Shape description using skeleton-like features

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Syllabus

- shapes
- shape representation
- continuous skeleton
- skeleton-like shape features
- skeletonization techniques
  - distance-based
  - Voronoi-based
  - thinning
- applications of skeletonization

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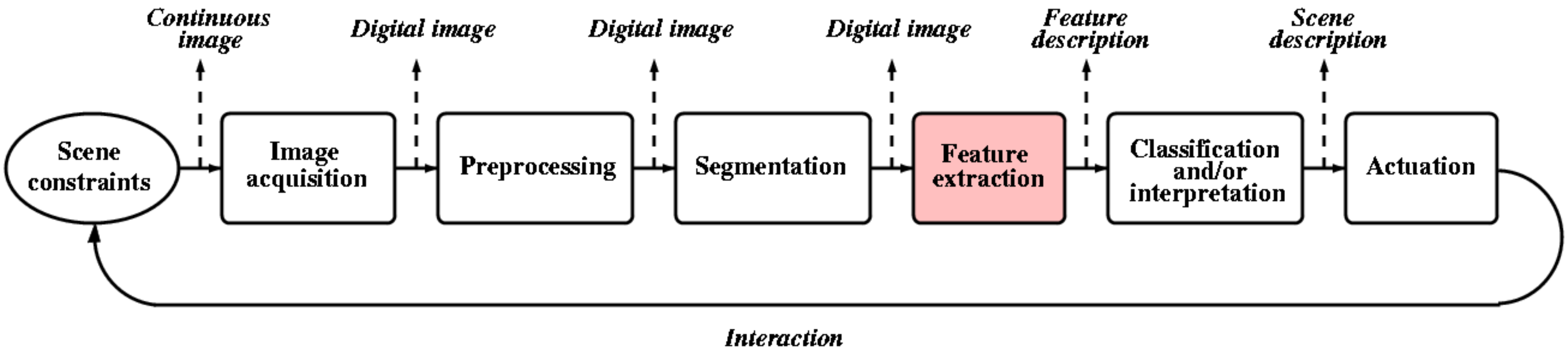
The generic model of a modular machine vision system



G.W. Awcock, R. Thomas

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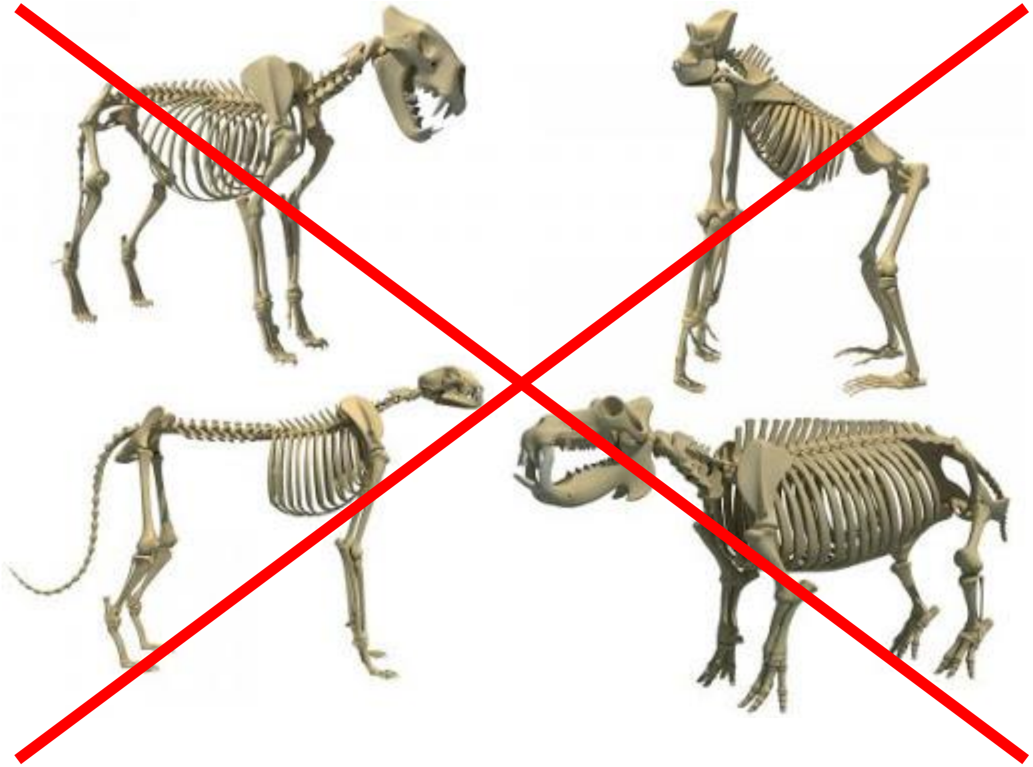
Shape representation techniques

- to apply a **transform** in order to represent an object in terms of the transform coefficients,
- to describe the **boundary** that surrounds an object,
- to describe the **region** that is occupied by an object.

Skeleton



Skeleton: region-based shape feature

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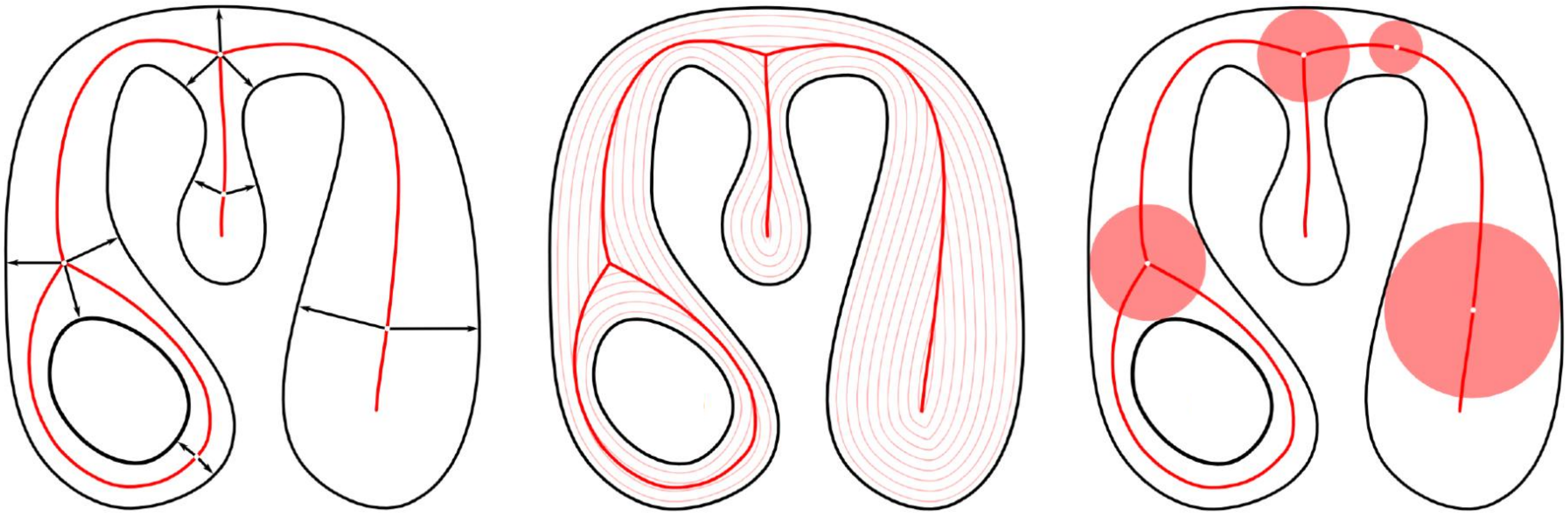
Definitions of the continuous skeleton

- result of the Medial Axis Transform: object points having at least two closest boundary points
- praire-fire analogy: the boundary is set on fire and skeleton is formed by the loci where the fire fronts meet and quench each other
- the locus of the centers of all the maximal inscribed hyper-spheres

Definitions of the continuous skeleton



MAT

fire-front propagation

centers of maximal inscribed disks

Tagliasacchi et al., 2016

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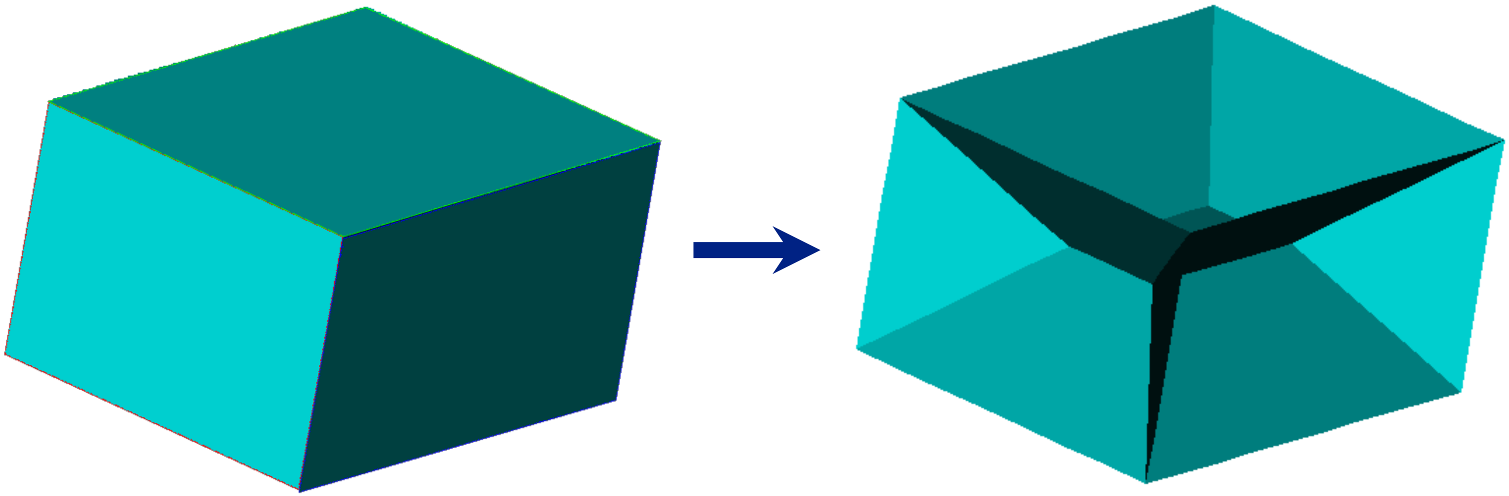
Continuous skeleton in 3D



3D skeletons generally contain 2D segments
(i.e., surface patches)

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Advantageous properties of the continuous skeleton

- represents
  - the general form of an object,
  - the topological structure of an object, and
  - local object symmetries.
- invariant to
  - translation,
  - rotation, and
  - (uniform) scale change.
- simplified and thin.

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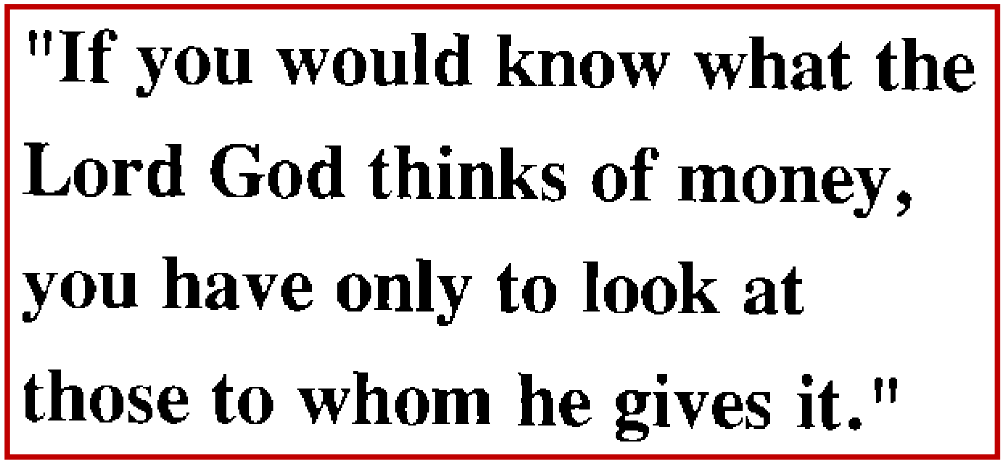
Skeleton-like shape features

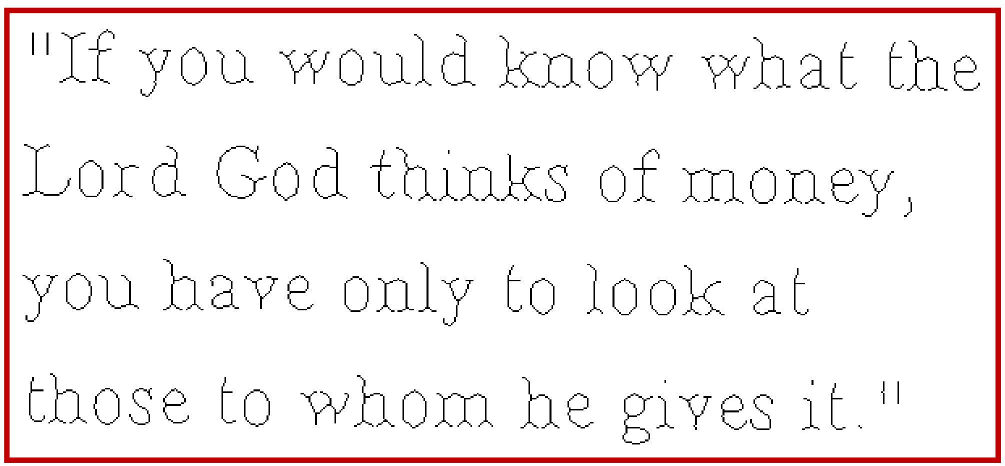
skeleton-like features in 2D:
- centerline
- topological kernel

skeleton-like features in 3D:
- medial surface
- centerline
- topological kernel

Skeleton-like shape features in 2D



original



centerline

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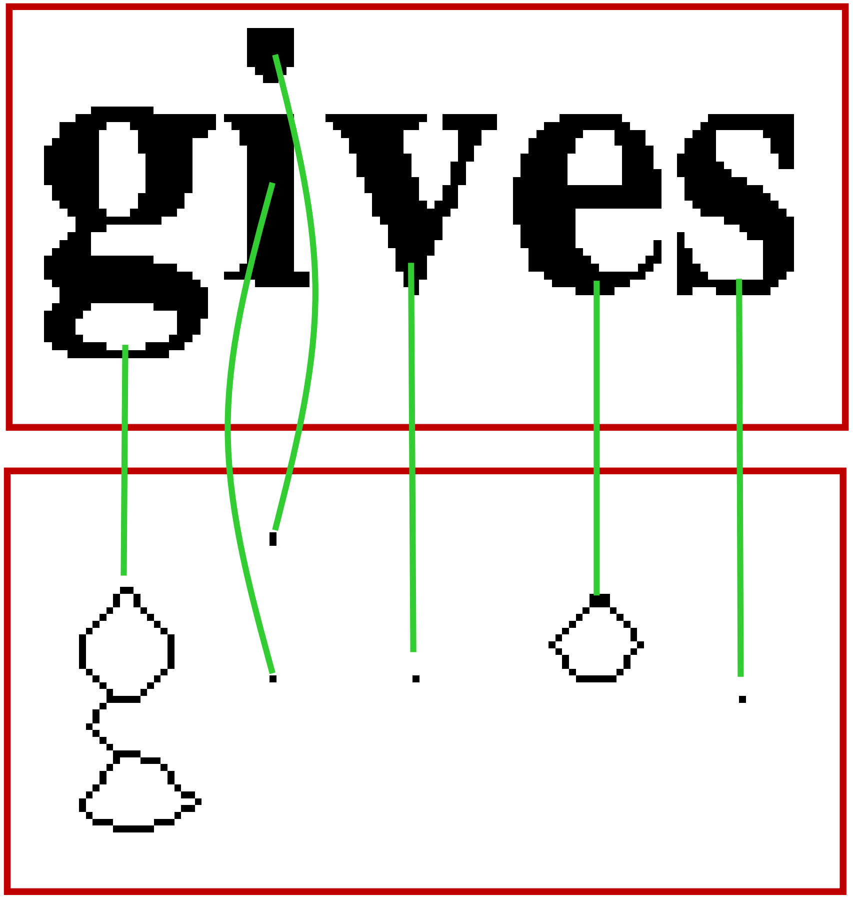
Topological kernel in 2D

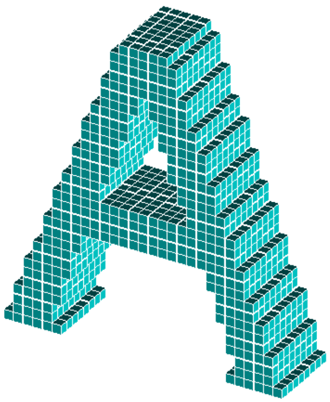


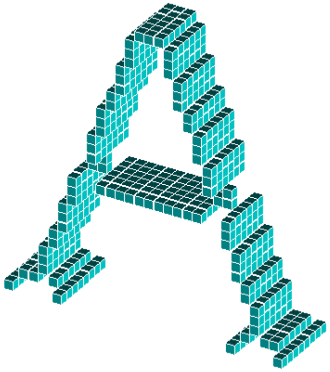
original objects with/without cavities

topological kernels

Skeleton-like shape features in 3D

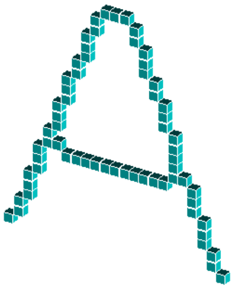
original object

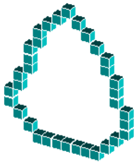




medial surface

centerline





topological kernel

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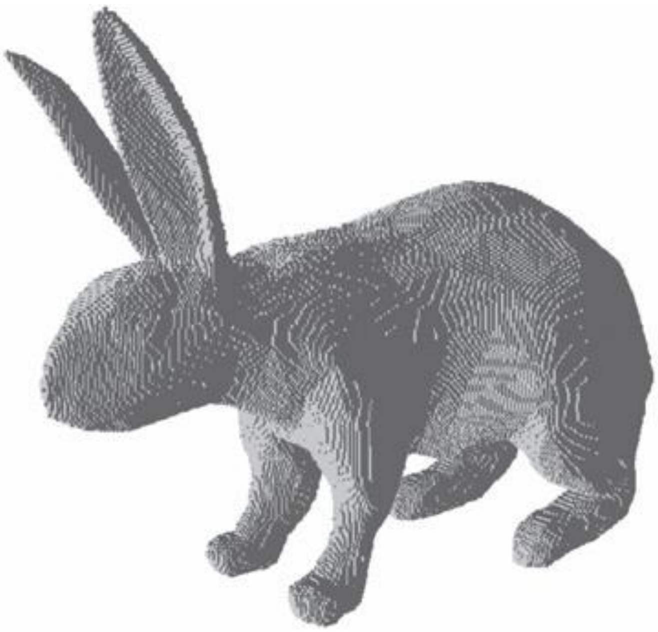
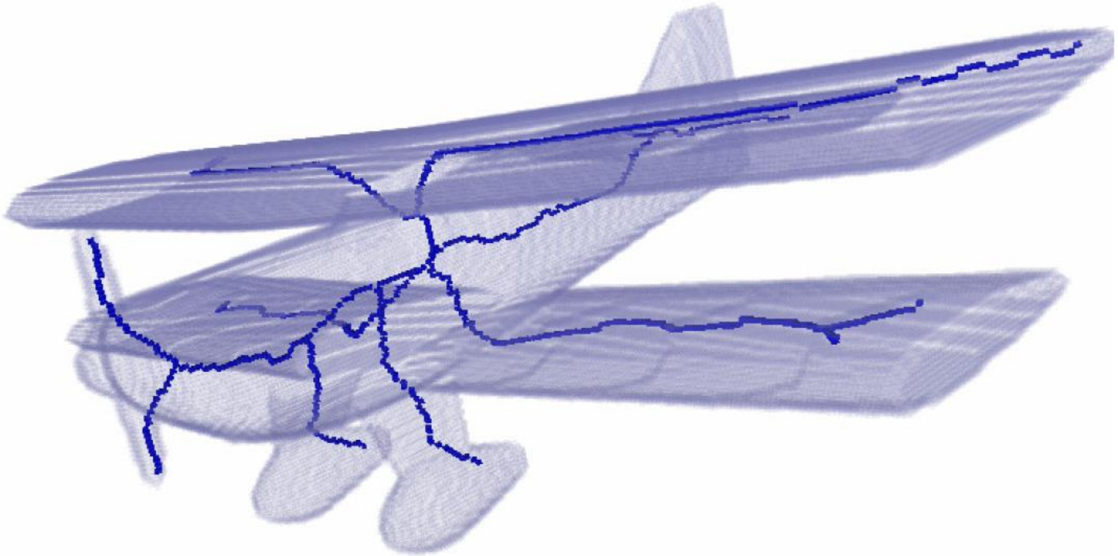
Skeleton-like shape features in 3D



original object

medial surface

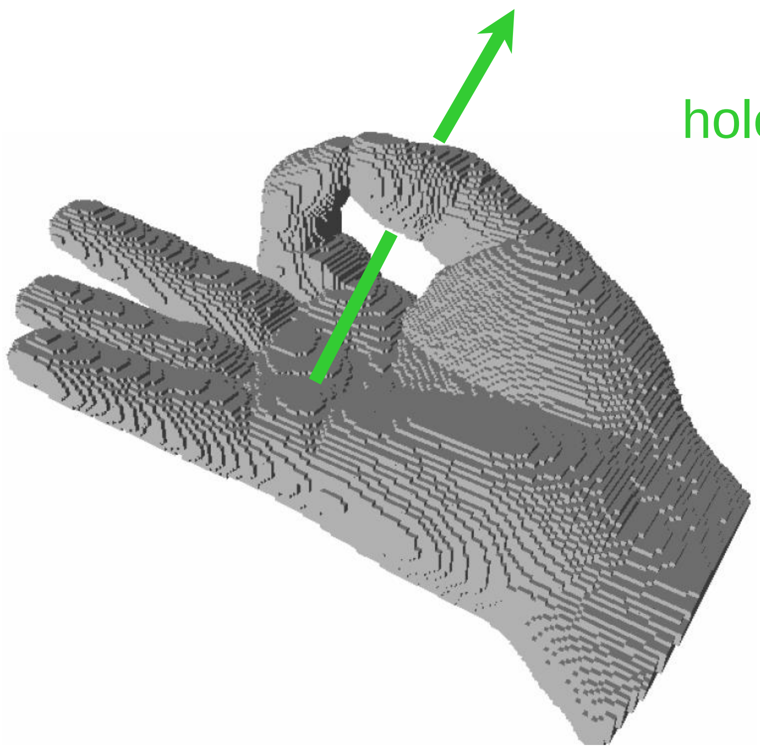
Skeleton-like shape features in 3D



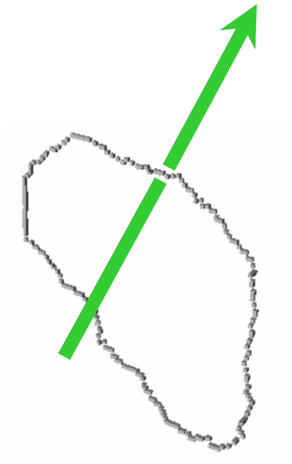
centerline

Skeleton-like shape features in 3D

hole / tunnel

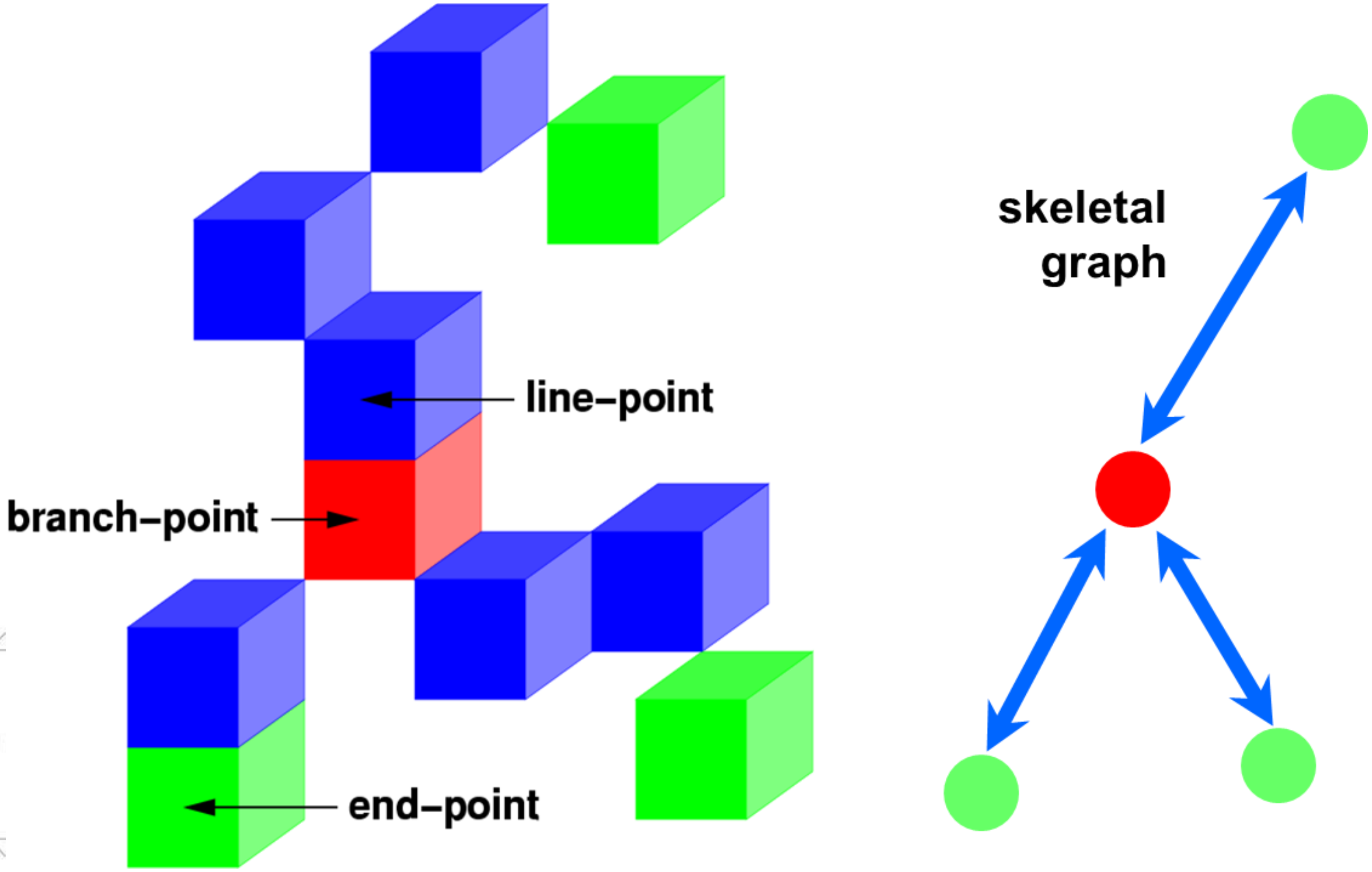


original object



topological kernel

Elements in centerlines



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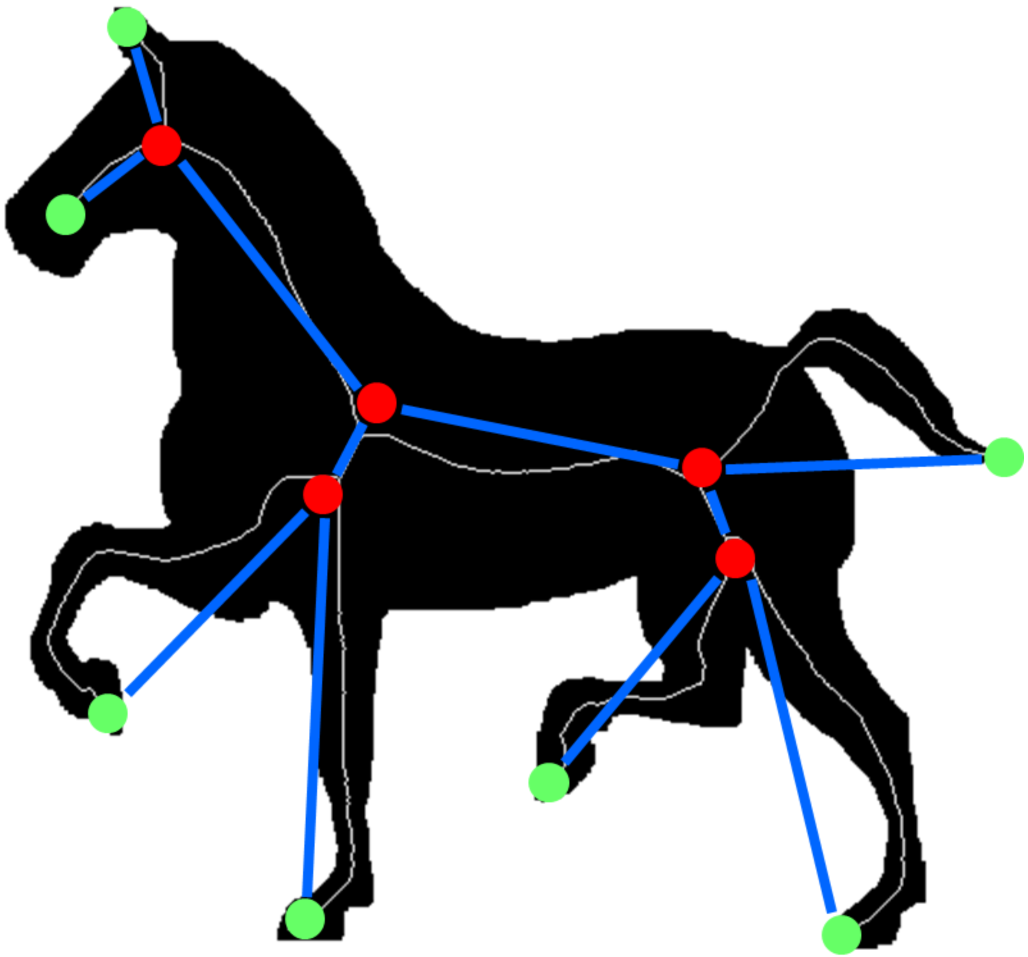
Centerlines and skeletal graphs



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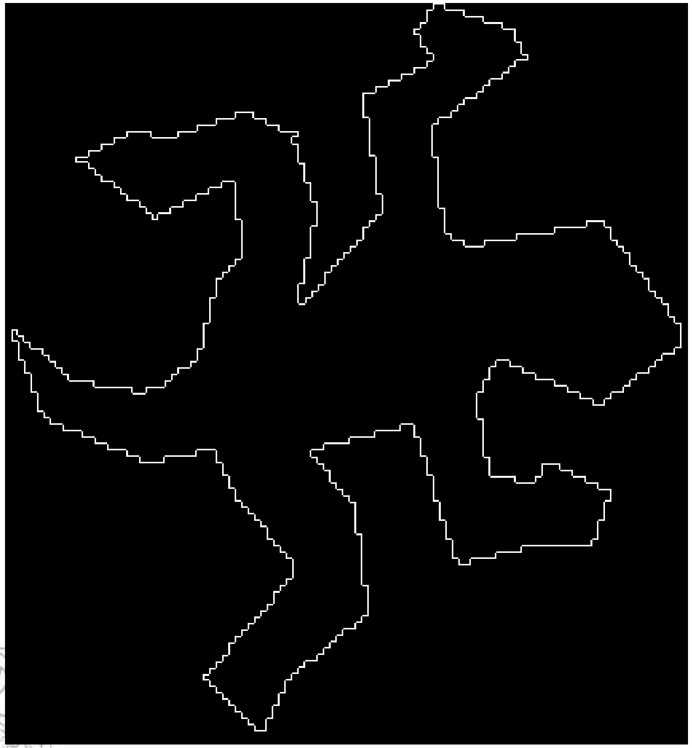
Distance transform (DT)

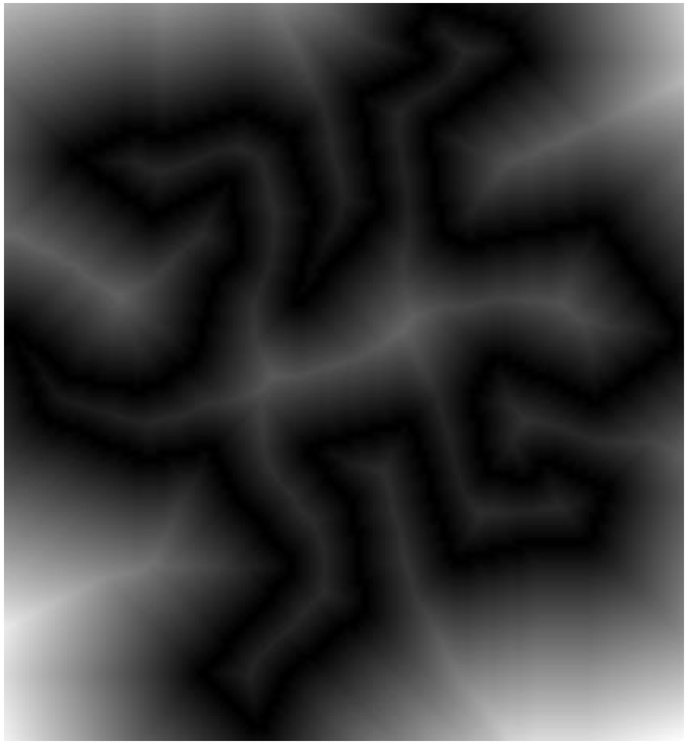
Input:
Binary array *A* containing feature elements (1's) and non-feature elements (0's).

Output:
Distance map *B*: non-binary array containing the distance to the closest feature element.

Distance transform



feature mask



distance map

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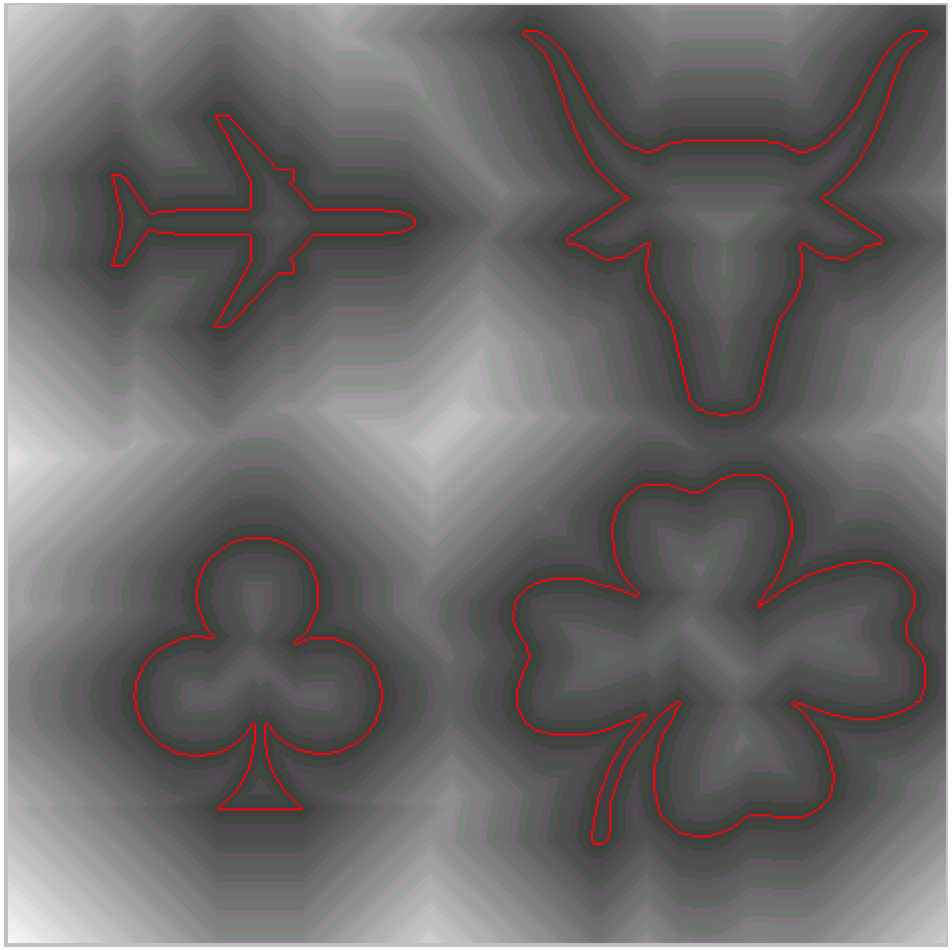
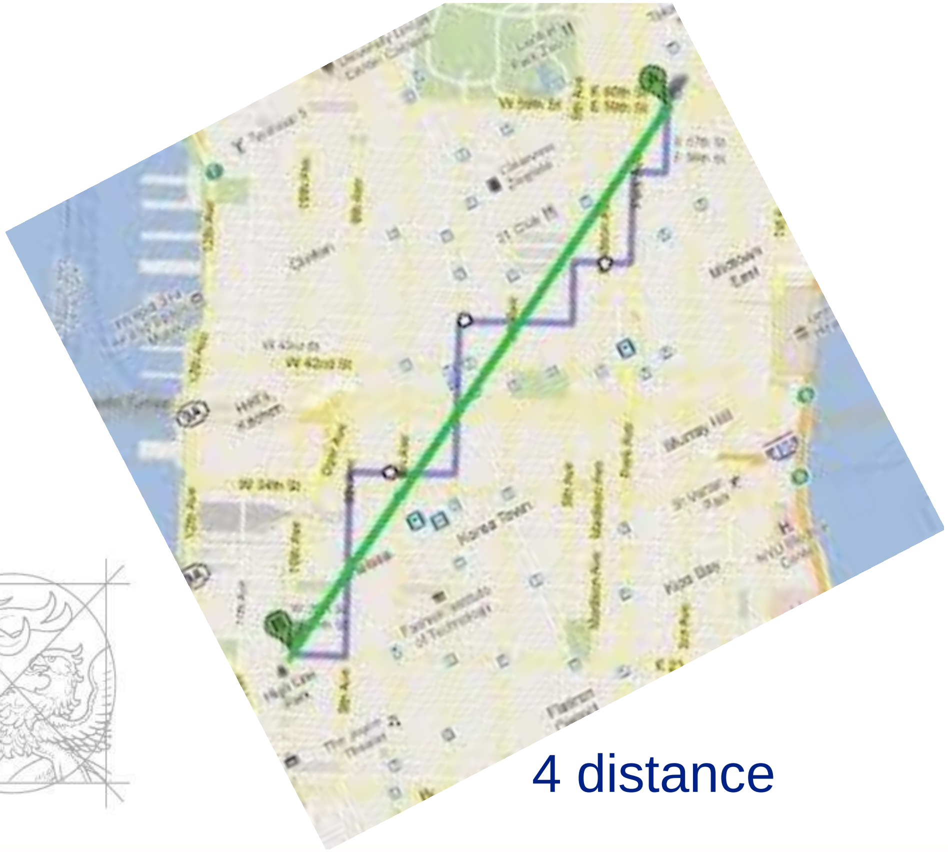
Distance map

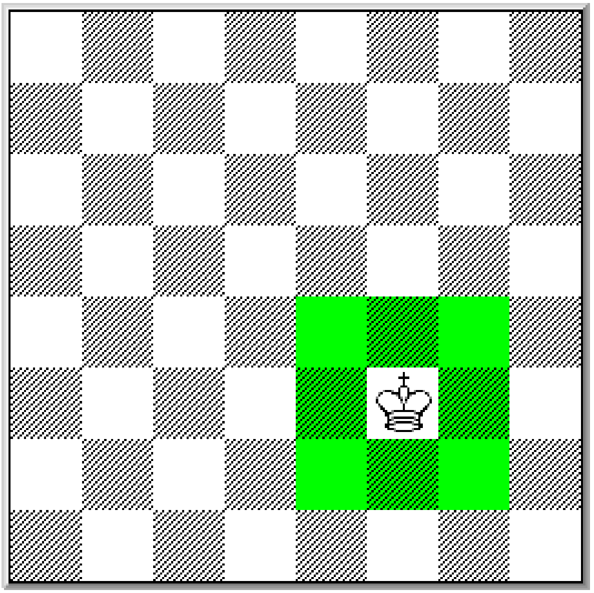


Distance map

discrete distances derived from adjacency relations



4 distance



8 distance

Distance map

4	3	2	1	2	3	4
3	2	1	0	1	2	3
2	1	0	1	0	1	2
2	1	0	1	1	0	1
1	0	1	2	2	1	0
1	0	1	2	3	2	1
0	1	2	3	4	3	2

	1	
1	0	1
	1	

DT using Manhattan, city-block, or 4 distance

Distance map

2	2	1	1	1	2	2
2	1	1	0	1	1	2
2	1	0	1	0	1	1
1	1	0	1	1	0	1
1	0	1	1	1	1	0
1	0	1	2	2	1	1
0	1	1	2	2	2	2

1	1	1
1	0	1
1	1	1

DT using chess-board or 8 distance

Distance map

4	3	2	3	2	3	2	3	4
3	2	3	2	3	2	3	2	3
2	3	4	1	2	1	4	3	2
3	2	1	2	3	2	1	2	3
2	3	2	3	0	3	2	3	2
3	2	1	2	3	2	1	2	3
2	3	4	1	2	1	4	3	2
3	2	3	2	3	2	3	2	3
4	3	2	3	2	3	2	3	4

DT using
knight distance

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Distance map

4	3	2	3	2	3	2	3	4
3	2	3	2	3	2	3	2	3
2	3	4	1	2	1	4	3	2
3	2	1	2	3	2	1	2	3
2	3	2	3	0	3	2	3	2
3	2	1	2	3	2	1	2	3
2	3	4	1	2	1	4	3	2
3	2	3	2	3	2	3	2	3
4	3	2	3	2	3	2	3	4

knight disk with radius 2

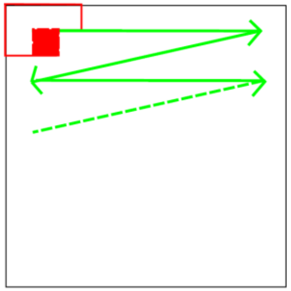
Linear time distance mapping

Input:
Binary array A=[**`a(i,j)`**] of size **`n1`**x**`n2`** containing feature elements (1's) and non-feature elements (0's)

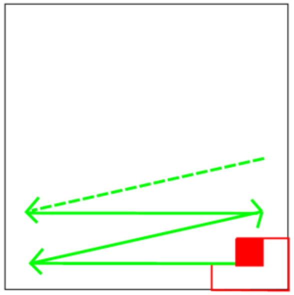
Output:
Distance map B =[**`b(i,j)`**] is a non-binary array containing the distance to the closest feature element

G. Borgefors (1984)

```
remark initialization
 for i=1 to n1 do
  for j=1 to n2 do
   if a(i,j)=1 then b(i,j)=0
   else             b(i,j)=∞
remark forward scan
 for i=1 to n1 do
  for j=1 to n2 do
   b(i,j)=min{
              b(i-1,j-1)+d2,
              b(i-1,j  )+d1,
              b(i-1,j+1)+d2,
              b(i  ,j-1)+d1,
              b(i  ,j  )
             }
```

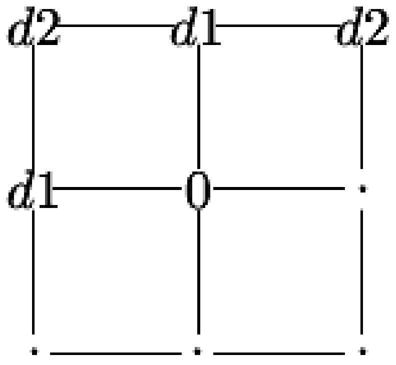


```
remark backward scan
 for i=n1 downto 1 do
  for j=n2 downto 1 do
   b(i,j)=min{
              b(i  ,j  )   ,
              b(i  ,j+1)+d1,
              b(i+1,j-1)+d2,
              b(i+1,j  )+d1,
              b(i+1,j+1)+d2
             }
```

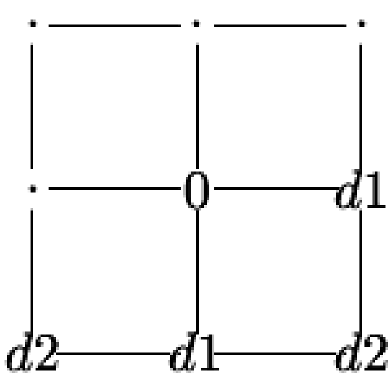


Linear time distance mapping

chamfer masks



forward scan



backward scan

best choice: $d1$=3, $d2$=4

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Linear time distance mapping

0	0	0	0
0	0	1	0
0	0	0	0
0	0	0	0
0	1	0	0
0	0	0	0

input (feature)

.	.	.	.
.	.	0	.
.	.	.	.
.	.	.	.
.	0	.	.
.	.	.	.

initialization („·” $\rightarrow \infty$)

Linear time distance mapping

·	·	·	·
·	·	0	·
·	·	·	·
·	·	·	·
·	0	·	·
·	·	·	·

initialization („·” → ∞)

·	·	·	·
·	·	0	3
·	4	3	4
8	7	6	7
11	0	3	6
4	3	4	7

forward scan

Linear time distance mapping

.	.	.	.
.	.	0	3
.	4	3	4
8	7	6	7
11	0	3	6
4	3	4	7

forward scan

7	4	3	4
6	3	0	3
7	4	3	4
4	3	4	7
3	0	3	6
4	3	4	7

backward scan

Linear time distance mapping

0	0	0	0
0	0	1	0
0	0	0	0
0	0	0	0
0	1	0	0
0	0	0	0

input (feature)

7	4	3	4
6	3	0	3
7	4	3	4
4	3	4	7
3	0	3	6
4	3	4	7

distance map

Distance-based skeletonization

1. Calculate the distance map from the background
   (i.e., zeroes in the input binary image form the set of feature points)
2. Detect ridges (i.e., local maxima)

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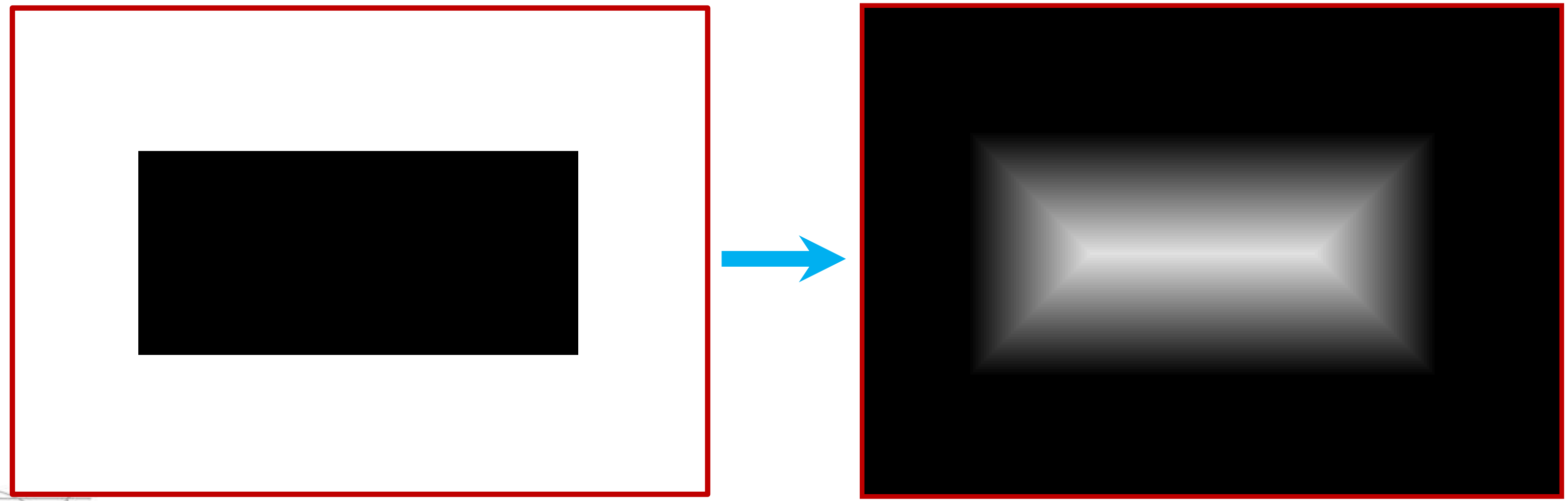
Distance-based skeletonization



original binary image

distance map

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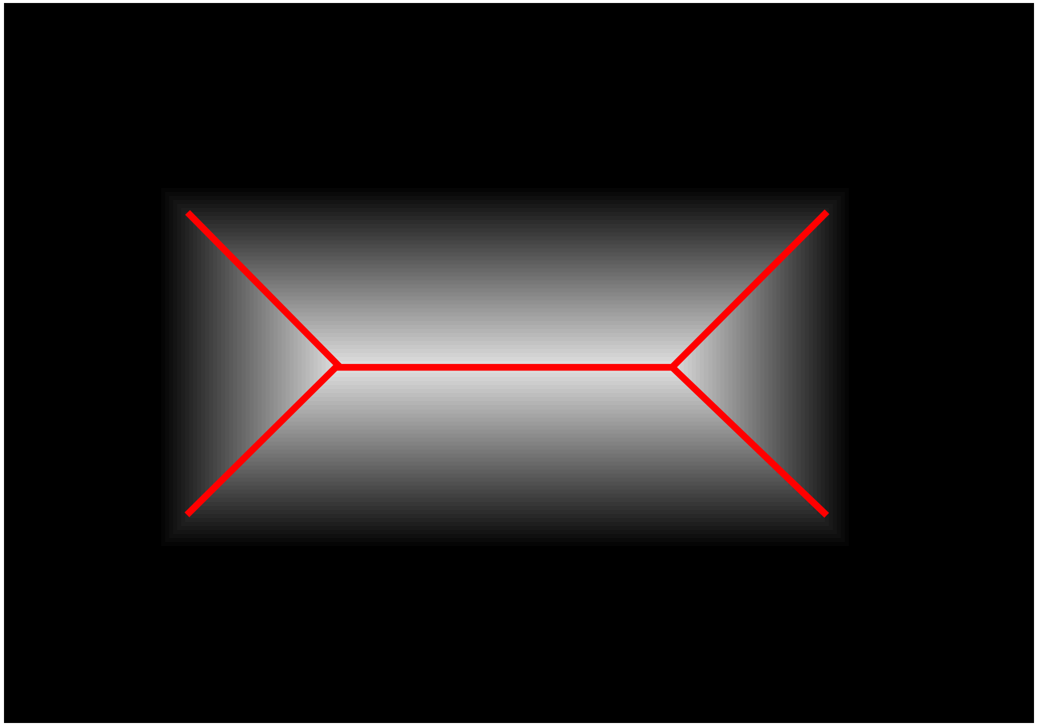
Distance-based skeletonization



detected ridges

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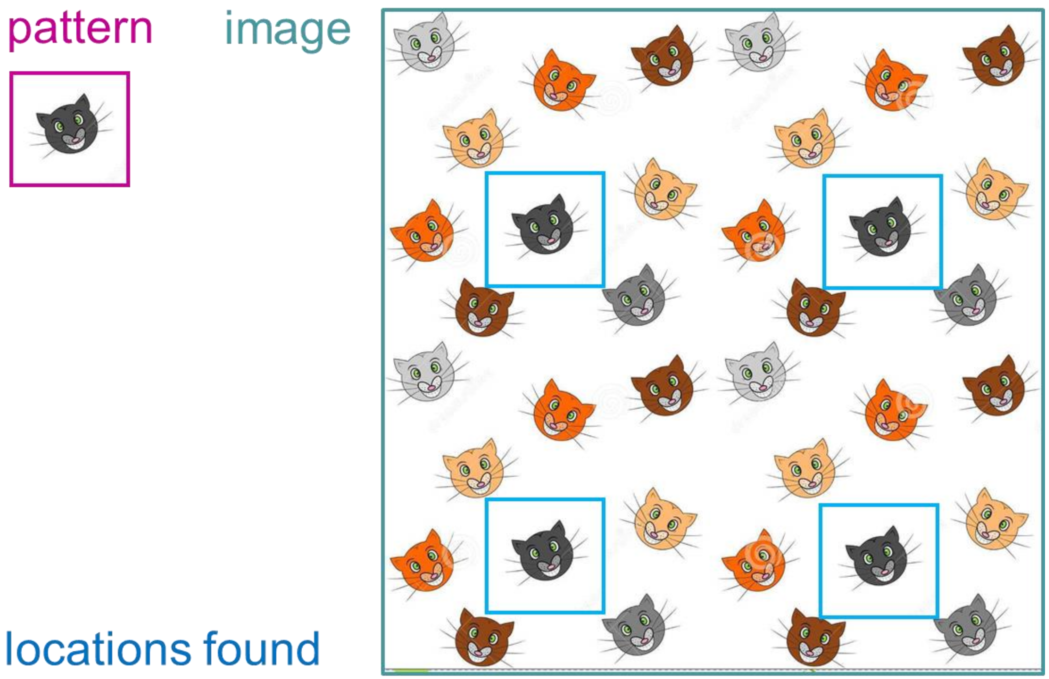
DT-based applications

- chamfer matching
- watershed segmentation
- wall thickness measurement

Chamfer matching

Matching is a basic approach to segmentation that can be used to locate known objects in an image.



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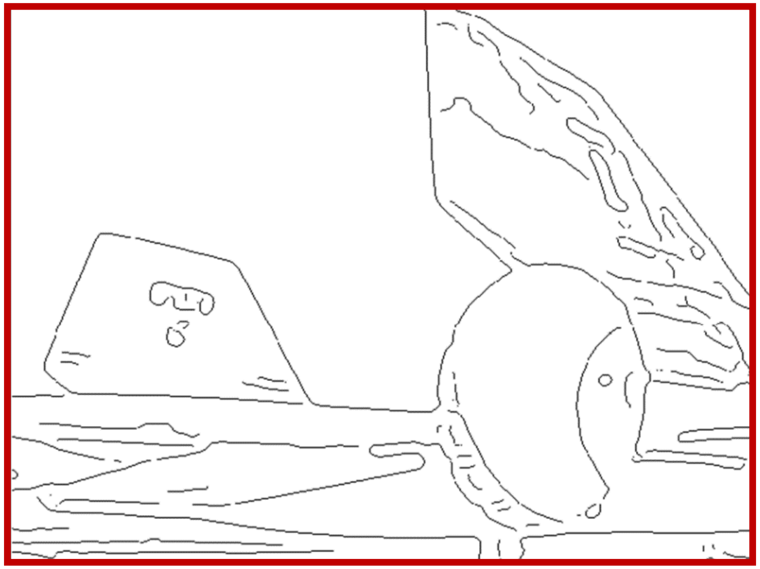
Chamfer matching

edges: pixels where brightness changes abruptly

original image



binary edge map

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Chamfer matching

1. perform edge detection
2. generate a distance map from edges (as feature pixels)
3. match the pattern (given by a contour), where the matching criterion: sum of elements in the distance map covered by the pattern.

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Chamfer matching

0	0	0	0	0	0	0	0
0	0	0	0	1	1	1	0
0	0	0	0	1	0	1	0
0	0	0	0	1	0	1	0
0	0	0	0	1	1	1	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

binary edge map

5	4	3	2	1	1	1	2
4	3	2	1	0	0	0	1
4	3	2	1	0	1	0	1
4	3	2	1	0	1	0	1
4	3	2	1	0	0	0	1
5	4	3	2	1	1	1	2
6	5	4	3	2	2	2	3
7	6	5	4	3	3	3	4

distance map

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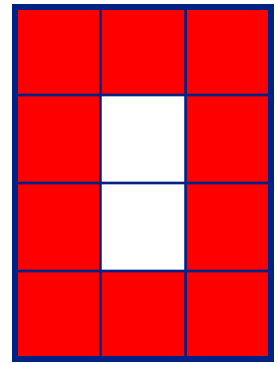
Chamfer matching

5	4	3	2	1	1	1	2
4	3	2	1	0	0	0	1
4	3	2	1	0	1	0	1
4	3	2	1	0	1	0	1
4	3	2	1	0	0	0	1
5	4	3	2	1	1	1	2
6	5	4	3	2	2	2	3
7	6	5	4	3	3	3	4

distance map



pattern

matching criterion:
sum of elements covered
by the pattern

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Chamfer matching

5	4	3	2	1	1	1	2
4	3	2	1	0	0	0	1
4	3	2	1	0	1	0	1
4	3	2	1	0	1	0	1
4	3	2	1	0	0	0	1
5	4	3	2	1	1	1	2
6	5	4	3	2	2	2	3
7	6	5	4	3	3	3	4

measure: 45

5	4	3	2	1	1	1	2
4	3	2	1	0	0	0	1
4	3	2	1	0	1	0	1
4	3	2	1	0	1	0	1
4	3	2	1	0	0	0	1
5	4	3	2	1	1	1	2
6	5	4	3	2	2	2	3
7	6	5	4	3	3	3	4

measure: 13

Chamfer matching

5	4	3	2	1	1	1	2
4	3	2	1	0	0	0	1
4	3	2	1	0	1	0	1
4	3	2	1	0	1	0	1
4	3	2	1	0	0	0	1
5	4	3	2	1	1	1	2
6	5	4	3	2	2	2	3
7	6	5	4	3	3	3	4

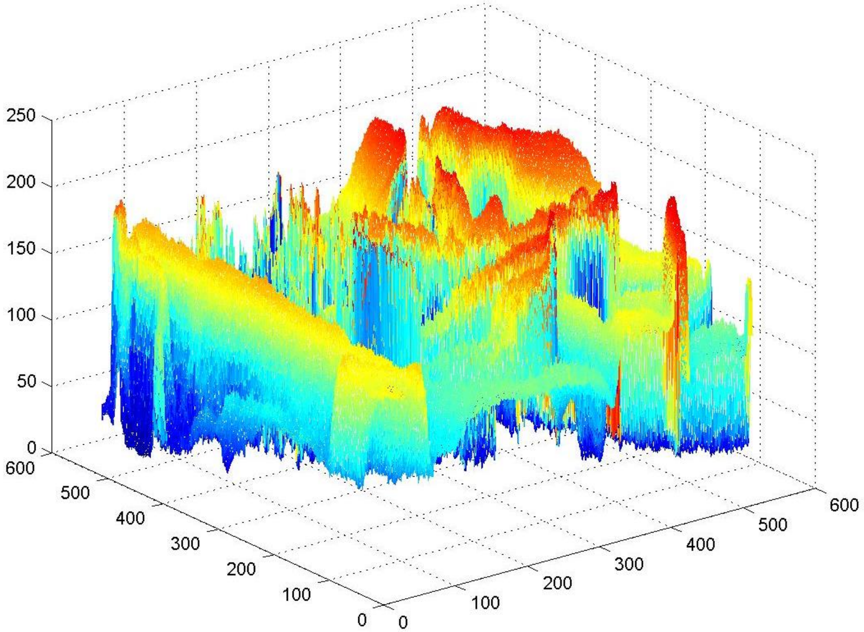
measure: 6

5	4	3	2	1	1	1	2
4	3	2	1	0	0	0	1
4	3	2	1	0	1	0	1
4	3	2	1	0	1	0	1
4	3	2	1	0	0	0	1
5	4	3	2	1	1	1	2
6	5	4	3	2	2	2	3
7	6	5	4	3	3	3	4

measure: 0

Watershed segmentation

gray-scale image



relief
(topographic representation)

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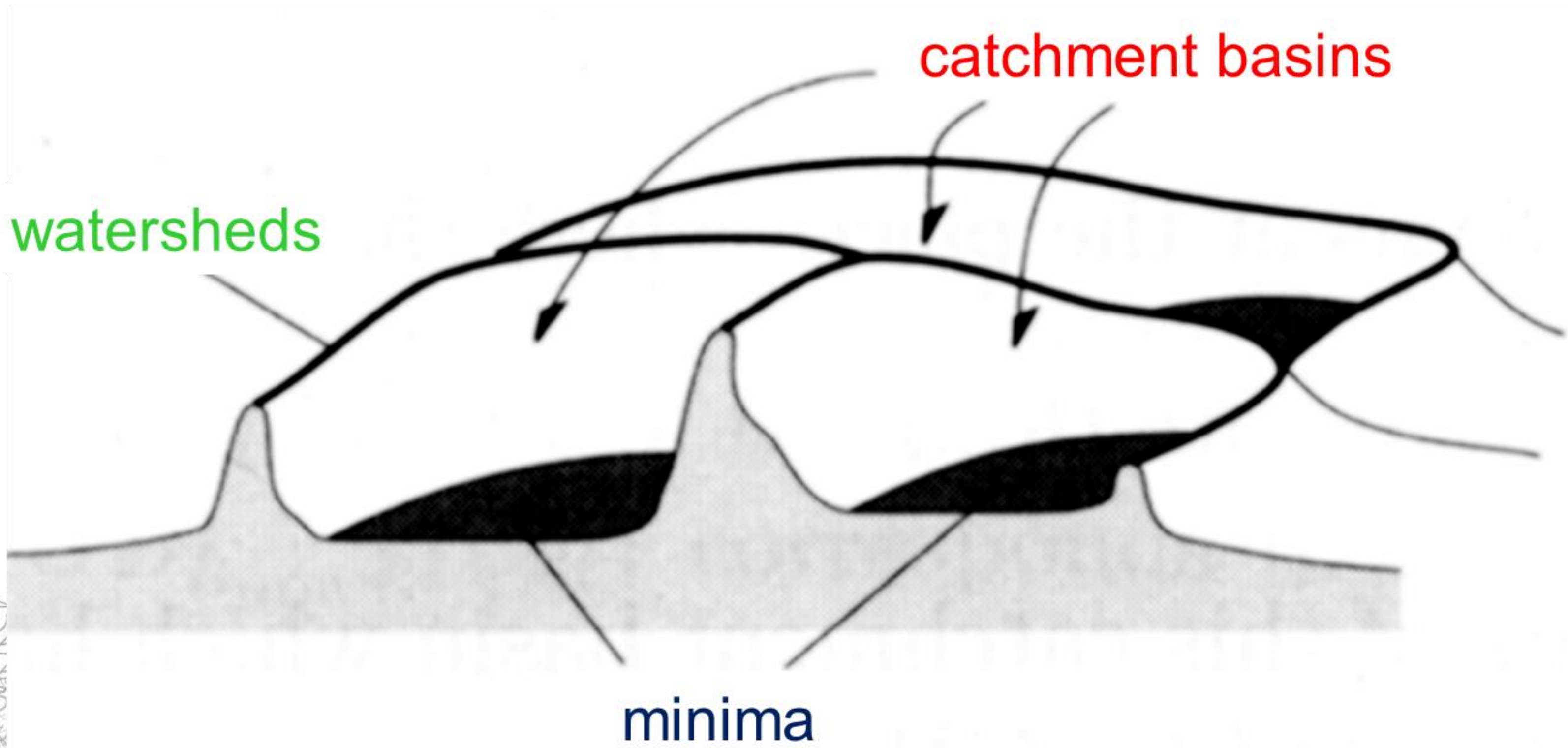
Watershed segmentation



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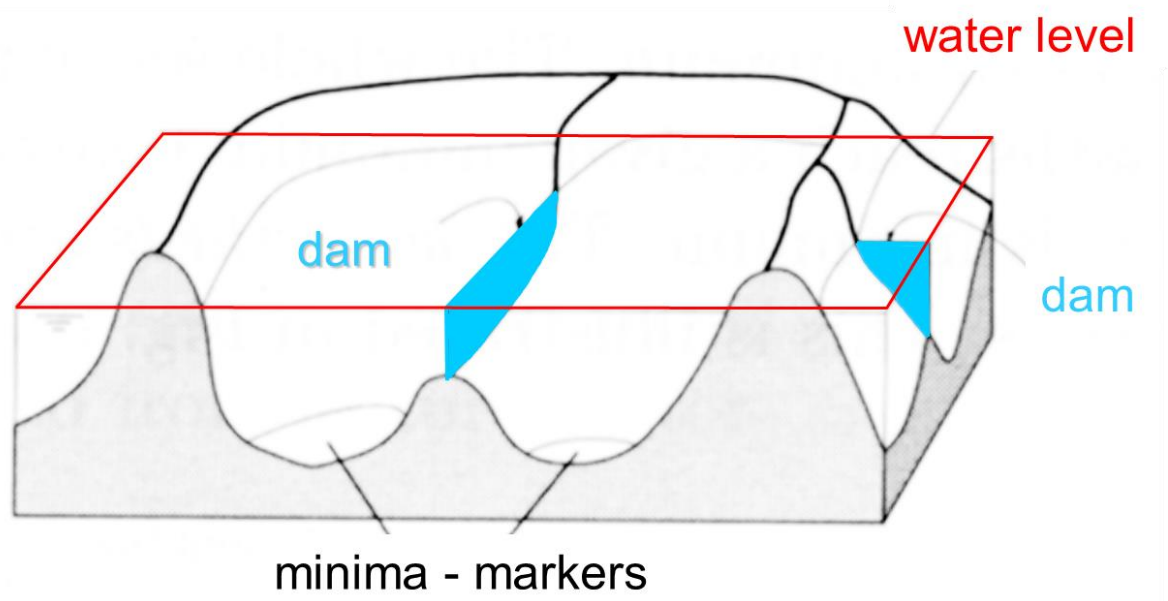
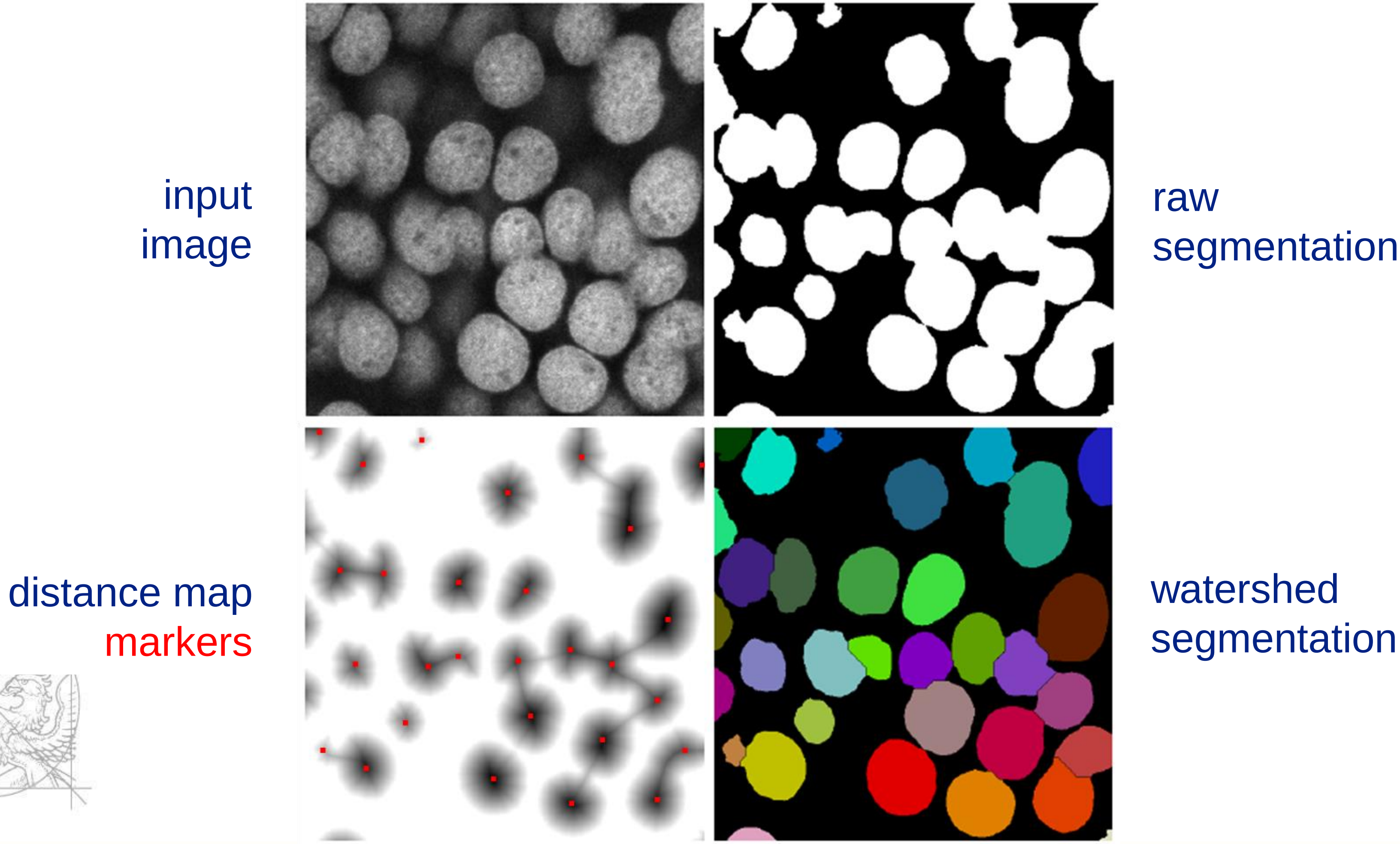
Watershed segmentation

flooding simulation



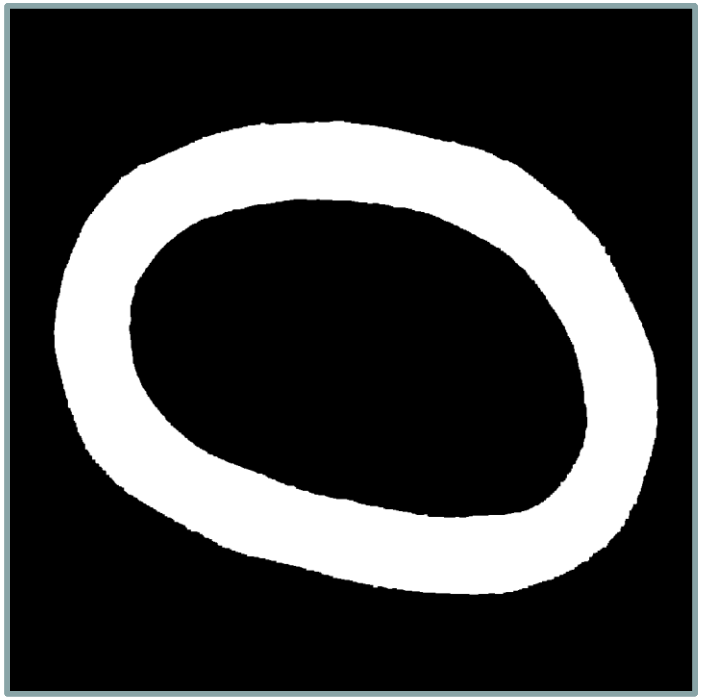
Starting from the minima the water will progressively flood the catchment basins. Dams are raised at the places where the waters coming from two different minima would merge. The whole set of dams corresponds to the watersheds.

Watershed segmentation



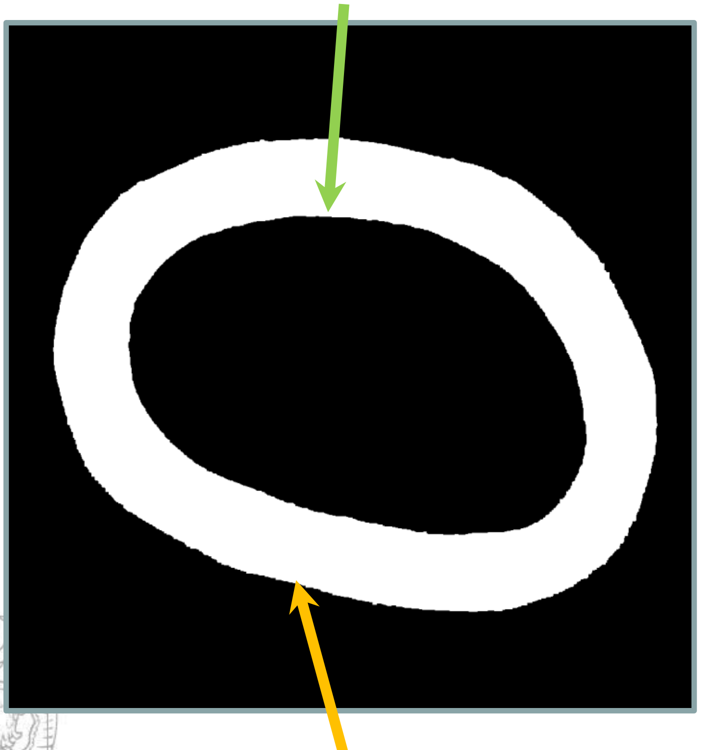
Wall thickness measurement

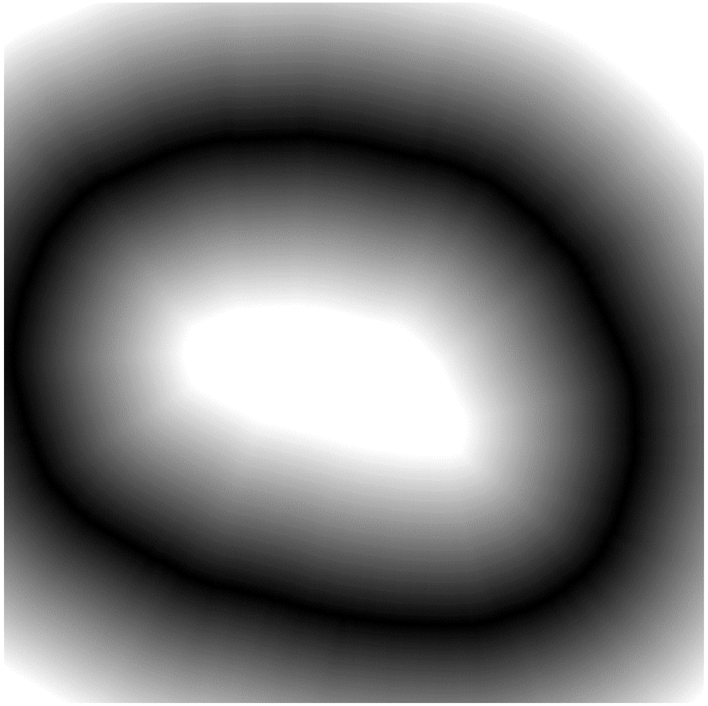
raw image
(end of a rubber tube)



segmented tube end

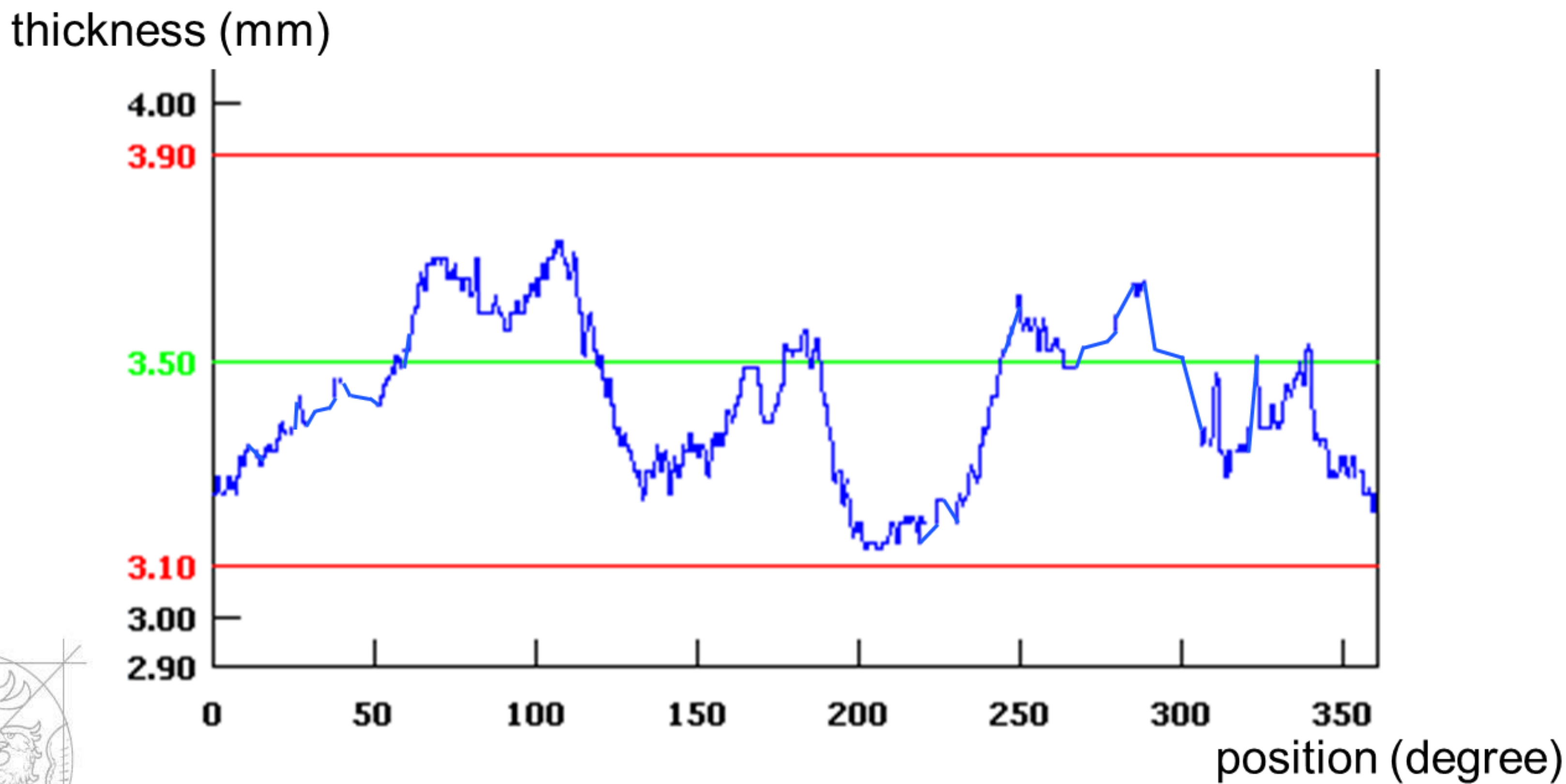
Wall thickness measurement





distance map from the outer contour

Wall thickness measurement



elements of the distance map at the points of the inner contour

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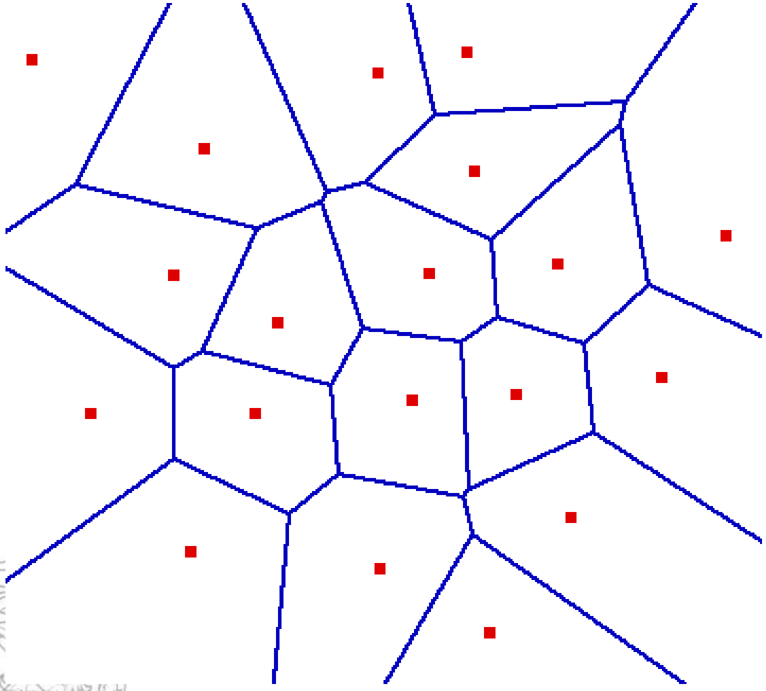
Syllabus

- shapes
- shape representation
- continuous skeleton
- skeleton-like shape features
- skeletonization techniques
  - distance-based
  - Voronoi-based
  - thinning
- applications of skeletonization

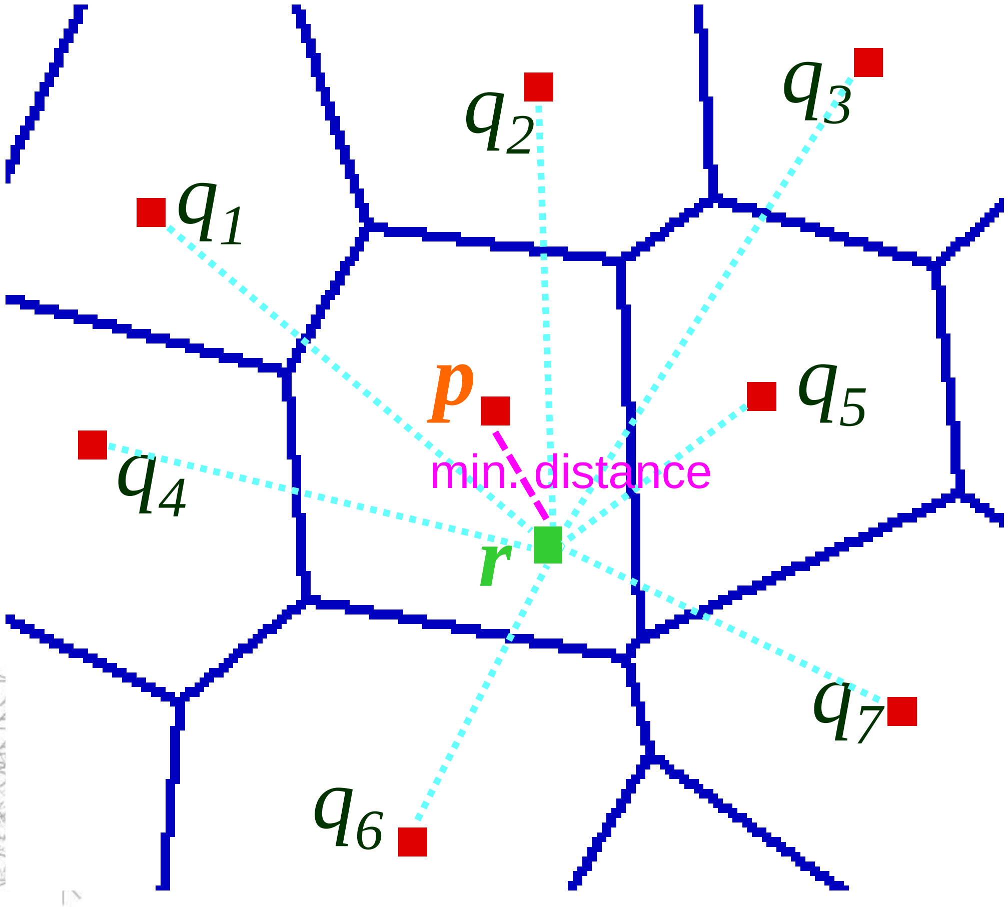
Voronoi diagram



Input:
Set of points (generating points)

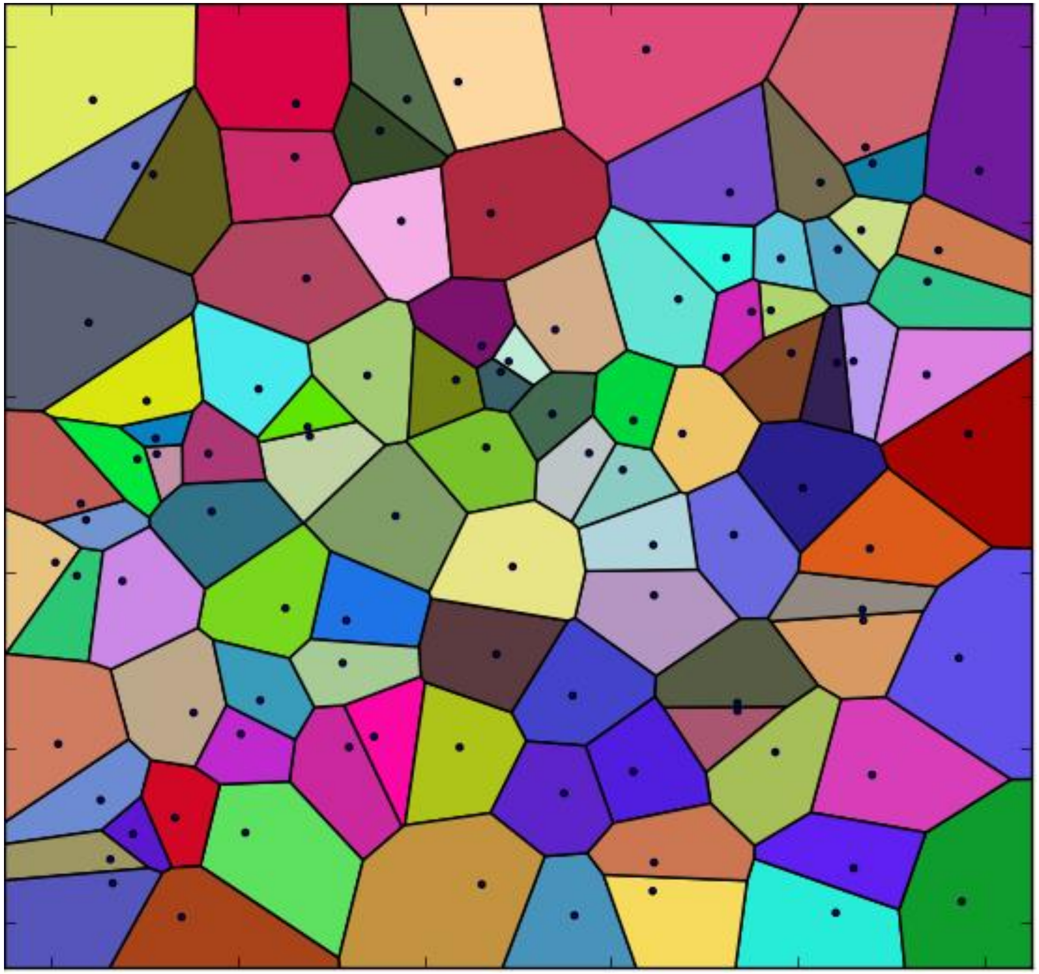
Output:
the partition of the space into cells so that each cell contains exactly one generating point and the locus of all points which are closer to this generating point than to others.

Voronoi diagram



$$d(r,p) \le d(r,q_i)$$
$$(i = 1,2,\ldots)$$

Voronoi diagram



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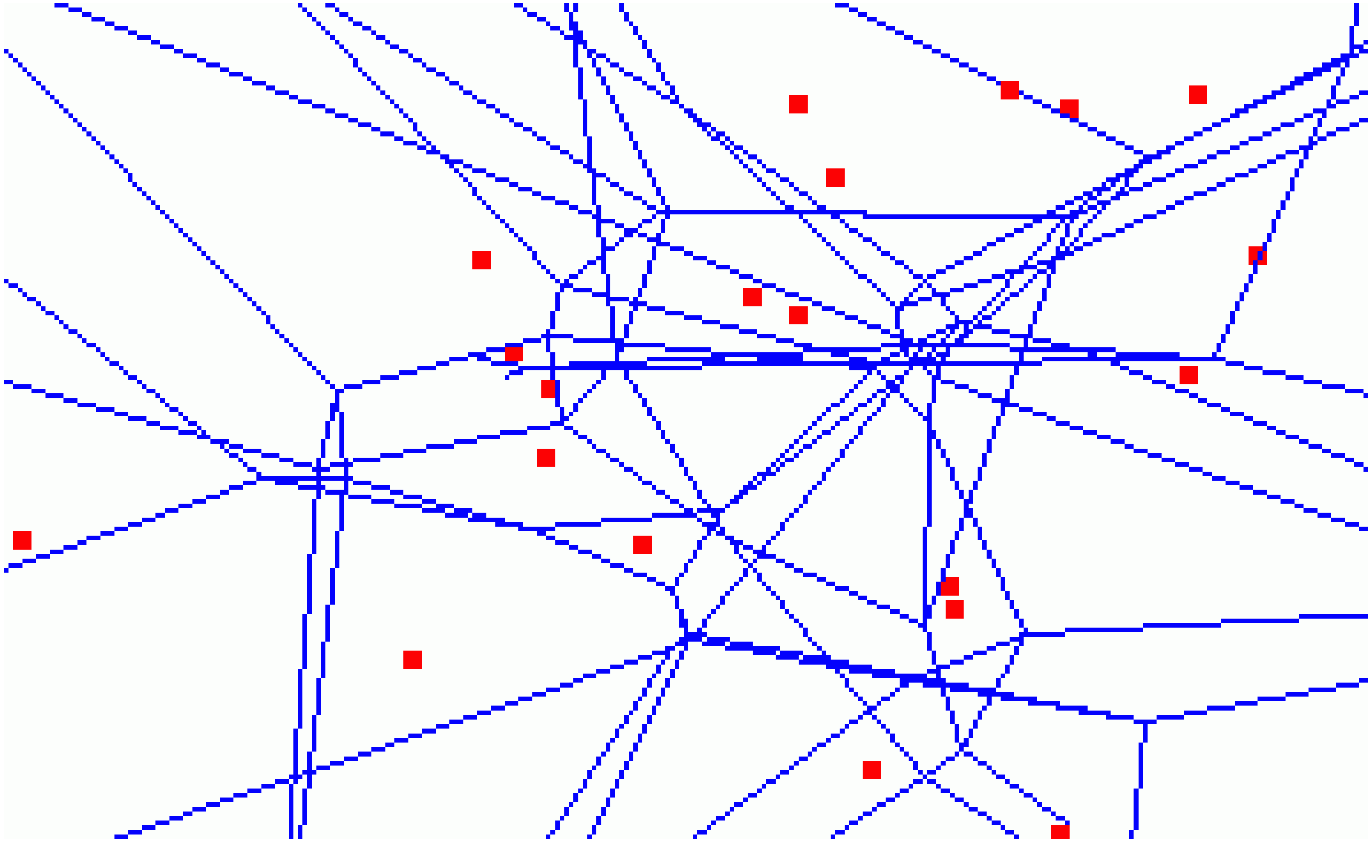
Voronoi diagram



3D Voronoi diagram of 20 generating points

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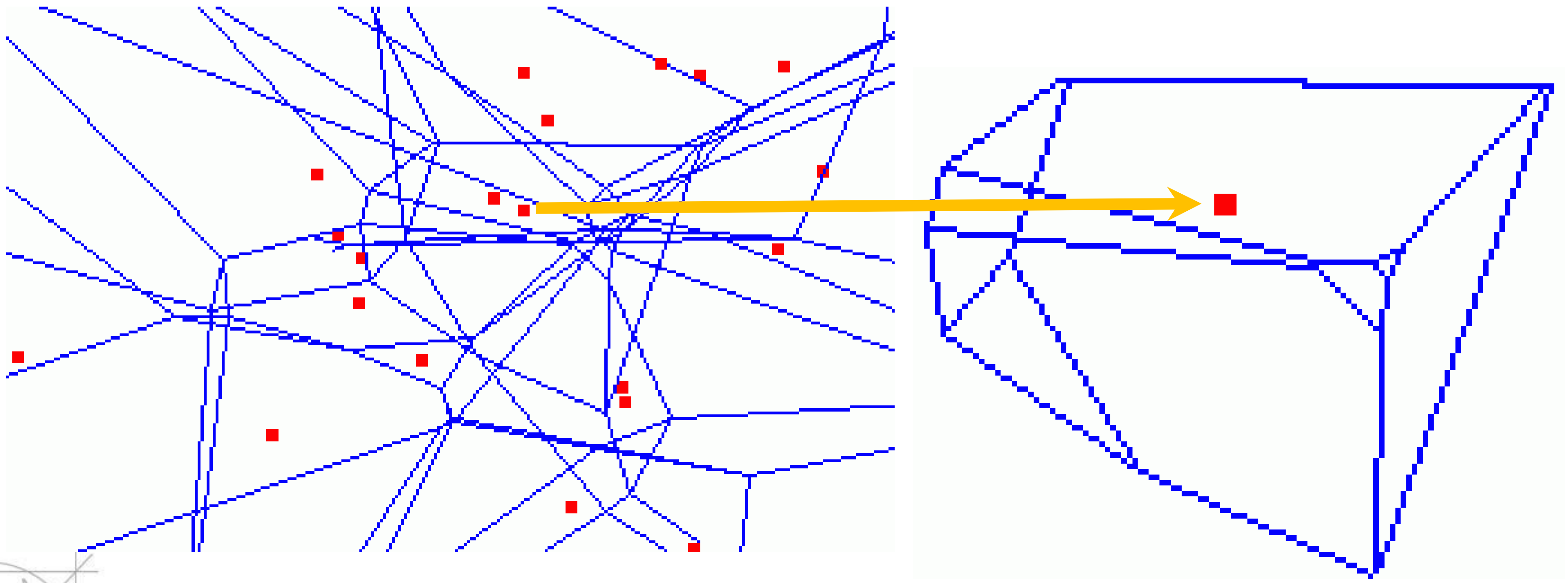
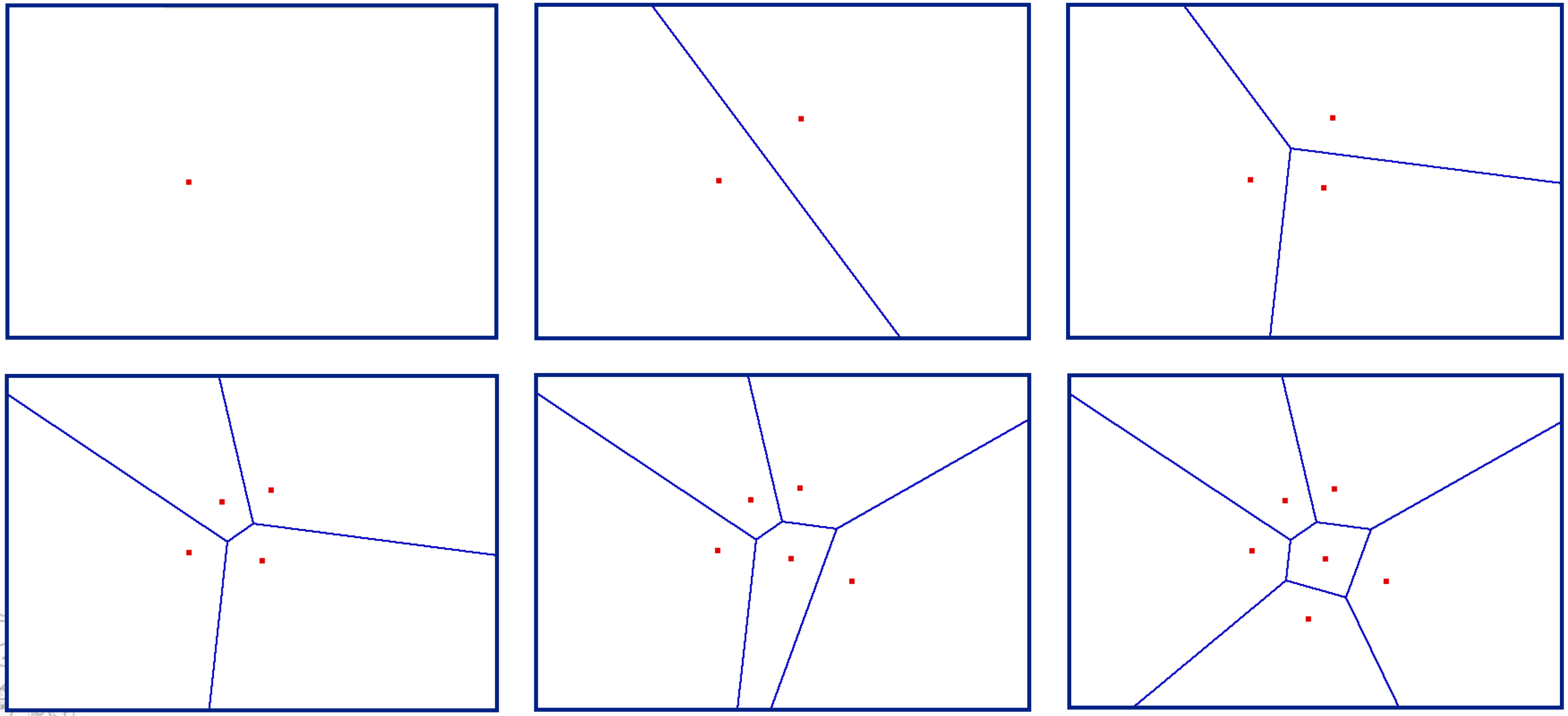
Voronoi diagram



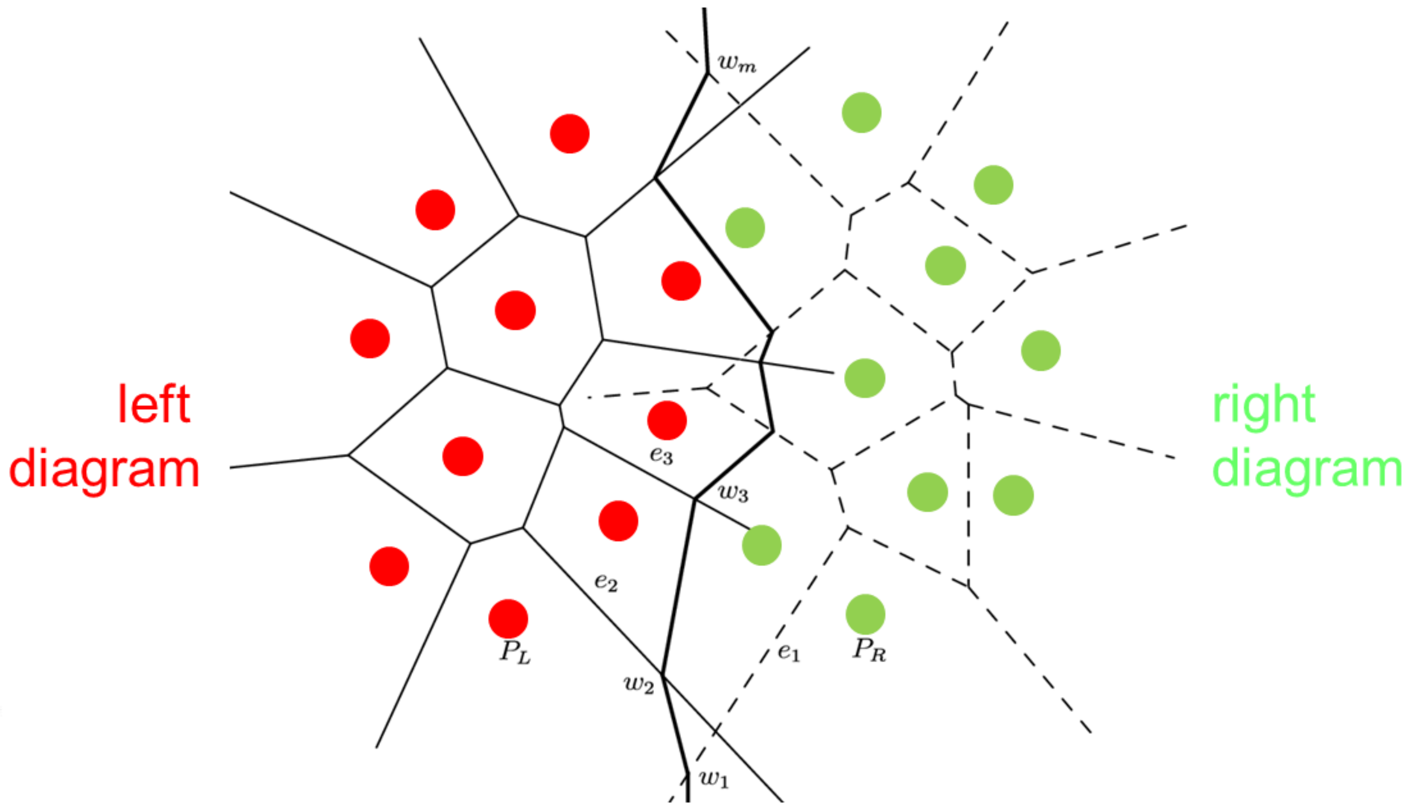
a cell (convex polyhedron) of a 3D Voronoi diagram

Voronoi diagram



incremental construction $O(n)$

Voronoi diagram



merging

divide and conquer $O(n \log n)$

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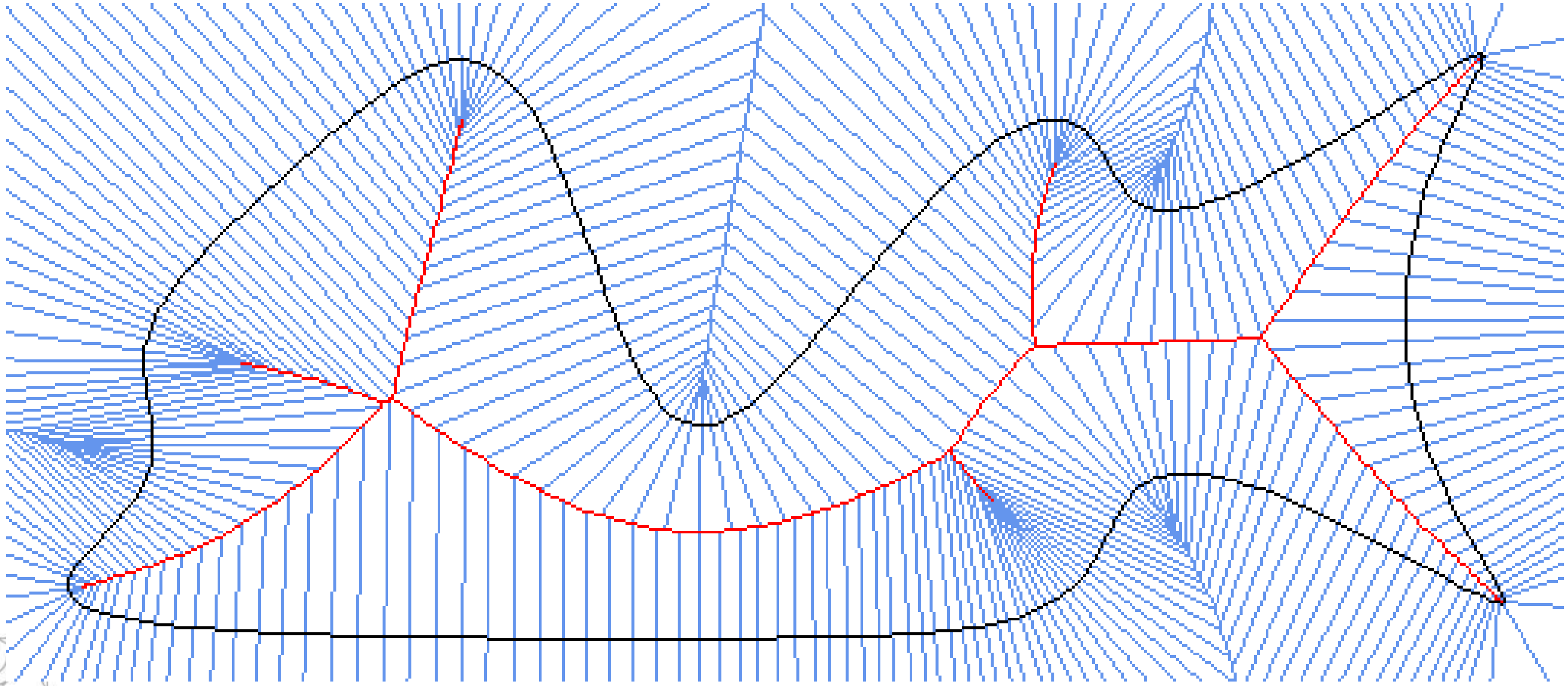
Voronoi diagram → skeleton



set of generating points = sampled boundary

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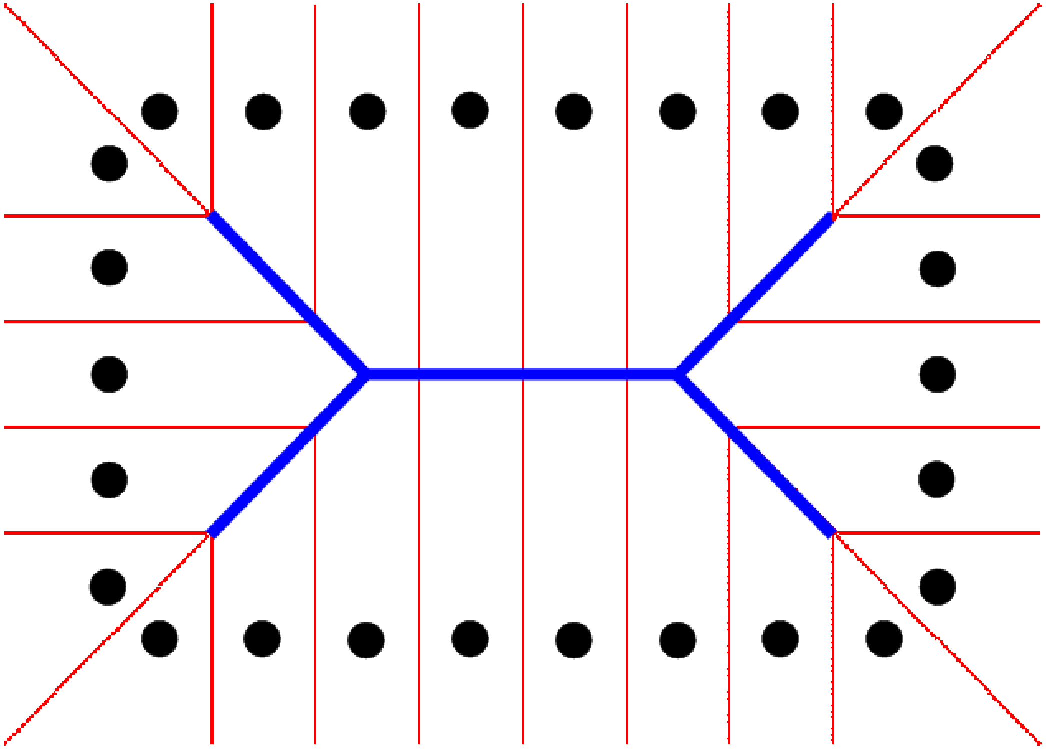
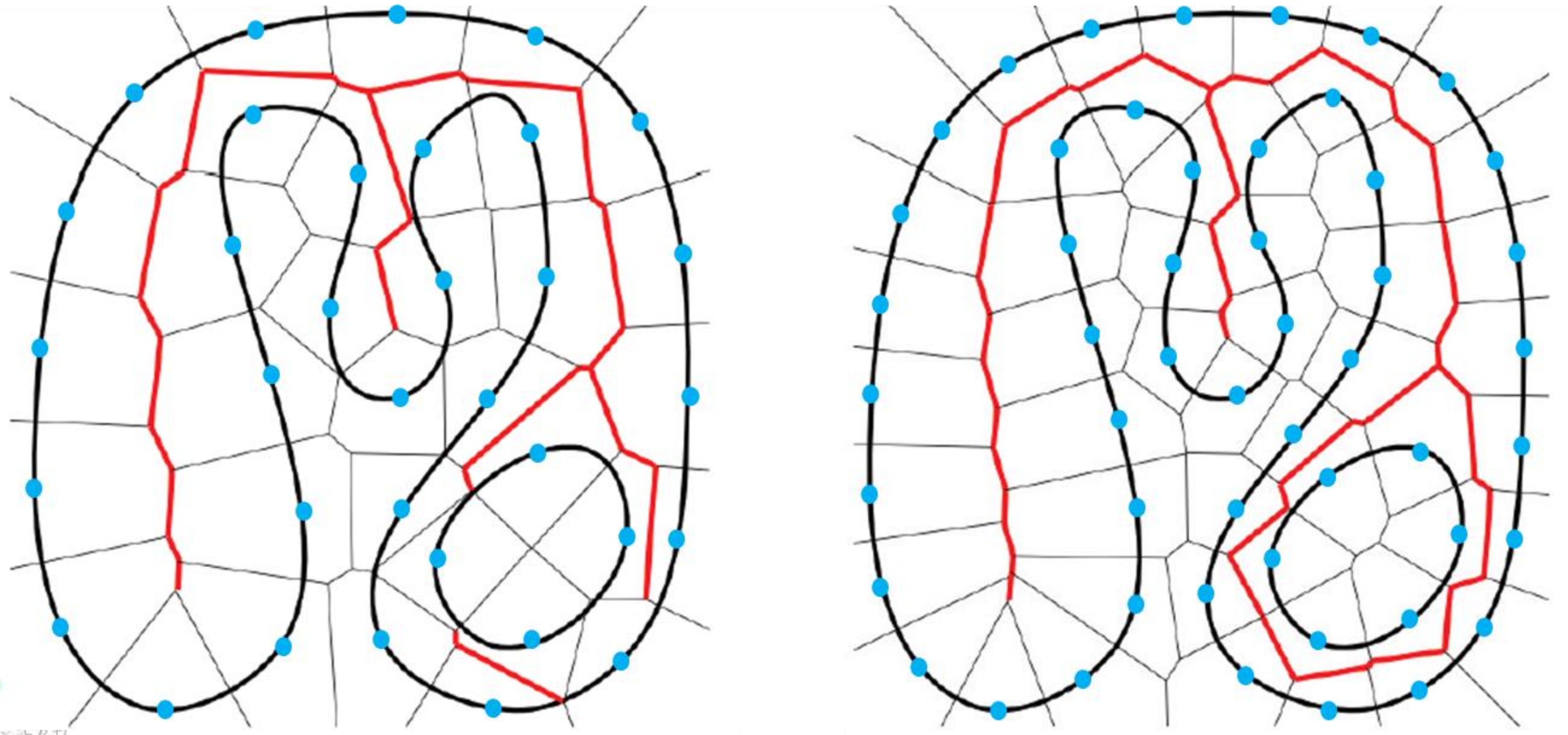
Voronoi diagram → skeleton



If the density of boundary points goes to infinity, then the corresponding Voronoi diagram converges to the skeleton.

Voronoi diagram → skeleton



Tagliasacchi et al., 2016

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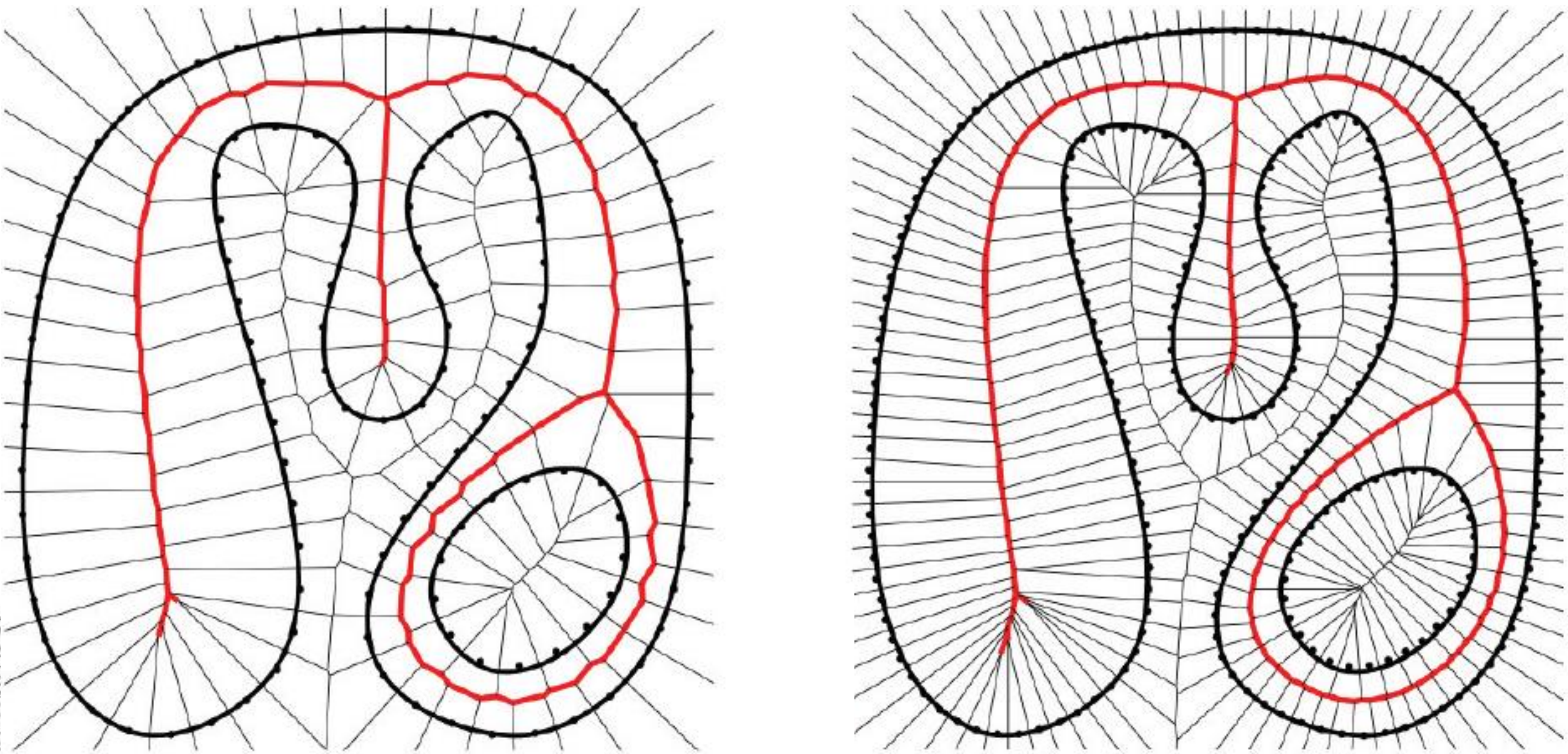
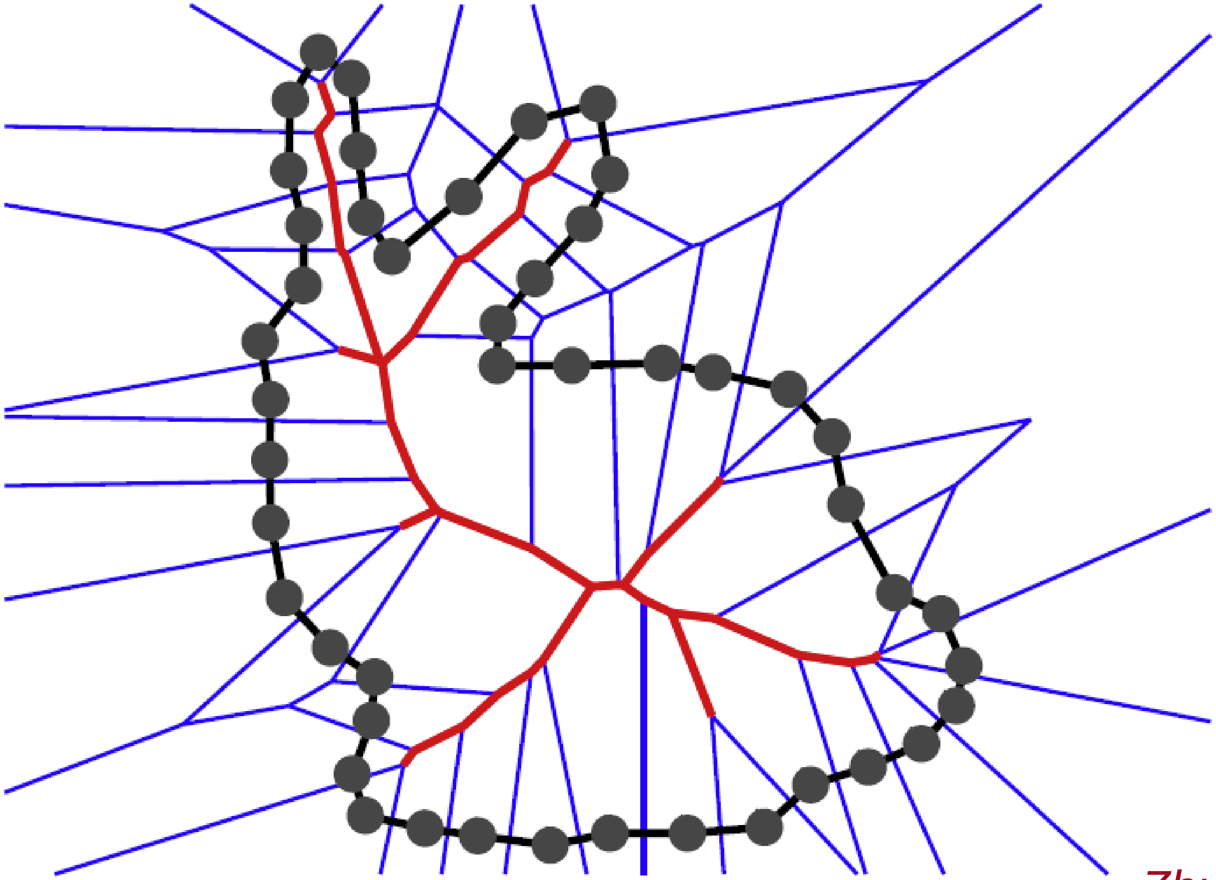
Voronoi diagram → skeleton



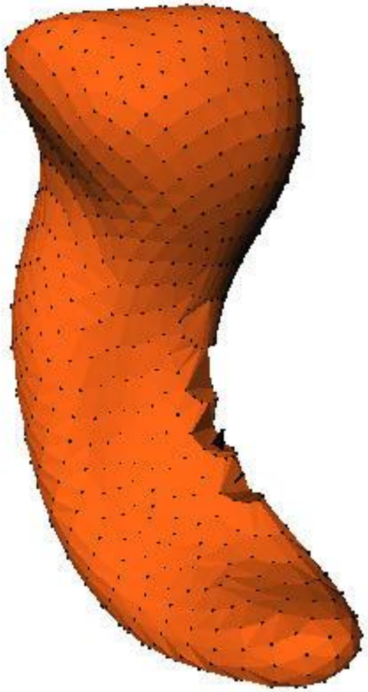
Tagliasacchi et al., 2016

Voronoi diagram → skeleton

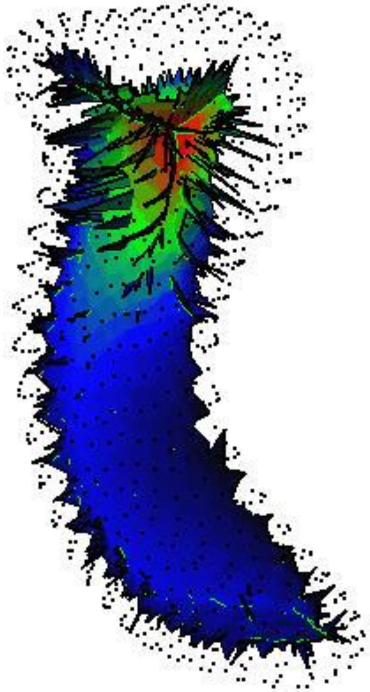


Zhu et al. (2014)

Voronoi skeleton



original 3D object



raw Voronoi skeleton

M. Styner (*UNC, Chapel Hill*)

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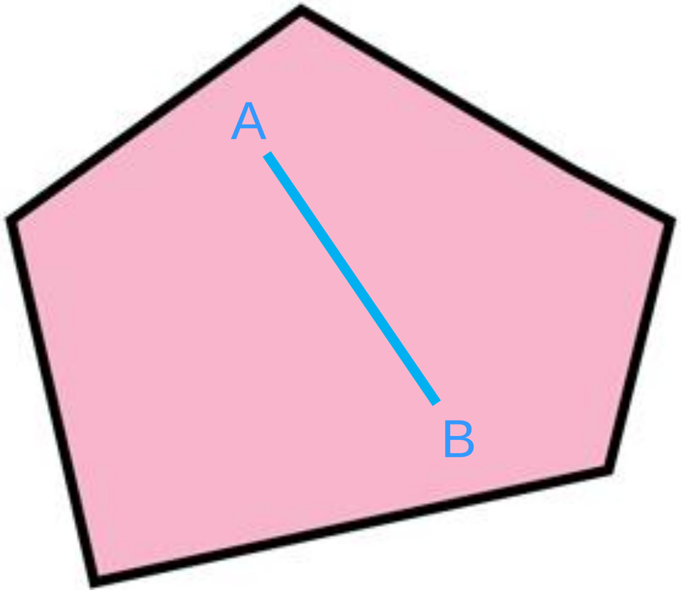
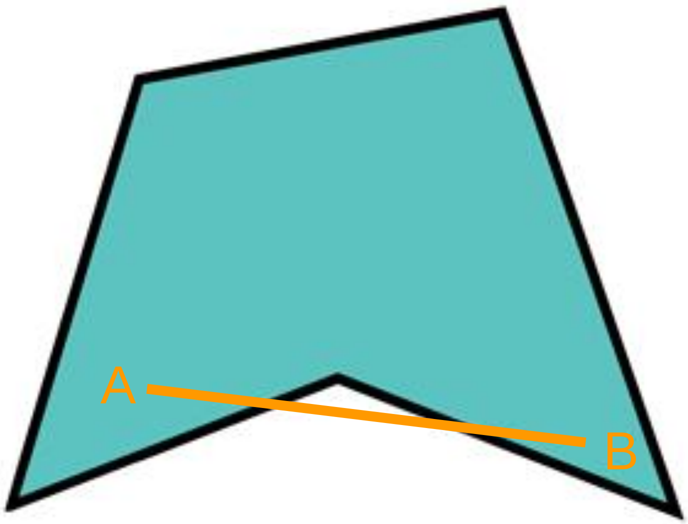
Applications of Voronoi diagrams

- network analysis
- computer graphics
- medical diagnostics
- astrophysics
- hydrology,
- robotics
- computational fluid dynamics

Convex vs. concave

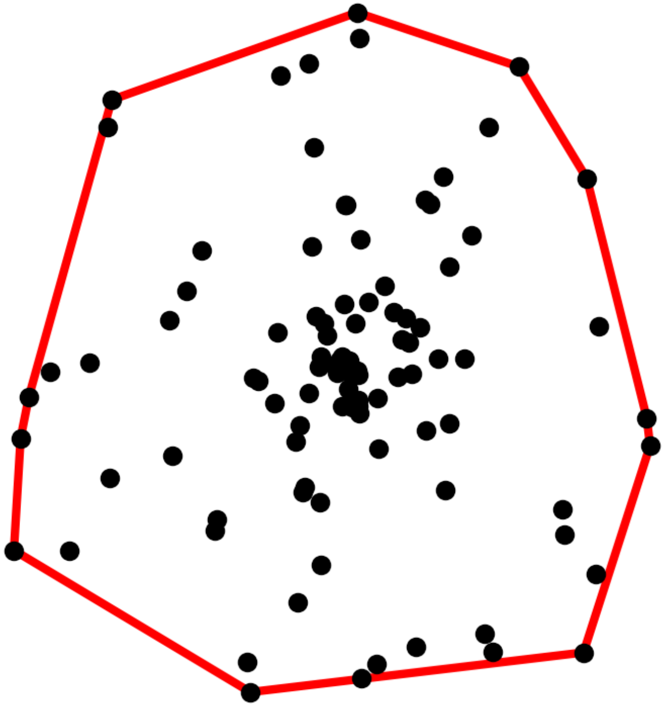


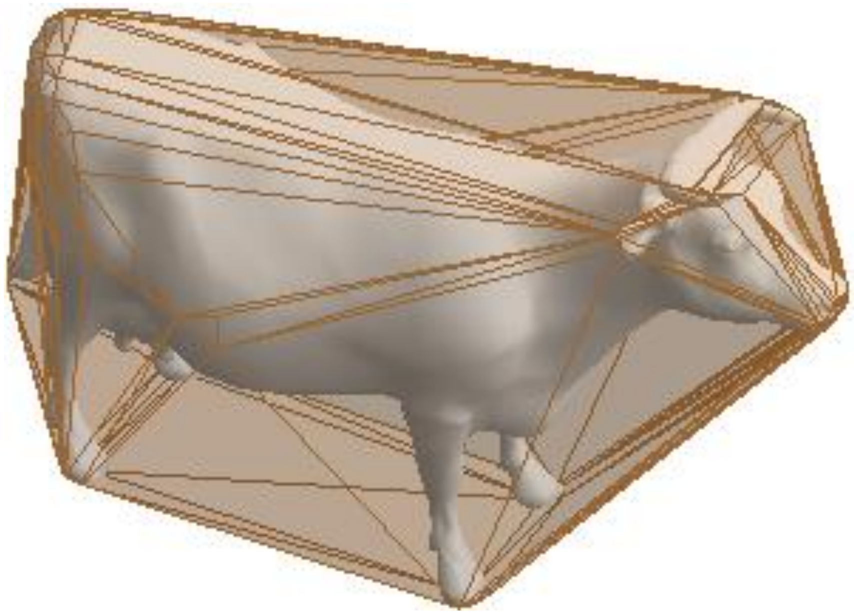
convex



concave

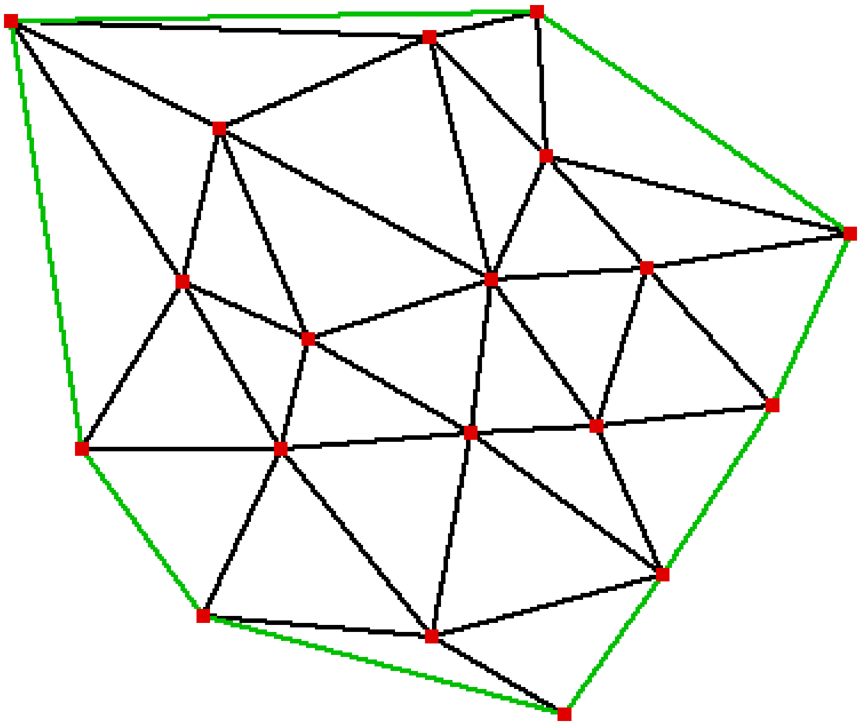
Convex hull





the smallest convex polygon/polyhedron, that encloses all input (generating) points.

Delaunay triangulation

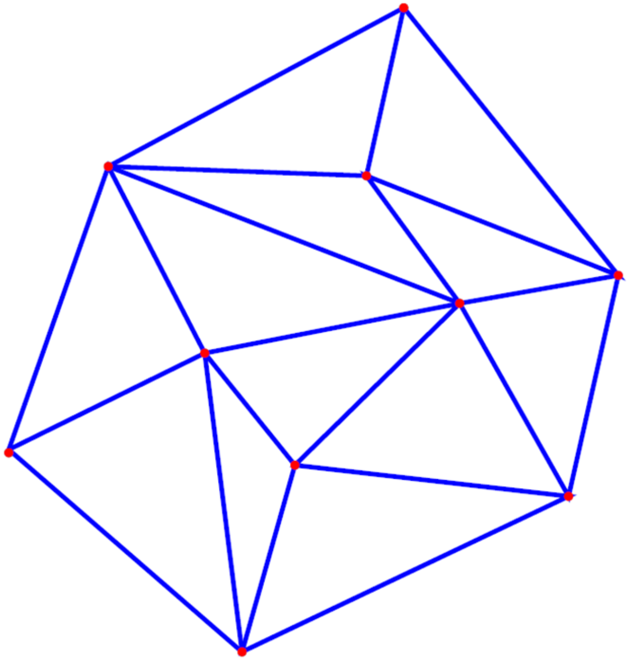


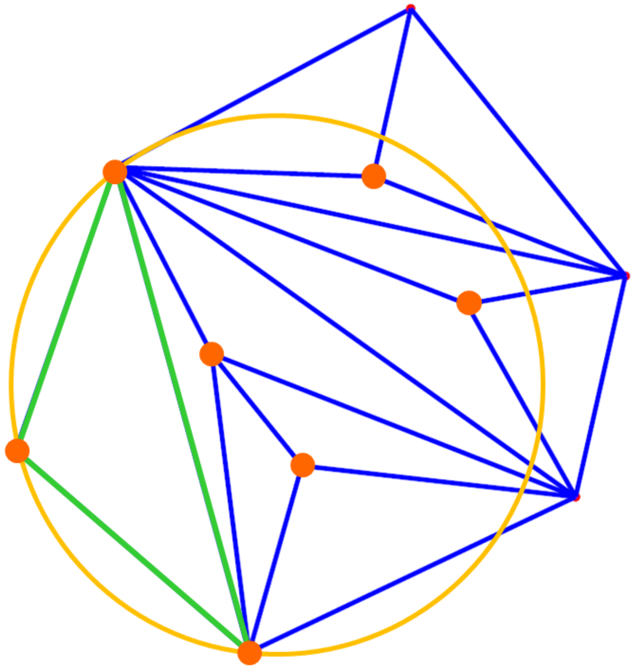
generating points

convex hull

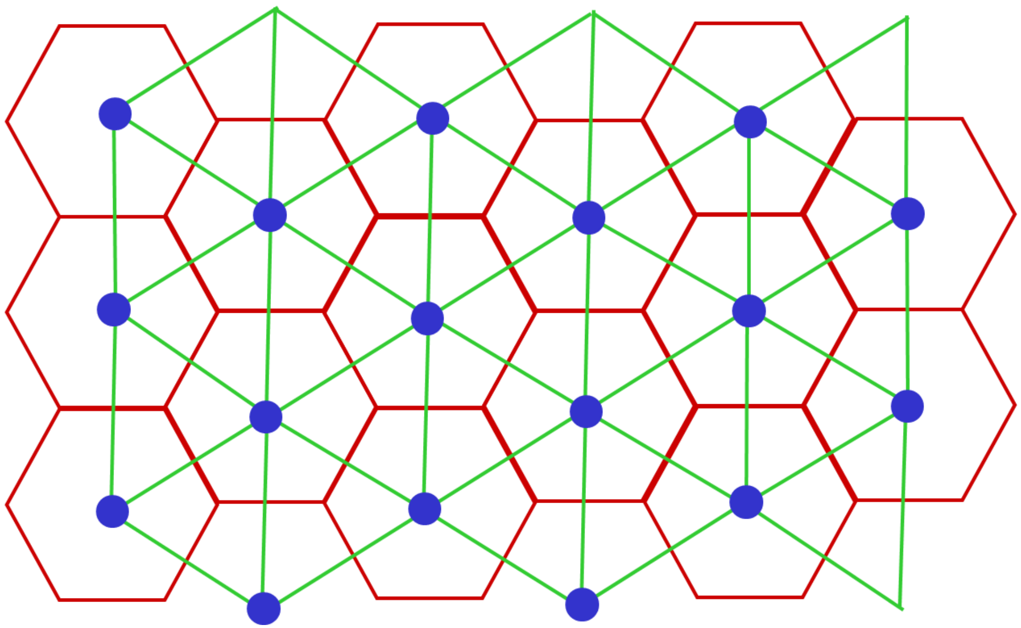
Rule: no generating point is inside the circumcircle of any triangle

Delaunay triangulation


correct


incorrect

Voronoi ↔ Delaunay



generating points
Voronoi diagram
Delaunay triangulation

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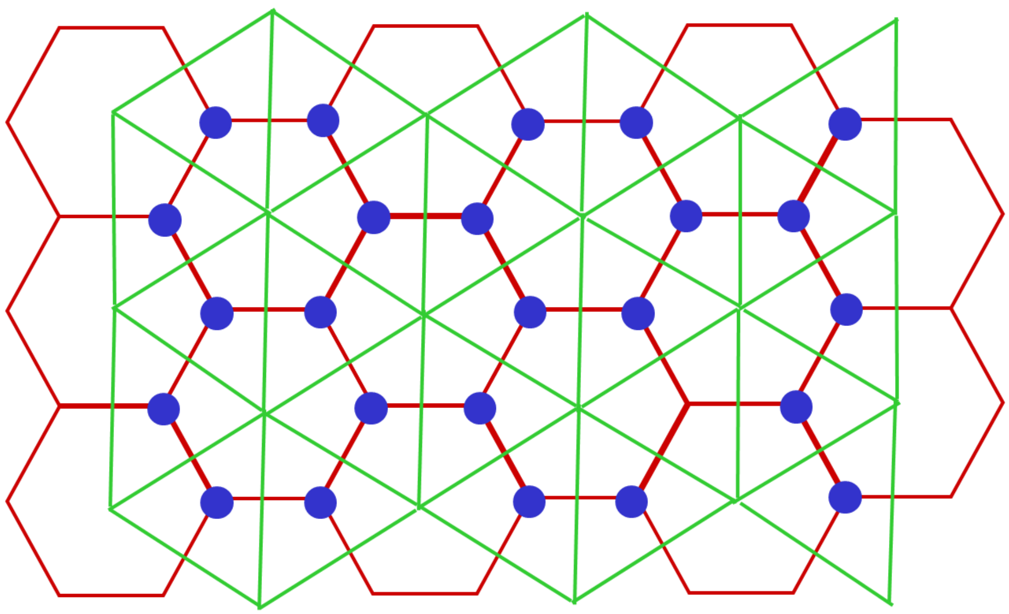
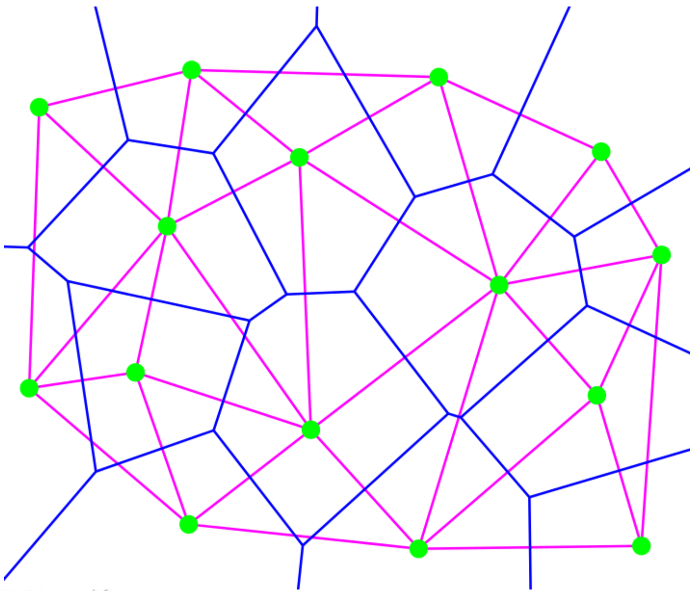
Voronoi ↔ Delaunay



generating points
Voronoi diagram
Delaunay **tessellation**

Voronoi ↔ Delaunay



Voronoi diagram		Delaunay triangulation
Voronoi cell (2D)	⟷	generating point (1D)
Voronoi edge (1D)	⟷	Delaunay edge (1D)
Voronoi vertex (0D)	⟷	Delaunay cell (2D)

one-to-one correspondence

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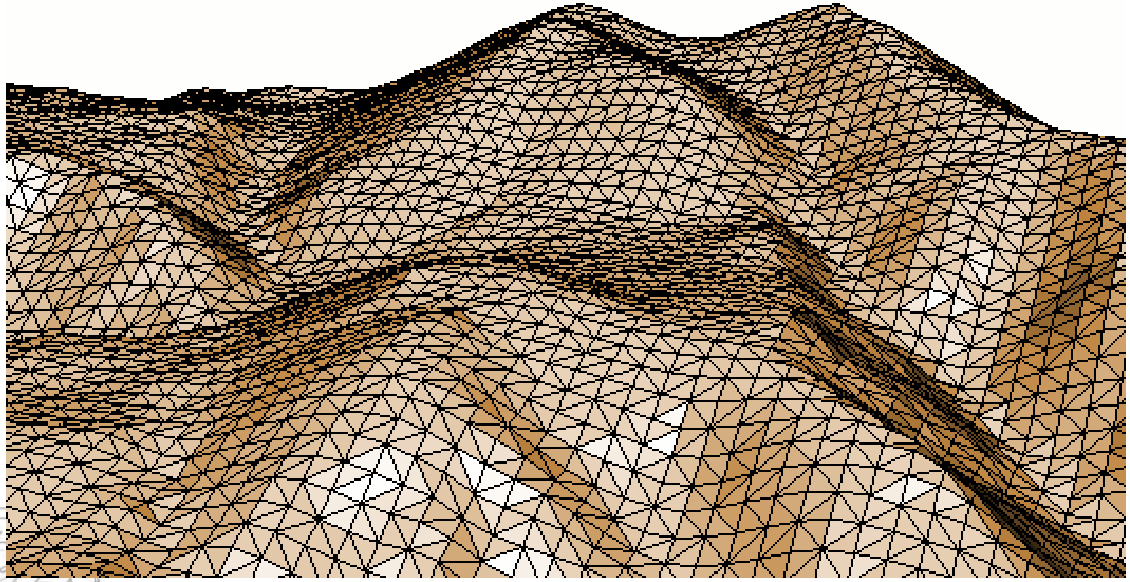
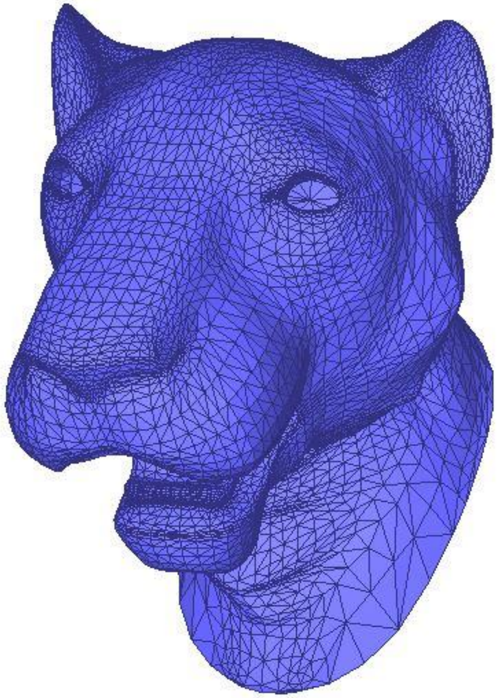
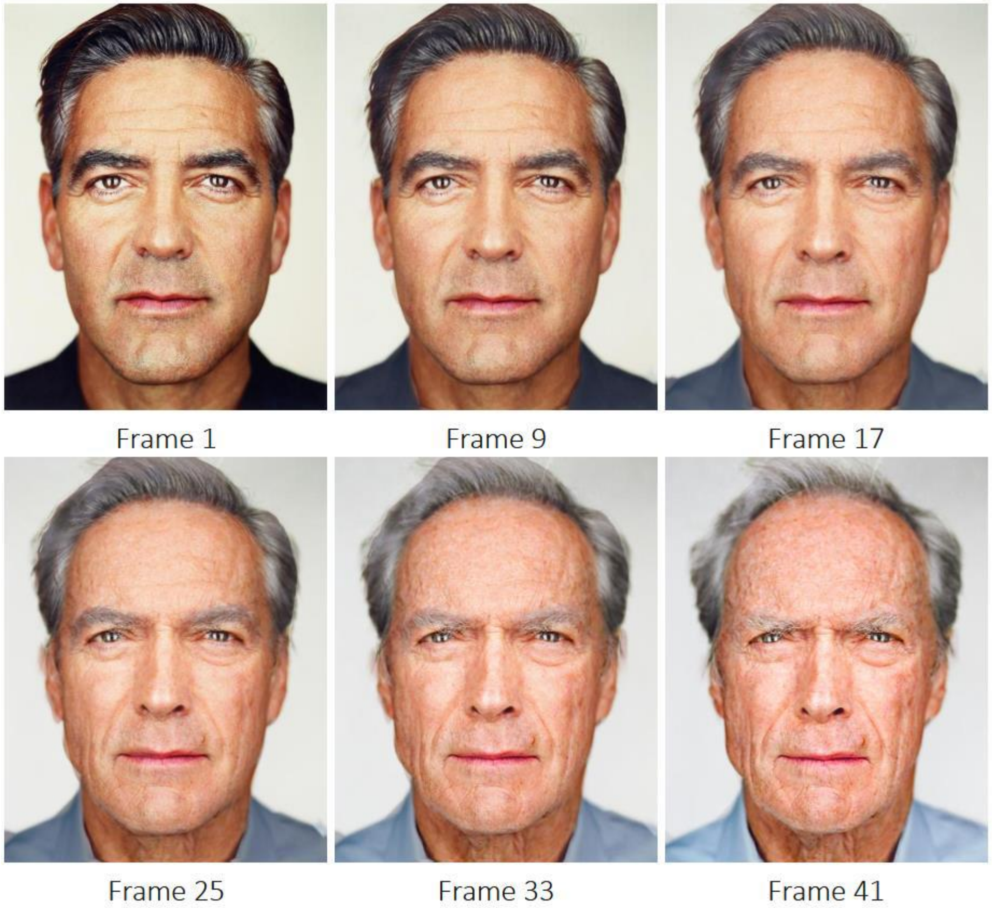
Delaunay in surface modeling





Delaunay in face morphing

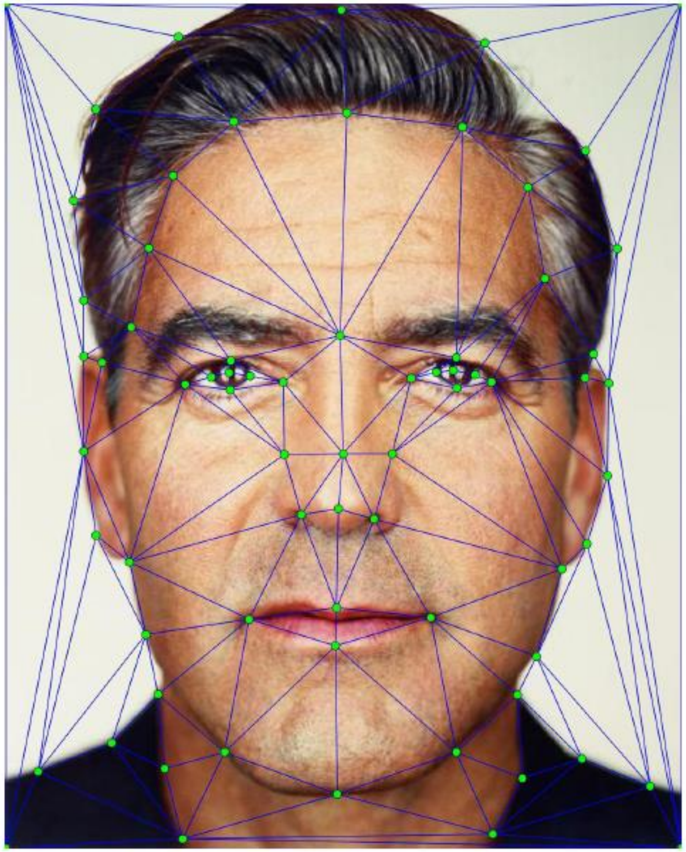
George Clooney (source)

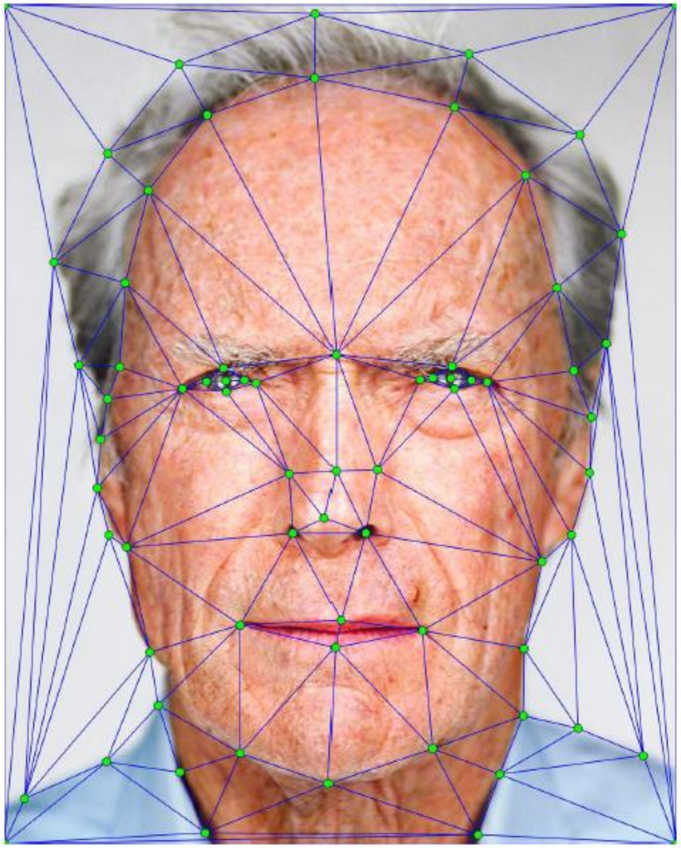


Clint Eastwood (destination)

https://inst.eecs.berkeley.edu/~cs194-26/fa17/upload/files/proj4/cs194-26-abw/

Delaunay in face morphing





https://inst.eecs.berkeley.edu/~cs194-26/fa17/upload/files/proj4/cs194-26-abw/

Syllabus

- shapes
- shape representation
- continuous skeleton
- skeleton-like shape features
- skeletonization techniques
  - distance-based
  - Voronoi-based
  - thinning
- applications of skeletonization

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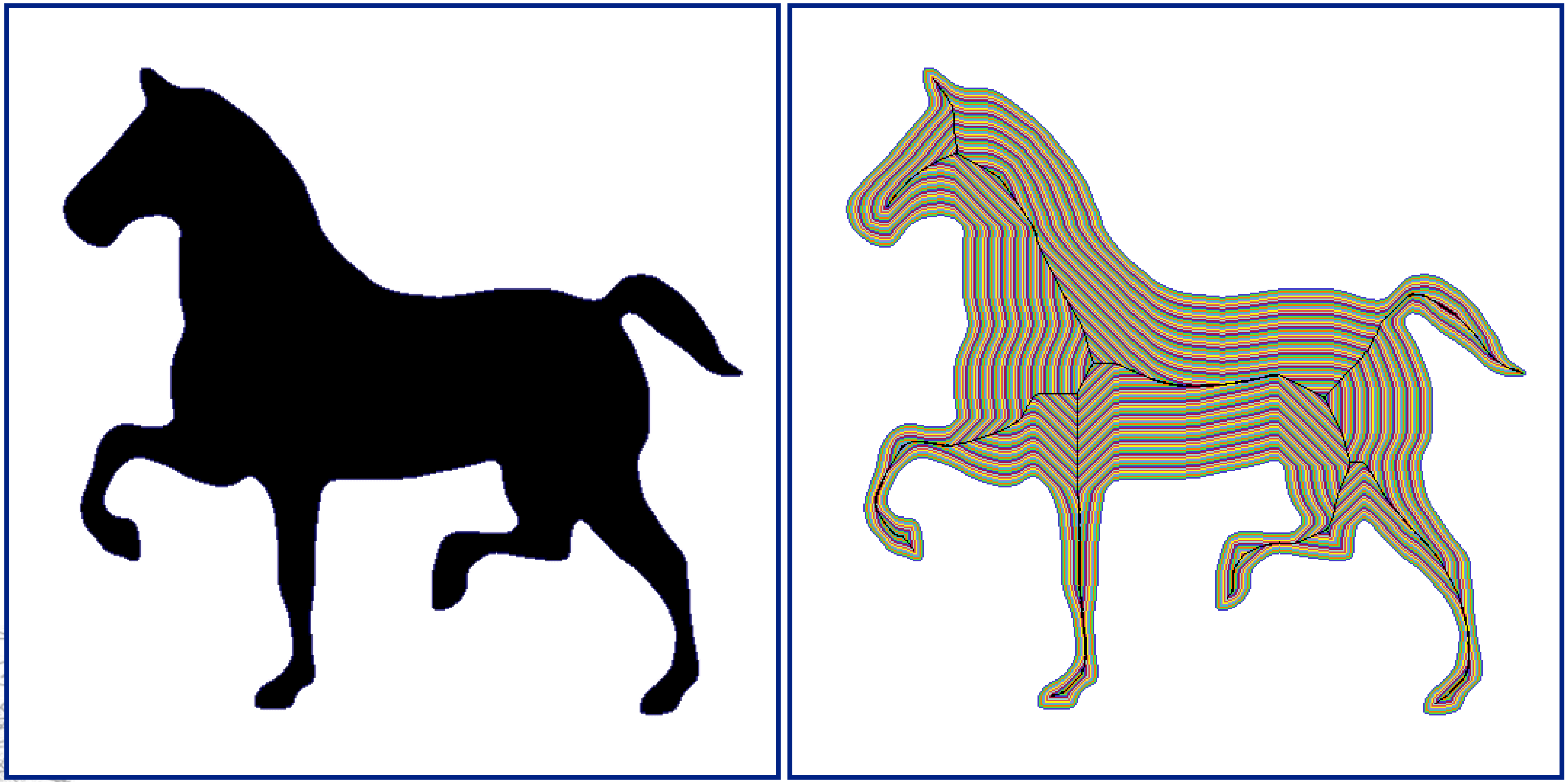
Thinning

Matryoshka: nesting wooden doll

original object → reduced structure

Thinning



modelling fire-front propagation

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Thinning algorithms

repeat

remove „***deletable***” points
from the actual binary image

one iteration step

until no points are deleted

degrees of freedom:

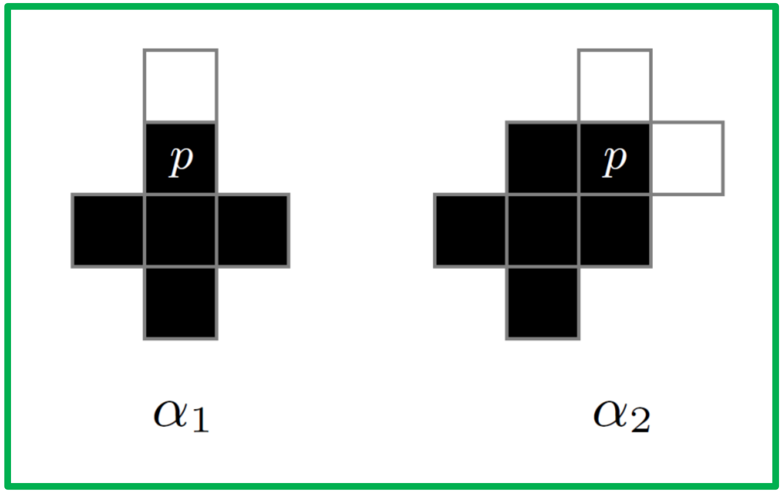
– which points are regarded as „***deletable***”?
– how to organize one iteration step?

A 2D parallel thinning algorithm

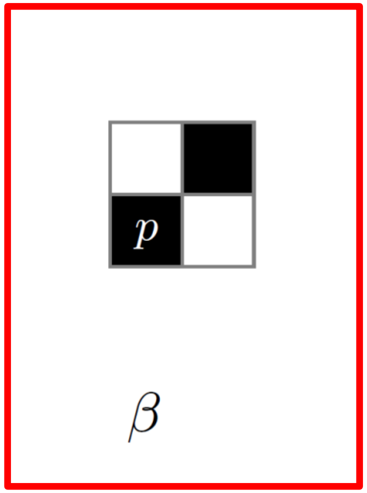
repeat
delete all points simultaneously
that are matched at least one removing pattern,
but are not matched by any restoring pattern
until no points are deleted

A. Manzanera et al. (*1999*)

Manzanera's fully-parallel 2D thinning algorithm



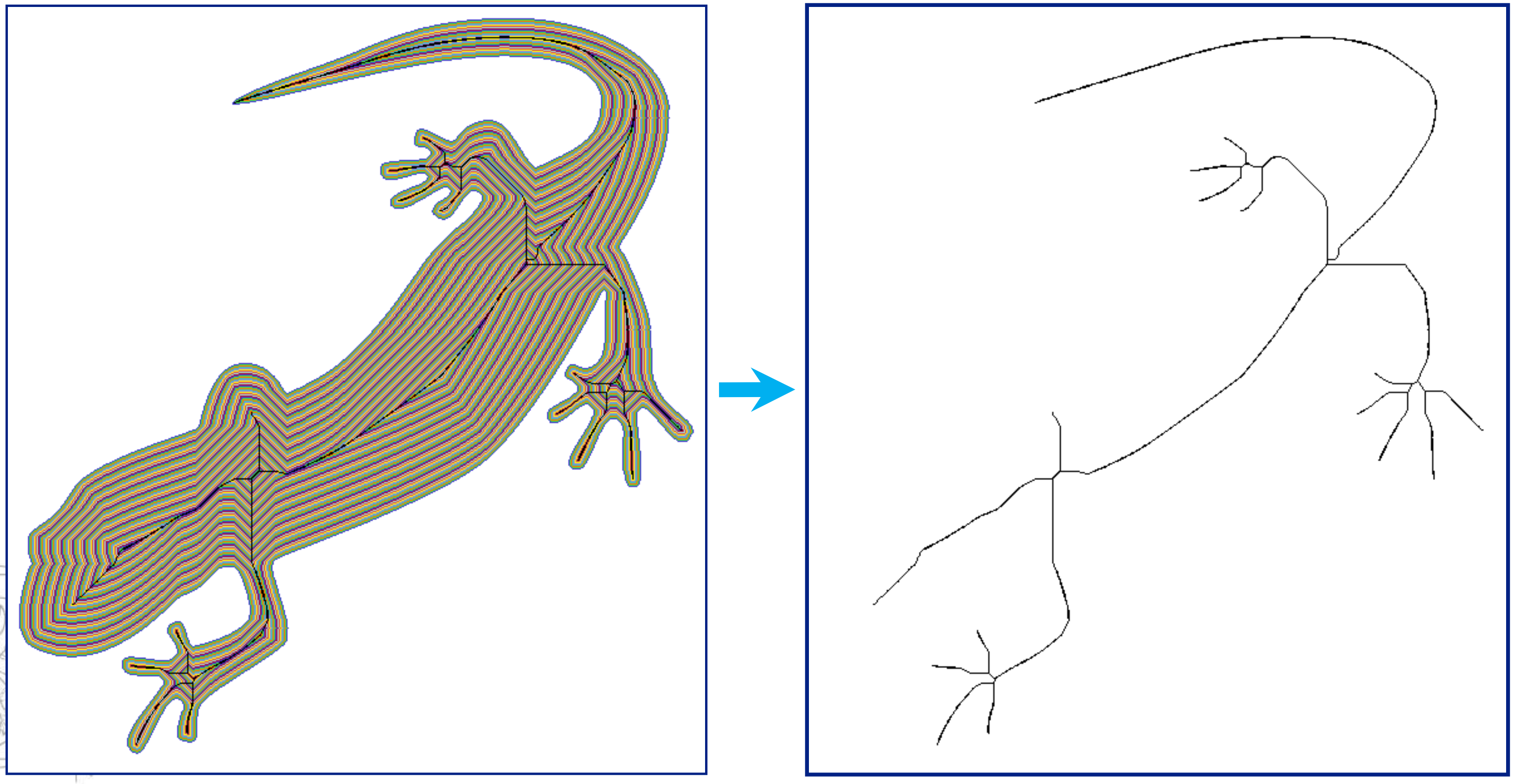
base removing patterns



base restoring pattern

A. Manzanera et al. (*1999*)

A 2D parallel thinning algorithm



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Thinning

- allows extraction of all kinds of skeleton-like shape features
- makes easy implementation possible
- takes the least computational costs
- can be executed in parallel

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  - distance-based
  - Voronoi-based
  - thinning
- applications of skeletonization

Applications of Skeletonization

- animation
- chordal surface generation
- computer graphics
- coding
- design and engineering applications
- fingerprint analysis
- generating mesh sizing functions
- measuring shape similarity
- motion analysis
- multiscale shape analysis
- object recognition and classification
- off-line character recognition
- part-patch segmentation
- object decomposition
- porous filter permeability
- analysis of porous media
- morphology
- raster-to-vector conversion
- image registration
- segmentation
- shape deformation and morphing
- shape matching and retrieval
- shape modeling
- terrain modeling
- tracing and virtual navigation
- …

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Character recognition

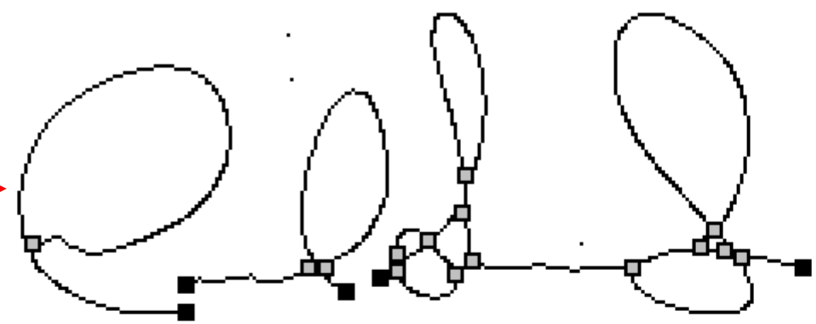
characters of a Japanese signature

K. Ueda

Signature verification

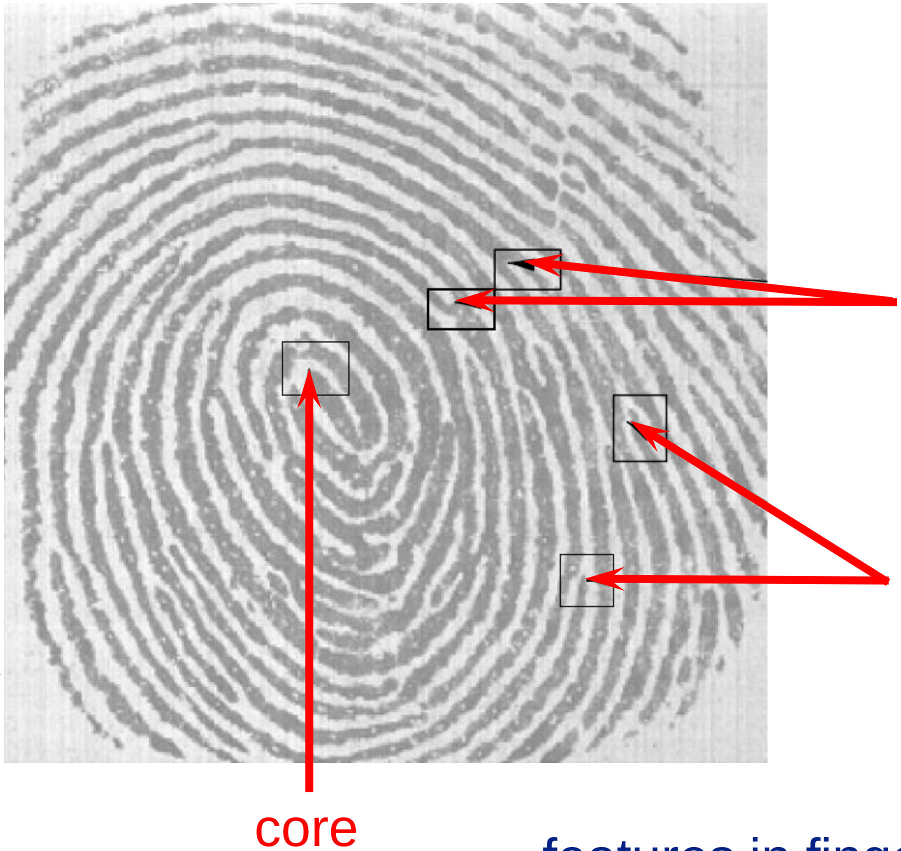
signature before and
after skeletonization

detected line-end points
and branch-points



L.C. Bastos et al.

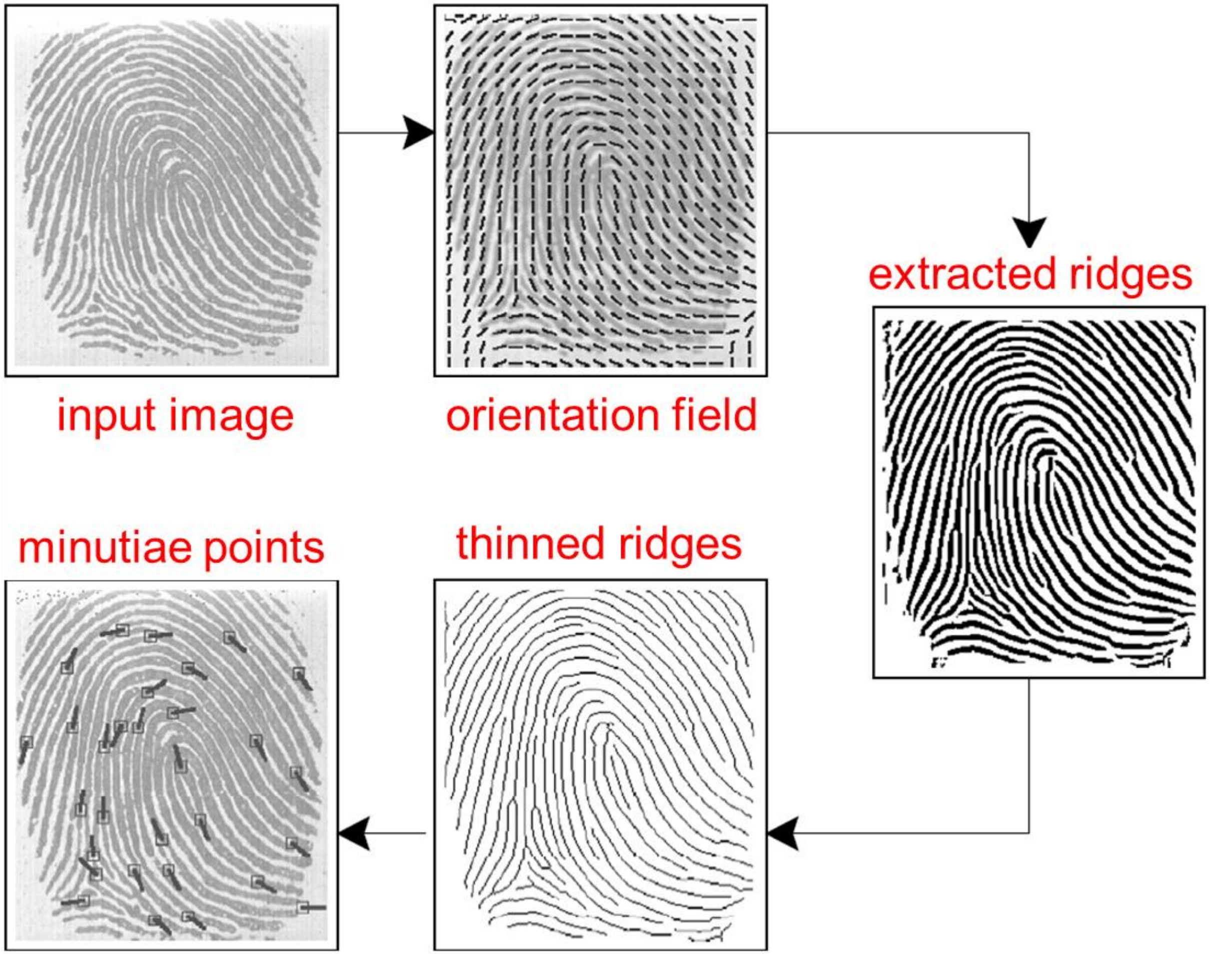
Fingerprint verification



features in fingerprints

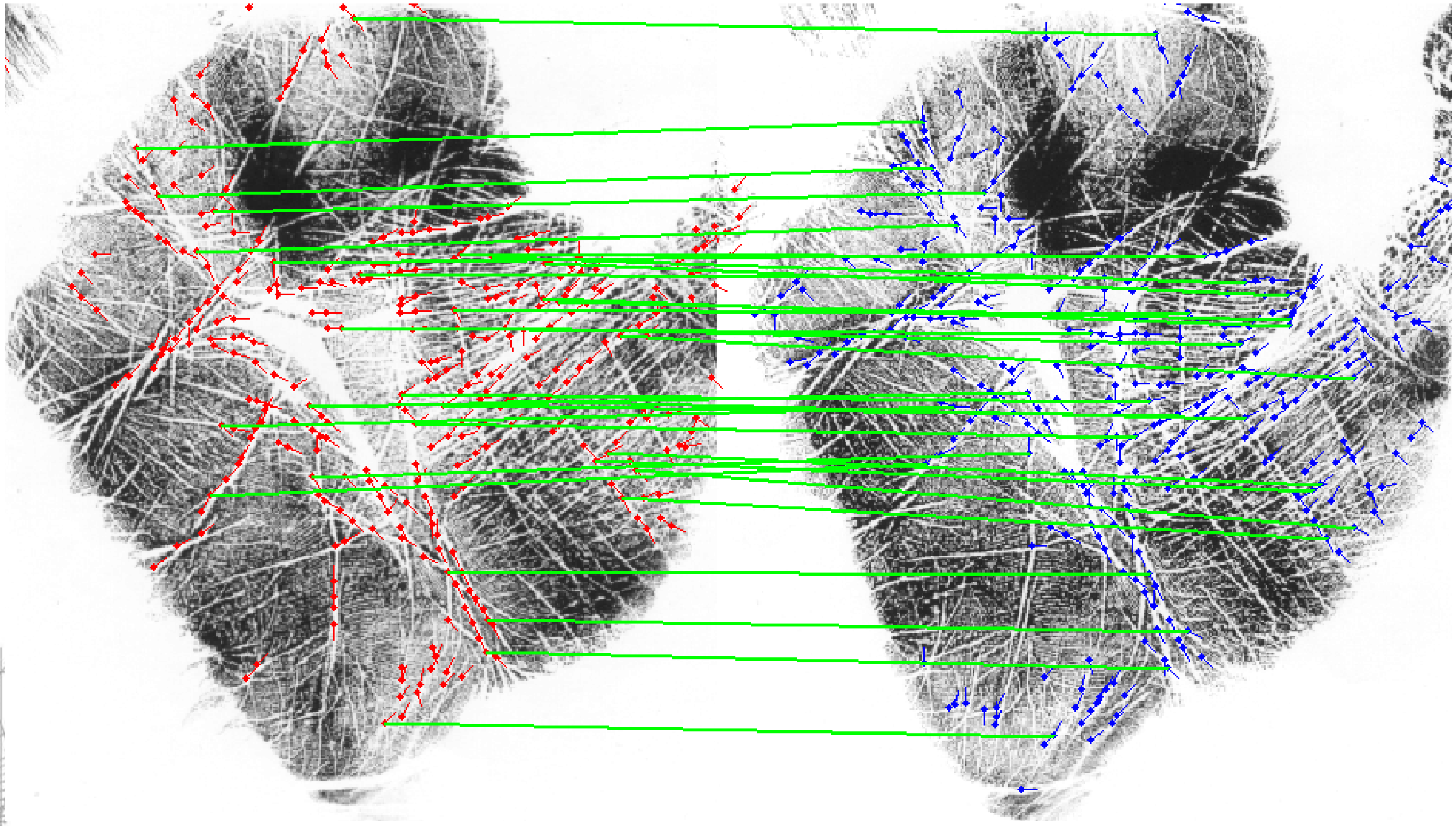
A. Ross

Fingerprint verification



A. Ross

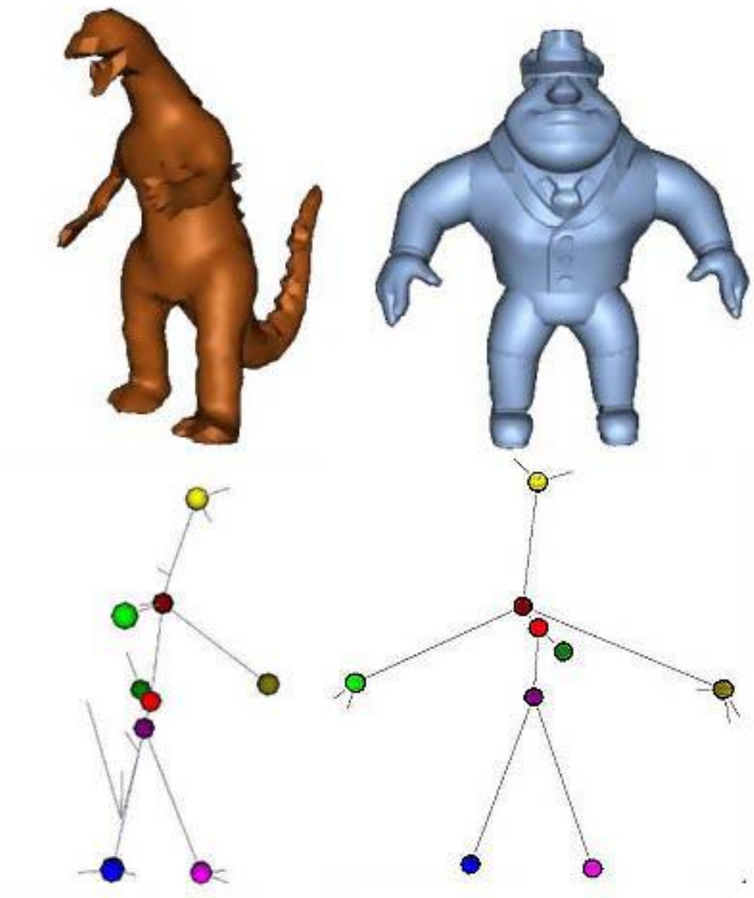
Palmprint verification



matching extracted features

N. Duta

Shape matching and retrieval

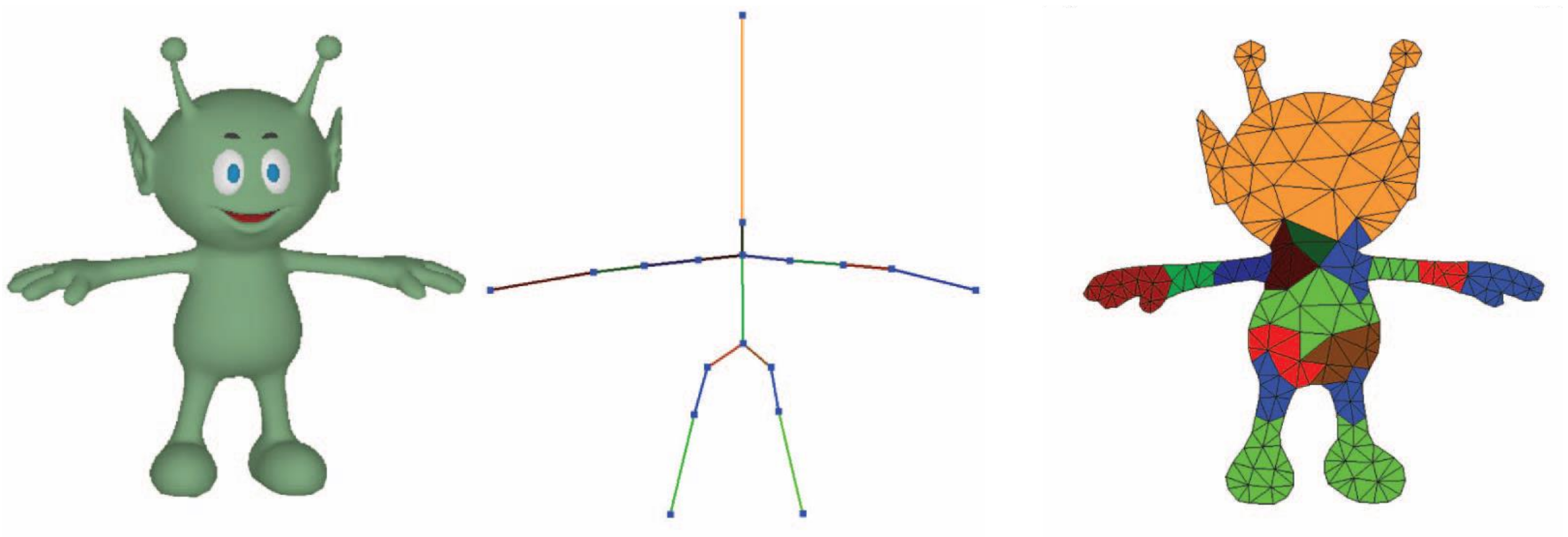


skeletal graph construction

graph matching

Sundar et al., 2003

Shape deformation



object

partitioned
skeleton

skeleton
control domain

Yan et al., 2008

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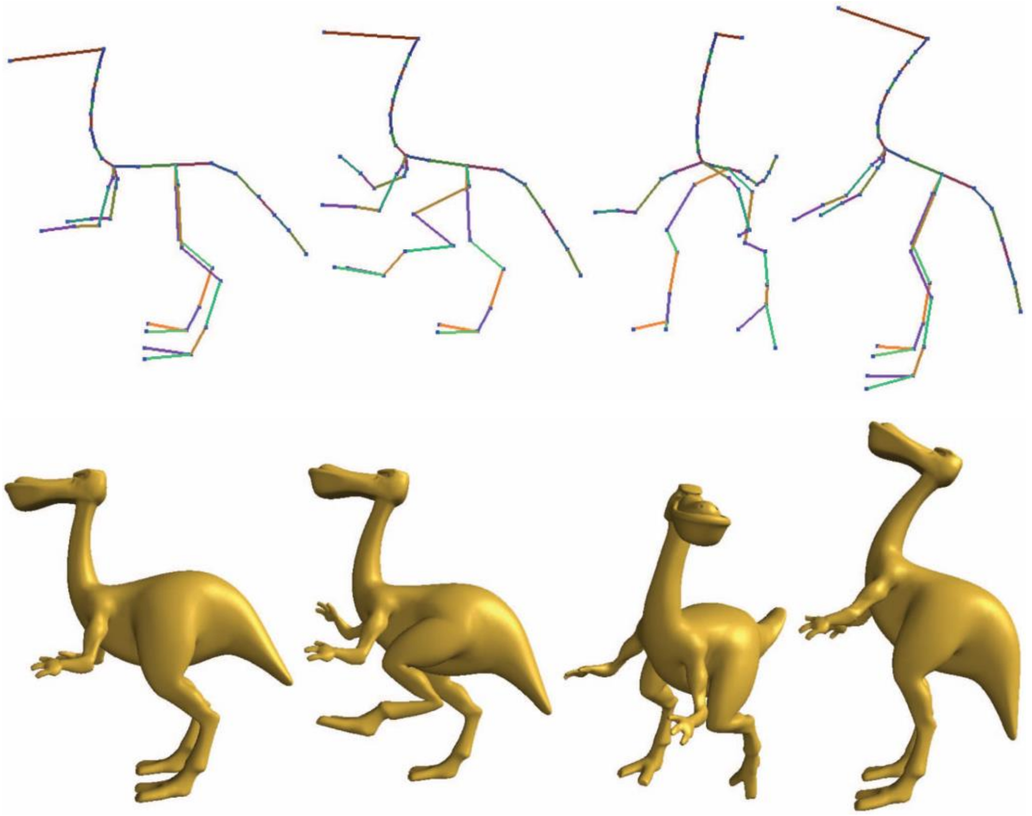
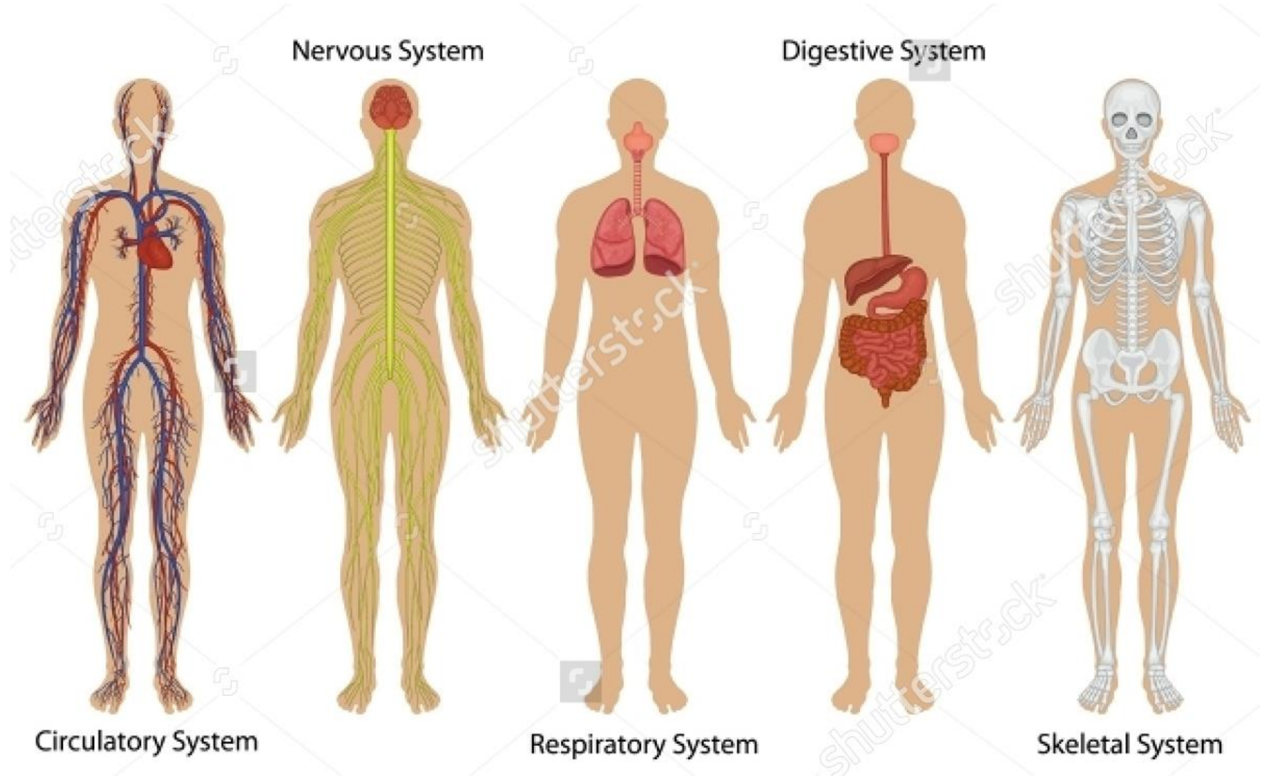
Shape deformation



deformed skeletons and objects

Yan et al., 2008

Medical applications in 3D



Tubular structures (e.g., blood vessels, airways) are frequently found in living organs. They can be represented by their centerlines (extracted by 3D curve-thinning algorithms).

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Cooperation with Medical University Graz

- assessment of laryngotracheal stenosis
- unravelling the colon

Medical University of Graz

E. Sorantin et al.

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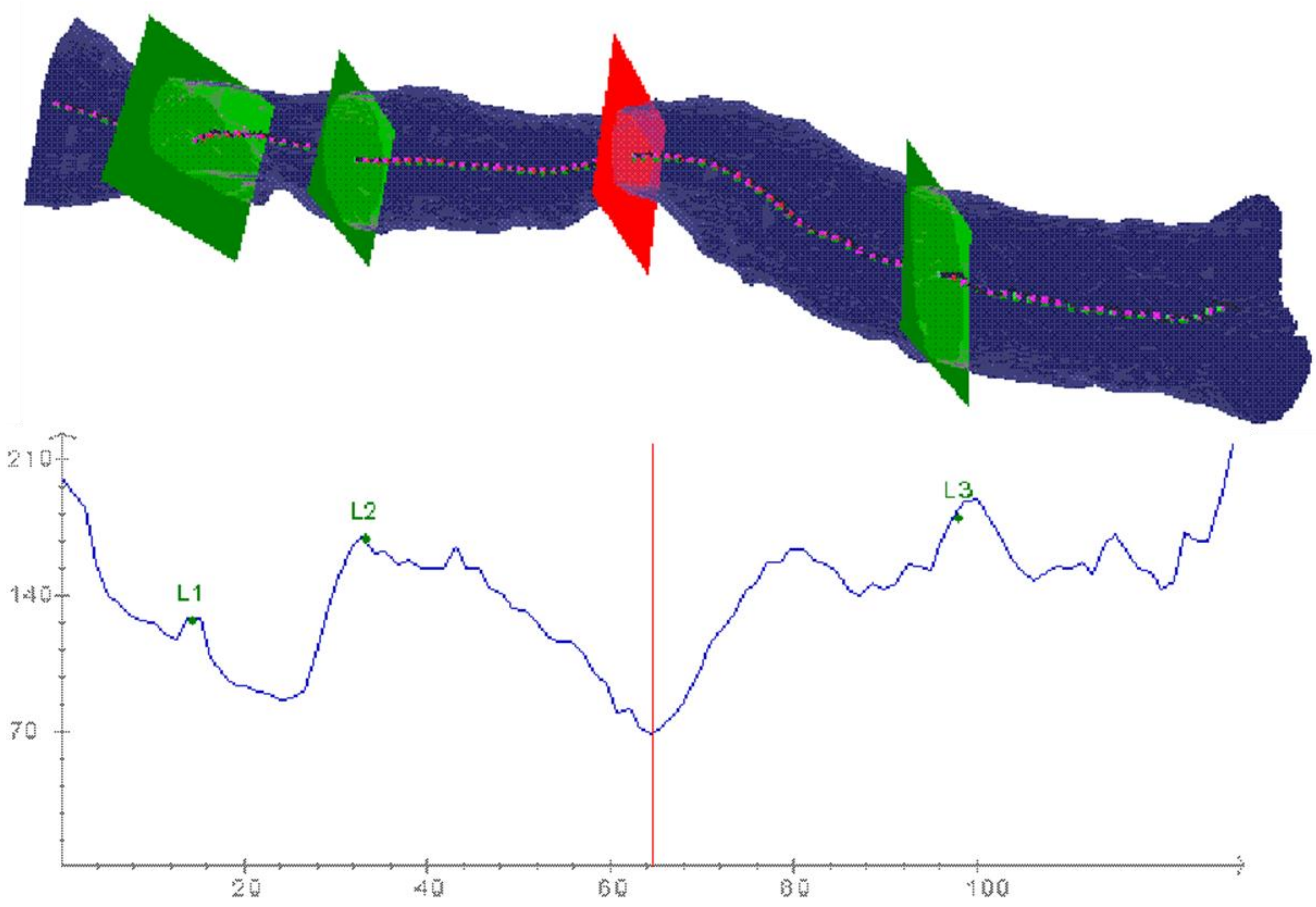
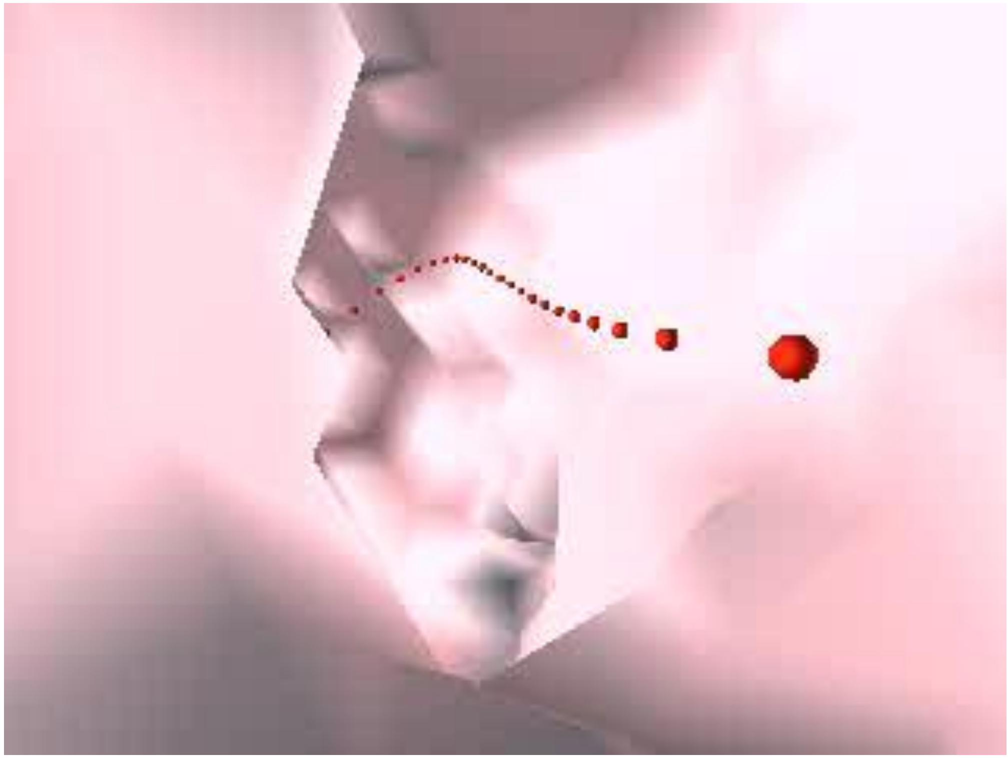
UNIVERSITAS SCIENTIARUM SZEGEDIENSIS

Assessment of laryngotracheal stenosis



Virtual colonoscopy



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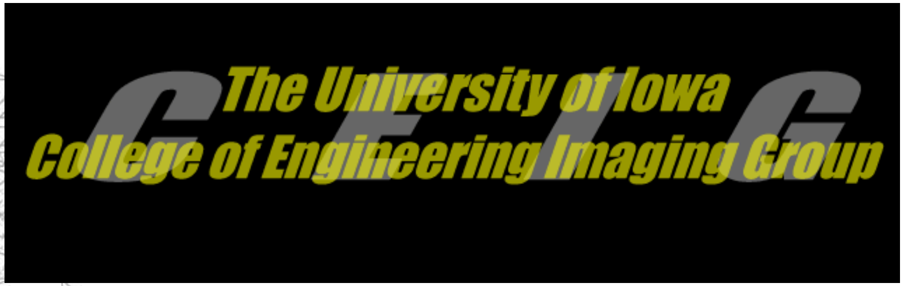
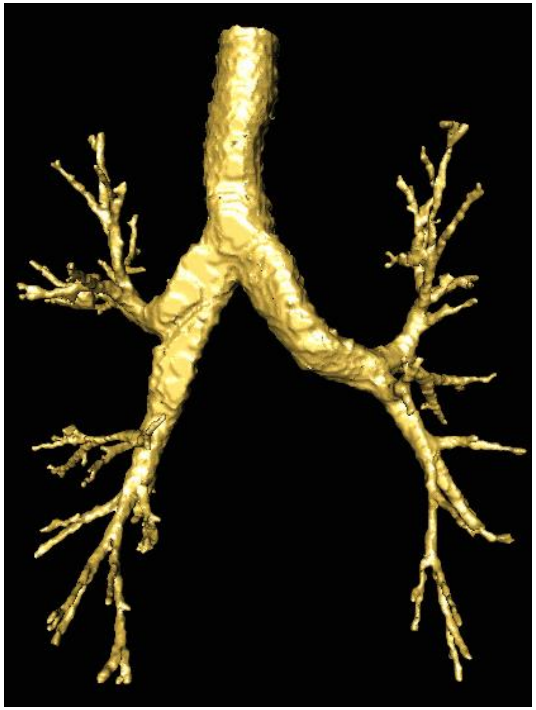
Cooperation with The University of Iowa

Quantitative analysis of pulmonary airway trees

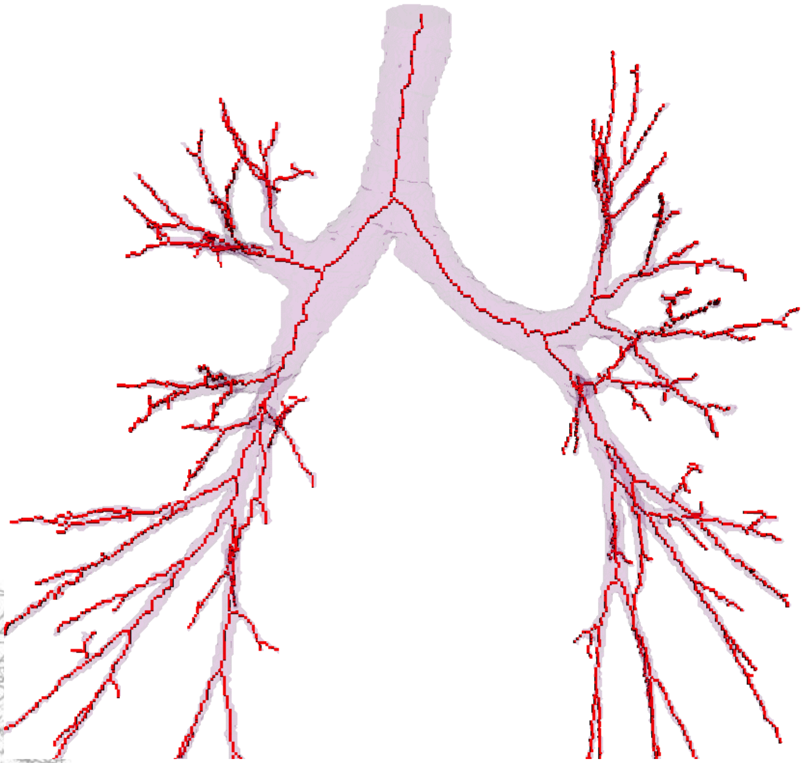


Quantitative analysis of pulmonary airway trees

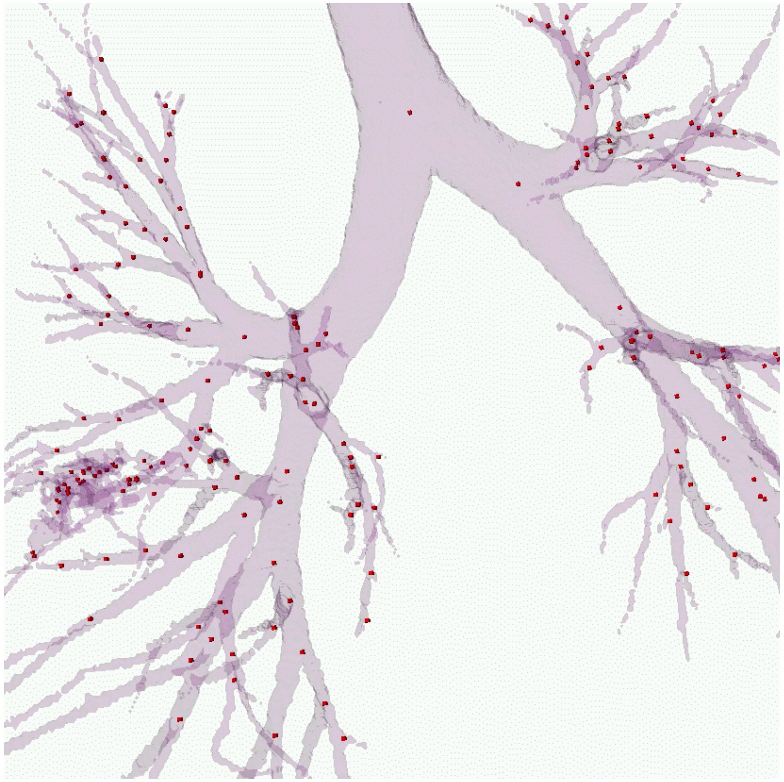


segmented lung
and airway tree

Quantitative analysis of pulmonary airway trees



centerline



identified branch-points

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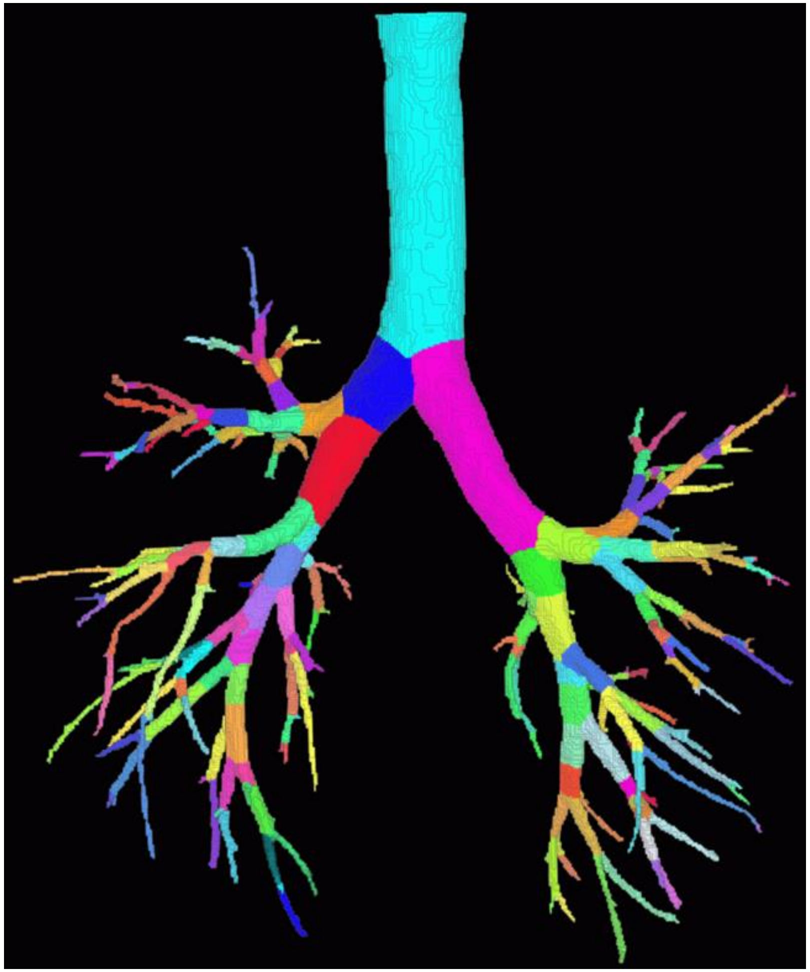

branch partitioning

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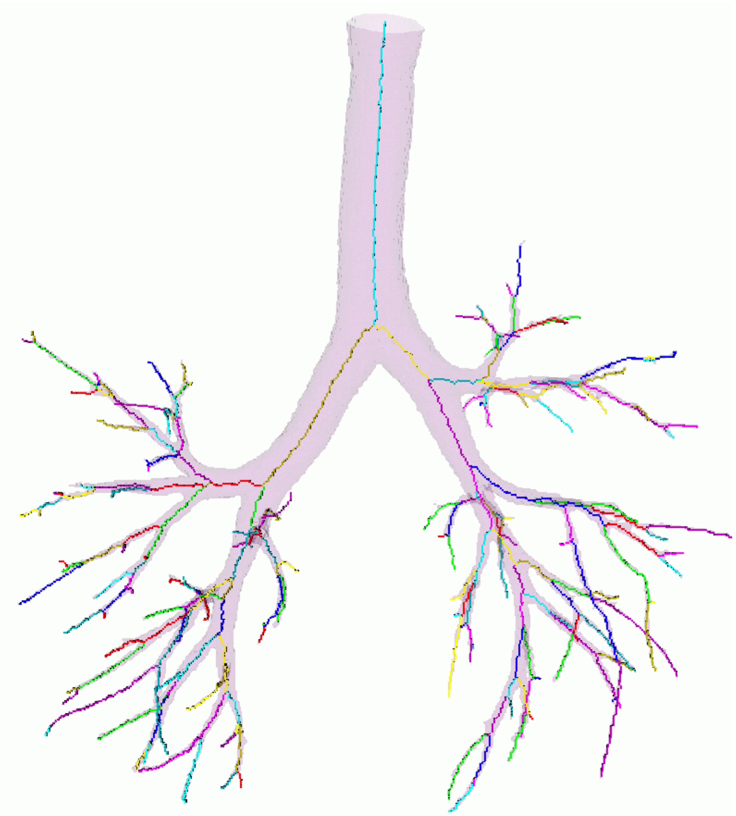
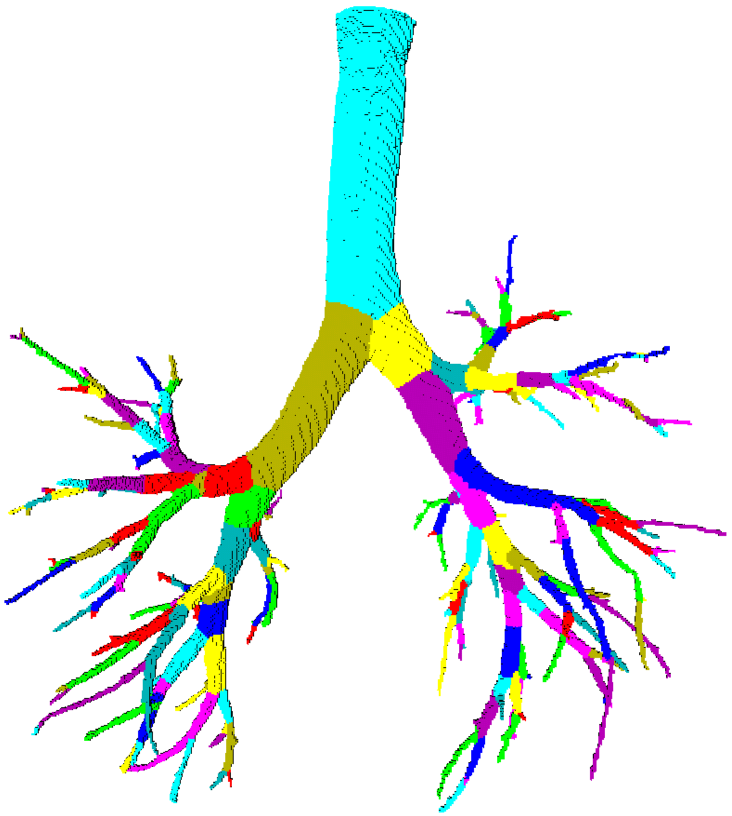
Quantitative analysis of pulmonary airway trees

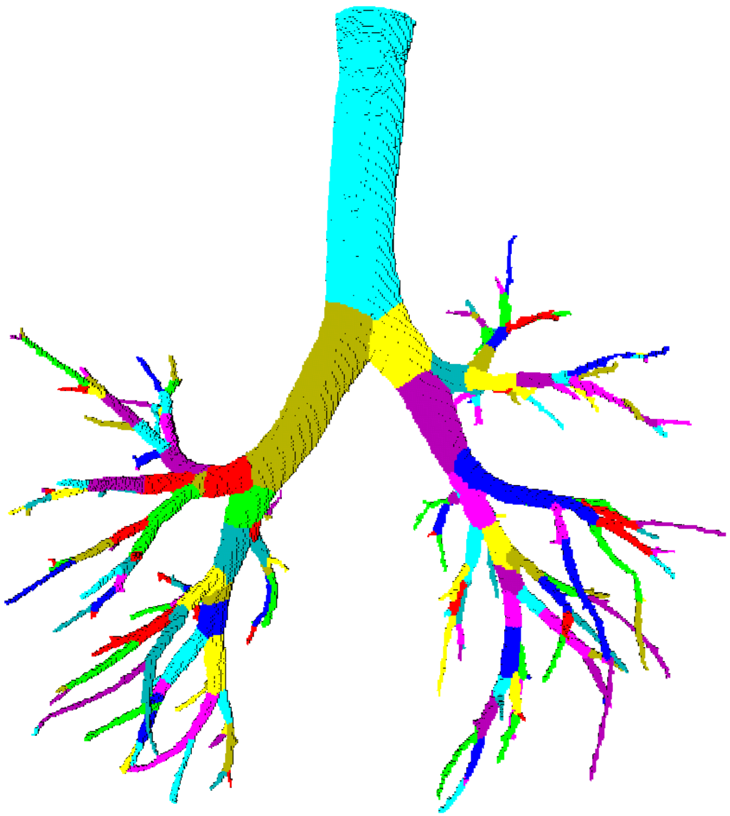


centerline labeling

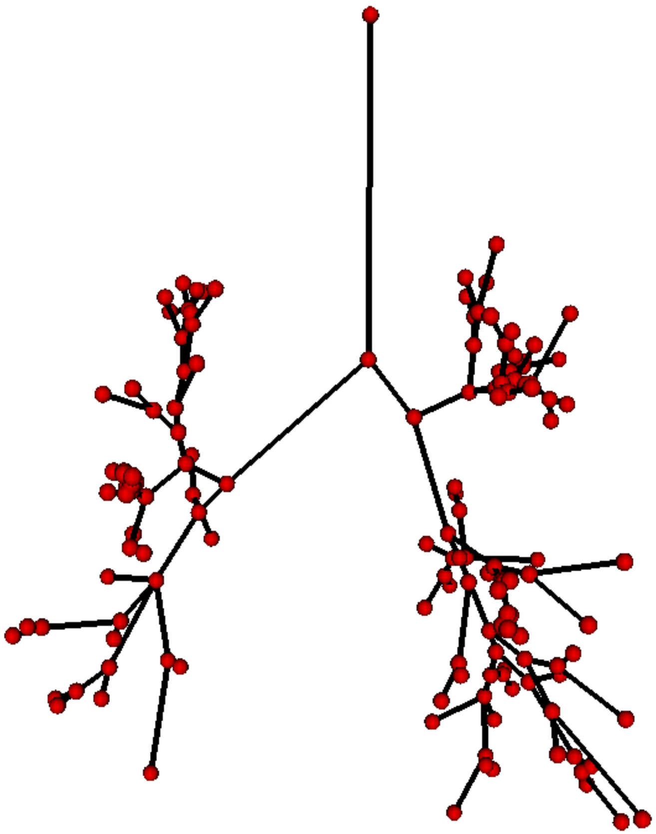


label propagation

Quantitative analysis of pulmonary airway trees



labeled tree



formal tree (in XML)

Quantitative analysis of pulmonary airway trees

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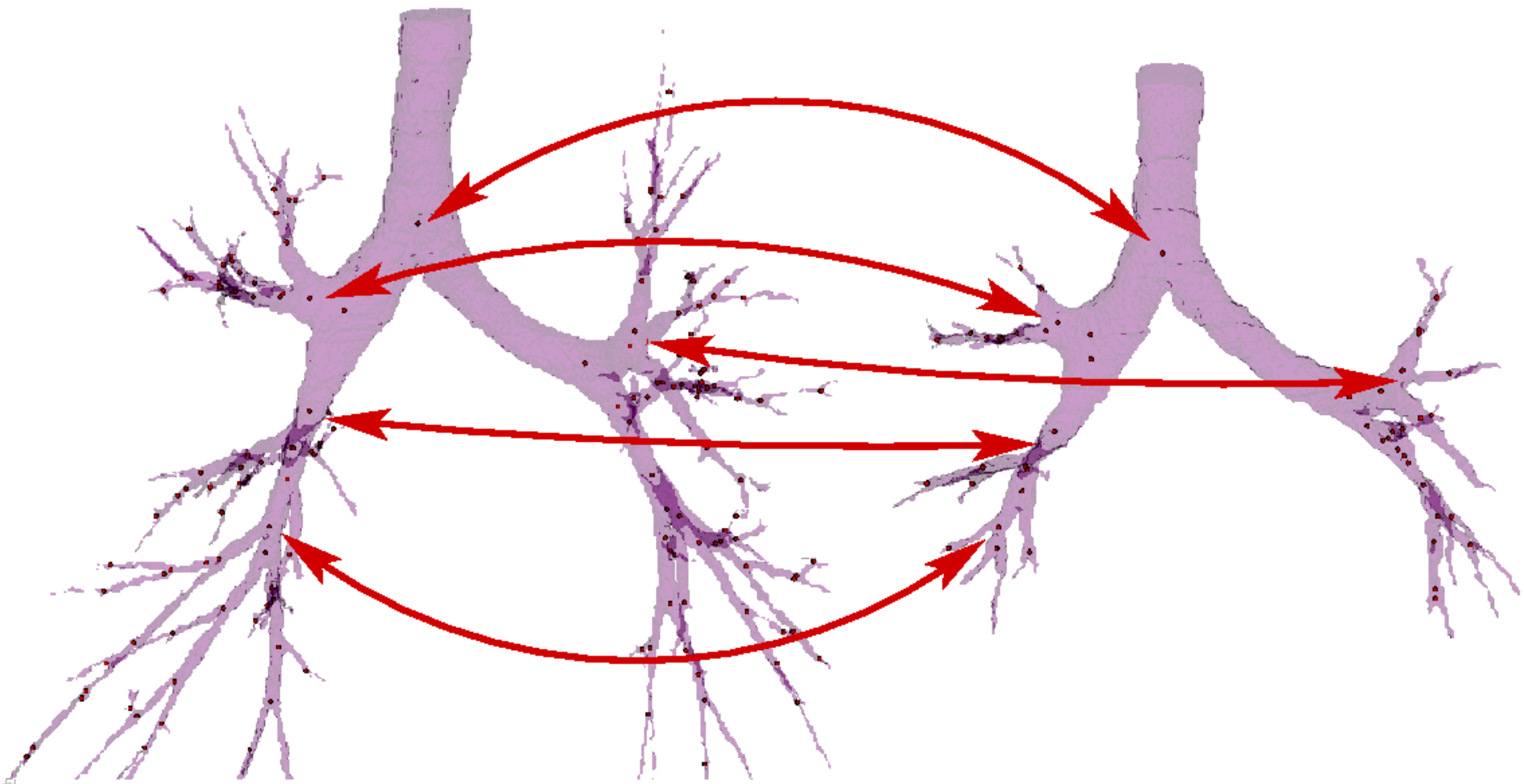
Quantitative indices for tree branches

- length (Euclidean distance between the parent and the child branch points)
- volume (volume of all voxels belonging to the branch)
- surface area (surface area of all boundary voxels belonging to the branch)
- average diameter (assuming cylindric segments)

Quantitative analysis of pulmonary airway trees



tree matching based on identified branch-points in the centerline

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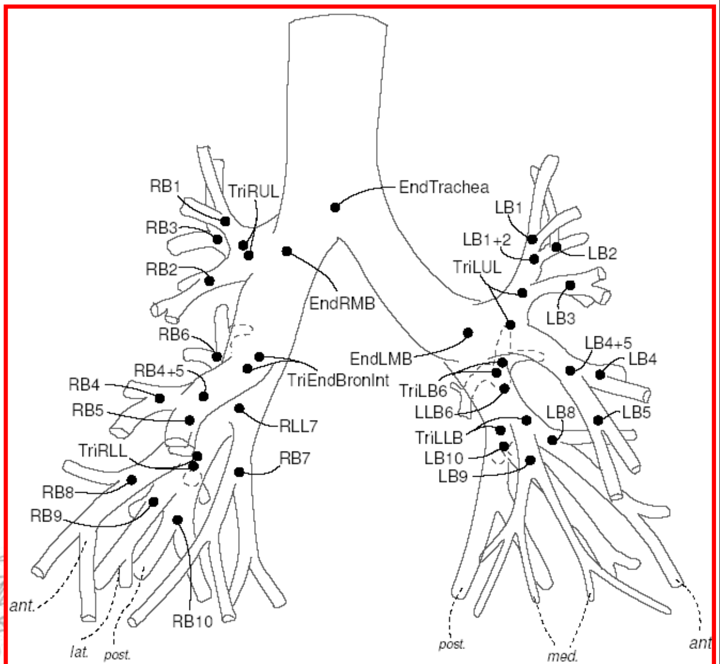
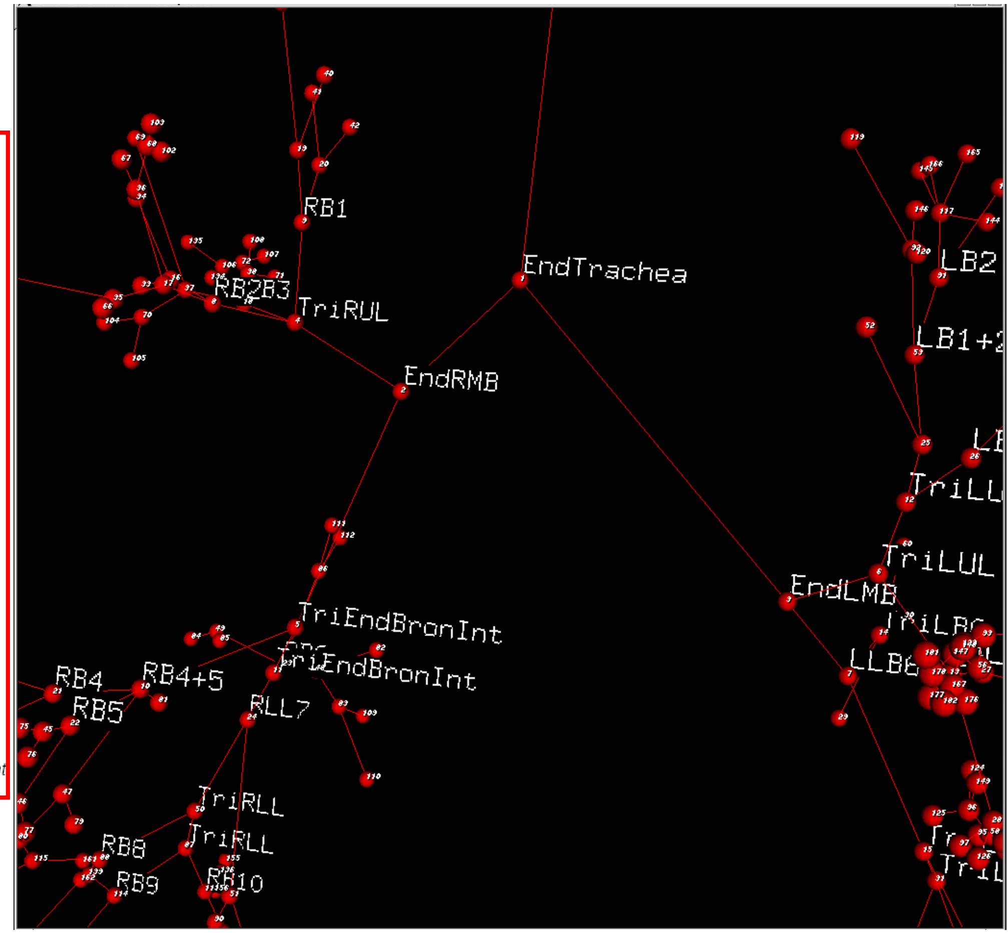
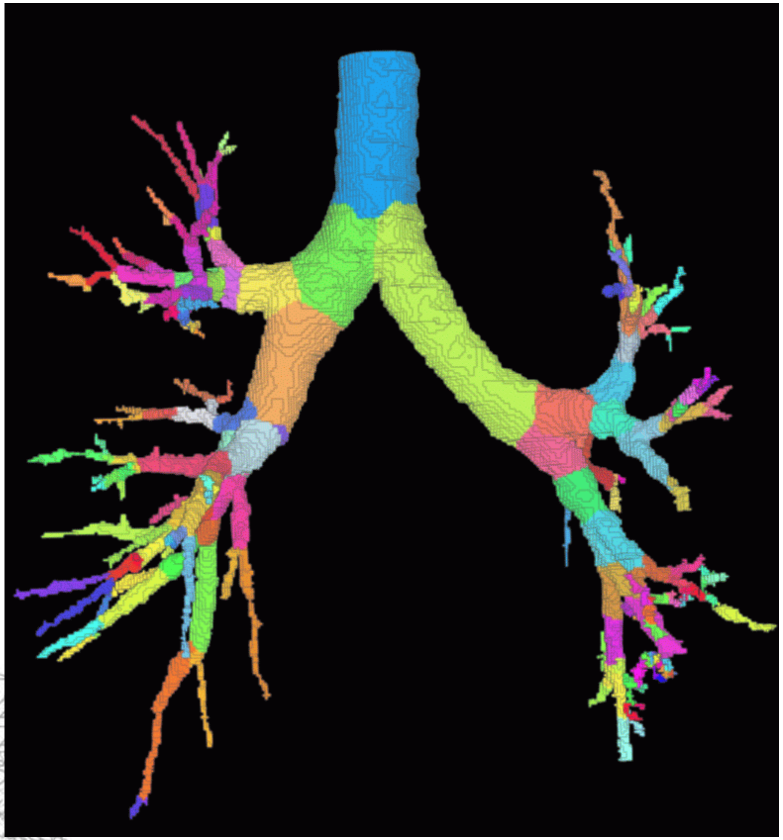
Quantitative analysis of pulmonary airway trees

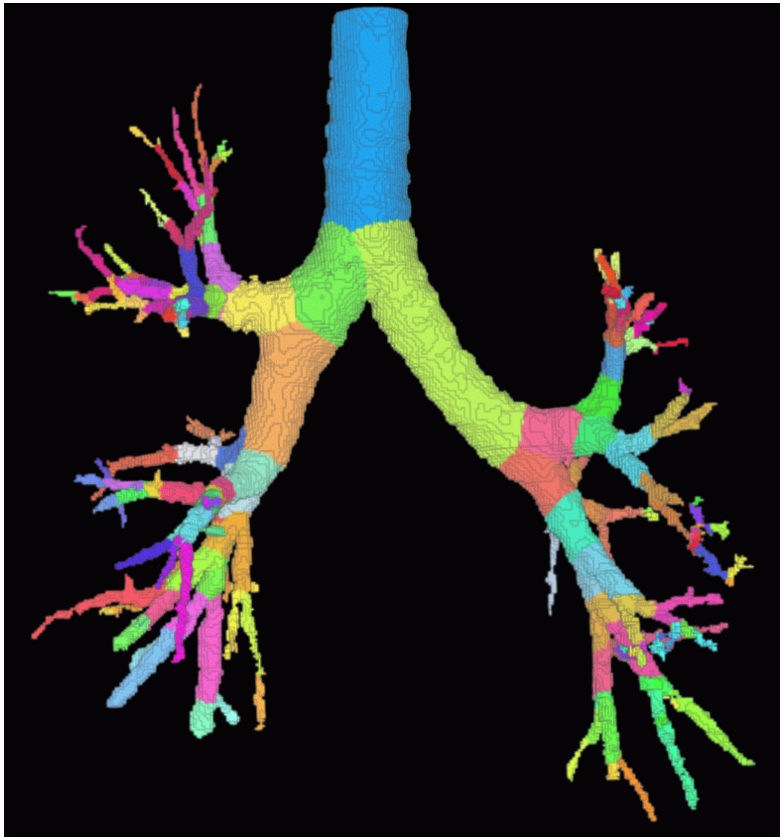




Quantitative analysis of pulmonary airway trees



functional residual capacity (FRC)



total lung capacity (TLC)

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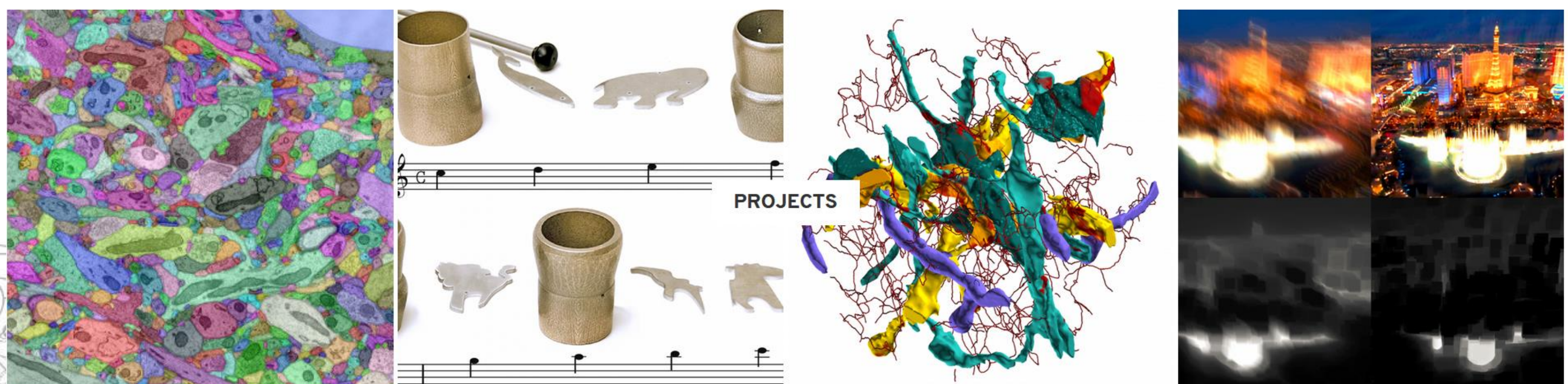
Cooperation with Harvard University

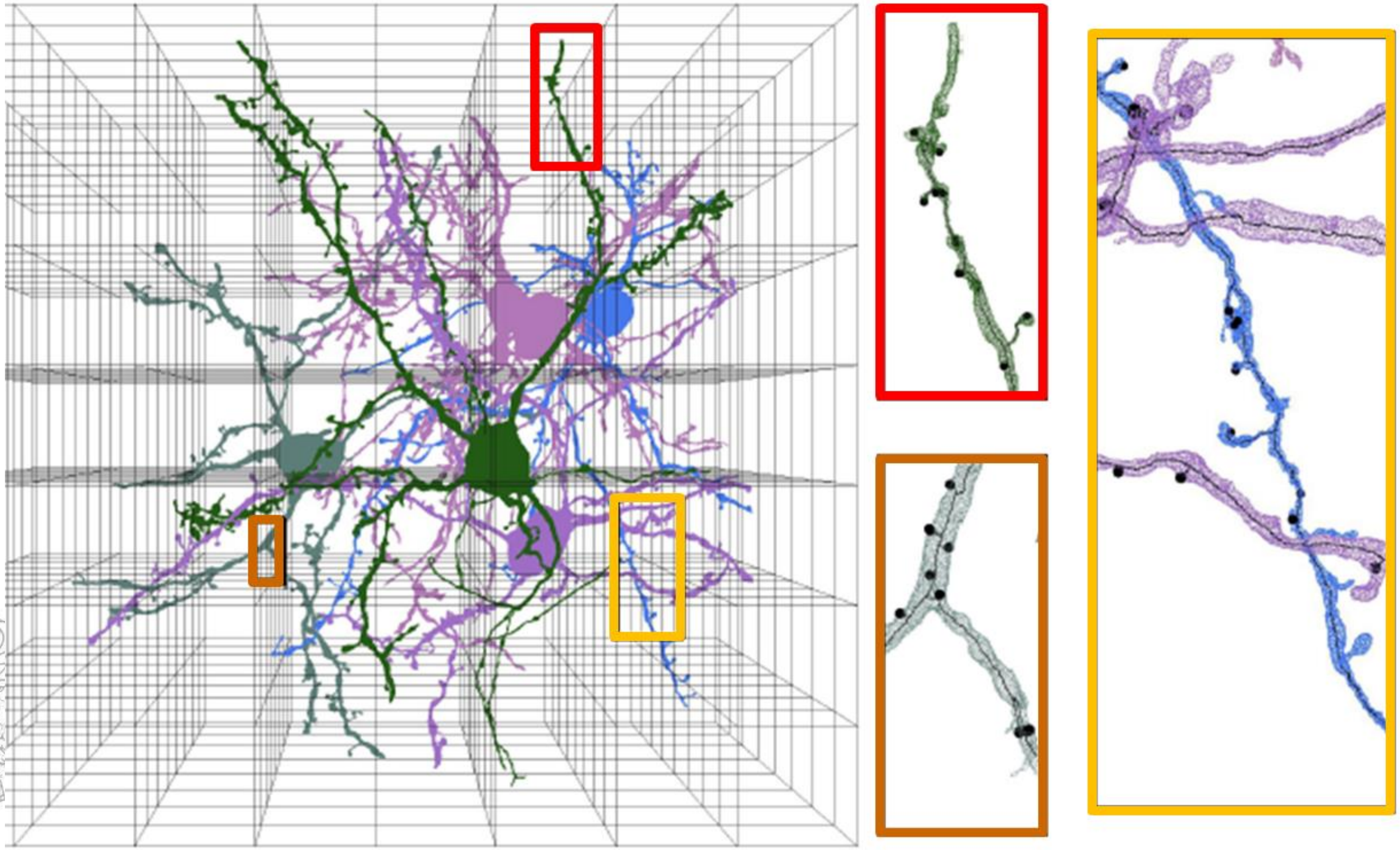
Synapse-aware skeleton generation for neural circuits

Harvard John A. Paulson
School of Engineering
and Applied Sciences

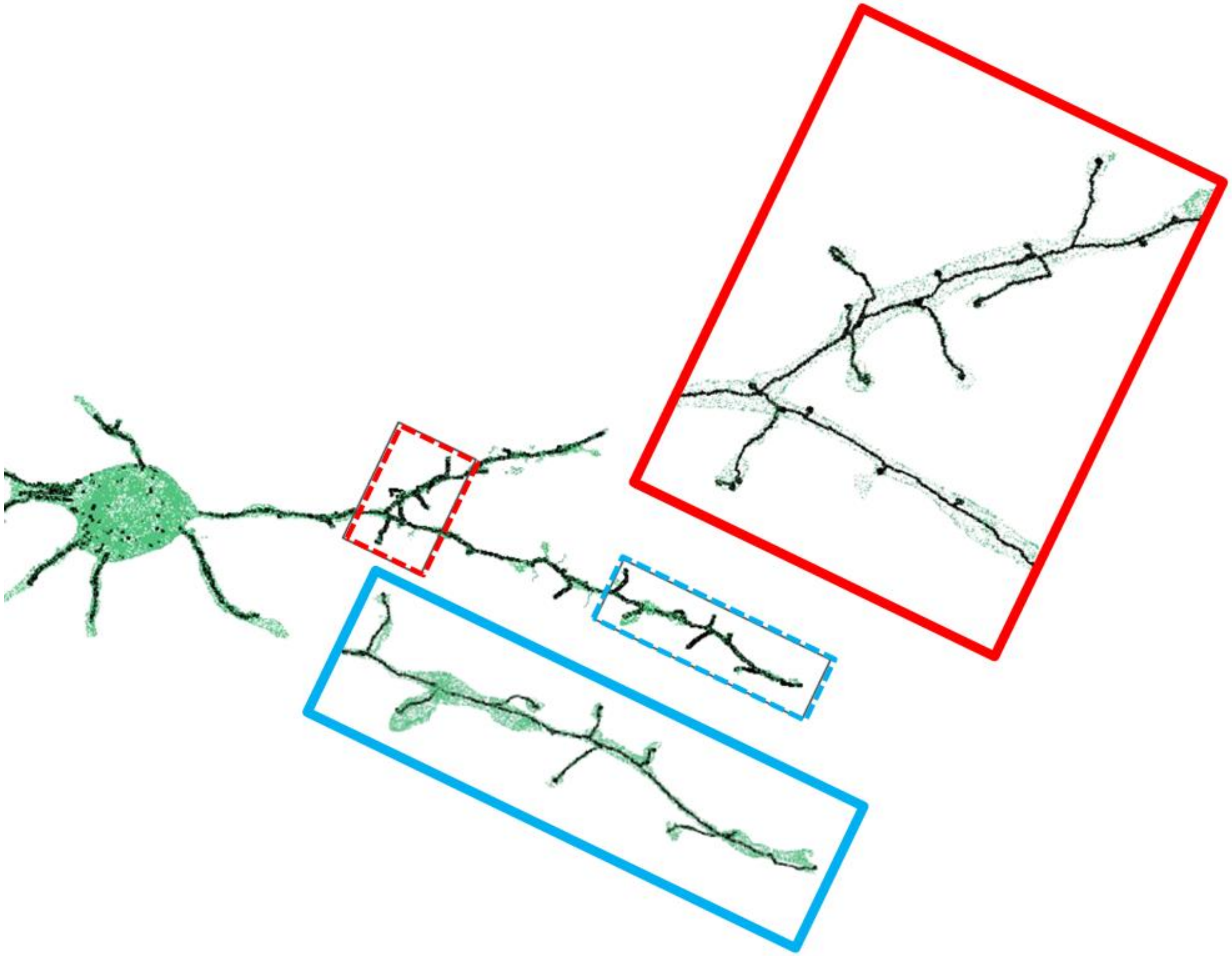


https://vcg.seas.harvard.edu/

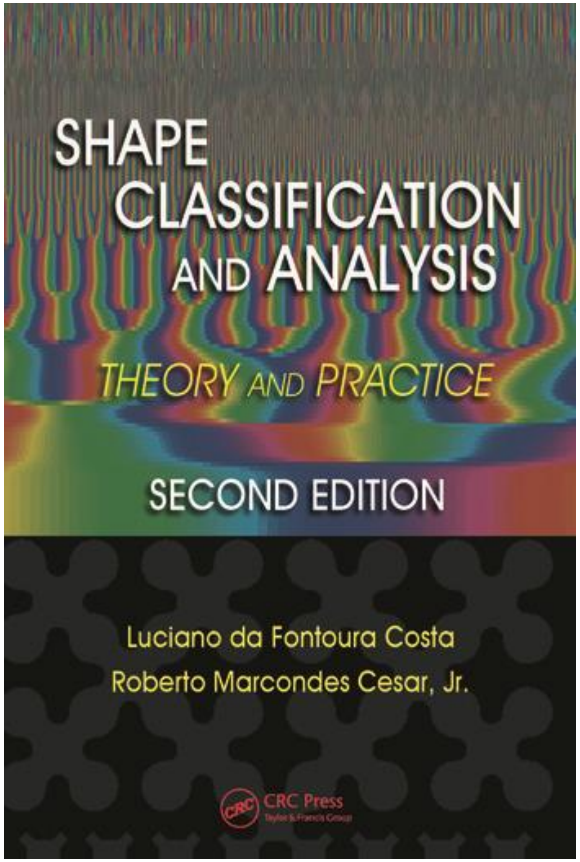
Synapse-aware skeleton generation



Synapse-aware skeleton generation

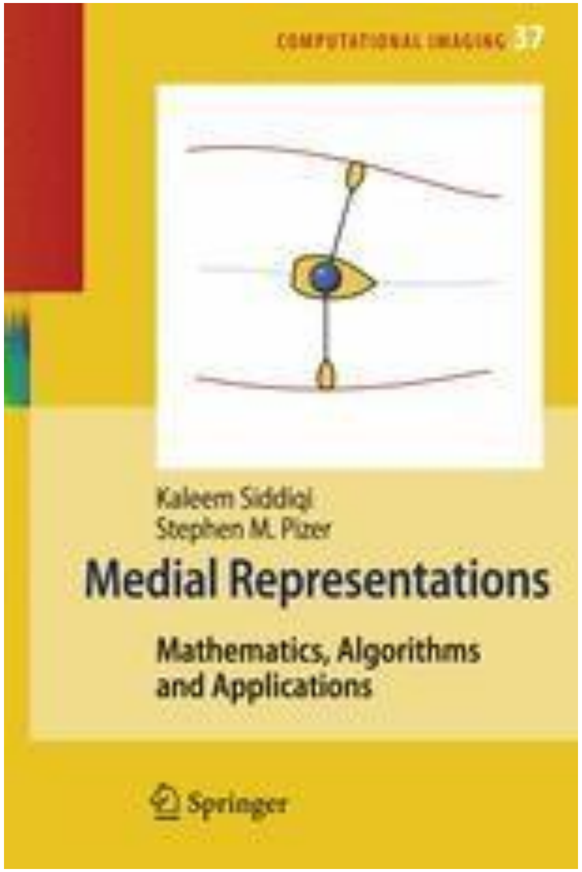


Suggested Readings



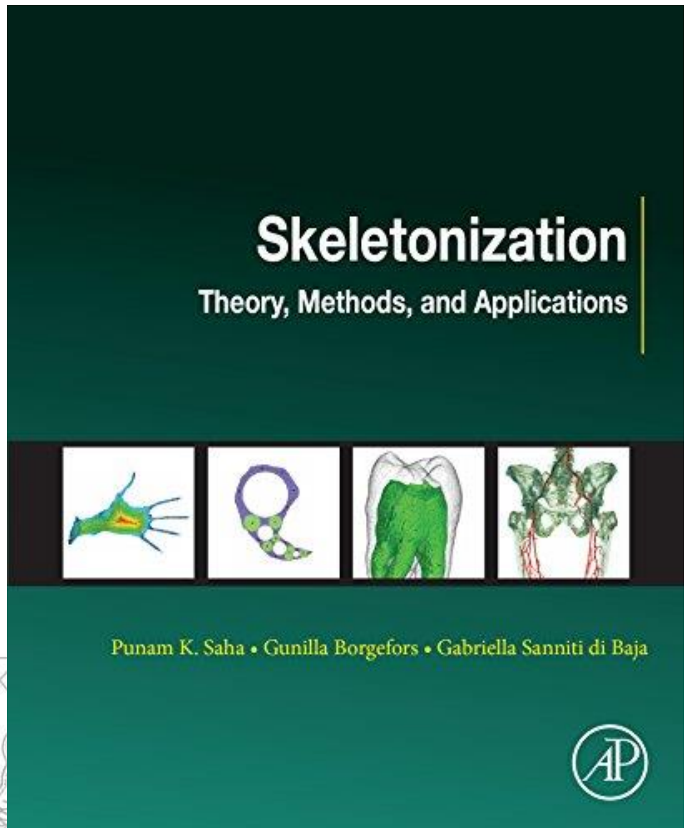
Luciano da Fona Costa and Roberto Marcond Cesar, Jr.: **Shape Classification and Analysis - Theory and Practice, Second Edition** *CRC Press, 2009.*

Suggested Readings



Kaleem Siddiqi and
Stephen Pizer (Eds.):
Medial Representations - Mathematics, Algorithms and Applications
Springer, 2008.

Suggested Readings



Punam K. Saha,
Gunilla Borgefors, and
Gabriella Sanniti di Baja (Eds.):
Skeletonization:
Theory, methods and applications,
Academic Press, 2017.

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Szeged has been the venue of the SSIP 14 times.

Szeged

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