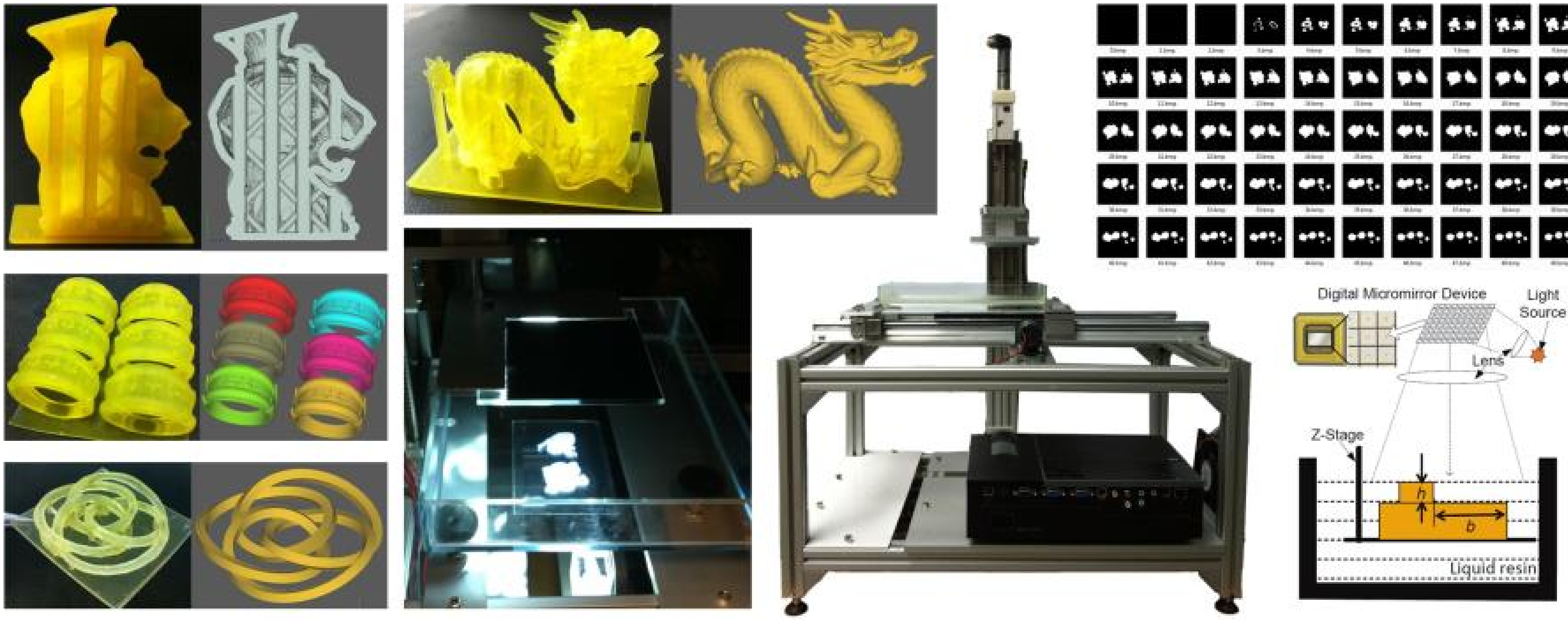
Fast Fabrication by Mask-Projection

- Mask-Project SLA (also called **D**igital **L**ight **P**rojection)



[Video]

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Thank you!

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