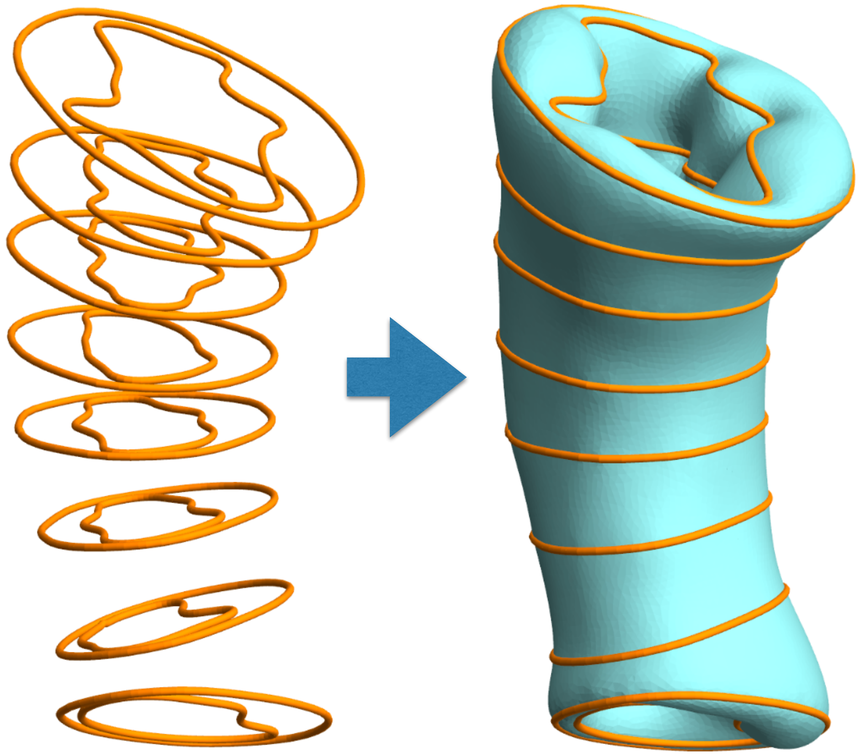
SIGGRAPH2015
Xroads of Discovery

The 42nd International Conference and Exhibition
on Computer Graphics and Interactive Techniques



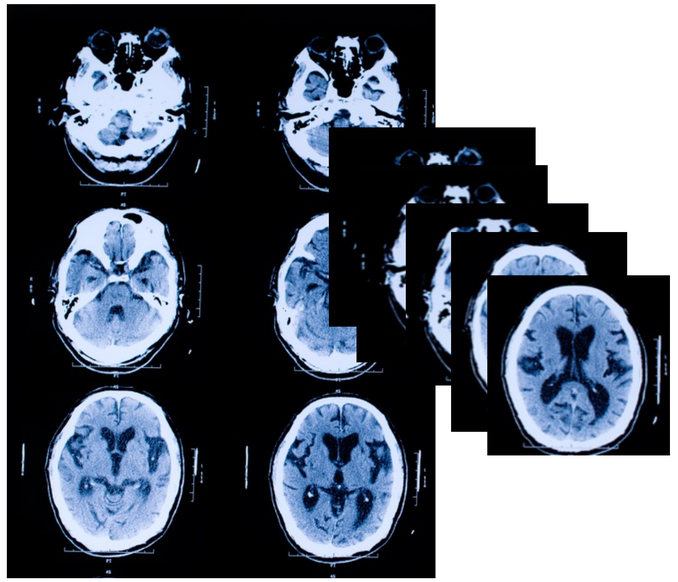
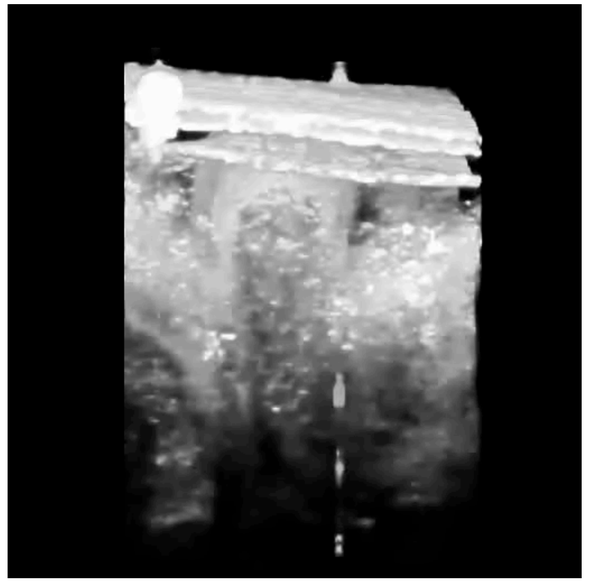
Topology-Constrained Surface Reconstruction From Cross Sections

Ming Zou [1] , Michelle Holloway [1] , Nathan Carr [2] , Tao Ju [1]

[1] Washington University in St. Louis
[2] Adobe Inc.

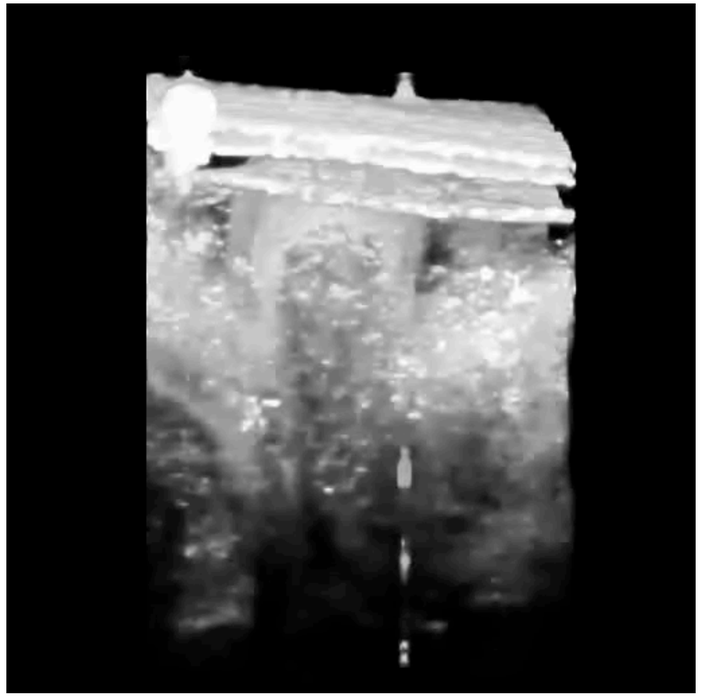
Motivation

- Medical imaging

		
CT scanner	A stack of CT scans (2D) of a human brain	A medical volume (3D) of a developing chicken heart

Segmentation

- In medical imaging, segmentation is **important** but **challenging**.

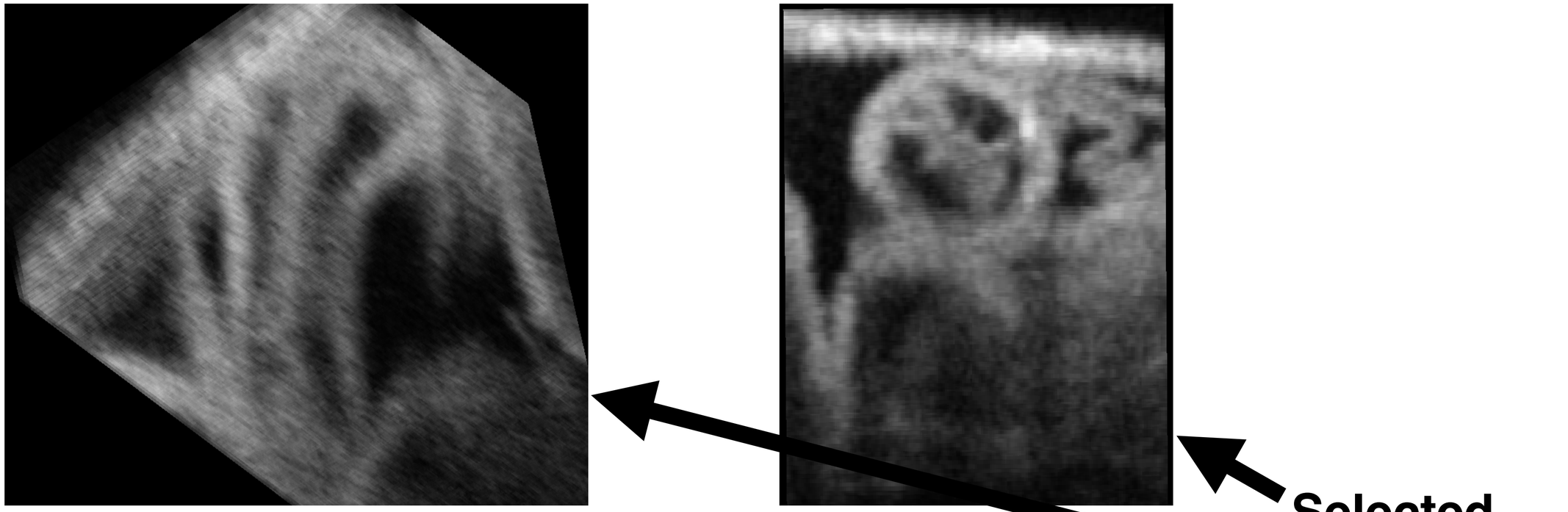




3D volume of a developing chicken heart

Segmentation

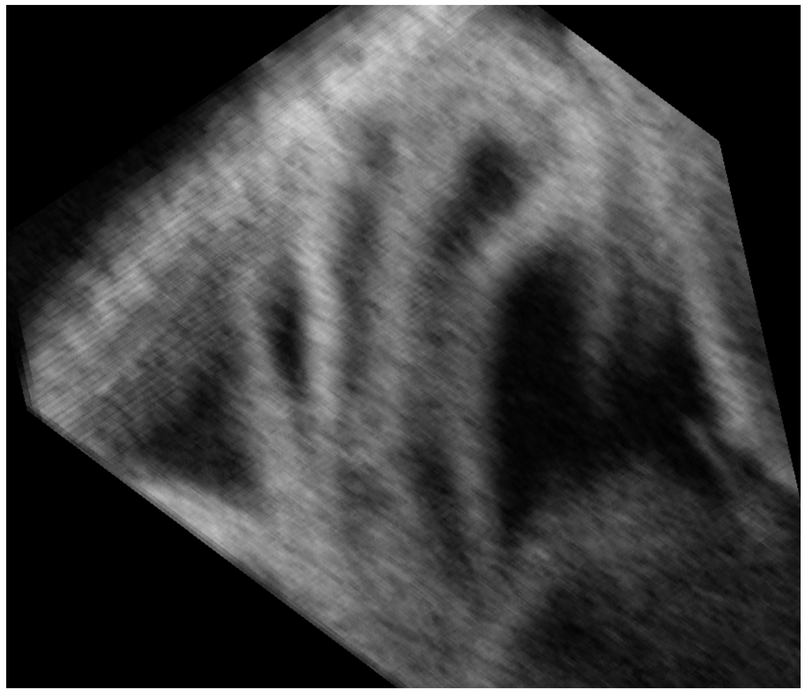
- In medical imaging, segmentation is **important** but **challenging**.

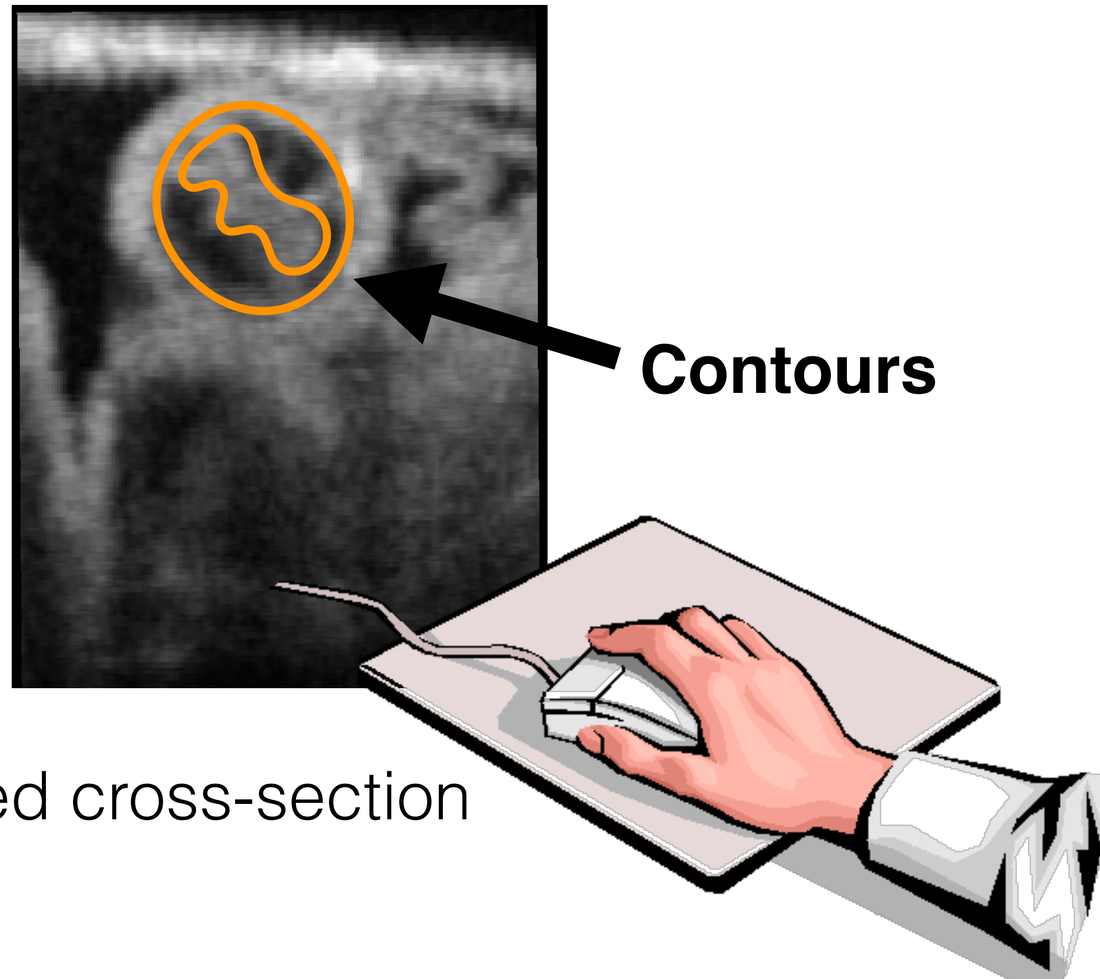


Cross-sections of a developing chicken heart

Segmentation

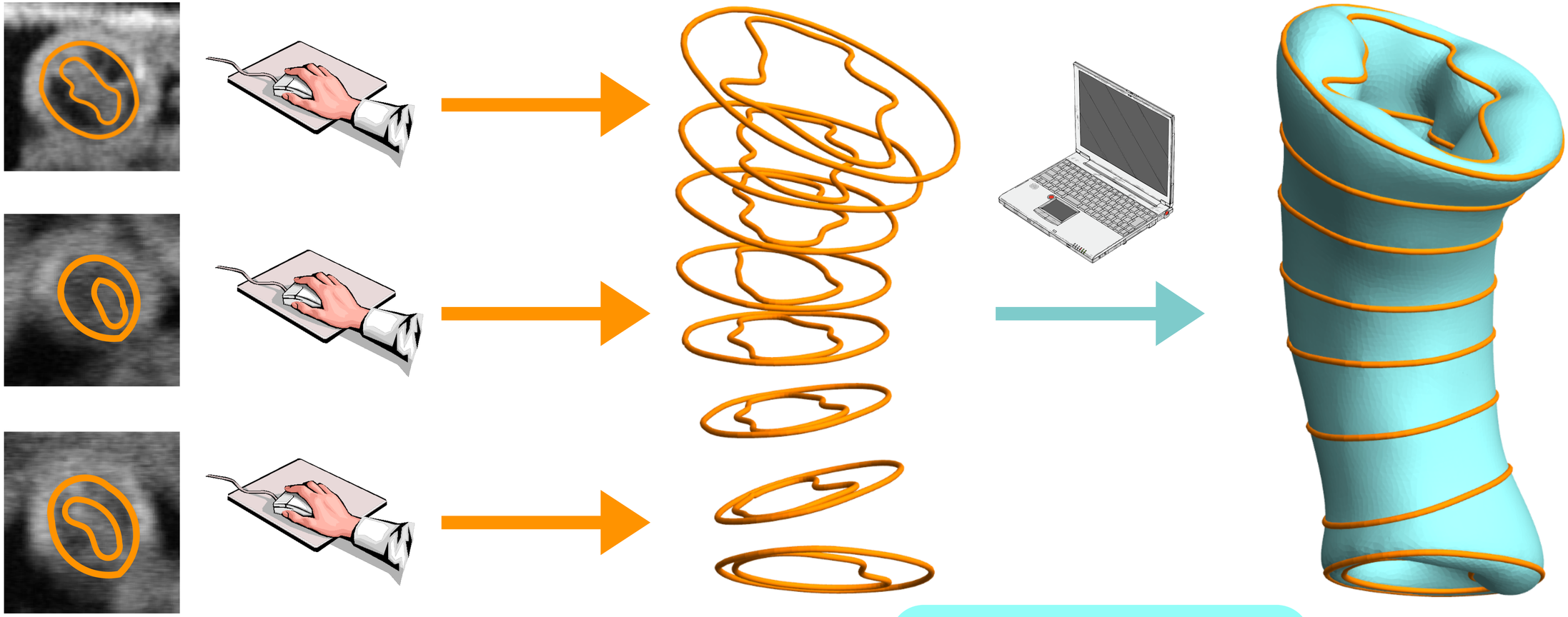
- In medical imaging, segmentation is **important** but **challenging**.





Drawing contours on selected cross-section

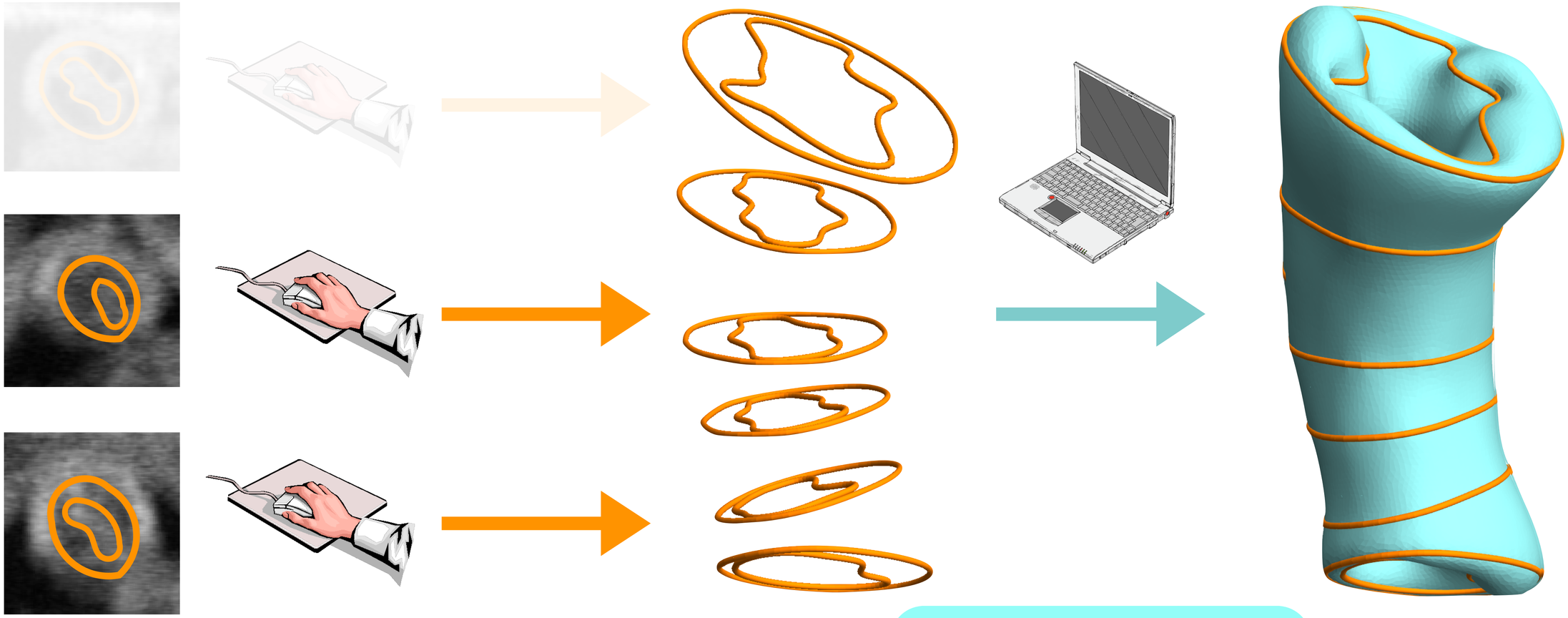
Segmentation



Contour drawing
(manual by doctors)

Reconstruction
(automatic)

Segmentation

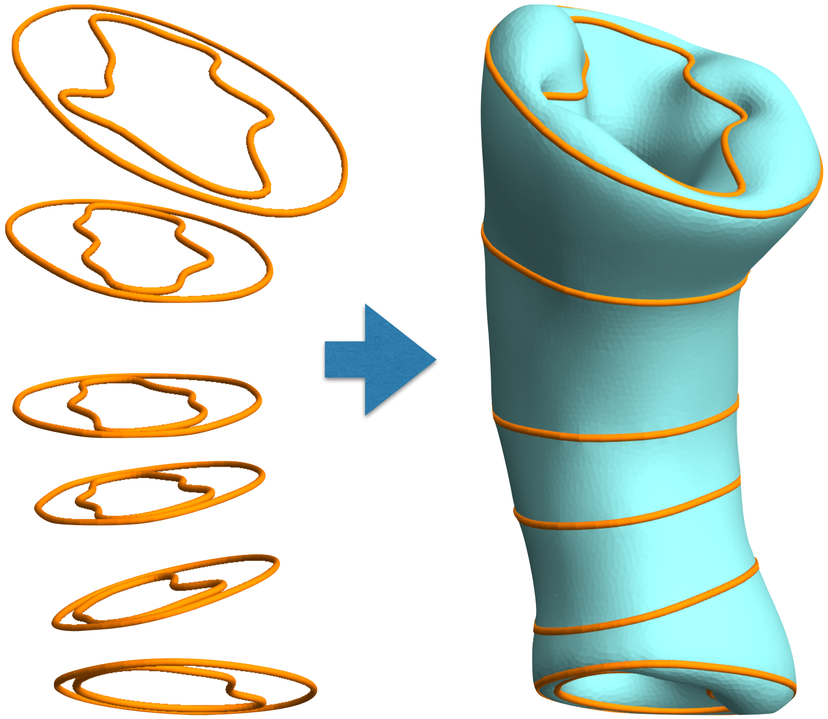


Contour drawing
(manual by doctors)

Reconstruction
(automatic)

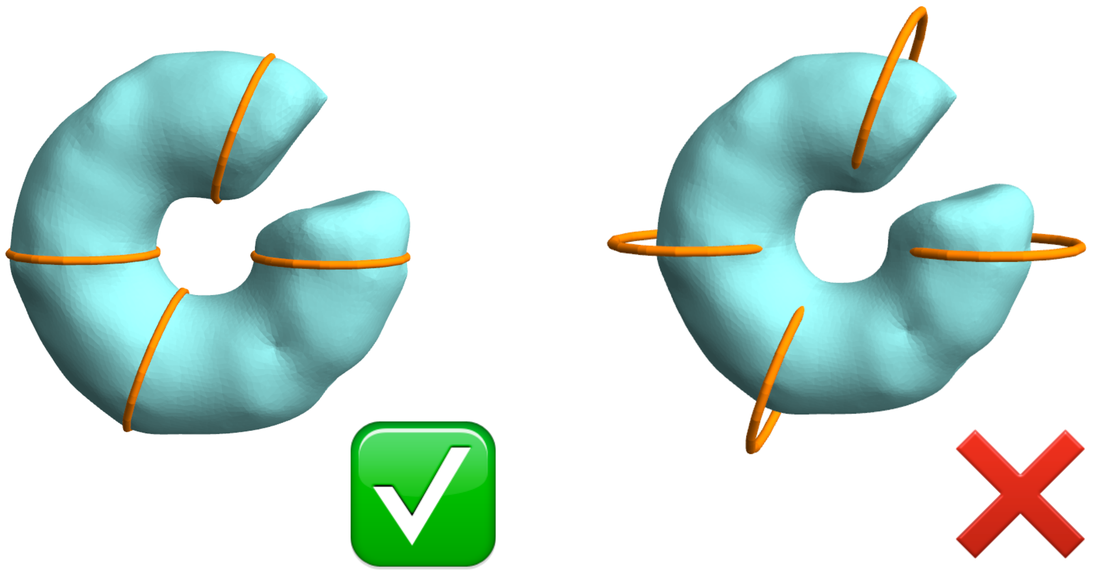
Problem Definition

- Given a set of contours, create a surface that interpolates the contours.
  - The **fewer** contours it requires, the better.
  - The **nicer** the surface, the better.



What's a "**nice**" surface?

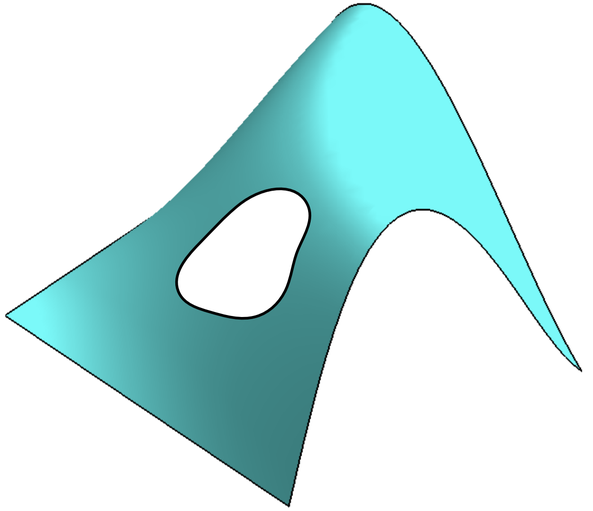
- **Interpolating**
  - Surface passes through contours



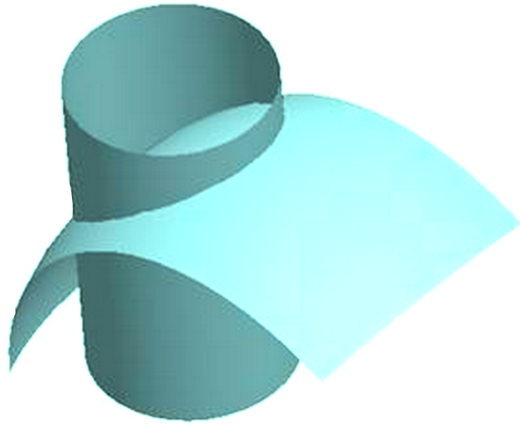
What's a "**nice**" surface?

- Interpolating
  - Surface passes through contours

- **Geometrically correct**
  - No hole, no intersection



holes



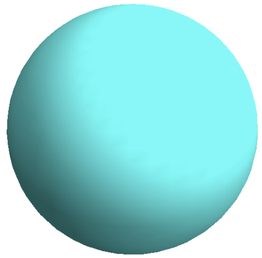
intersections

What's a "**nice**" surface?

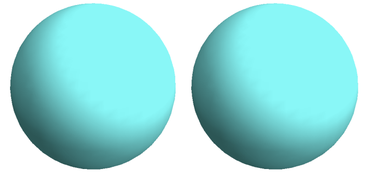
- Interpolating
  - Surface passes through contours

- Geometrically correct
  - No hole, no intersection

- **Topologically correct**
  - Desired genus and # of components



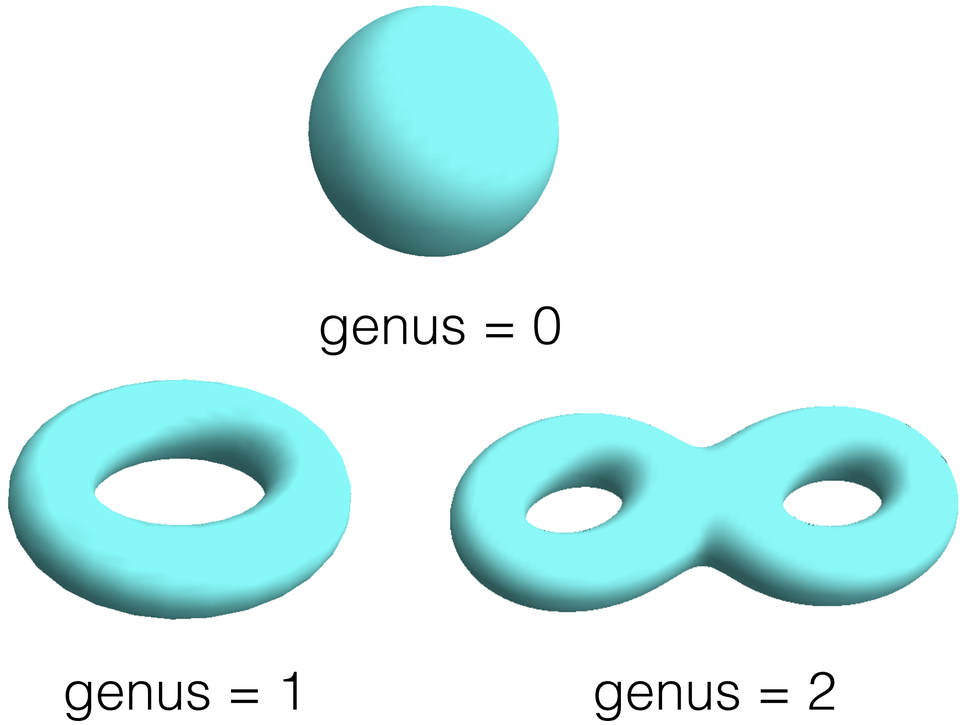
component = 1



component = 2

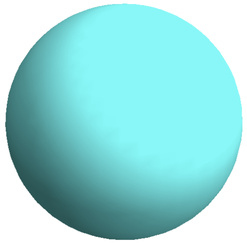
What's a "**nice**" surface?

- Interpolating
  - Surface passes through contours
- Geometrically correct
  - No hole, no intersection
- **Topologically correct**
  - Desired genus and # of components

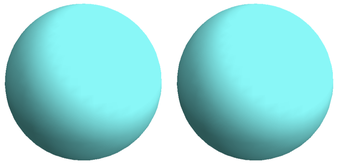


What's a "**nice**" surface?

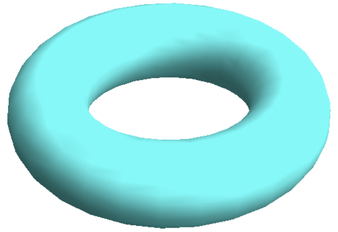
- Interpolating
  - Surface passes through contours
- Geometrically correct
  - No hole, no intersection
- Topologically correct
  - Desired genus and # of components



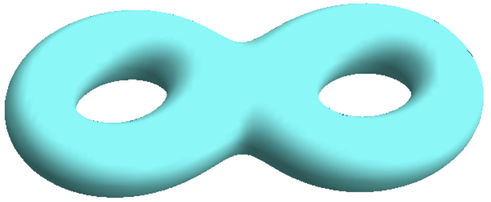
c=1, g=0



c=2, g=0



c=1, g=1

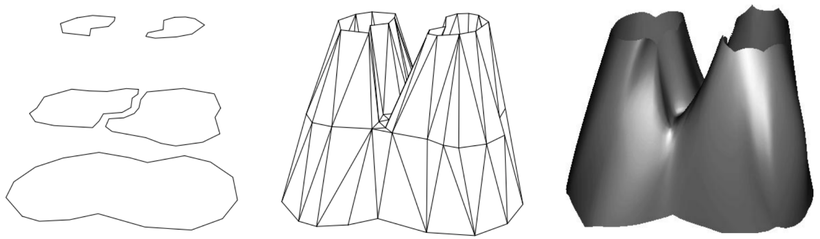


c=1, g=2

Previous work

- Contour based surface reconstruction

  - Parallel cross-sections
    [Keppel 75] [Fuchs 77] [Meyers 92]

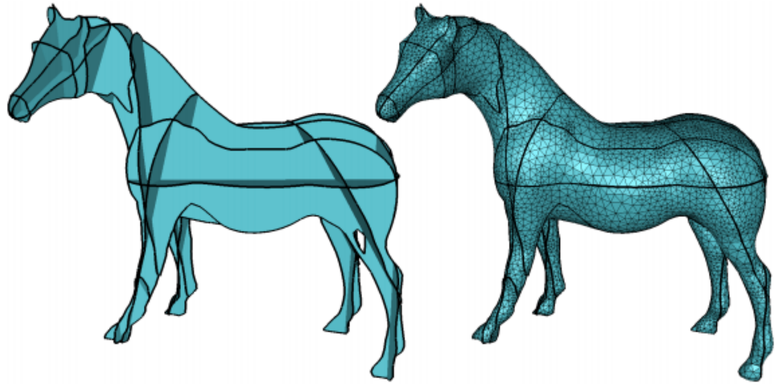


[Meyers 92]

  - Non-parallel cross-sections
    [Boissonnat 88] [Herman 92] [Bajaj 96] [Oliva 96]
    [Cheng 99] [Turk 99] [Barequet 96,04, 07,09] [Ju 05]
    [Boissonnat 07] [Liu 08] [Bermano 11] [Zhou 14]



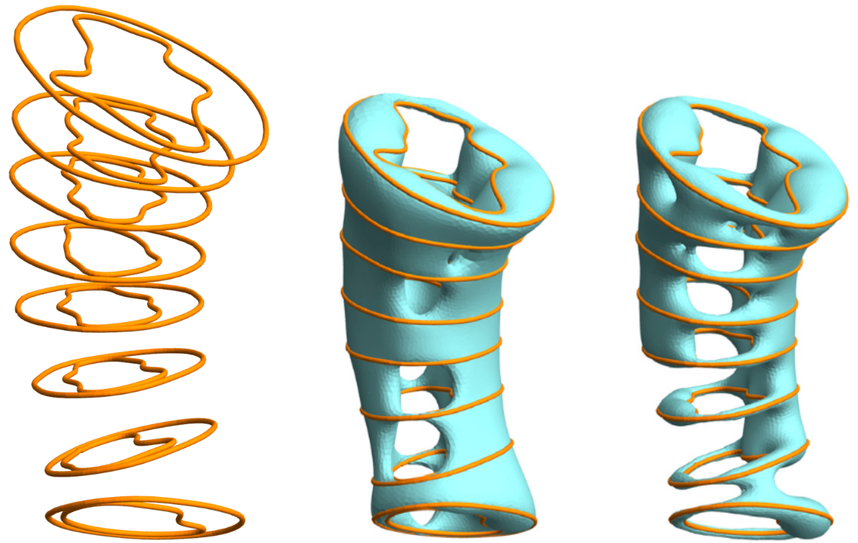
- Interpolating
- Geometrically correct



[Liu 08]

Previous work

- Contour based surface reconstruction
  - Parallel cross-sections
    [Keppel 75] [Fuchs 77] [Meyers 92]
  - Non-parallel cross-sections
    [Boissonnat 88] [Herman 92] [Bajaj 96] [Oliva 96]
    [Cheng 99] [Turk 99] [Barequet 96,04, 07,09] [Ju 05]
    [Boissonnat 07] [Liu 08] [Bermano 11] [Zhou 14]



[Liu 08] [Bermano 11]



- Interpolating
- Geometrically correct



- No topology control

Previous work

- Topology repairing as post process
  [Wood 04] [Zhou 07] [Attene 13]



Oblivious of the original input data.
May not interpolate contours.

- Reconstruction with topology control (not from contours)
  [Sharf 07] [Bazin 07] [Zeng 08] [Yin 14] [Ijiri 14]



Requires human interaction or initial templates.

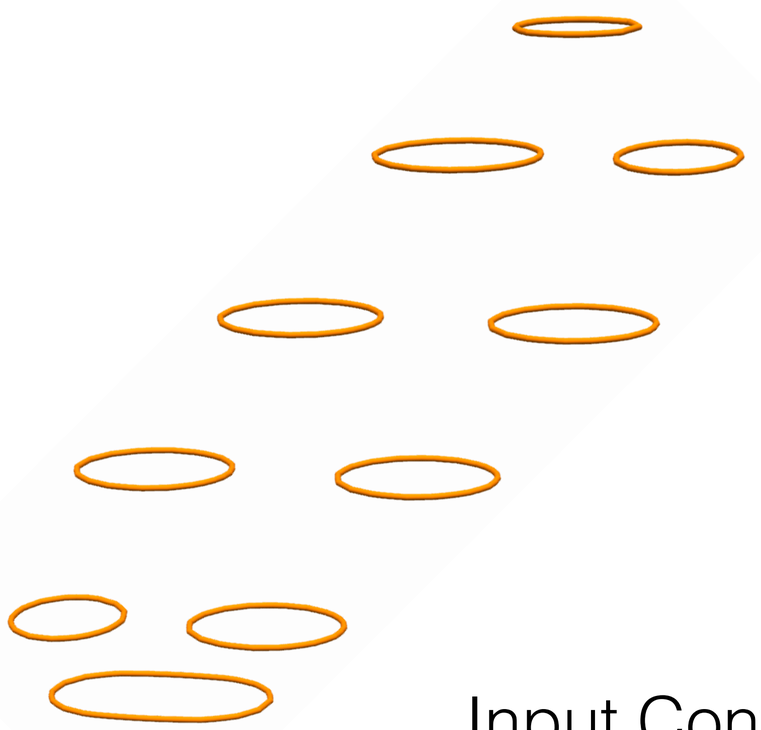
Our Contribution

First contour-based reconstruction method with topology control

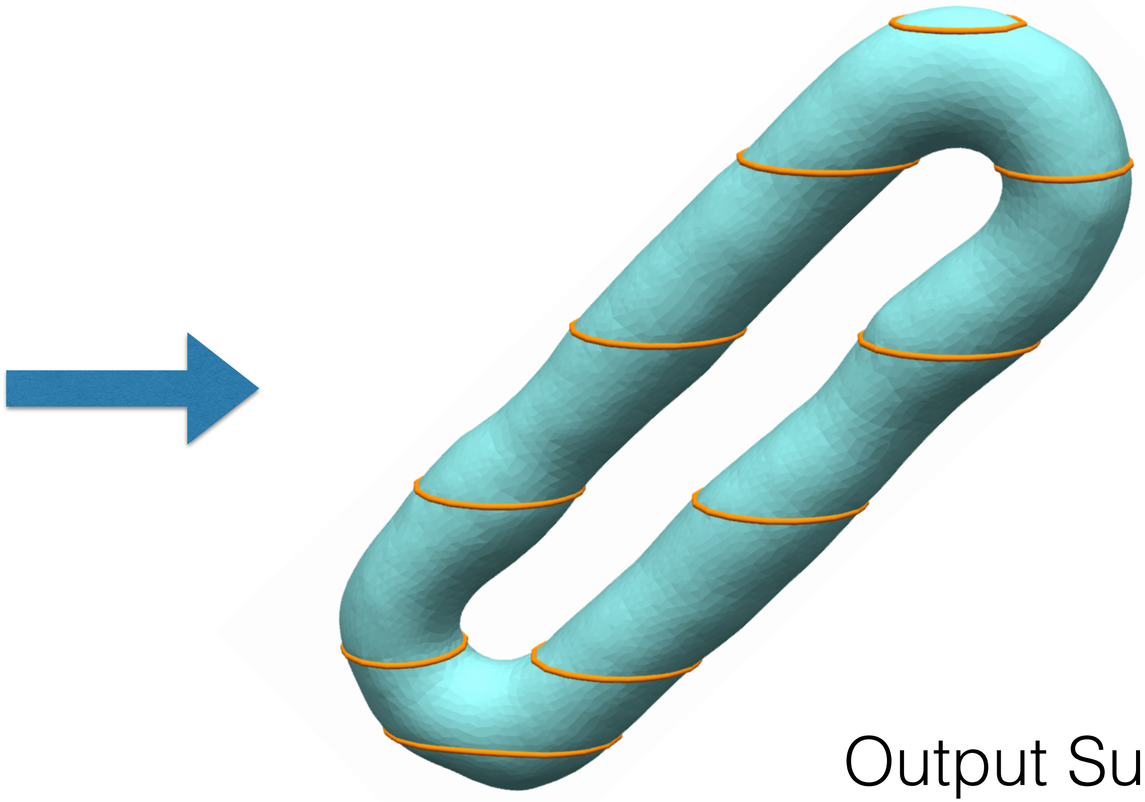
- Creates a single connected surface with user-specified genus
- Requires no user interaction or templates

Algorithm

Algorithm

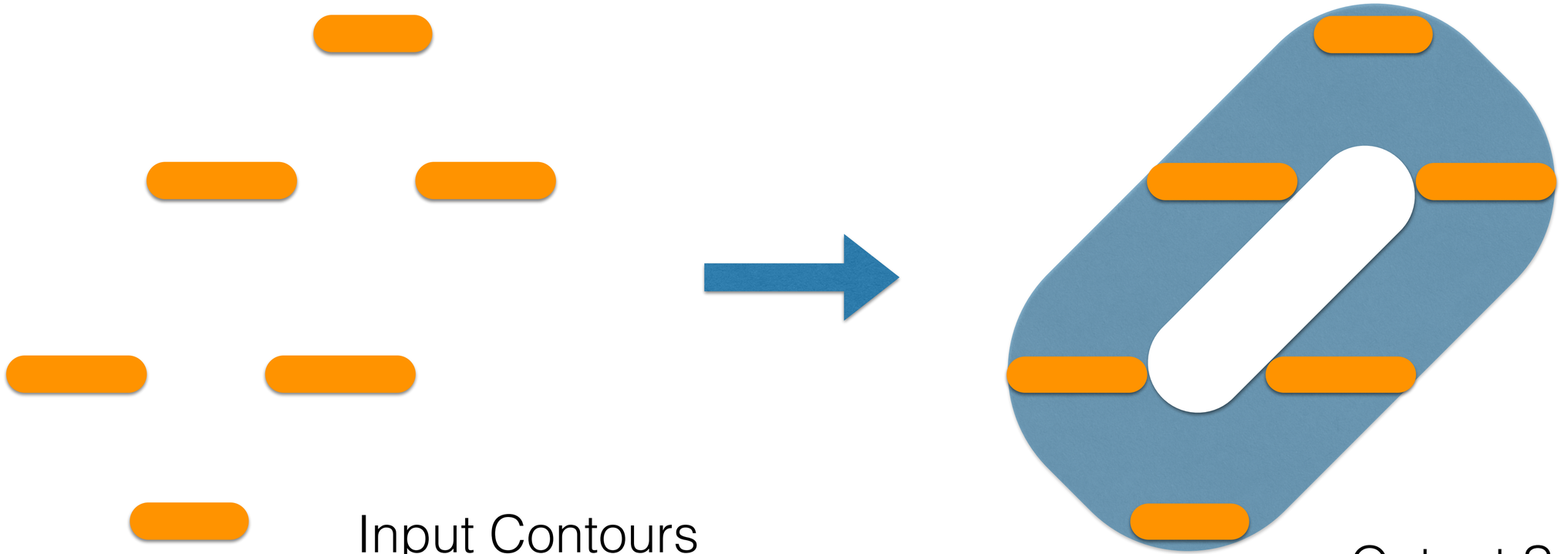


Input Contours
(Genus = 1)



Output Surface

Algorithm: 2D illustration

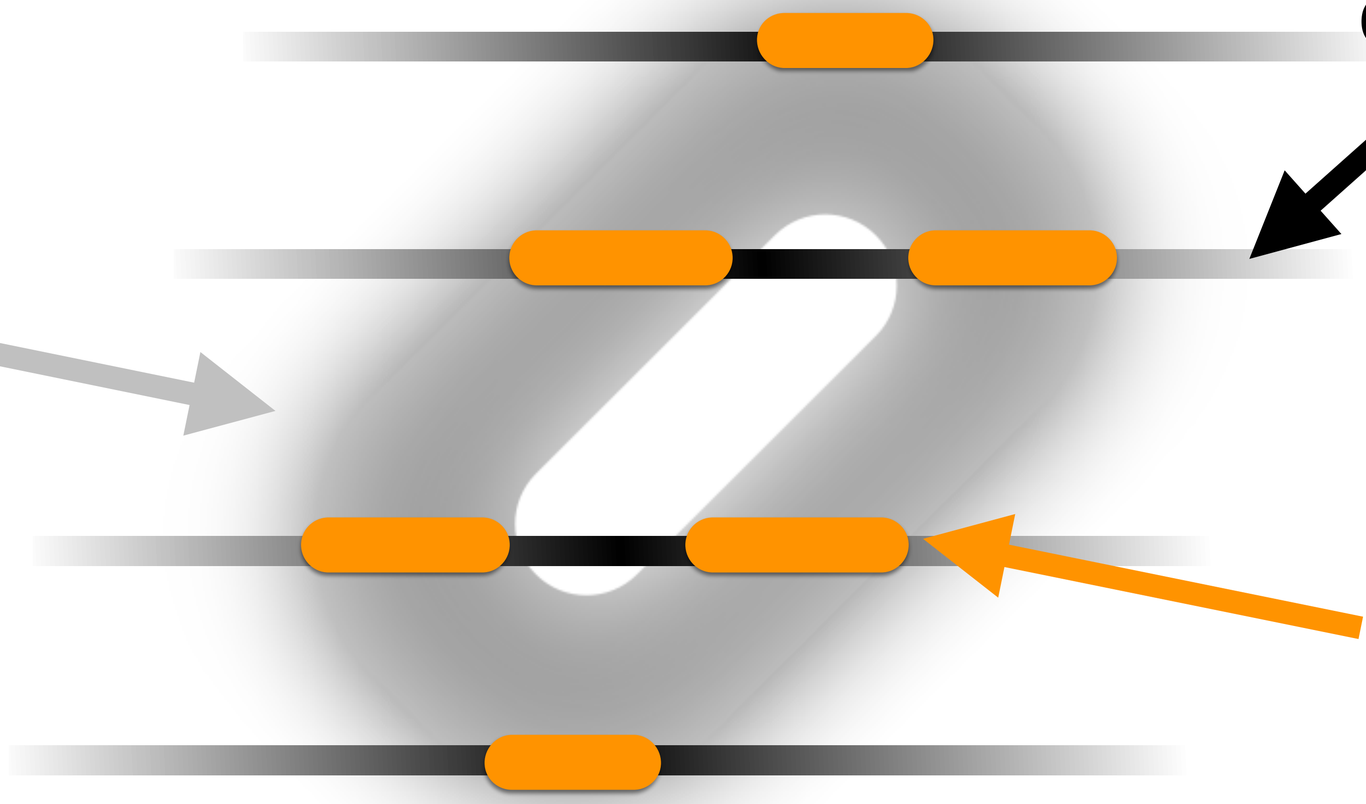


Input Contours
(Genus = 1)

Output Surface

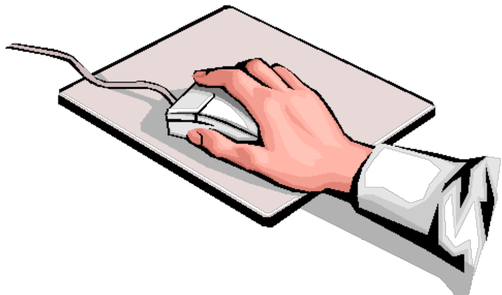
Algorithm: 2D illustration

(parallel or non-parallel)
Cross sections

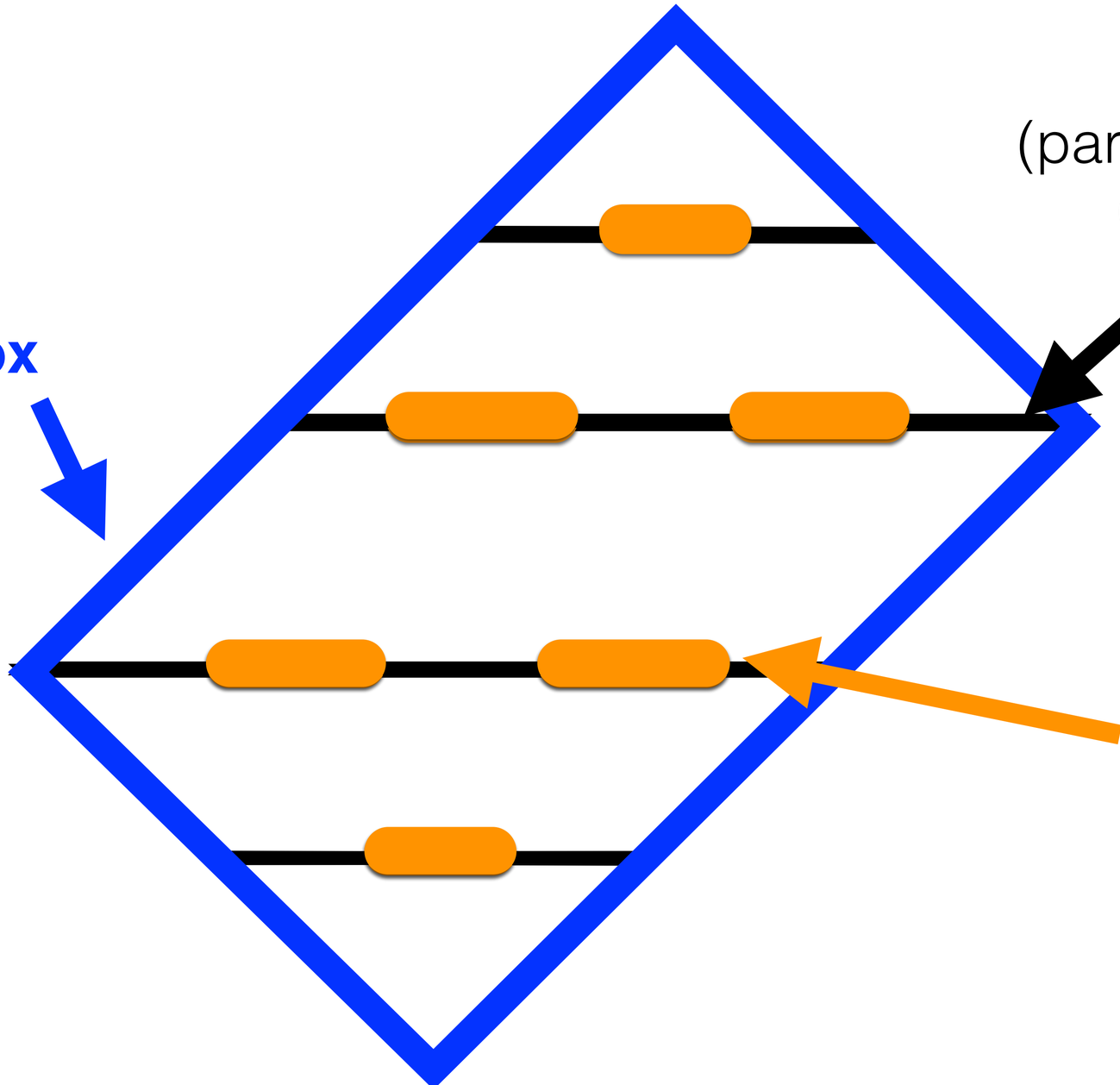


Volume

Contours



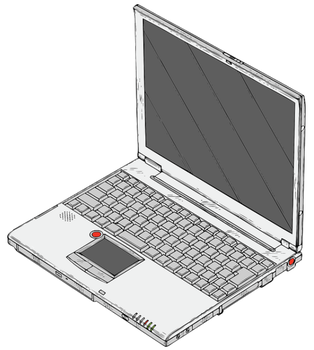
Algorithm: 2D illustration



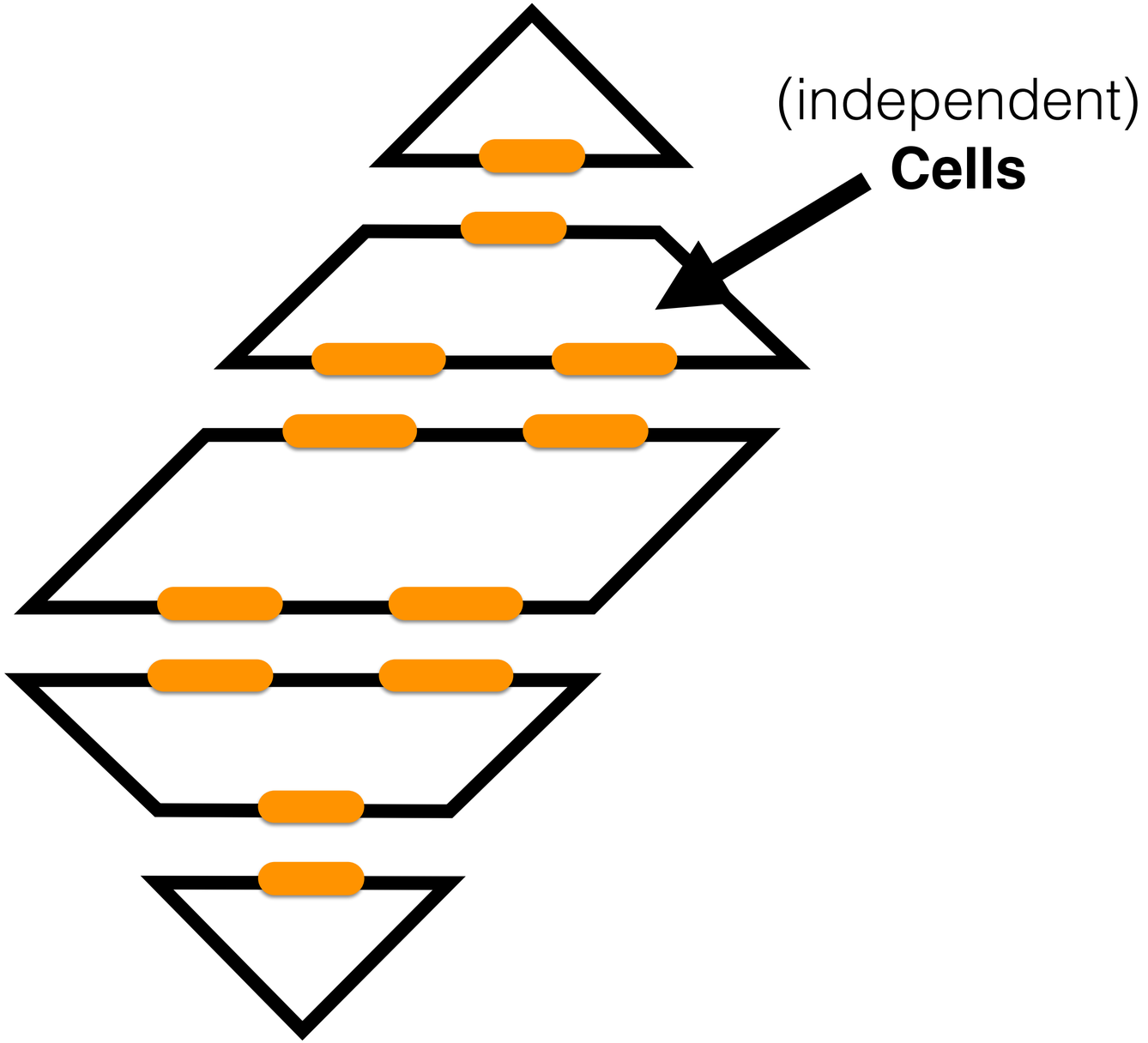
(parallel or non-parallel)
Cross sections

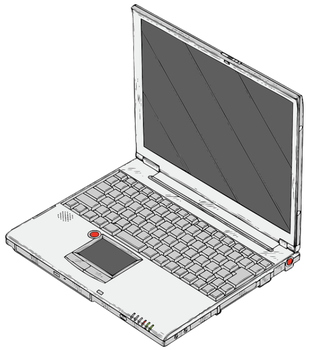
Bounding box

Contours

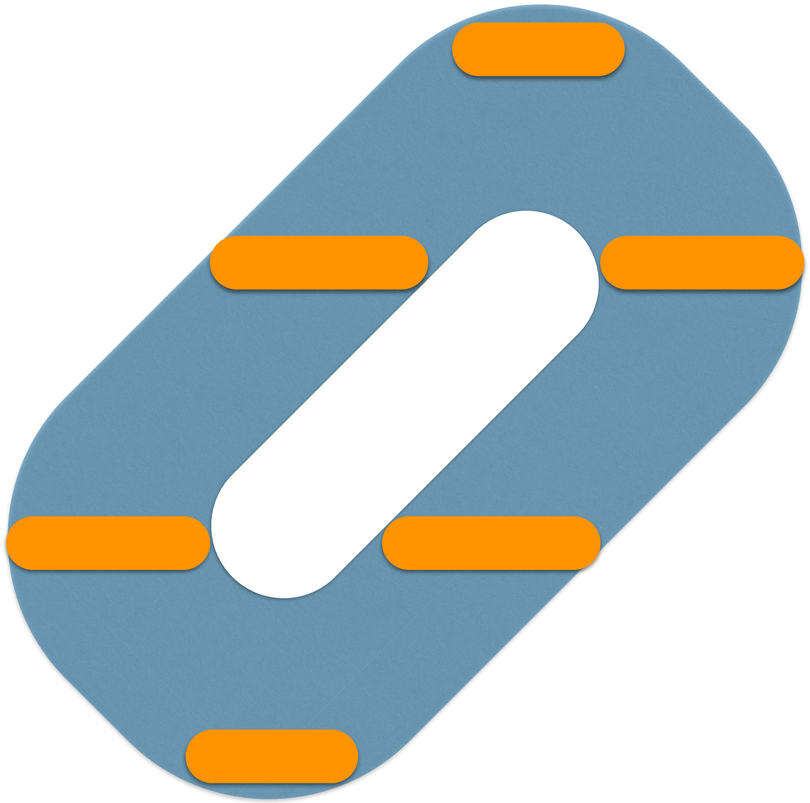


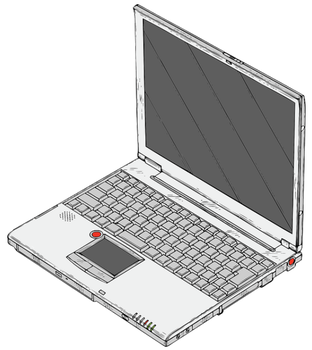
Algorithm: 2D illustration



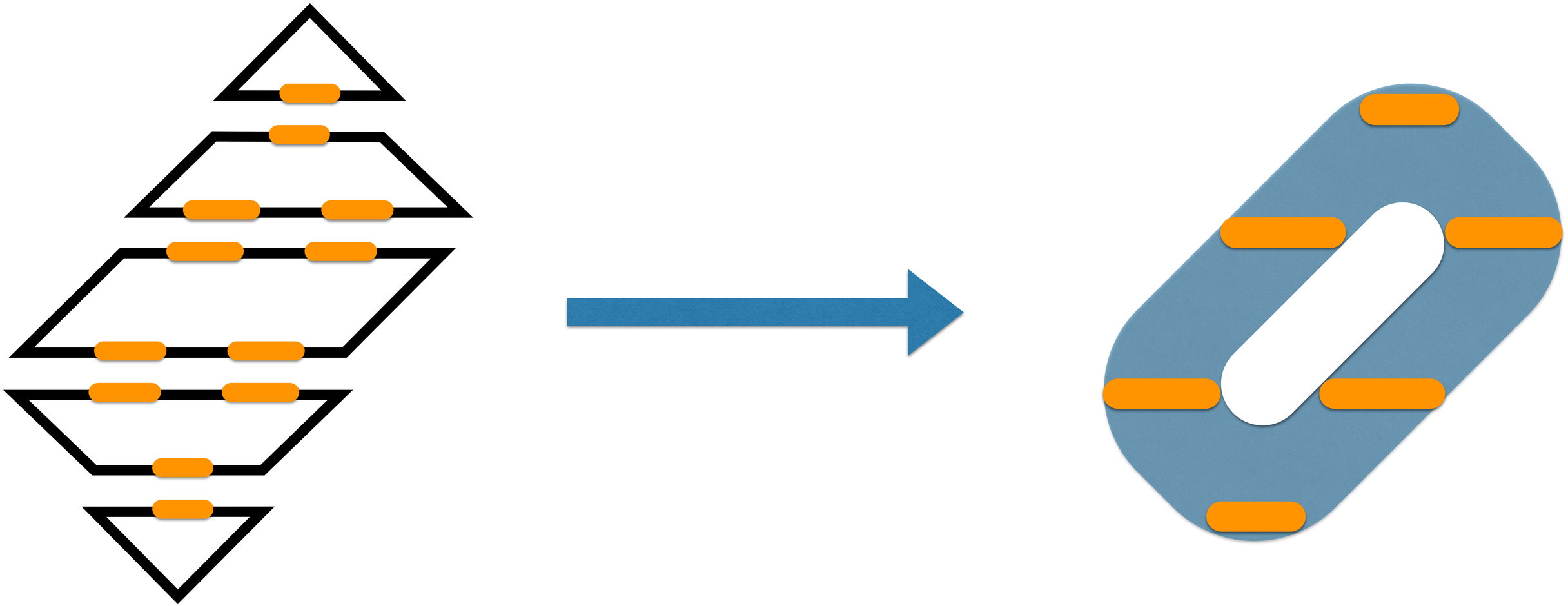


Algorithm: 2D illustration

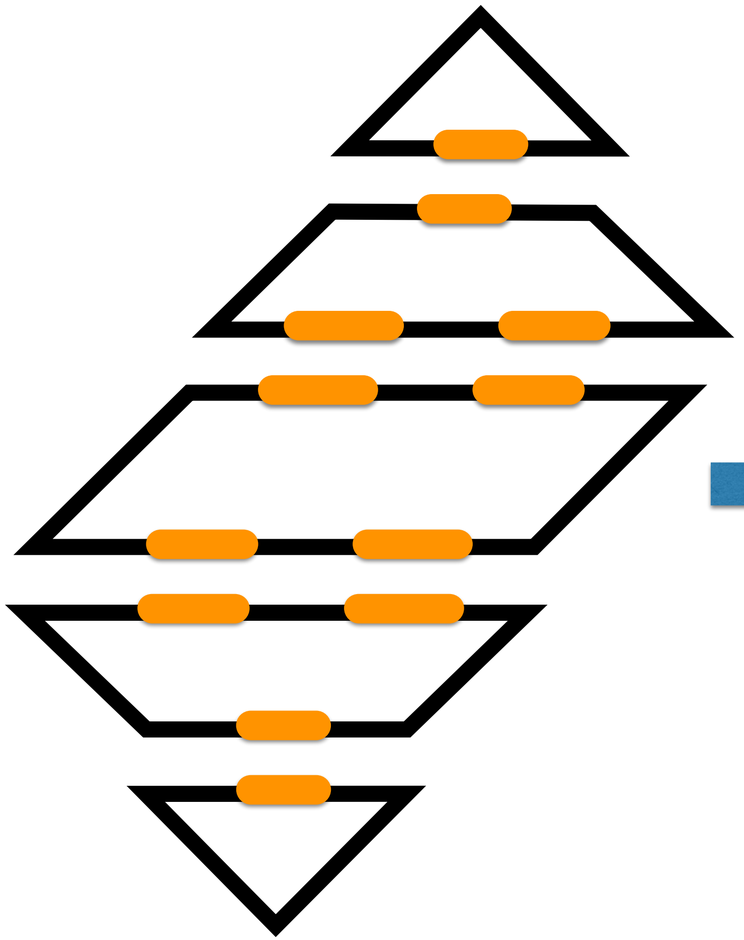




2-step approach : explore and select



2-step approach : explore and select



1

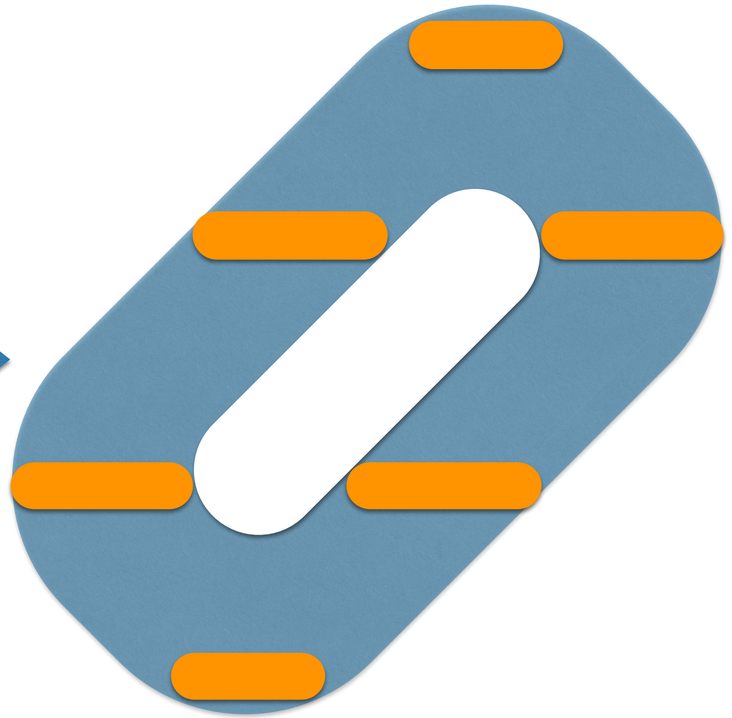
Explore

Explore topologies in each independent cell

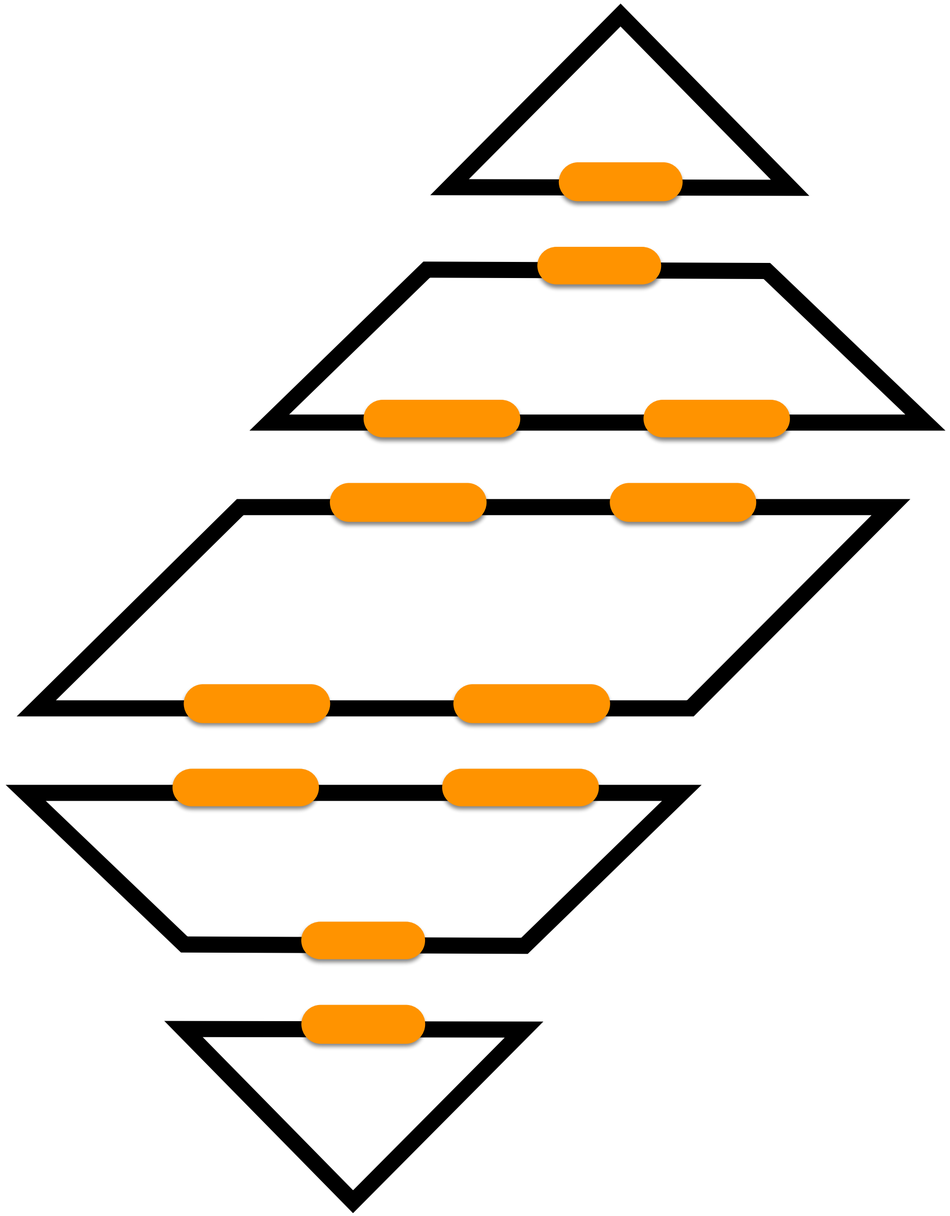
2

Select

Select one topology per cell to form the best surface



Step 1 : explore



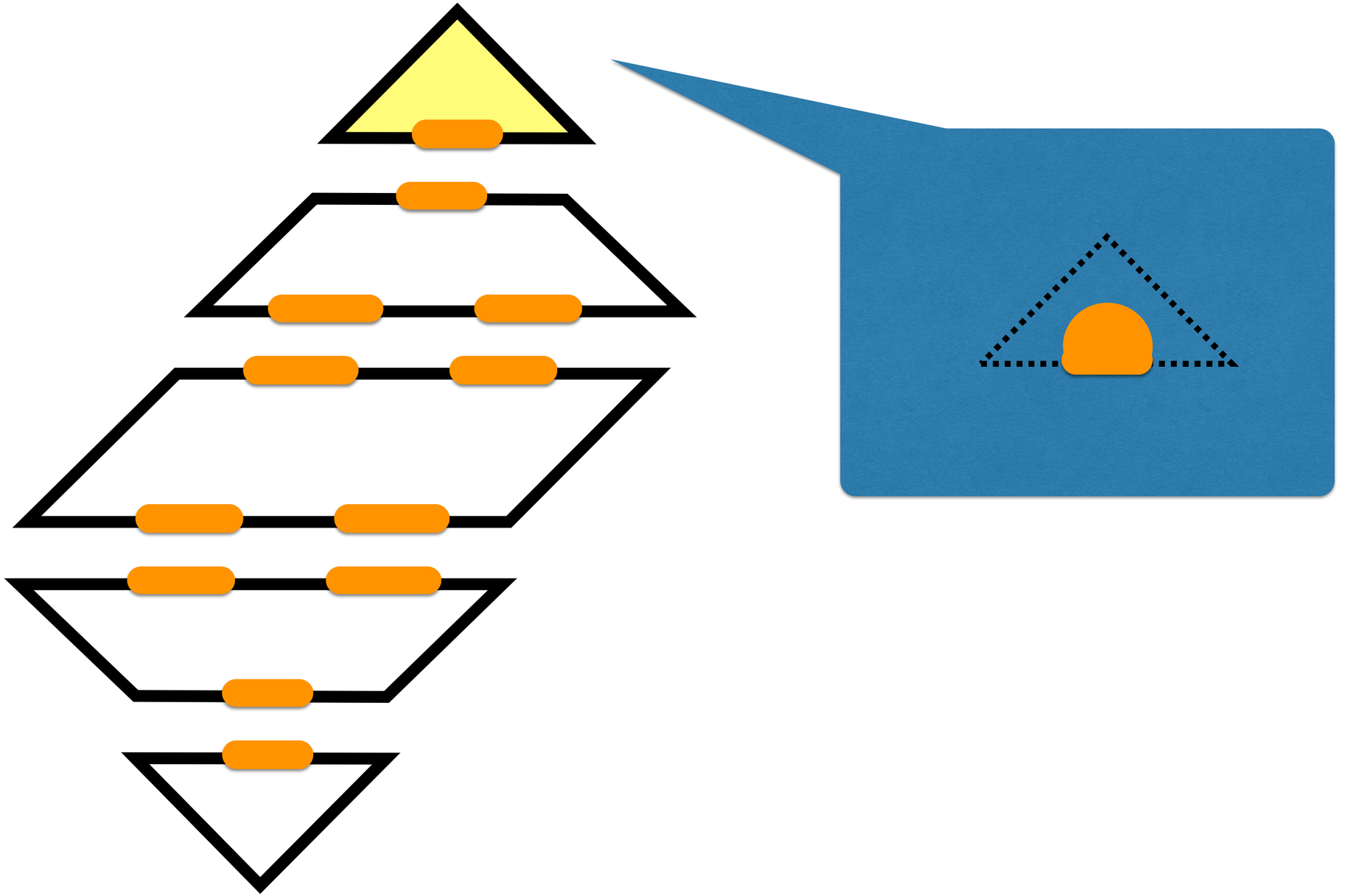
(If limited to simple topology)

one topology within a cell

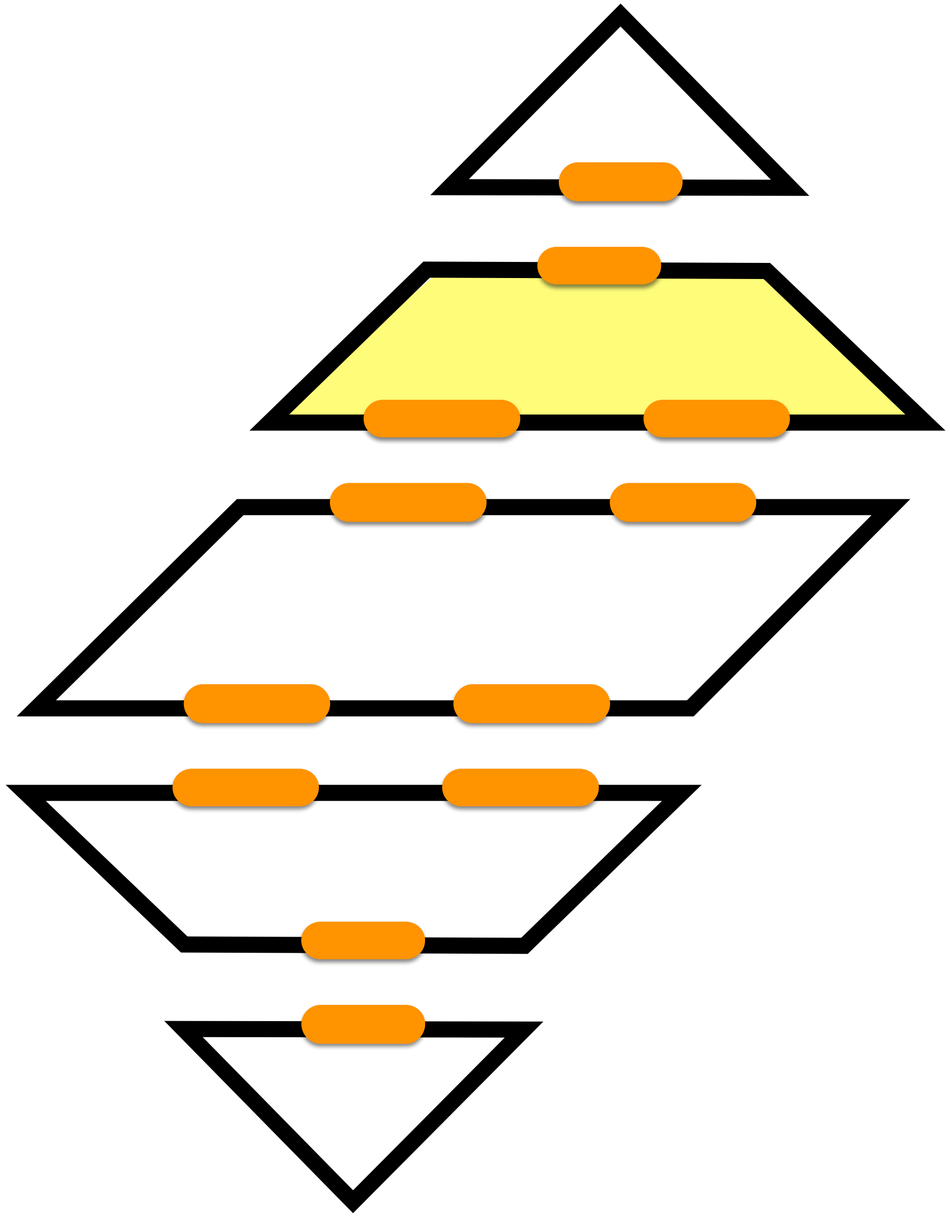
=

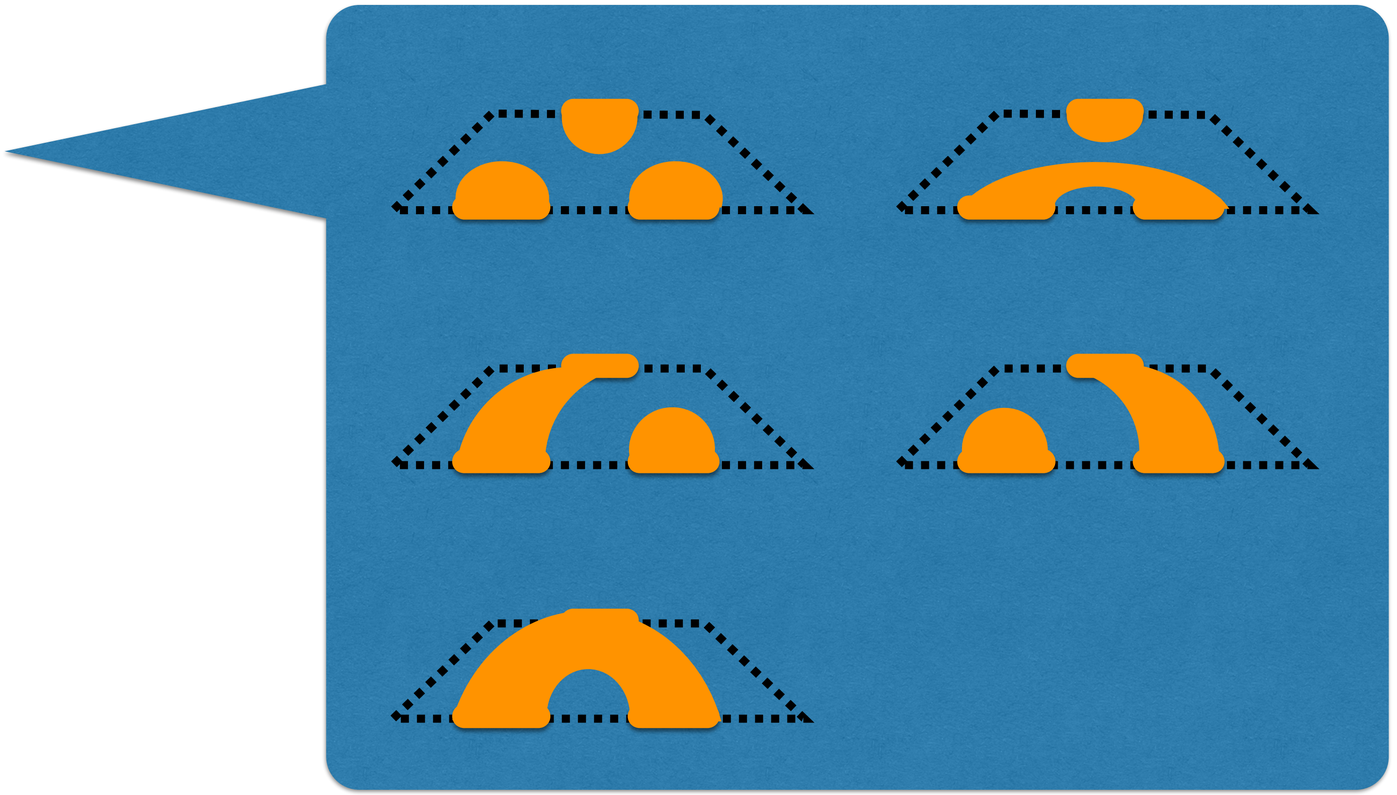
one grouping of the contours

Step 1 : explore

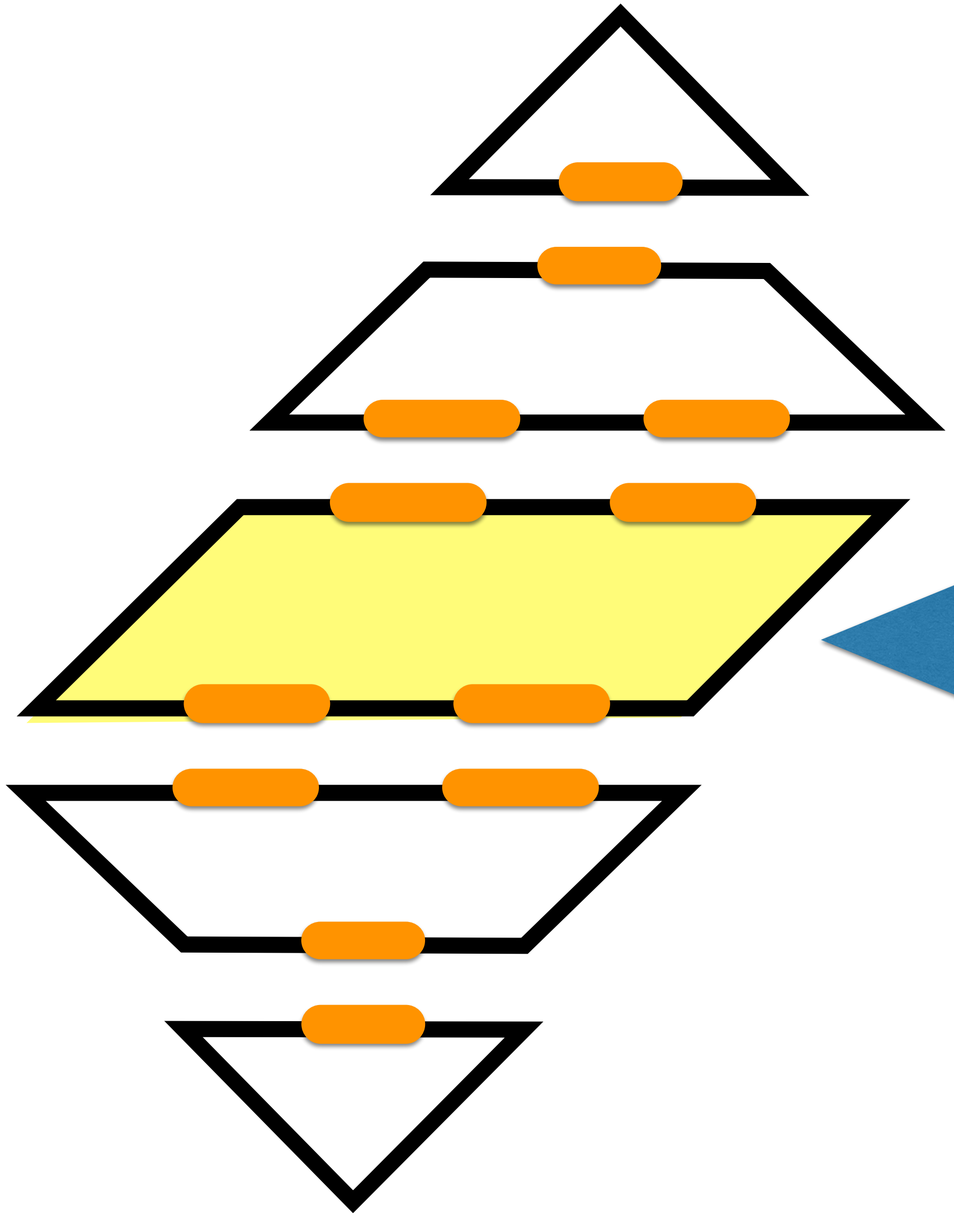


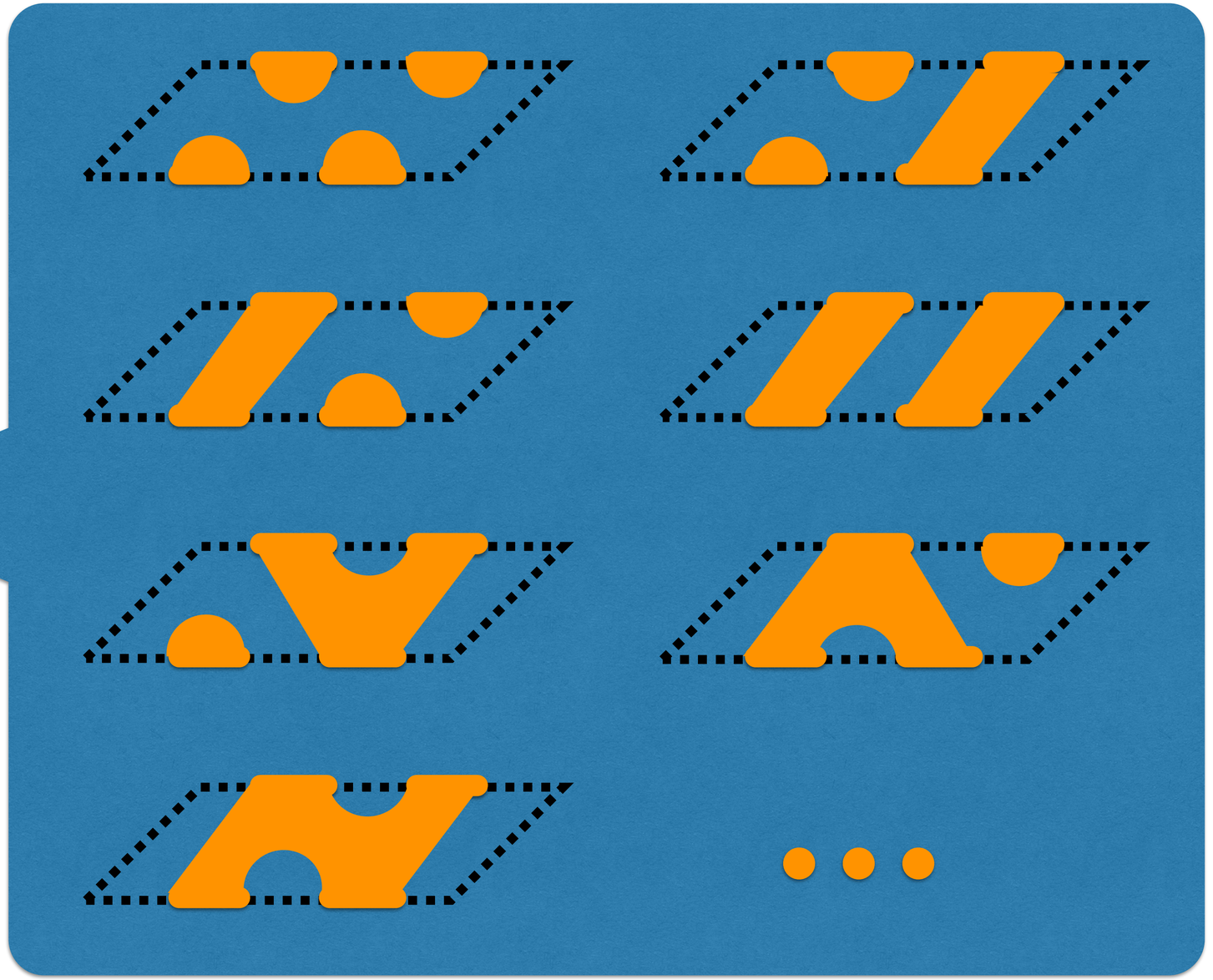
Step 1 : explore





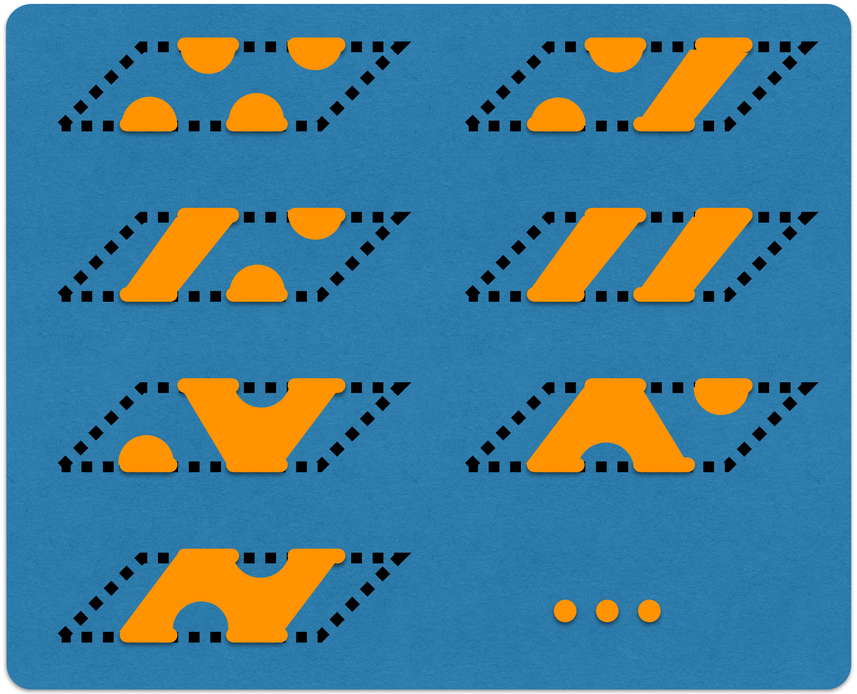
Step 1 : explore





Step 1: explore | difference

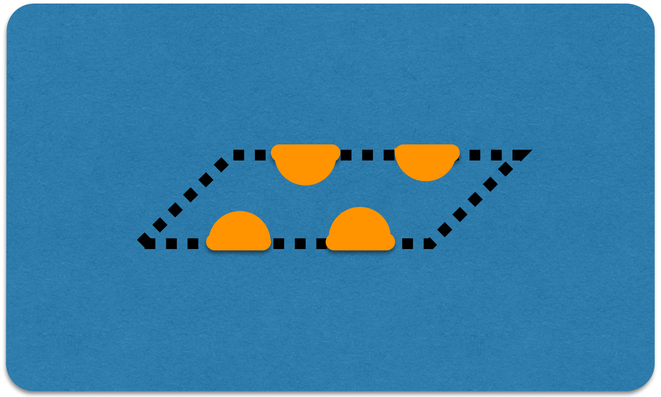
- Ours: Explore and keep **multiple** topologies within one cell.



[Ours]

VS.

- Previous methods: Generate **one** single topology per cell.



[Liu 08]
[Bermano 11]

Step 1 : explore | challenges

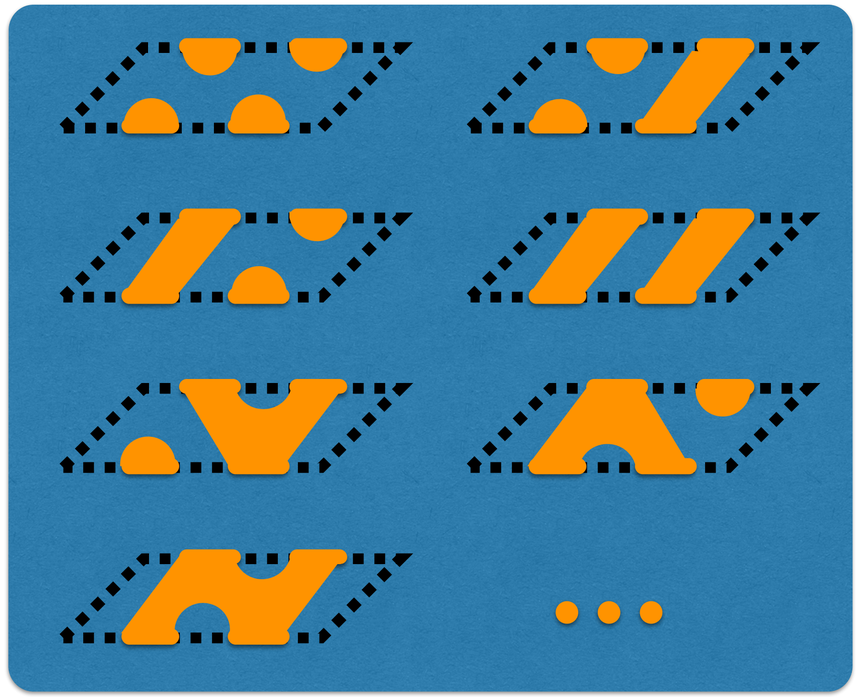
- Huge search space
  - # of possible connections is a bell number

    B(4)=15; B(6)=203; B(10)=115,975

- Non-trivial surfacing problem
  - No self-intersection
  - Simple topology (no extra handle, tunnel)

- Score the naturalness of the surfaces





Step 1 : explore | iso-surface

- Huge search space

  Much smaller search space.

- Non-trivial surfacing problem

  Always geometrically correct.

- Score the naturalness of the surfaces

  Define with the implicit function.

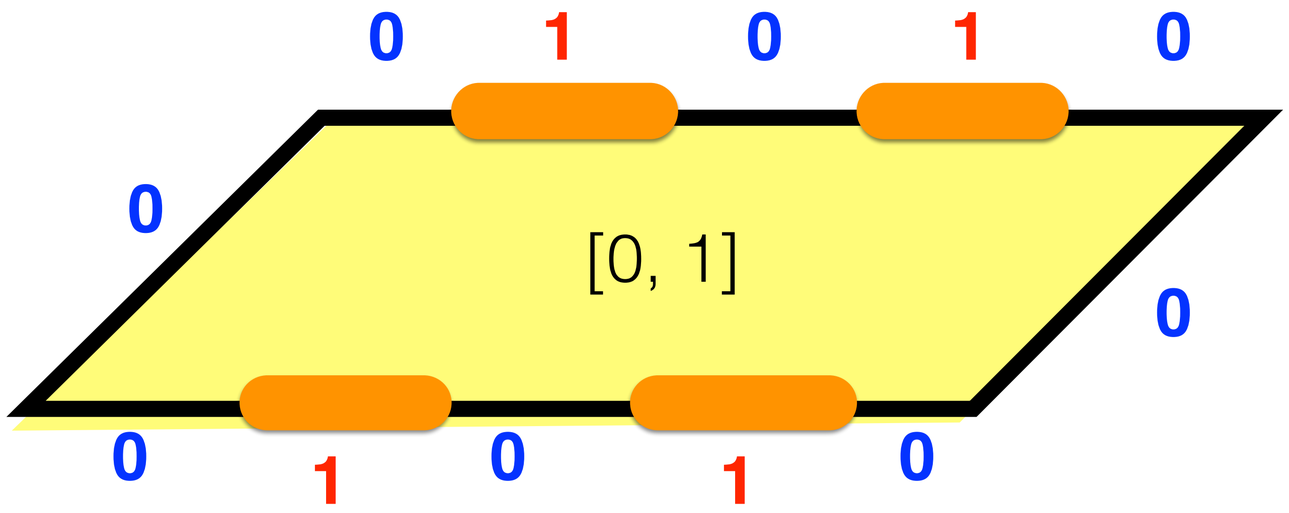
Iso-surface

of

an implicit function

Step 1 : explore | implicit function

- What implicit function to choose?
  - Satisfy boundary conditions
  - Continuous inside the cell and bounded by [0,1]
  - Good indication of the likelihood of a point being inside/outside

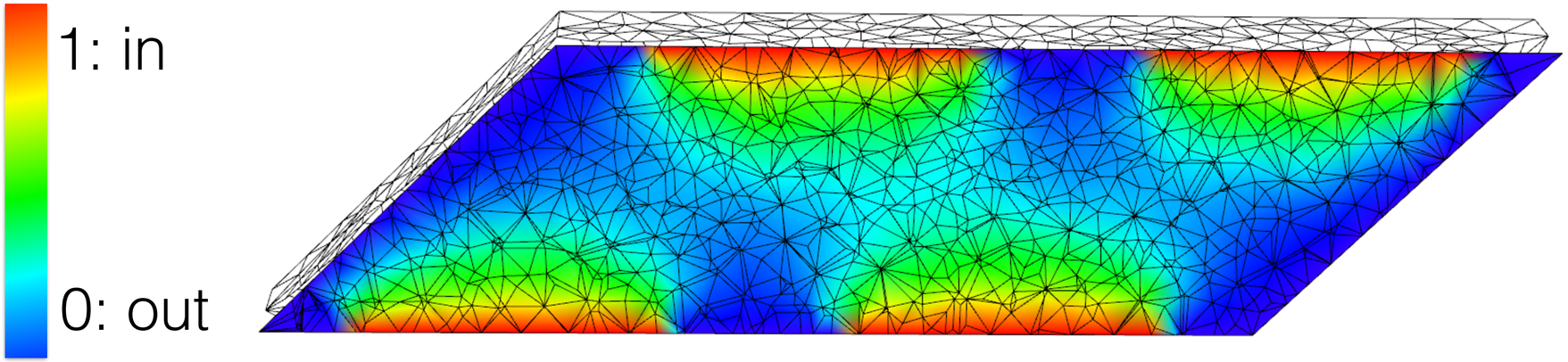


Iso-surface

of

an implicit function

Step 1 : explore | random walk

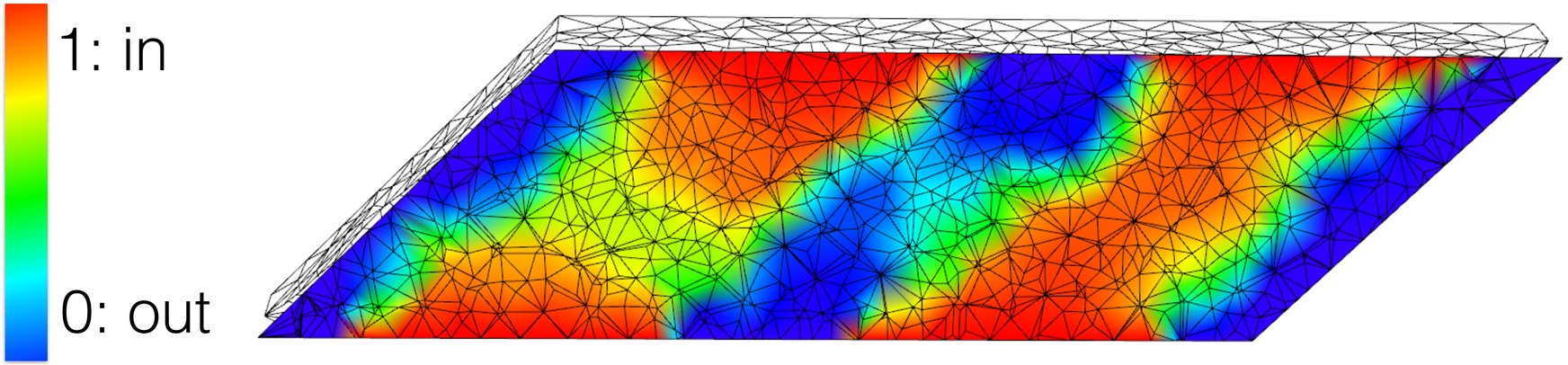


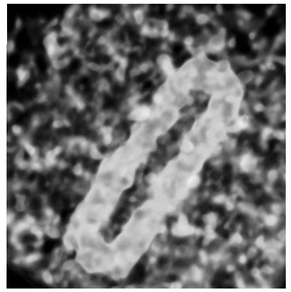
discrete harmonic function
if w_{ij} is a constant

$$x_i - \frac{\sum_{j \in N(i)} w_{ij} x_j}{\sum_{j \in N(i)} w_{ij}} = 0$$

x_i the probability of point i being labeled with 1 $N(i)$ neighbors of point i w_{ij} weight between point i and j

Step 1 : explore | random walk





$$x_i - \frac{\sum_{j \in N(i)} w_{ij} x_j}{\sum_{j \in N(i)} w_{ij}} = 0 \qquad w_{ij} = \exp(-\beta (I_i - I_j)^2)$$

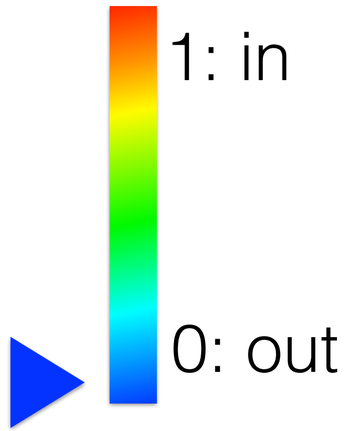
x_i the probability of point i being labeled with 1

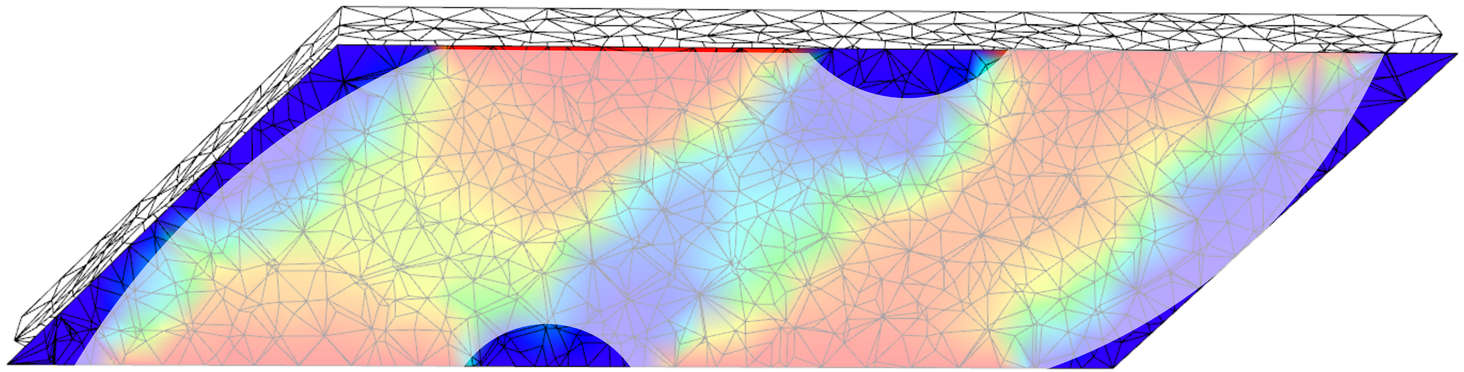
$N(i)$ neighbors of point i

w_{ij} weight between point i and j

I_i intensity of point i in input volume

Step 1 : explore | iso-surface

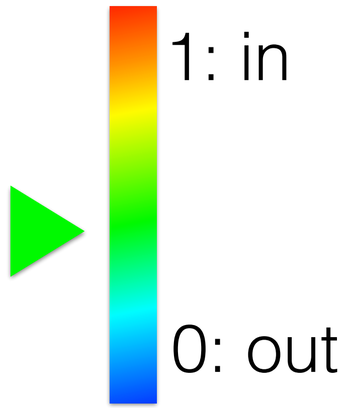


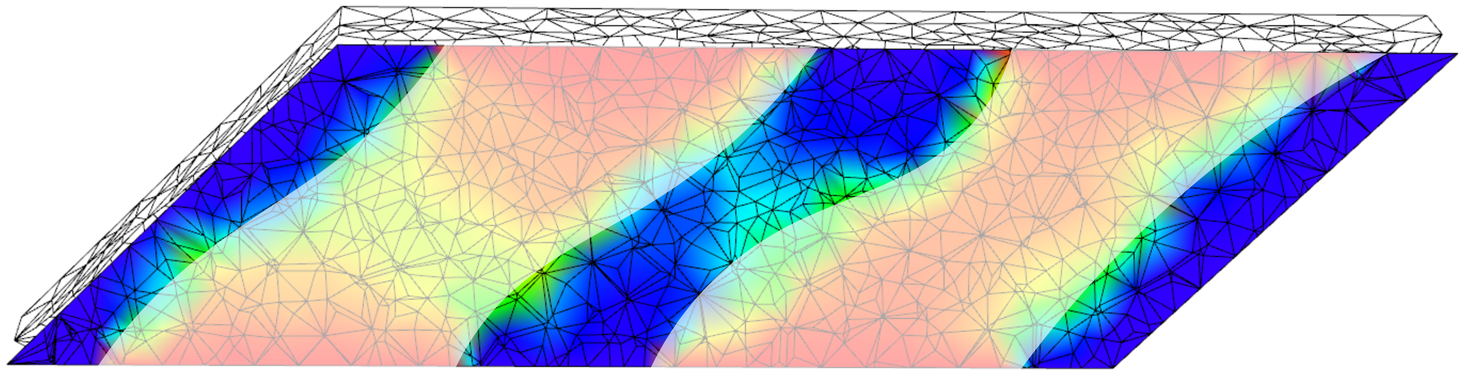






Step 1 : explore | iso-surface



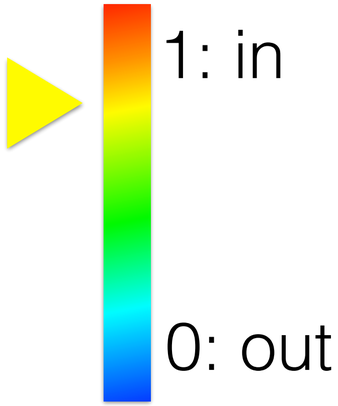


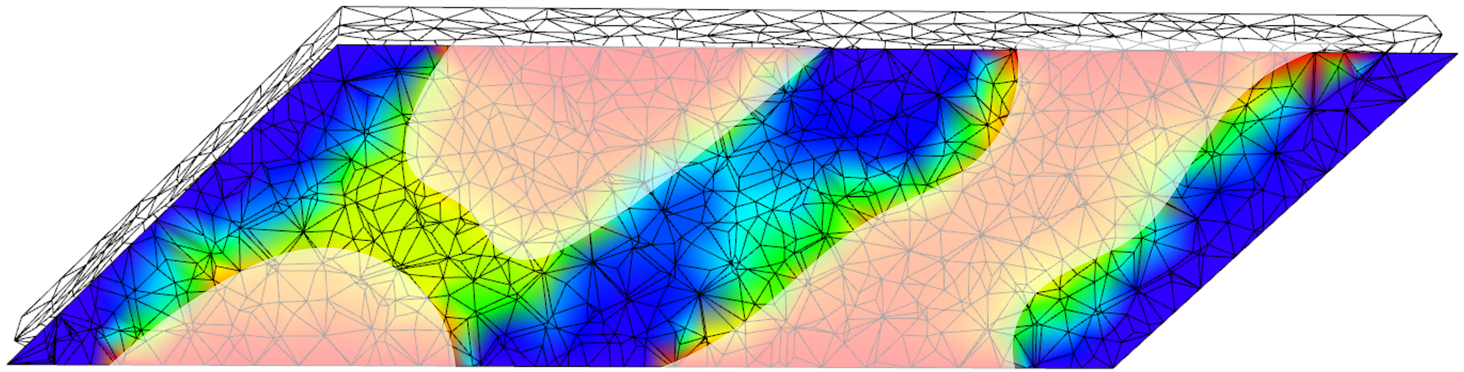






Step 1 : explore | iso-surface

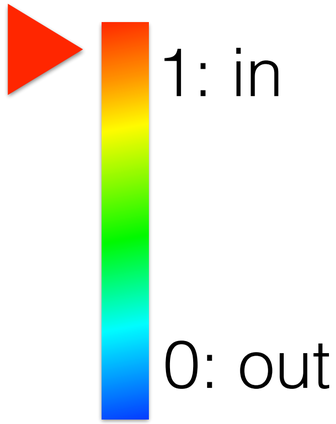


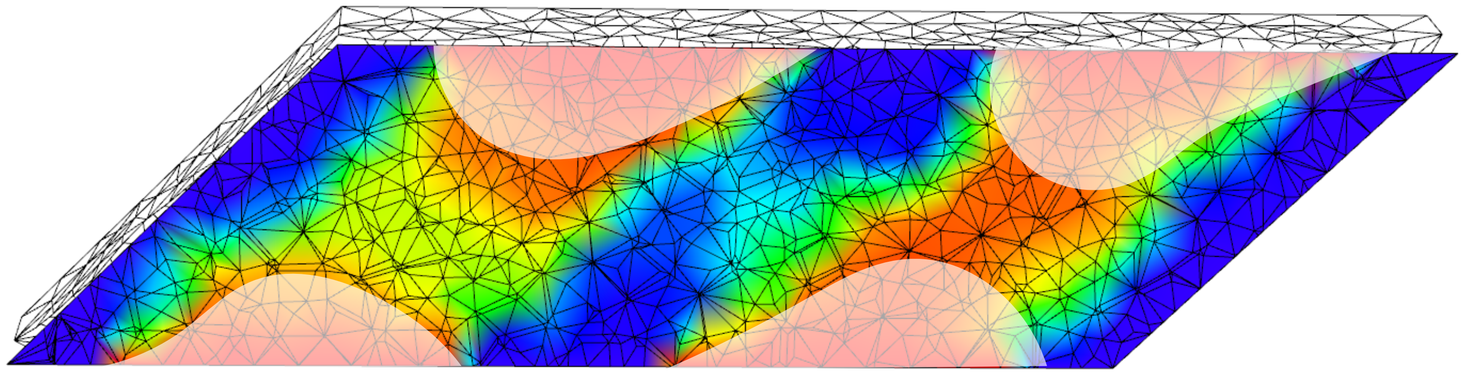






Step 1 : explore | iso-surface

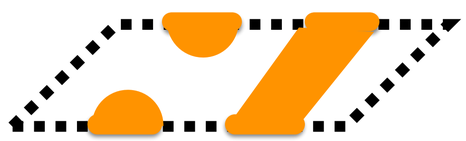


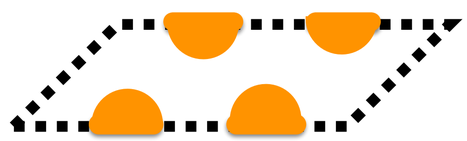






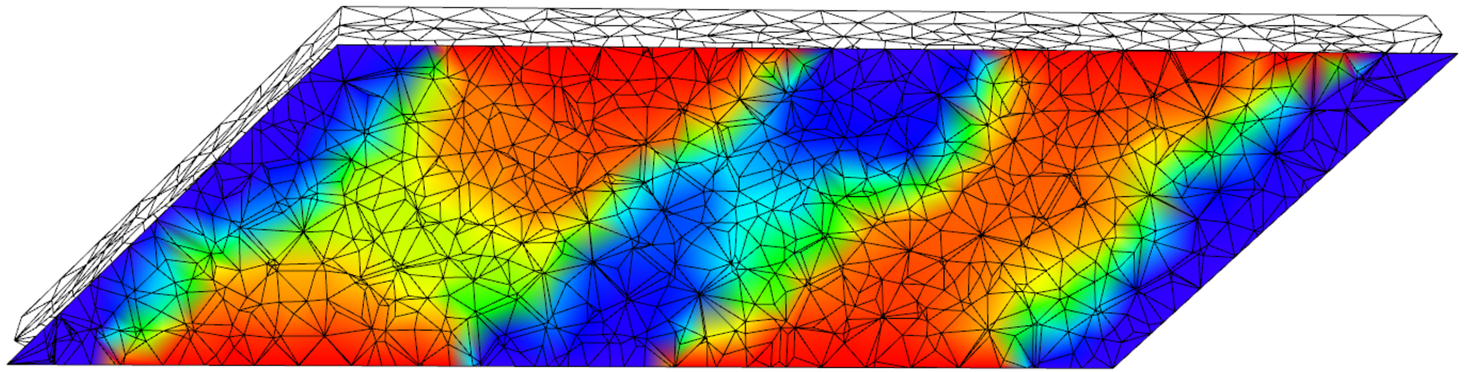






Step 1 : explore | score

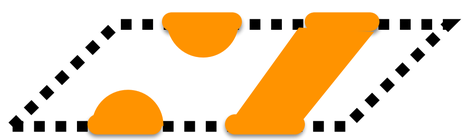


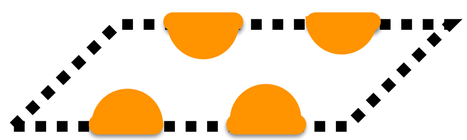








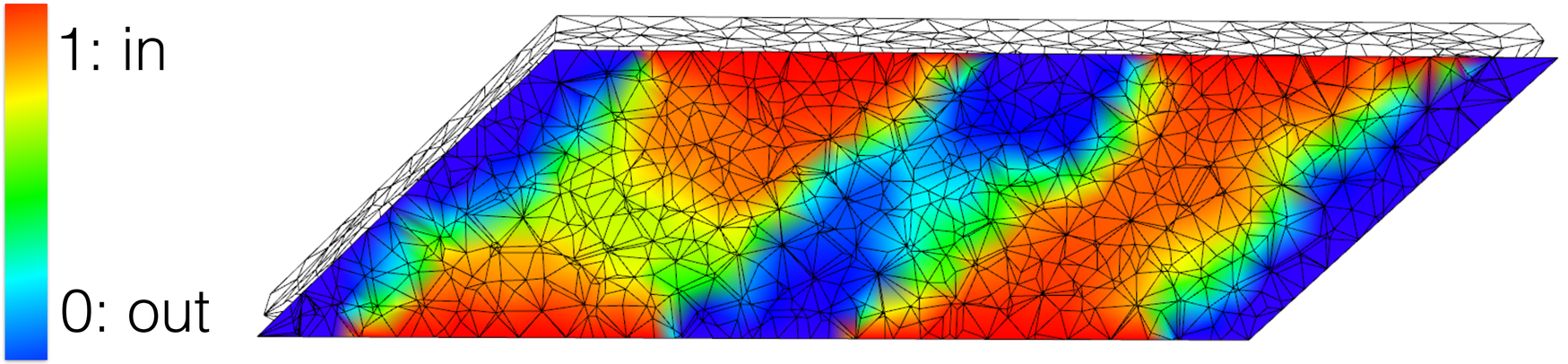




Score: joint likelihood of all the points having the inside or outside label.

$$h(T) = \int_{\Omega} h_T(x)dx \qquad h_T(x) = \begin{cases} \log(f(x)) & \text{inside} \\ \log(1-f(x)) & \text{outside} \end{cases}$$

Step 1 : explore | score







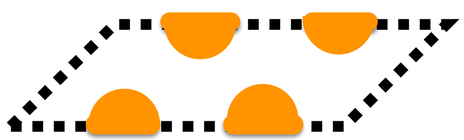
score = -5383



score = -3810

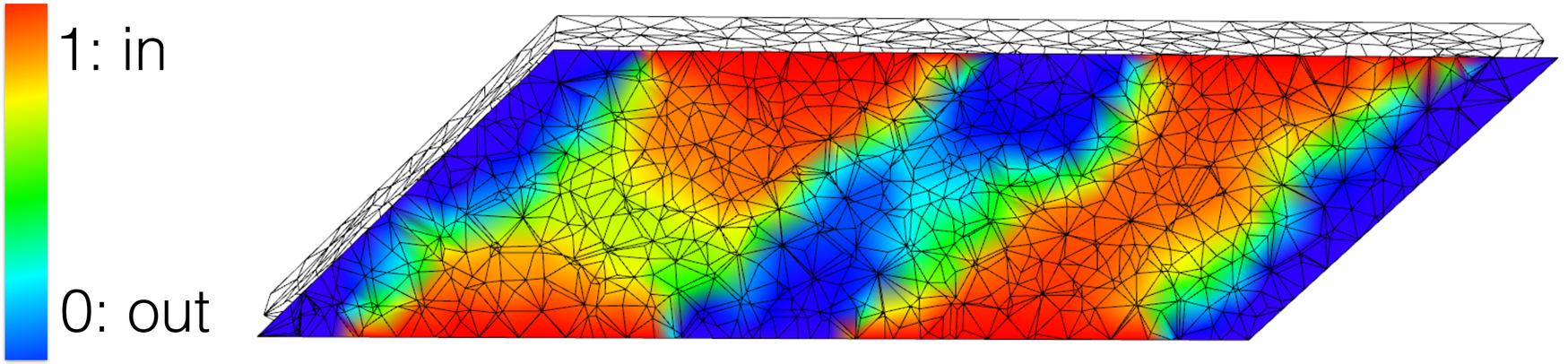


score = -5123

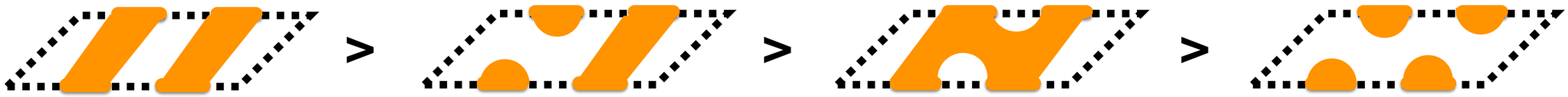


score = -13510

Step 1 : explore | score

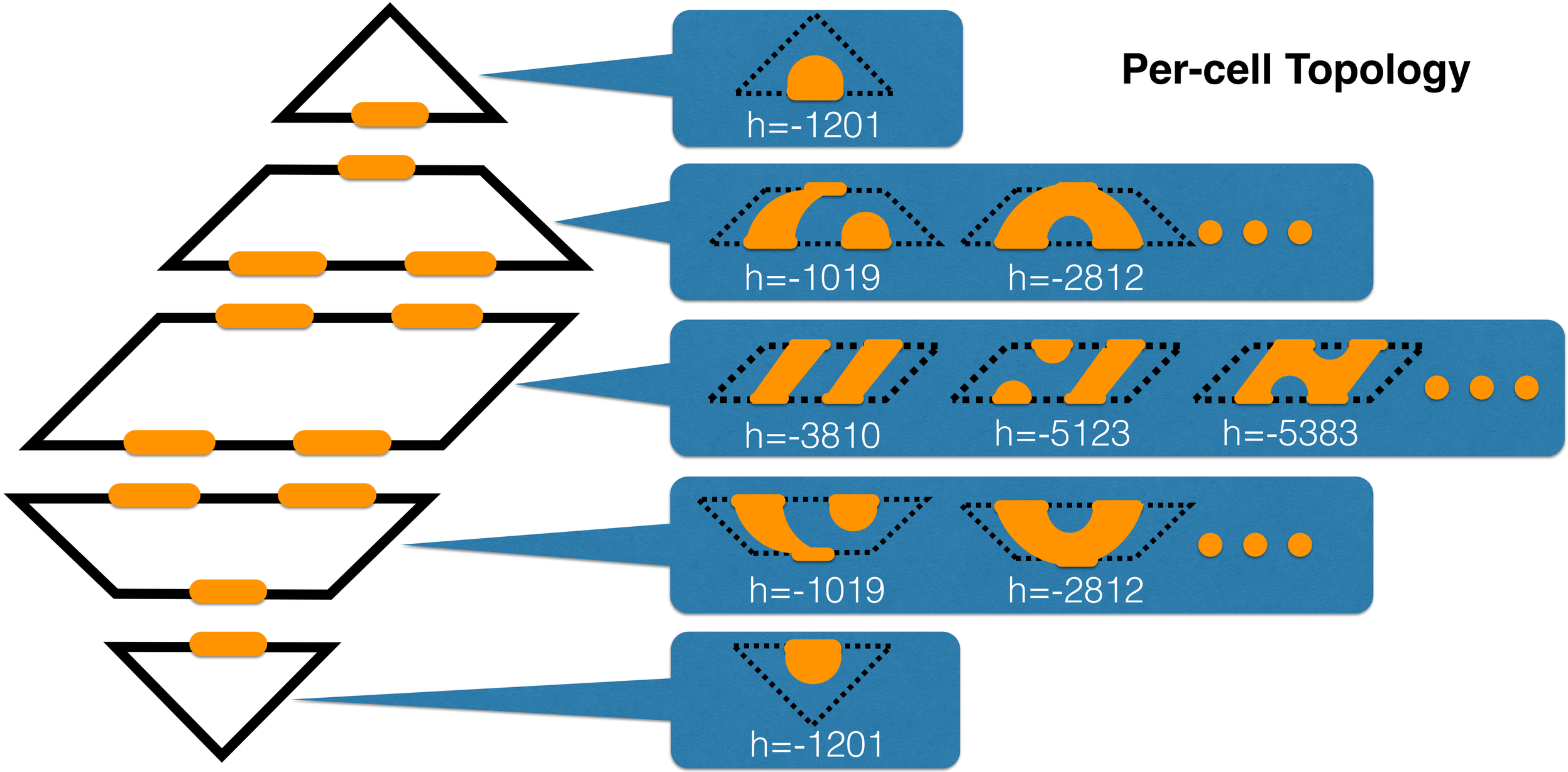






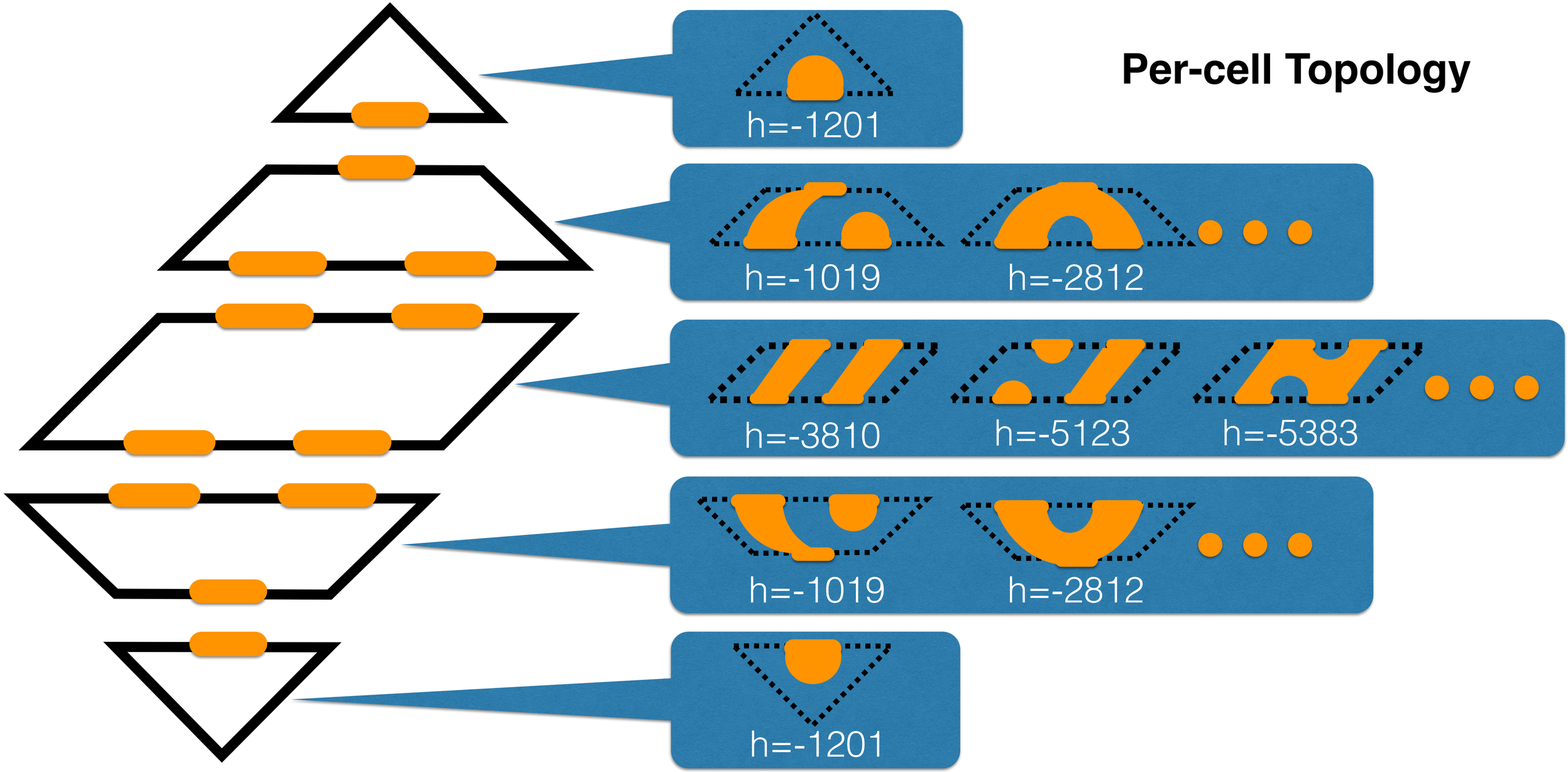
score = -3810 > score = -5123 > score = -5383 > score = -13510

Step 1 : explore



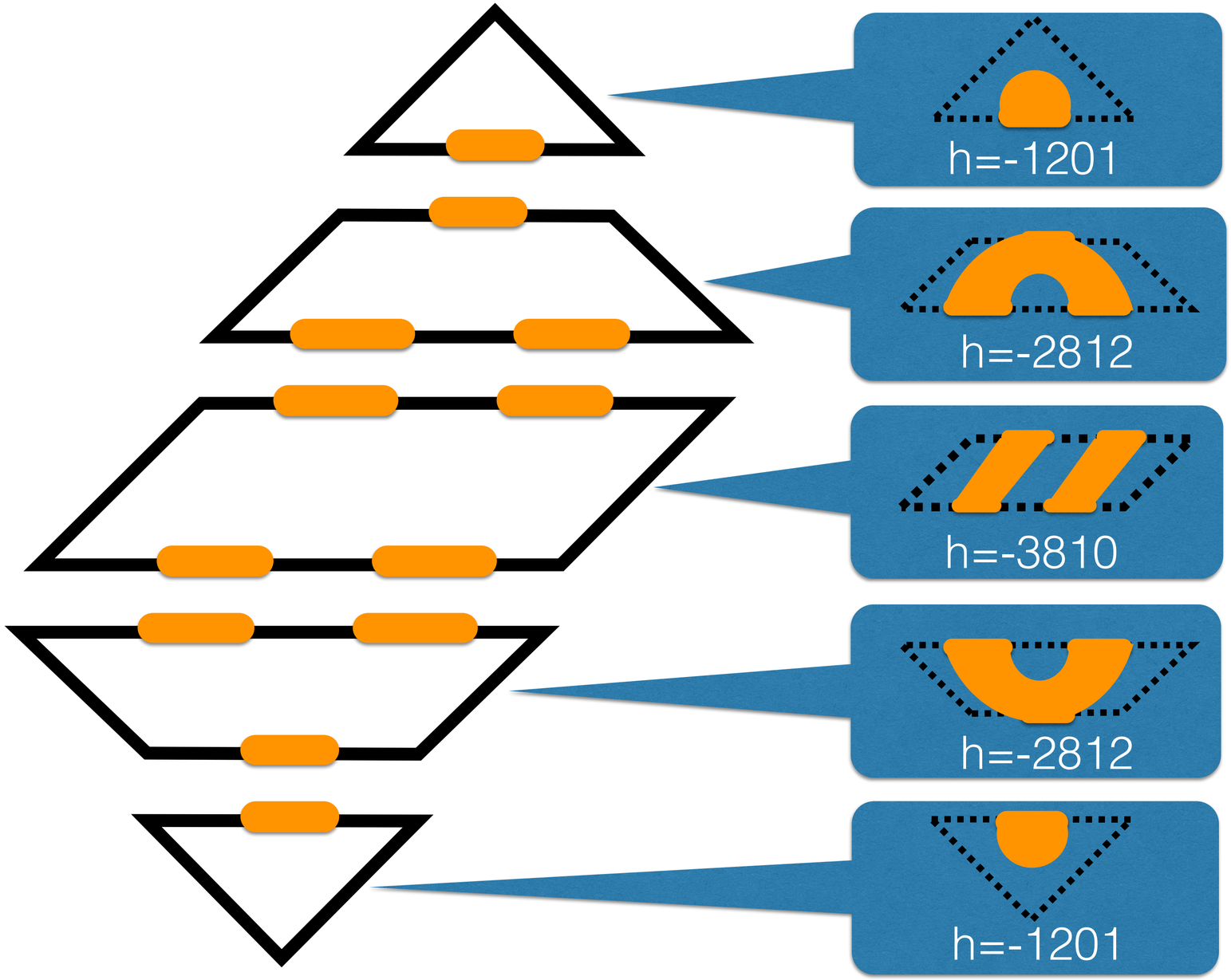
Per-cell Topology

Step 2 : select



Per-cell Topology

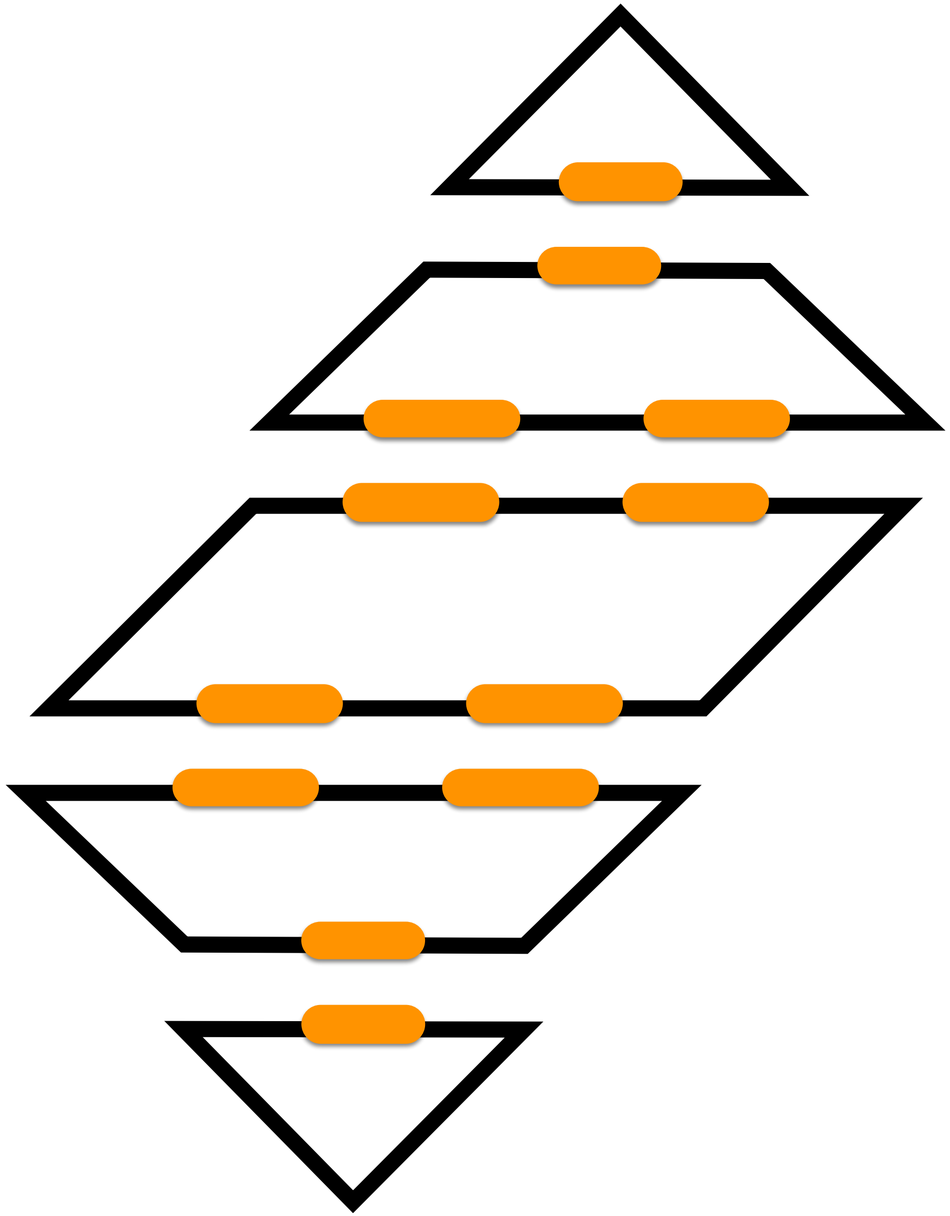
Step 2 : select



Select one topology per cell, such that:

- The merged surface is one single component and has desired genus
- The summation of the scores of the selected topologies is maximized

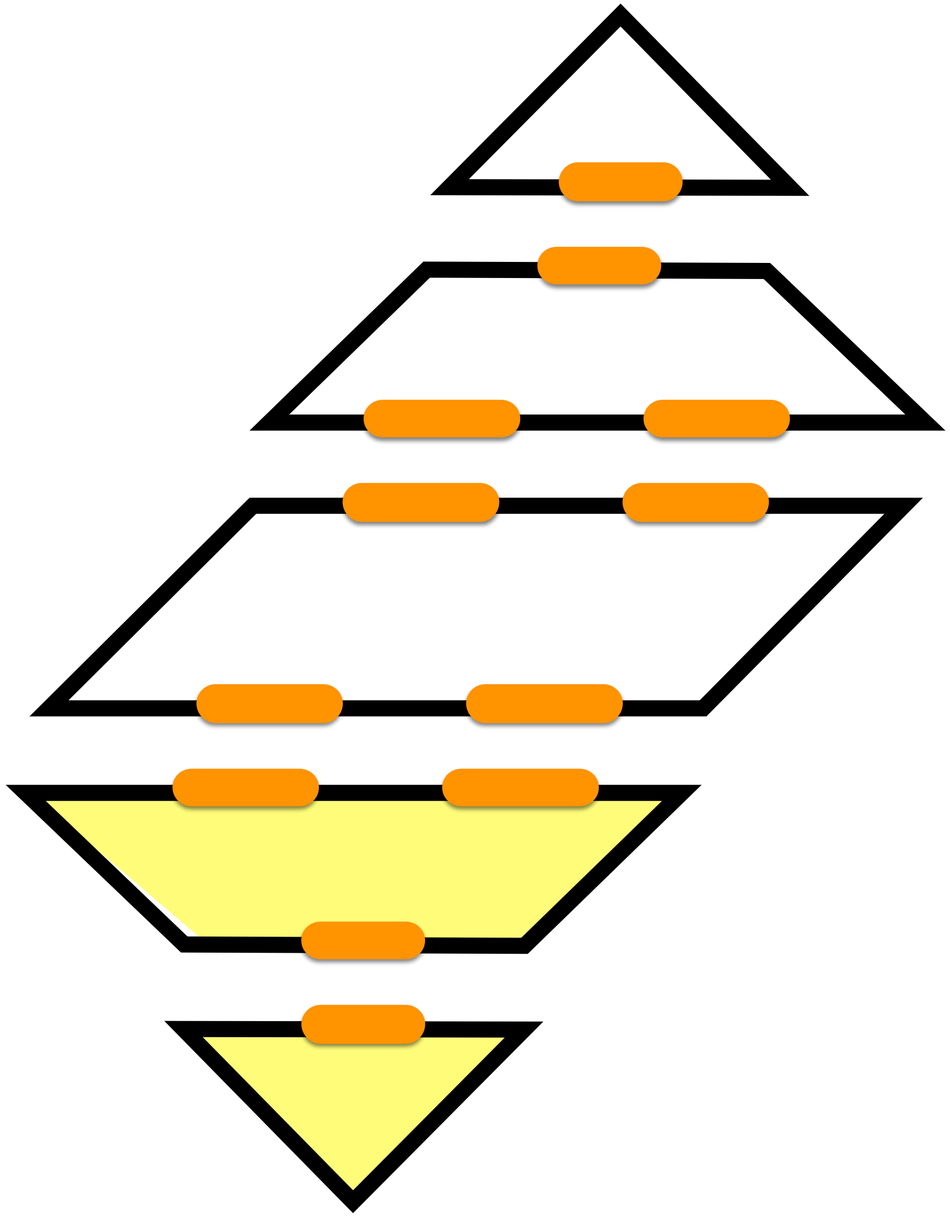
Step 2 : select



Algorithm:

Bottom-up Dynamic Programing

Step 2 : select

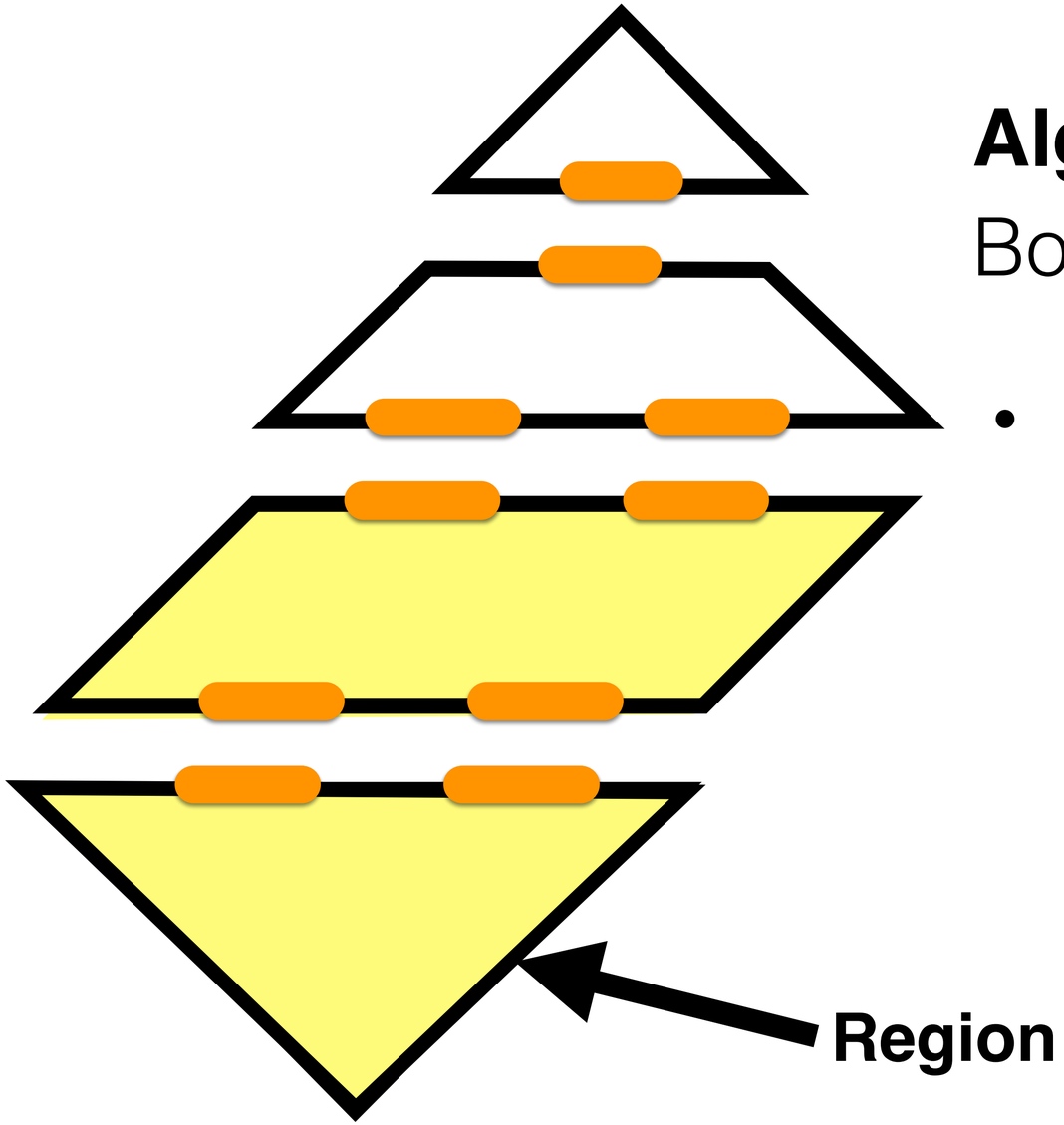


Algorithm:

Bottom-up Dynamic Programing

- Merge ***cells*** into ***regions***, one cell at a time

Step 2 : select

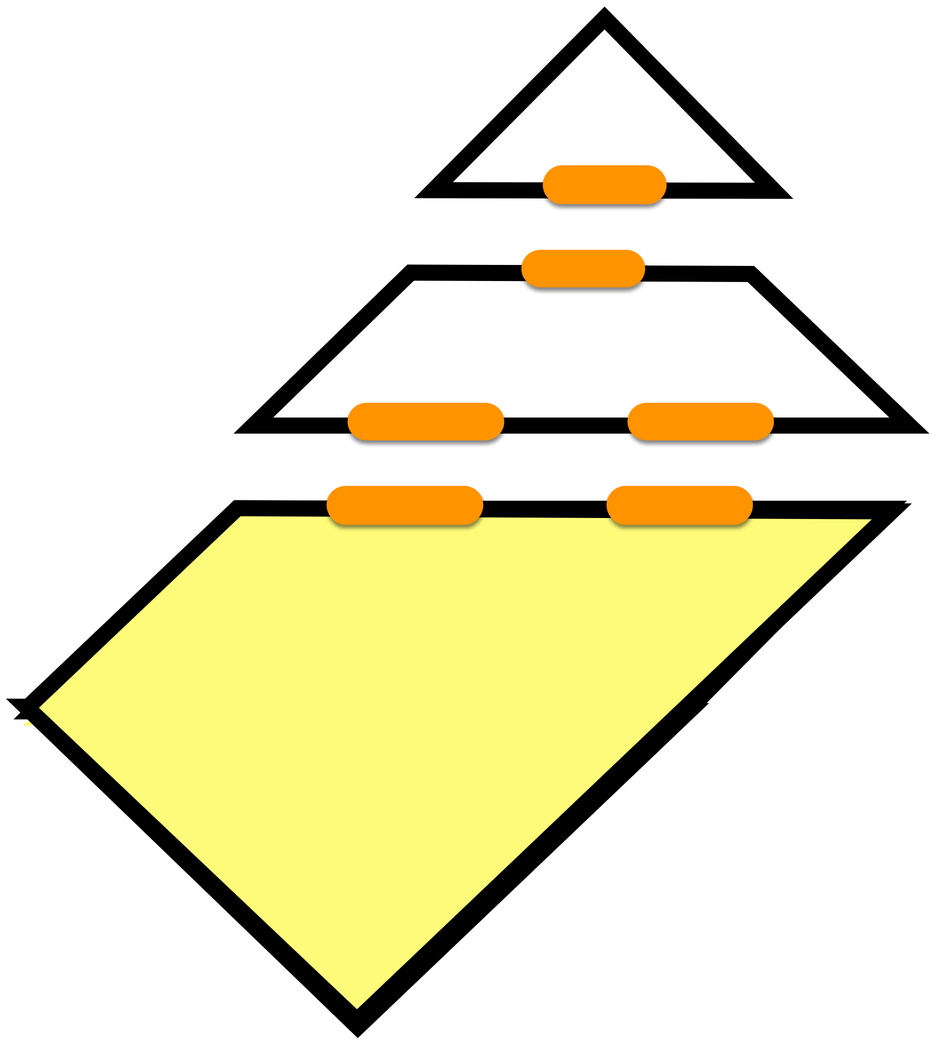


Algorithm:

Bottom-up Dynamic Programing

- Merge ***cells*** into ***regions***, one cell at a time

Step 2 : select

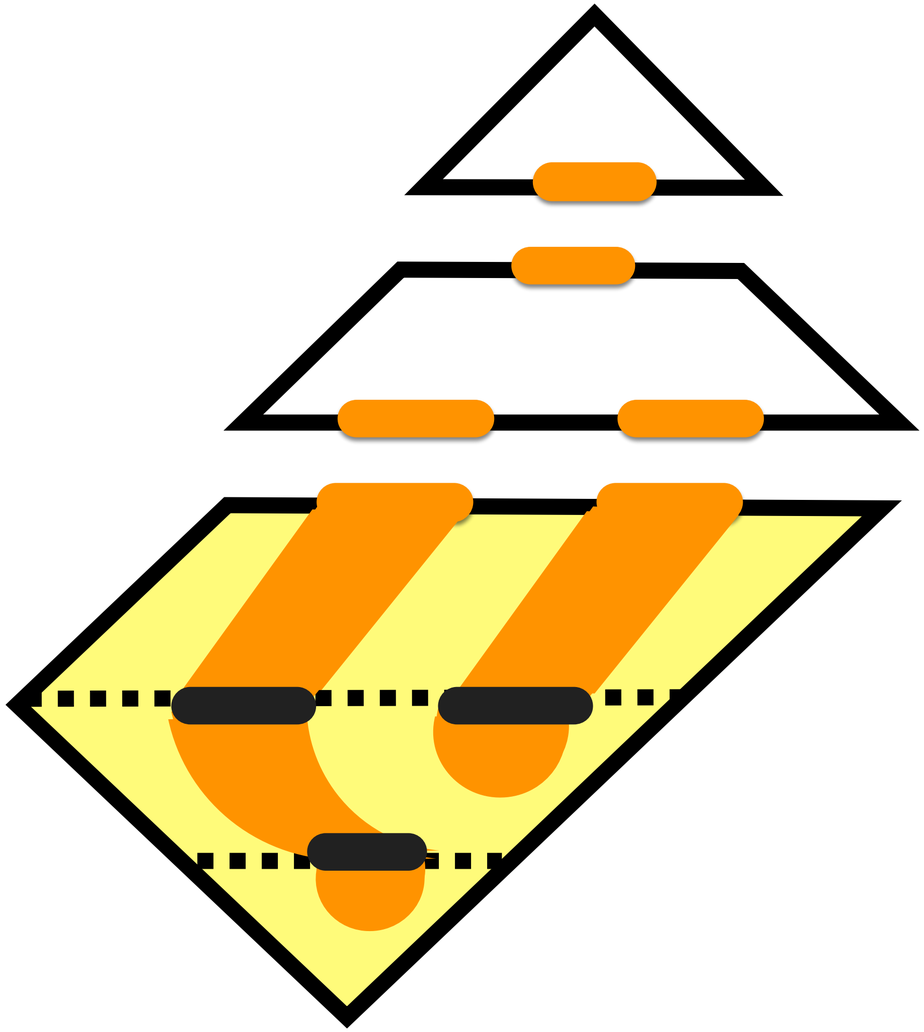


Algorithm:

Bottom-up Dynamic Programing

- Merge ***cells*** into ***regions***, one cell at a time

Step 2 : select

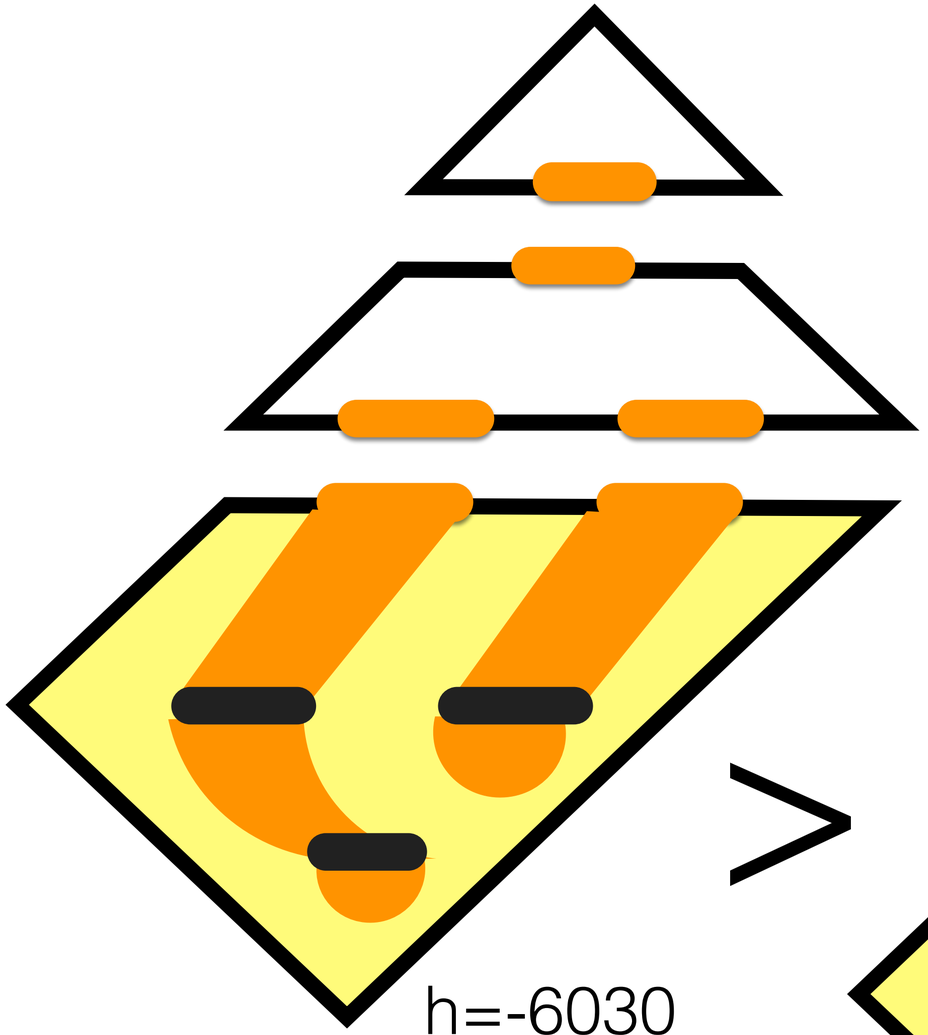


Algorithm:

Bottom-up Dynamic Programing

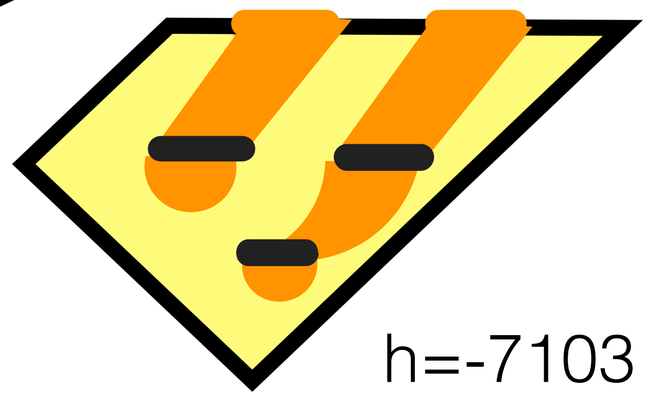
- Merge *cells* into *regions*, one cell at a time
- Merge ***per-cell topologies*** to ***per-region topologies***

Step 2 : select



h=-6030

>



h=-7103

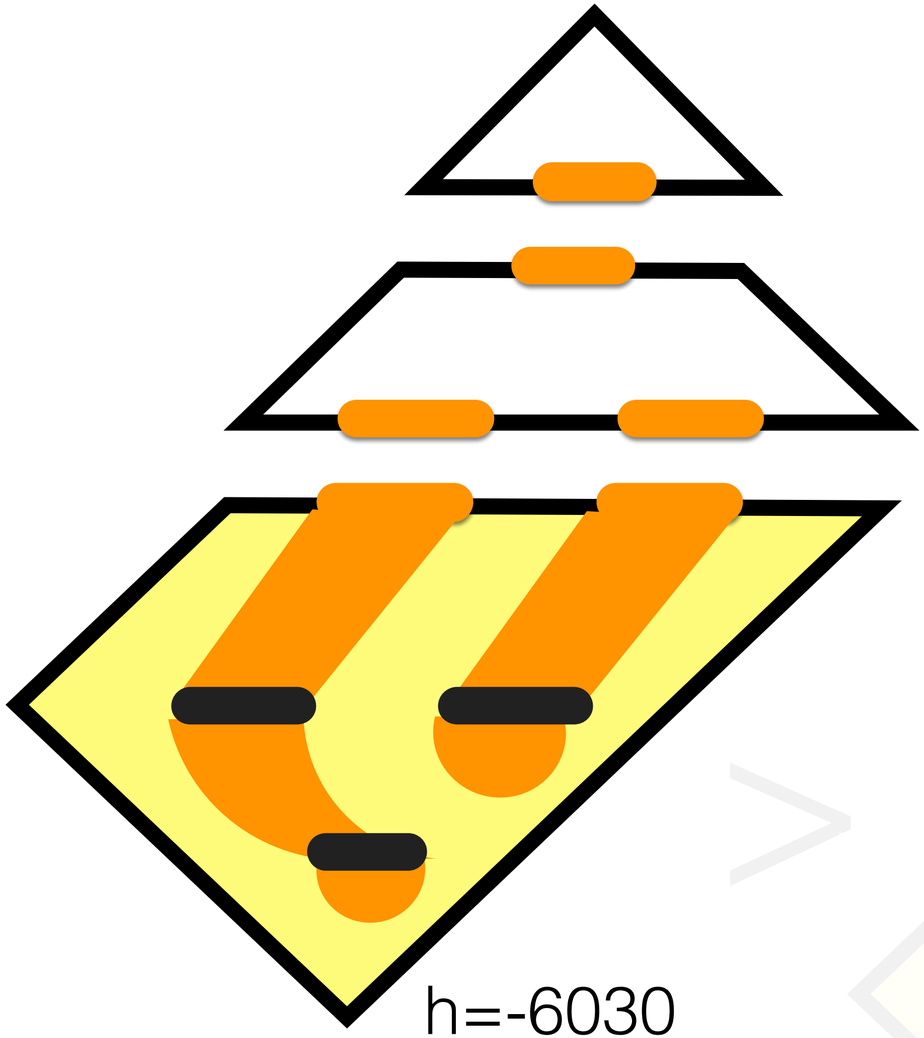
Algorithm:

Bottom-up Dynamic Programing

- Merge *cells* into *regions*, one cell at a time
- Merge *per-cell topologies* to *per-region topologies*
  - *keep the **highest-score** combination of per-cell topologies*

comp = 2
genus = 0

Step 2 : select



Algorithm:

Bottom-up Dynamic Programing

- Merge *cells* into *regions*, one cell at a time
- Merge *per-cell topologies* to *per-region topologies*
  - *keep the **highest-score** combination of per-cell topologies*

comp = 2
genus = 0

Step 2 : select



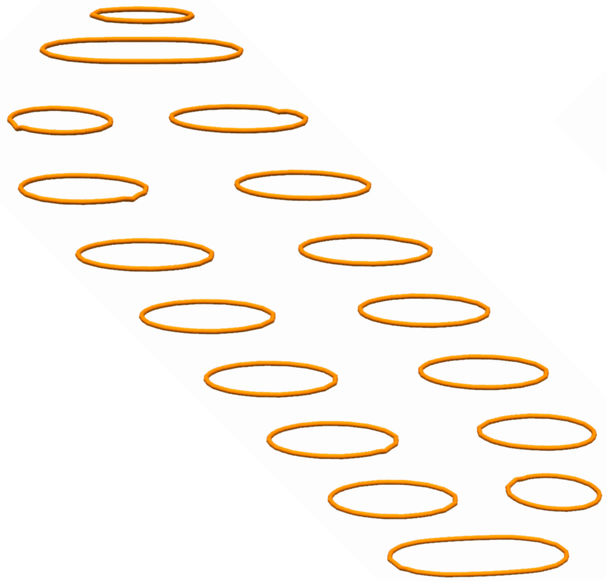
Algorithm:

Bottom-up Dynamic Programing

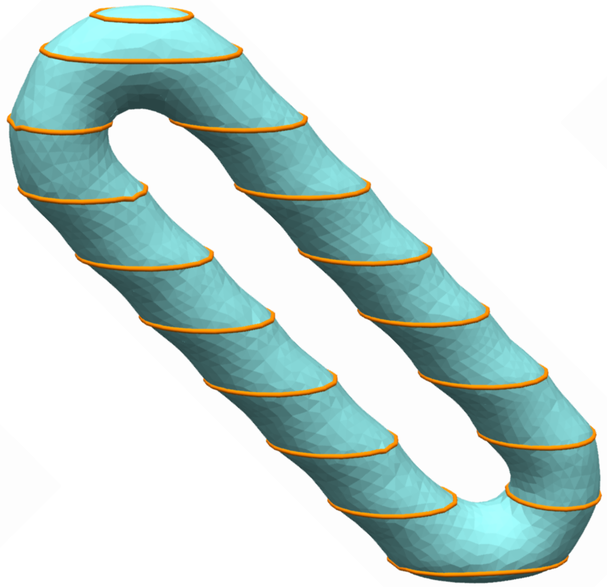
- Merge *cells* into *regions*, one cell at a time
- Merge *per-cell topologies* to *per-region topologies*
  - *keep the highest-score combination of per-cell topologies*

Results

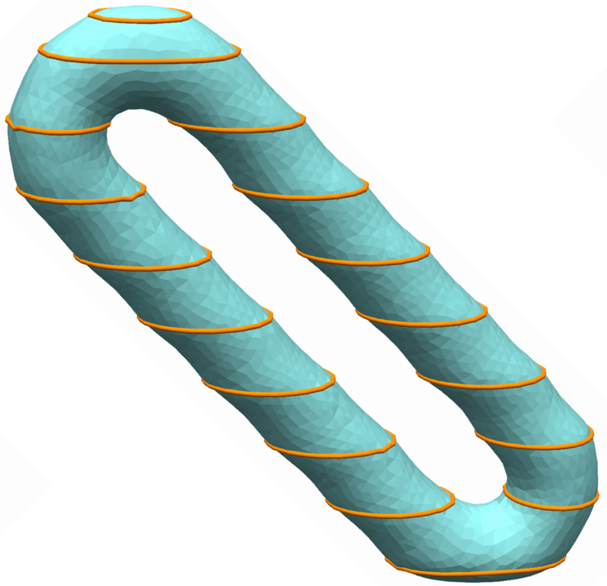
Requires fewer slices



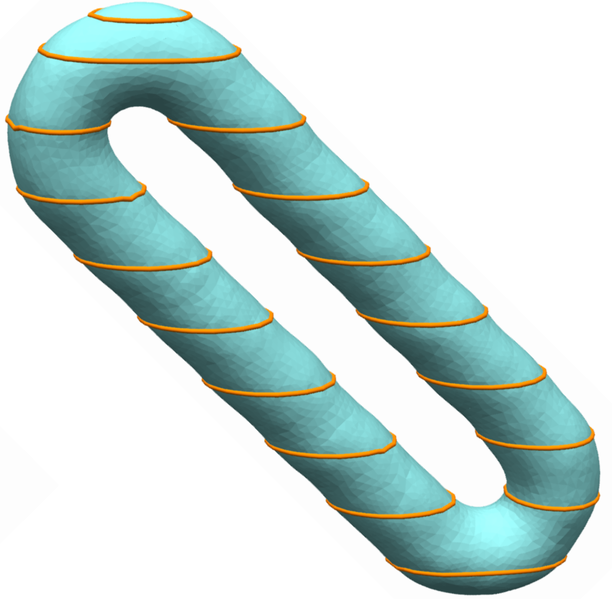
# of slices = 10



[Liu et al. 2008]

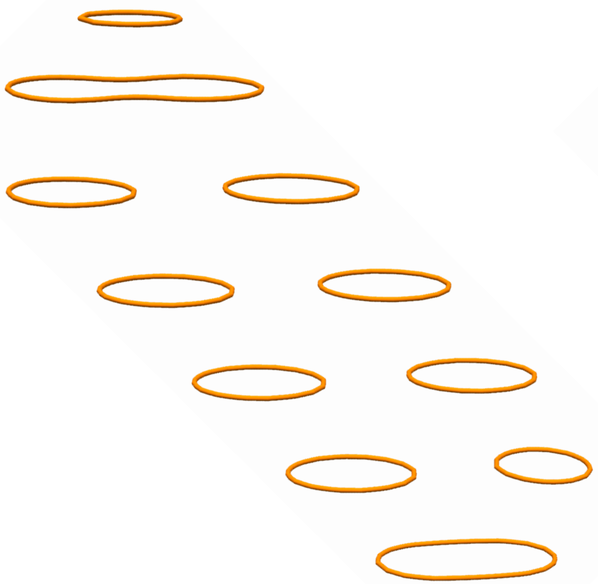


[Bermano et al. 2011]

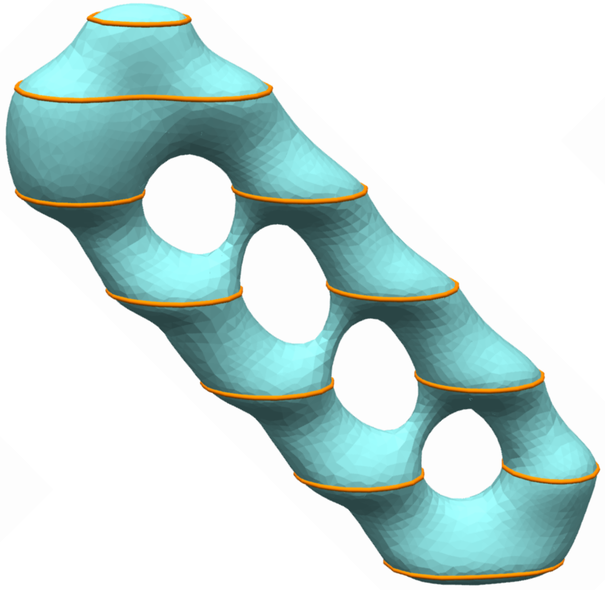


Ours

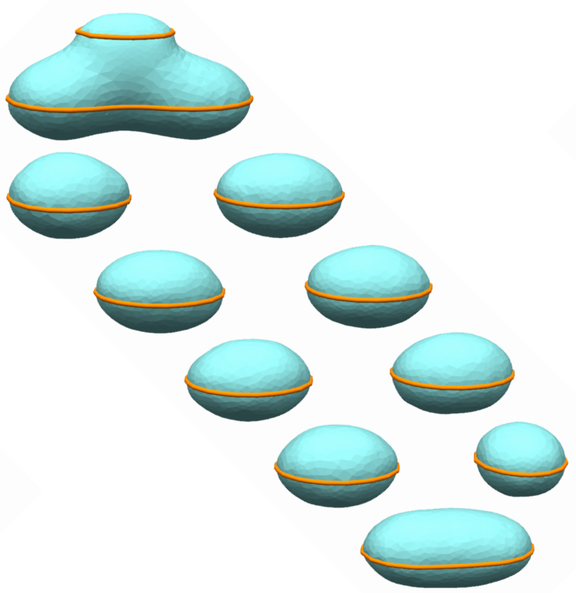
Requires fewer slices



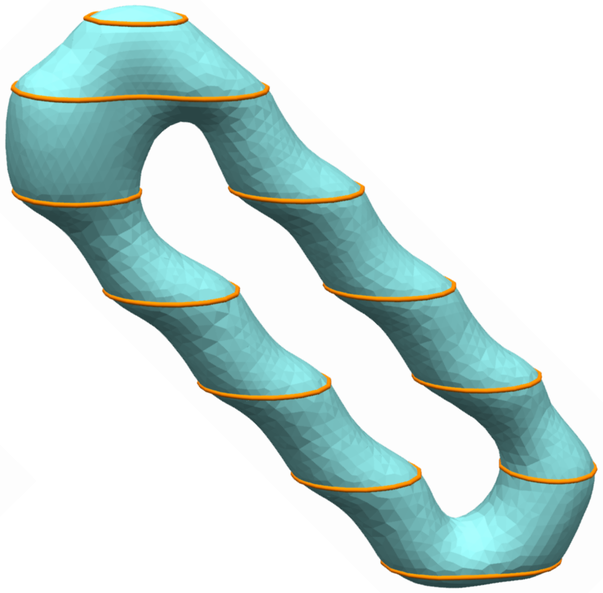
# of slices = 7



[Liu et al. 2008]

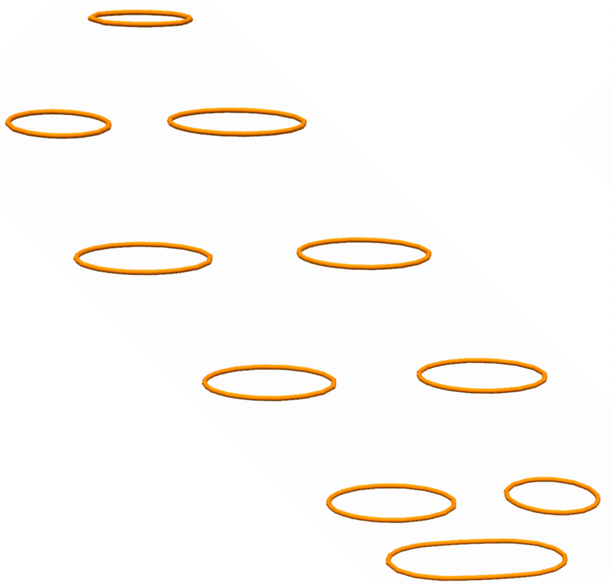


[Bermano et al. 2011]

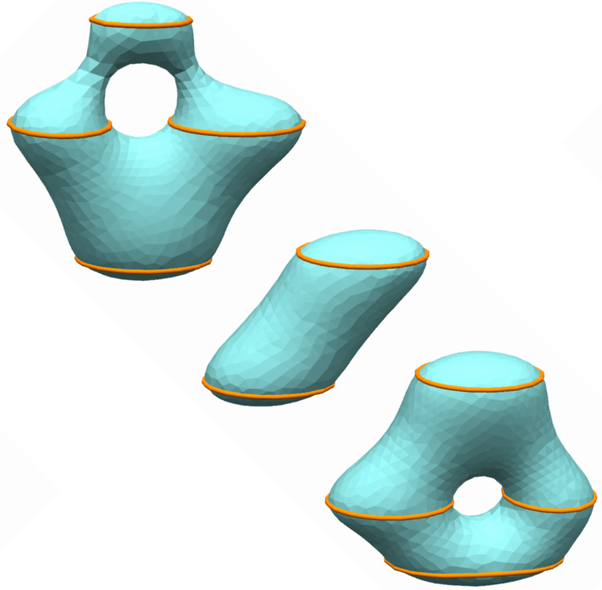


Ours

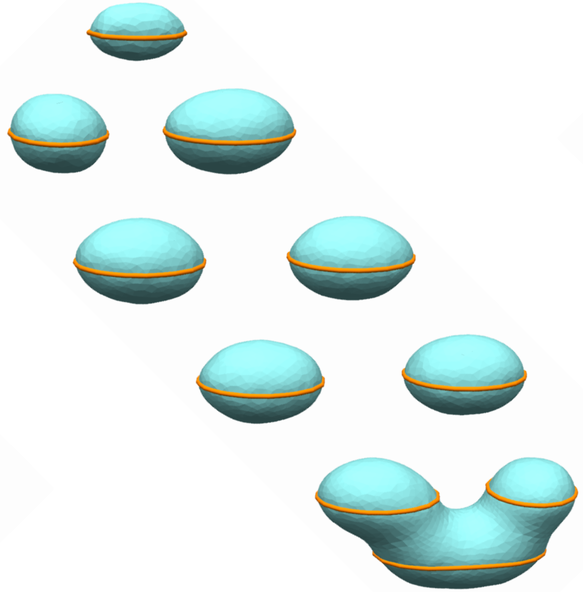
Requires fewer slices



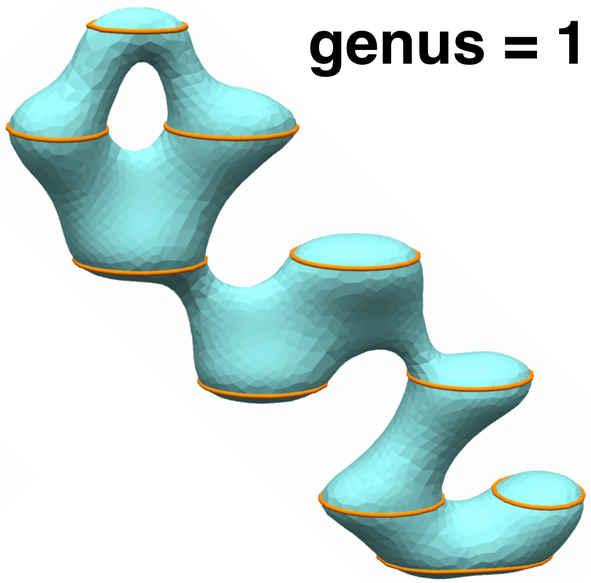
# of slices = 6



[Liu et al. 2008]

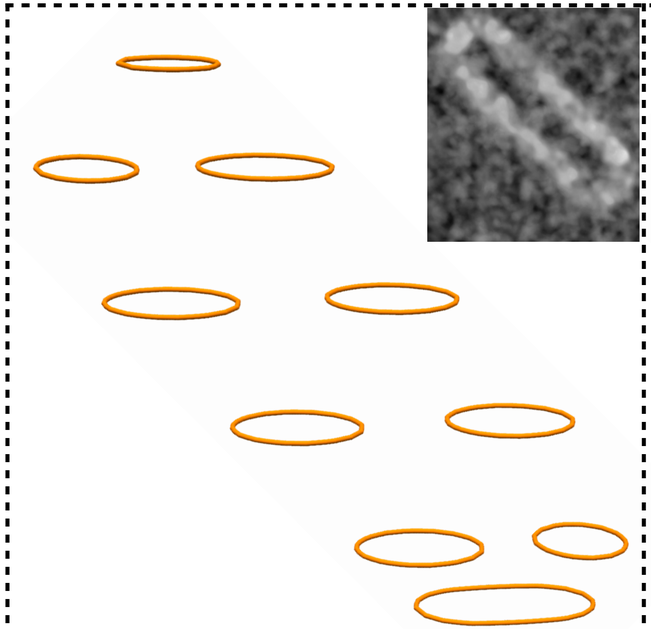


[Bermano et al. 2011]



Ours

Add additional volume data

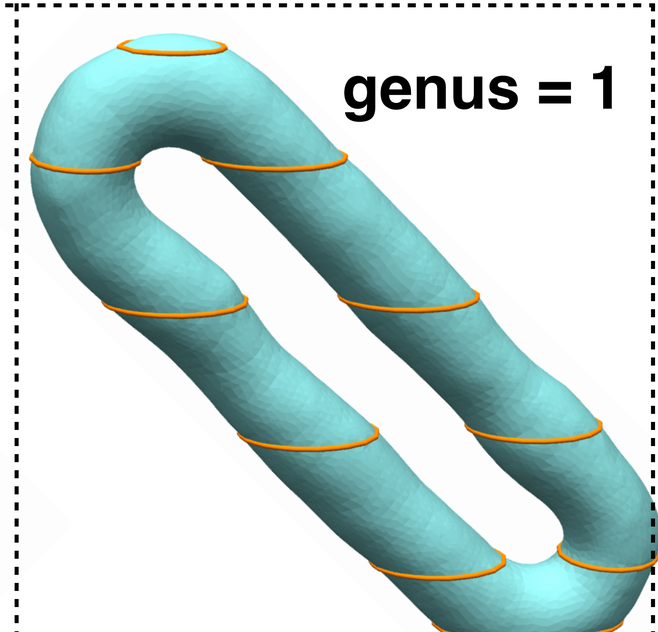


input slices
+ 3D volume

[Liu et al. 2008]

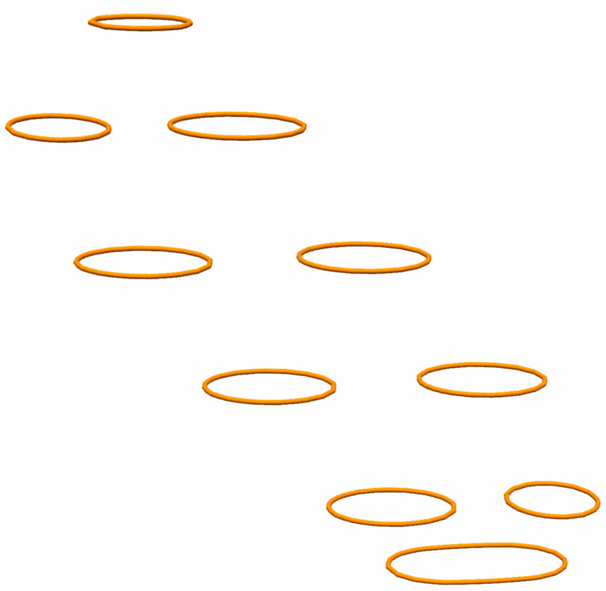


[Bermano et al. 2011]

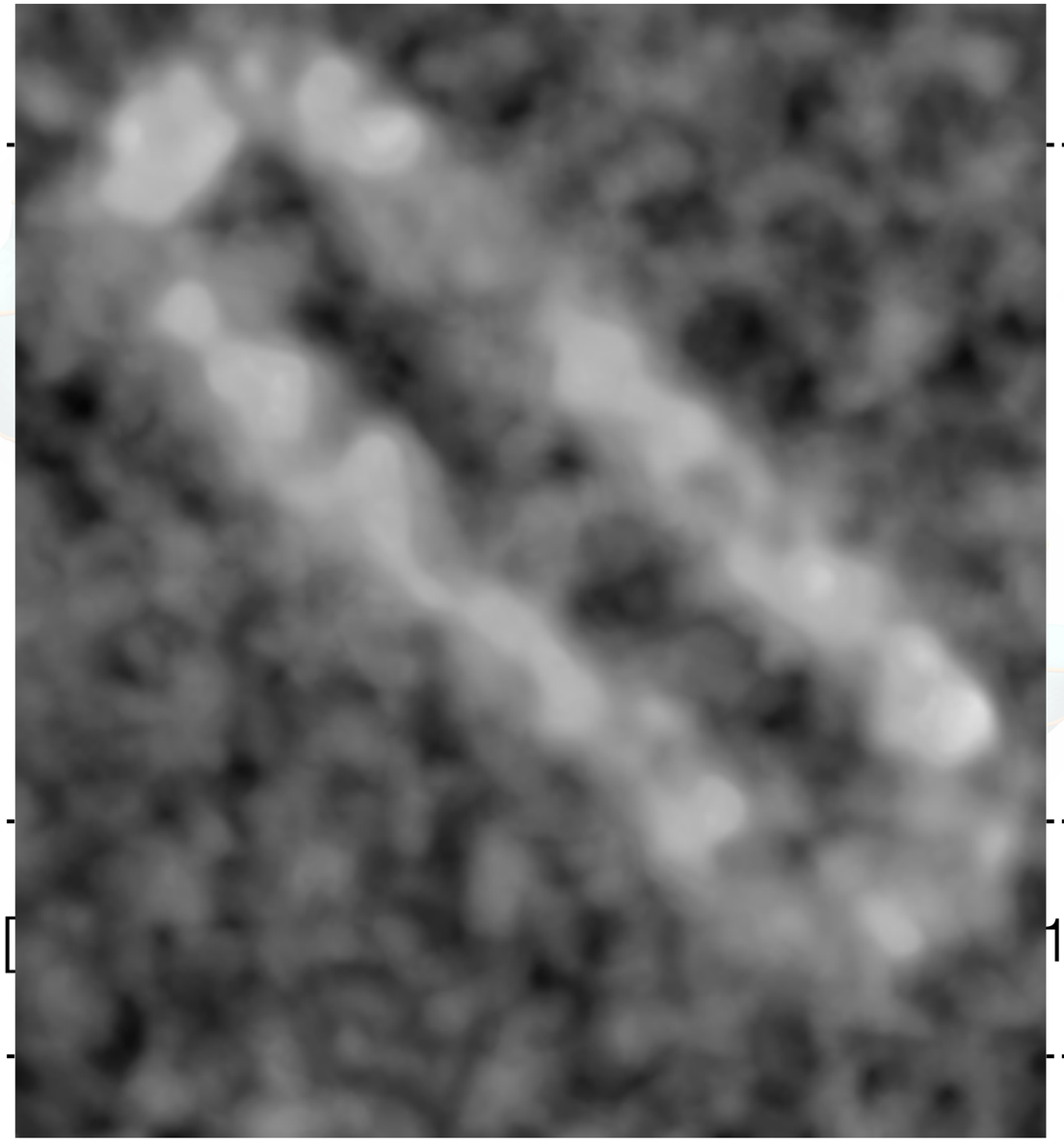


Ours

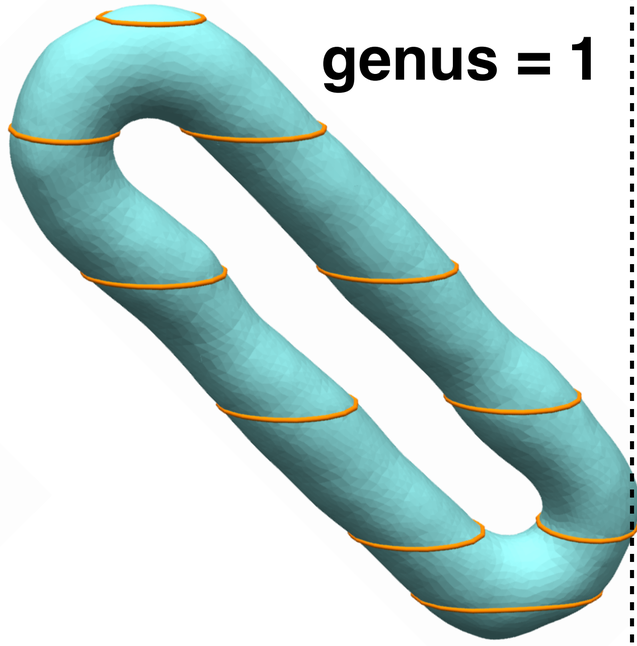
Add additional volume data



input slices
+ 3D volume

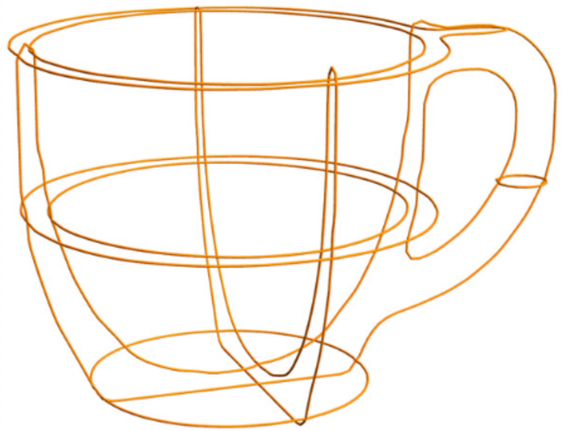


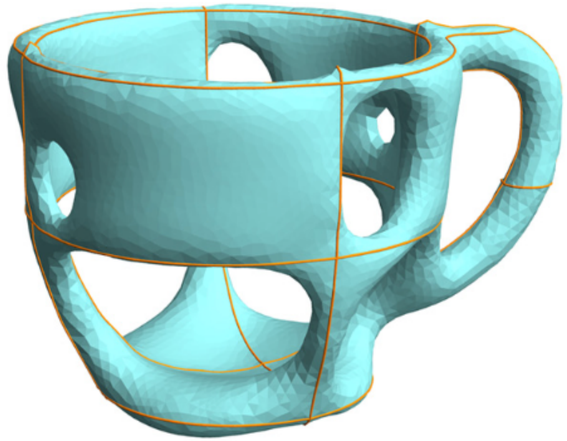
[11]

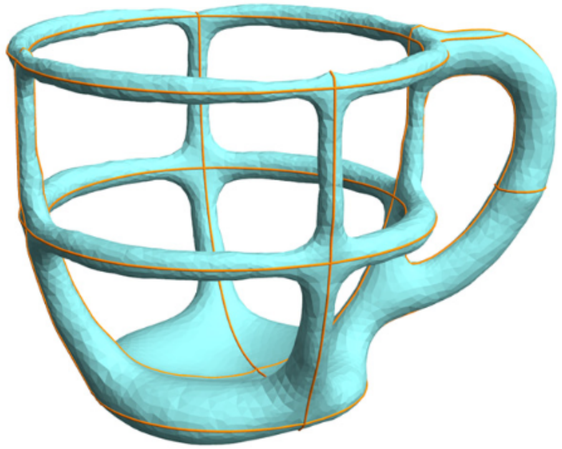


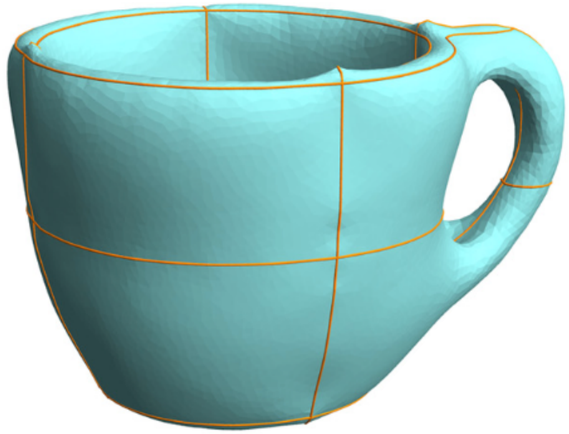
Ours

More results





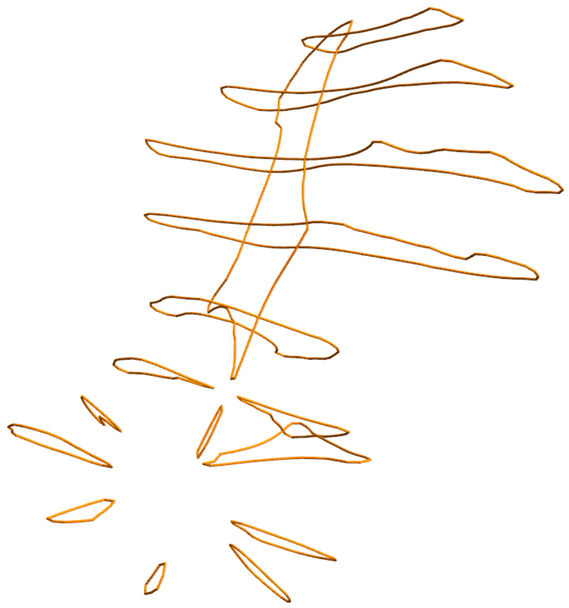




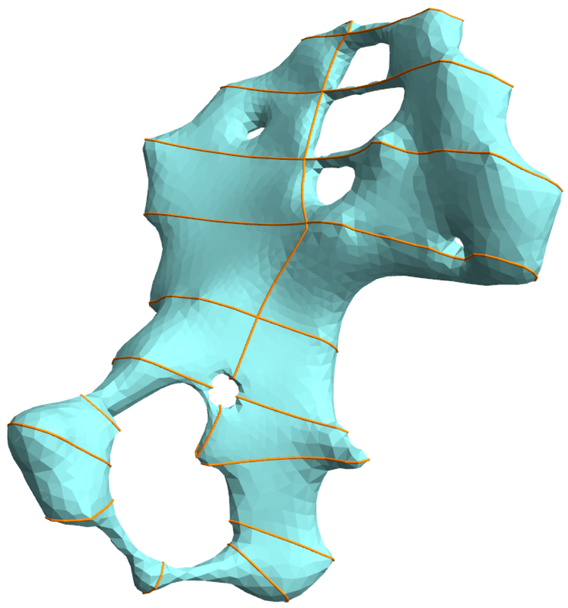
genus = 1
time: 23.16s

Input slices	[Liu et al. 2008]	[Bermano et al. 2011]	Ours w/o volume

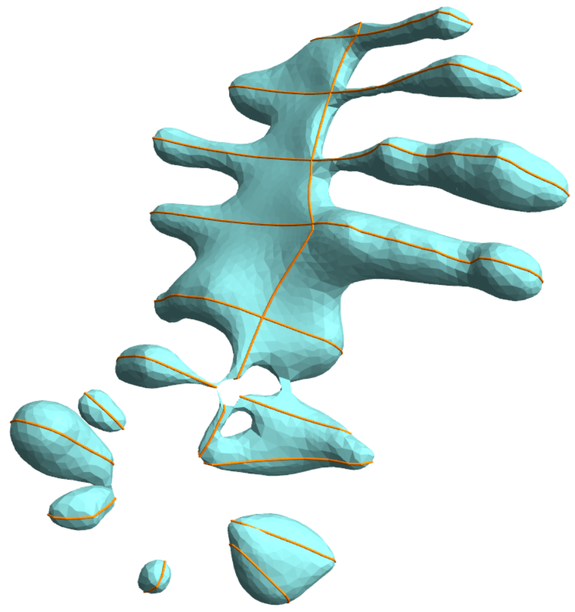
More results



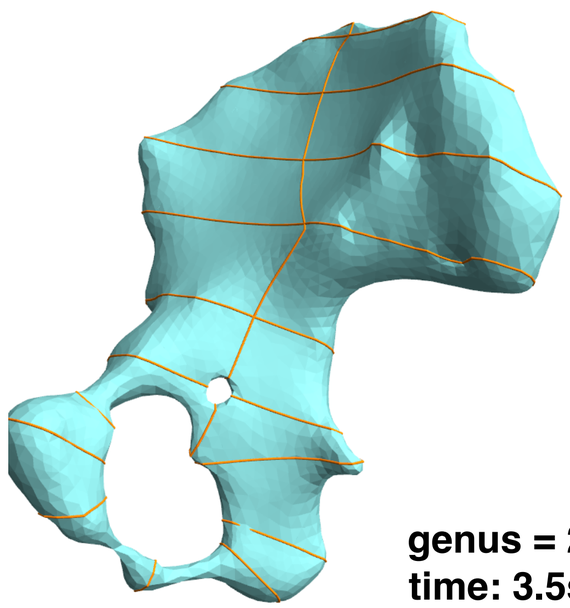
Input slices



[Liu et al. 2008]

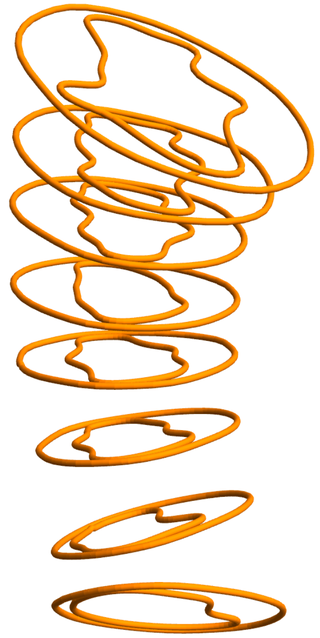


[Bermano et al. 2011]

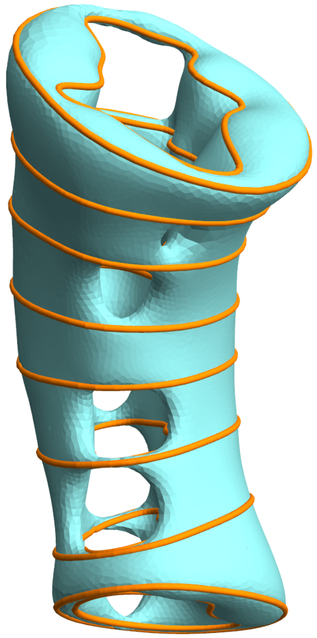


Ours w/o volume

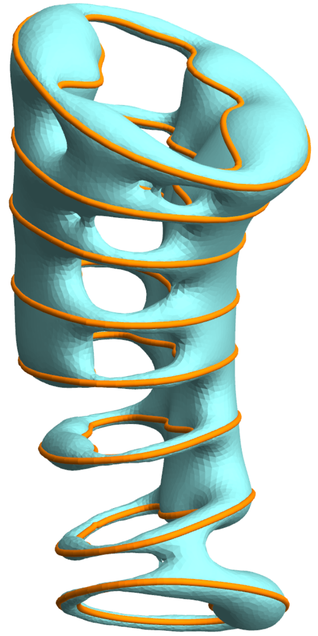
More results



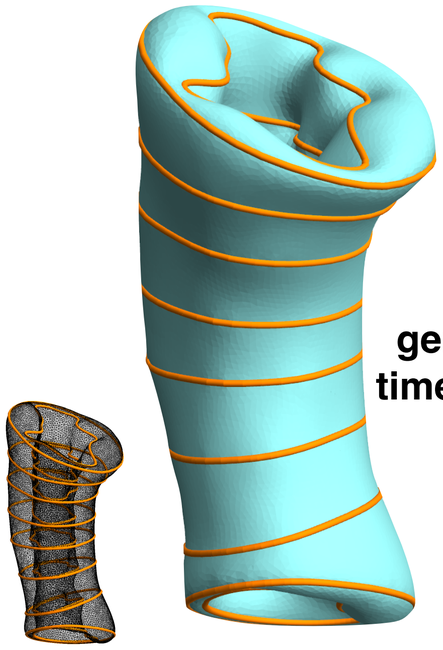
Input slices



[Liu et al. 2008]



[Bermano et al. 2011]

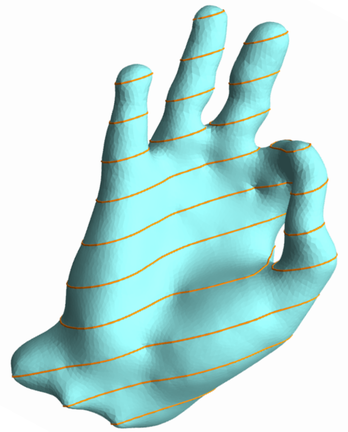


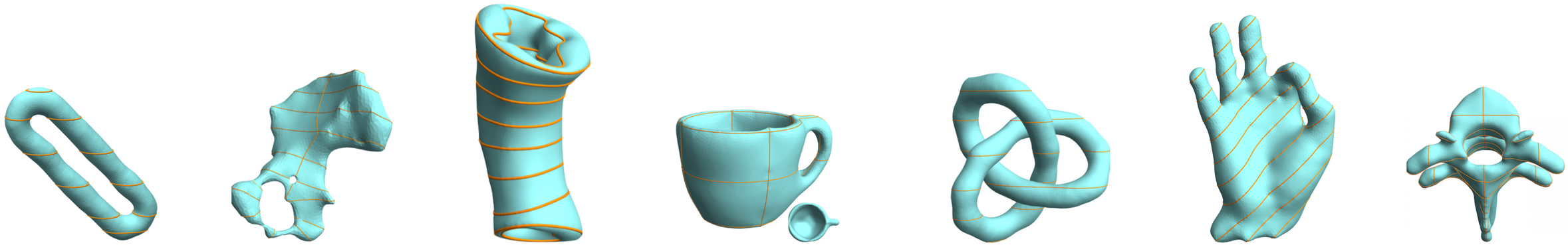
Ours w/o volume

Conclusion

- Contour based reconstruction method with topology control
  - Requires fewer contours while guaranteeing topology correctness
  - 2-step algorithm:
    (1) Local exploration
    (2) Global selection

- Future work
  - Explore larger space of surface topology
  - Reconstruct from other data with topology control





Thank You!

Q&A

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http://www.cse.wustl.edu/~zoum

(code & data)