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Department of Image Processing and Computer Graphics

Skeletonization in 3D via thinning and its applications

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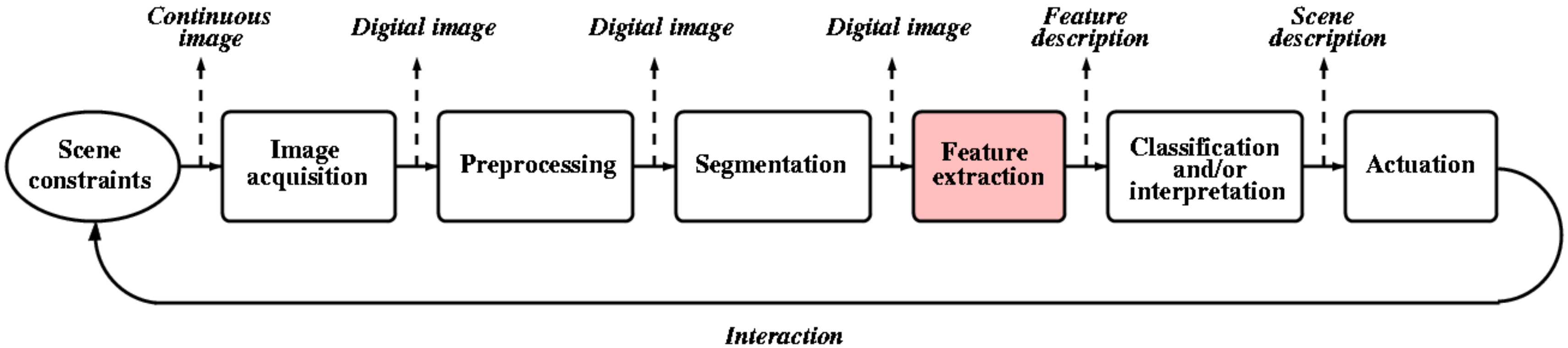
Syllabus

- Shape representation
- Skeleton-like shape features
- Skeletonization via thinning
- Thinning algorithms in 3D
- Applications

The generic model of a modular machine vision system



G.W. Awcock, R. Thomas (1996)

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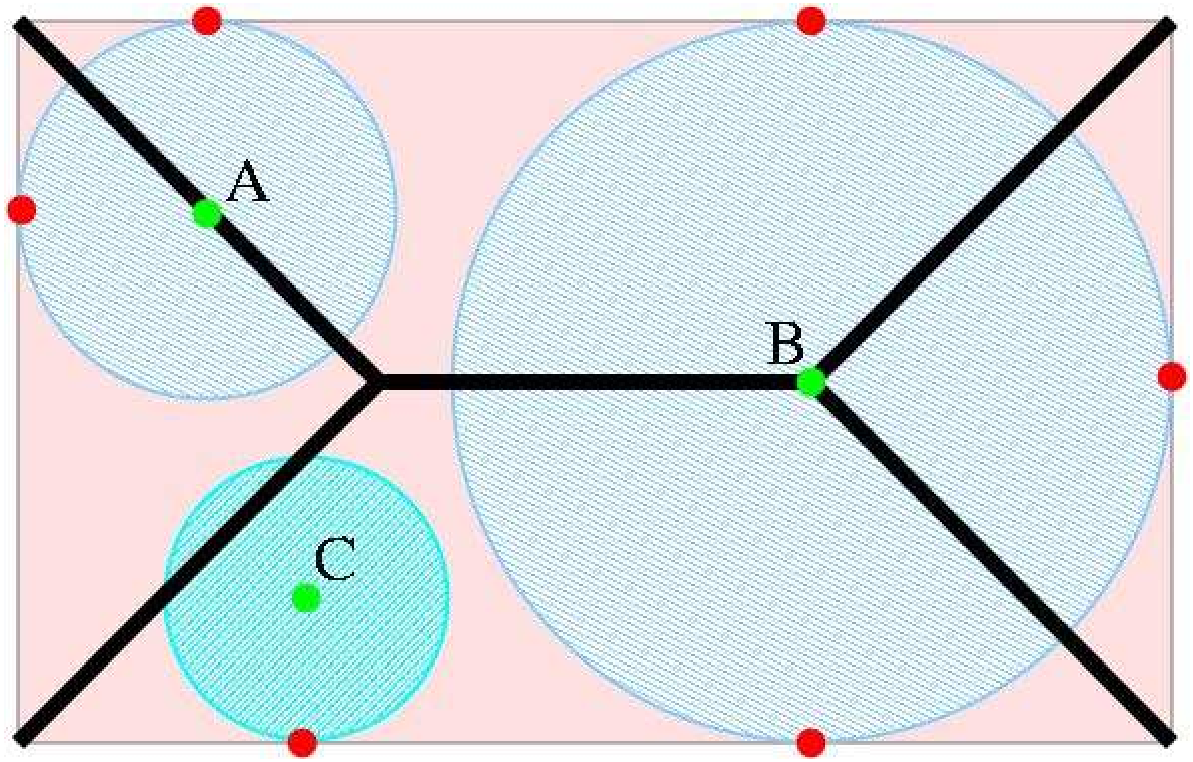
Skeleton

- 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

Skeleton in 2D



Skeleton in 3D

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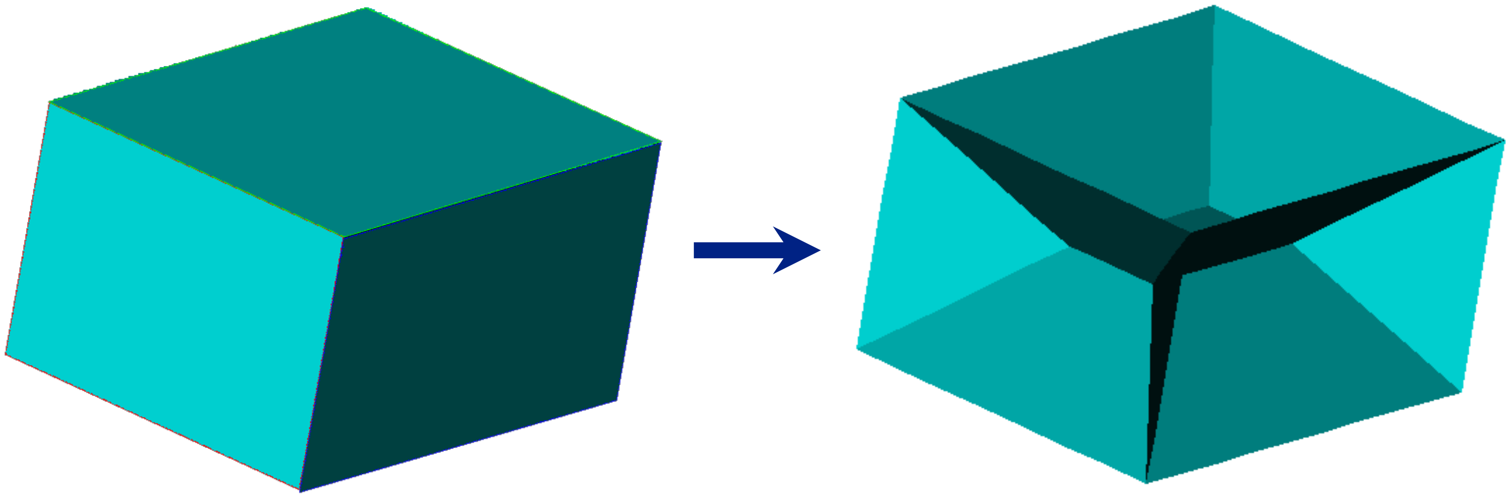
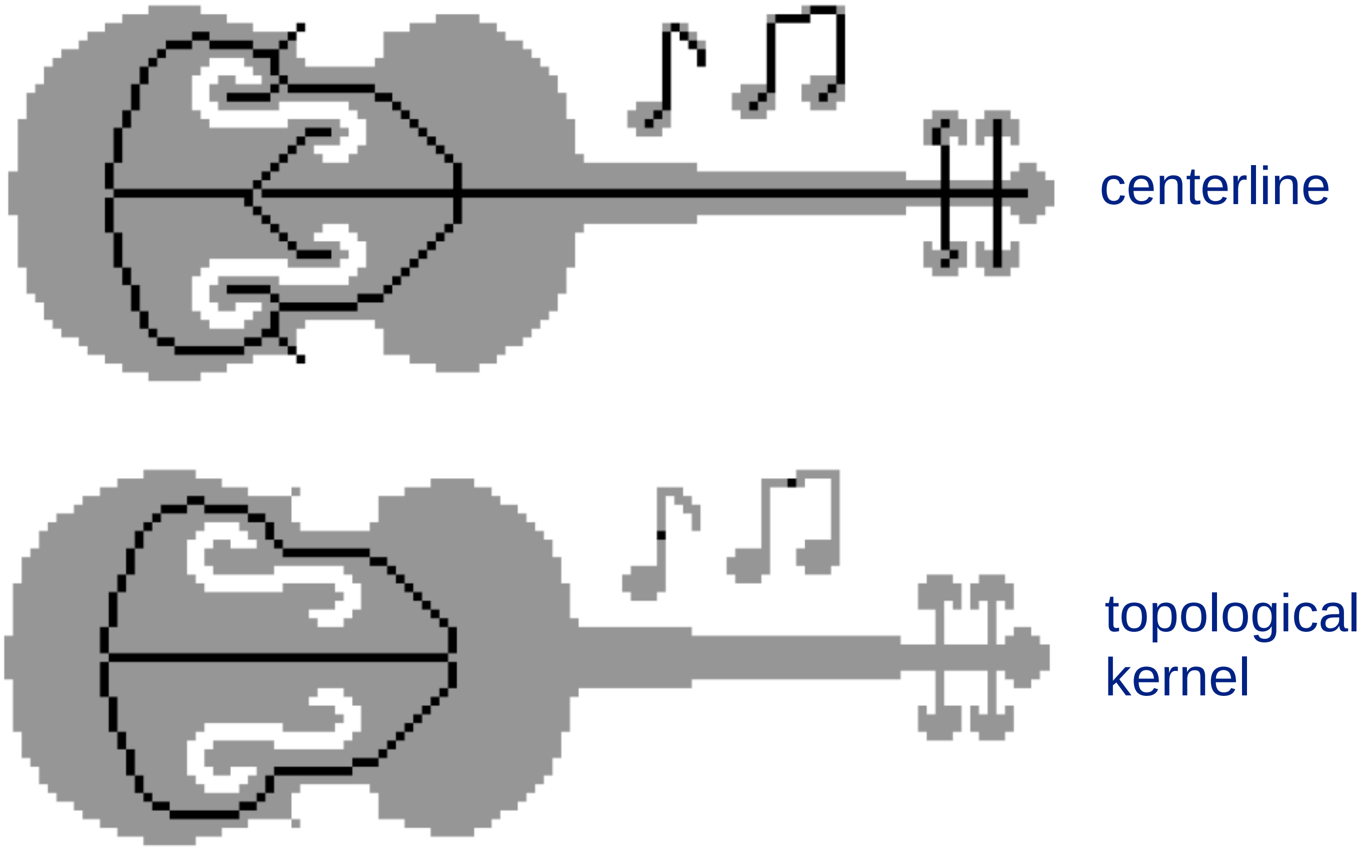


Skeleton

- 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.

Skeleton-like shape features in 2D



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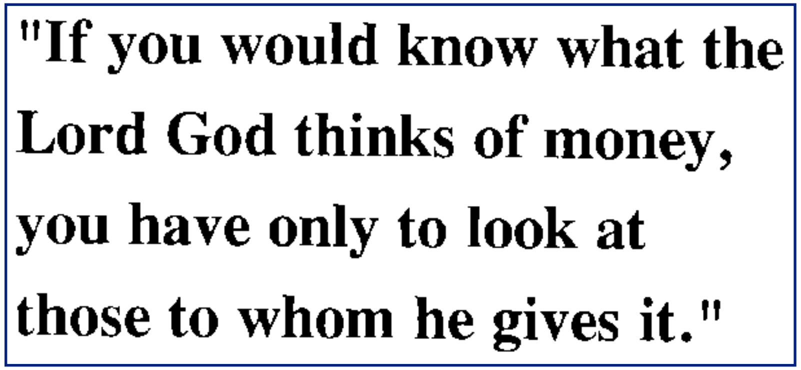
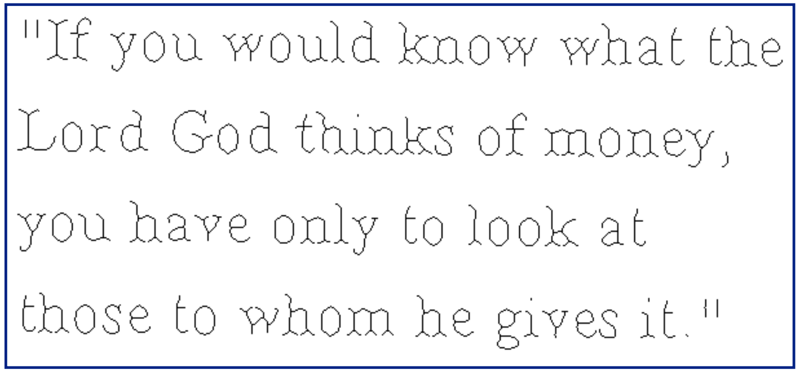
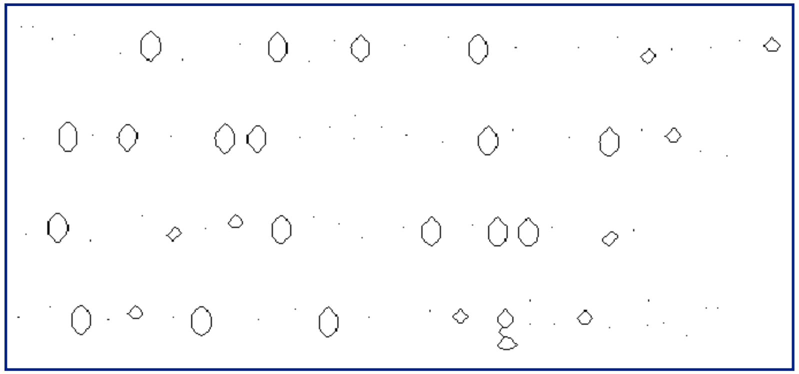
Skeleton-like shape features in 2D



original image

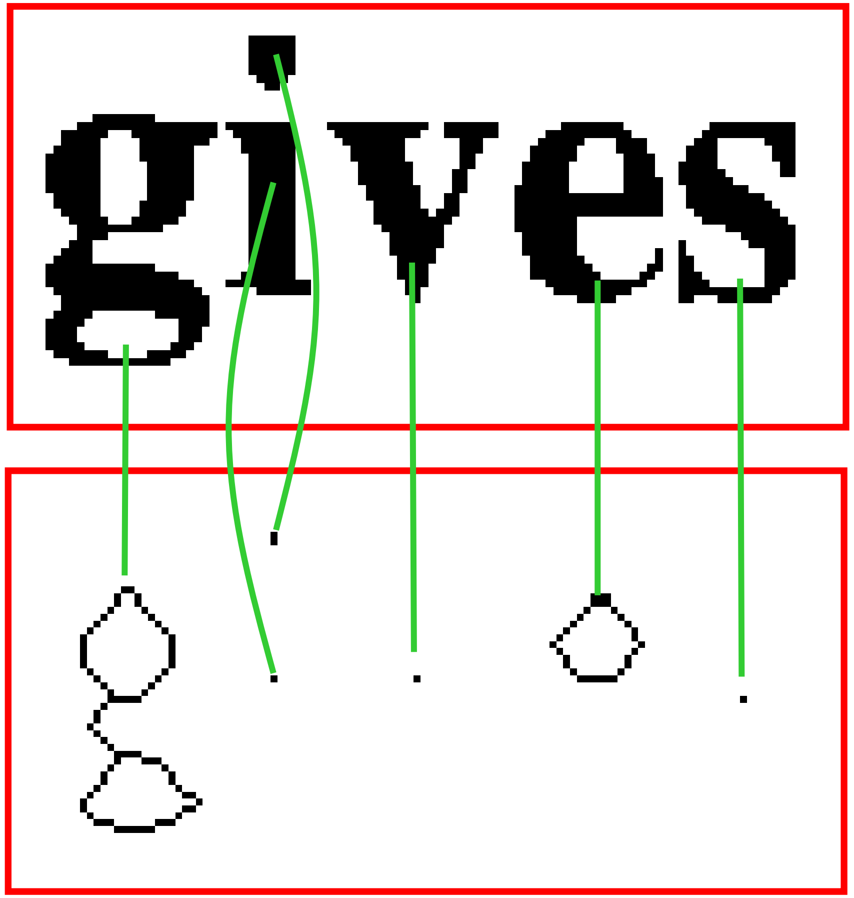


centerline



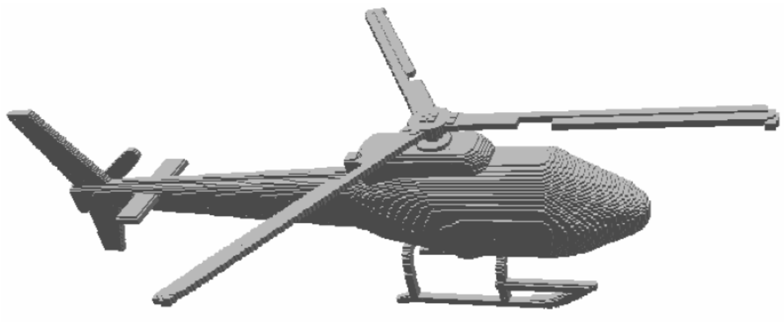
topological kernel

Skeleton-like shape features in 2D

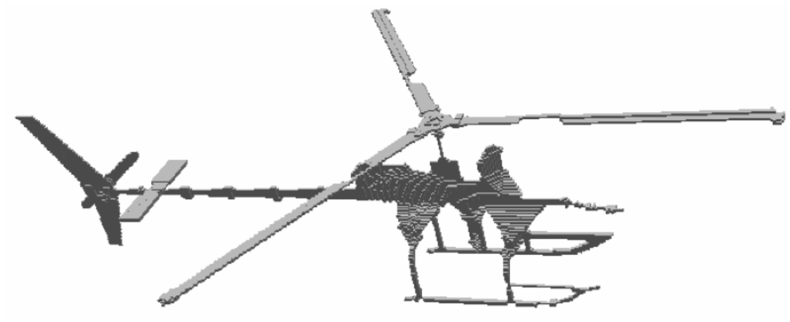


topological kernels
of objects
with/without cavities

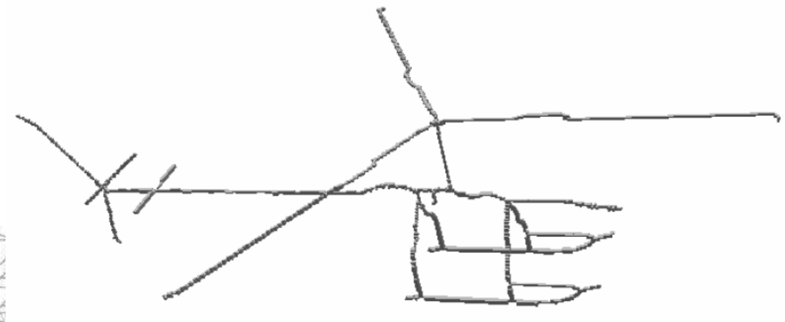
Skeleton-like shape features in 3D



original object



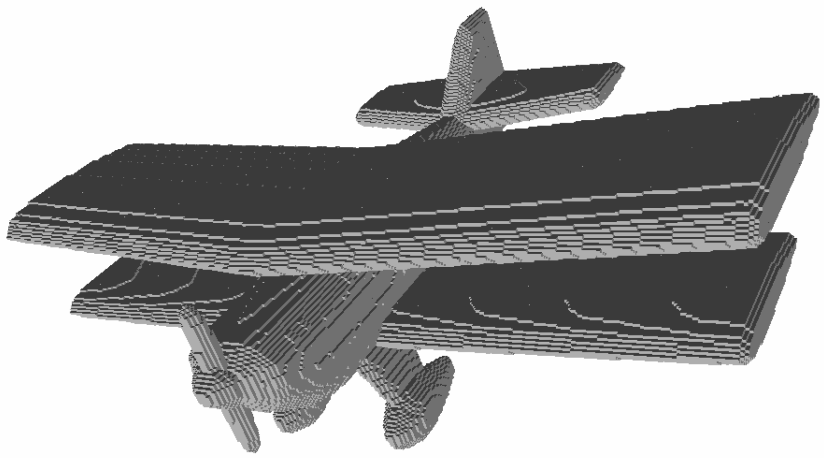
medial surface



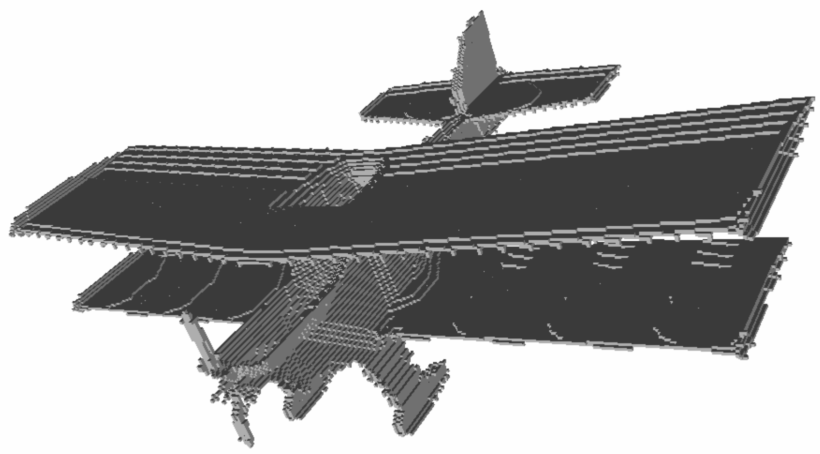
centerline

topological kernel

Skeleton-like shape features in 3D



original object



medial surface

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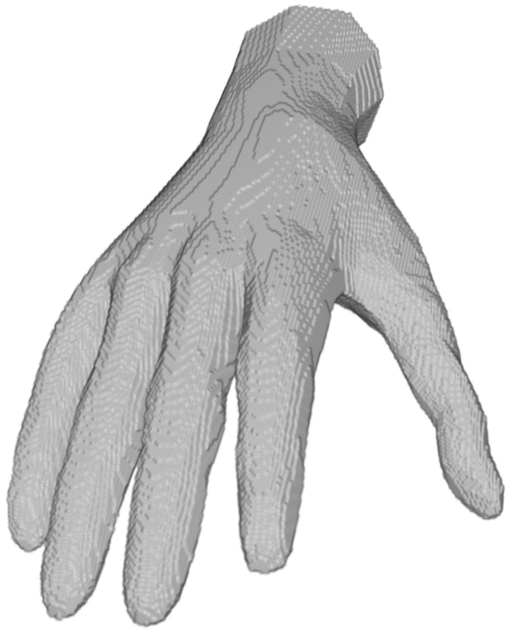
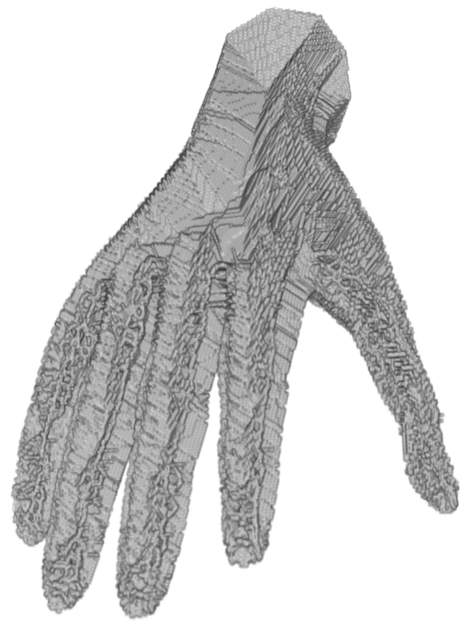
Skeleton-like shape features in 3D

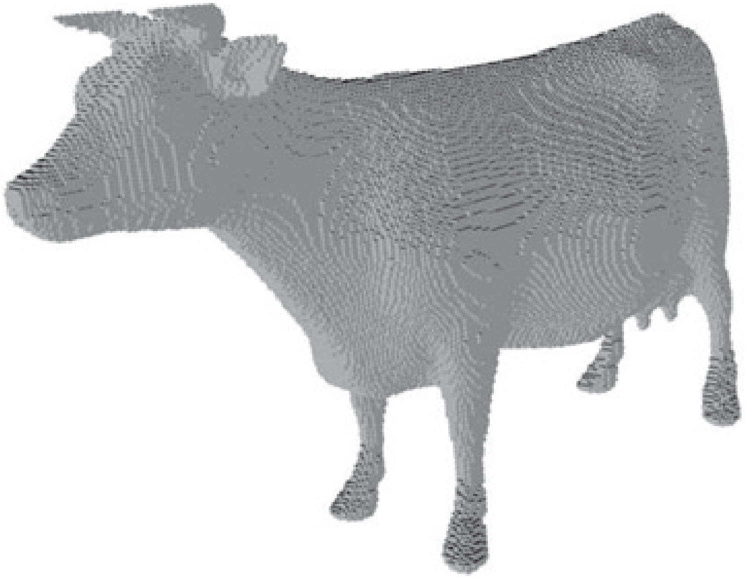


original object



medial surface

Skeleton-like shape features in 3D



original object

centerline

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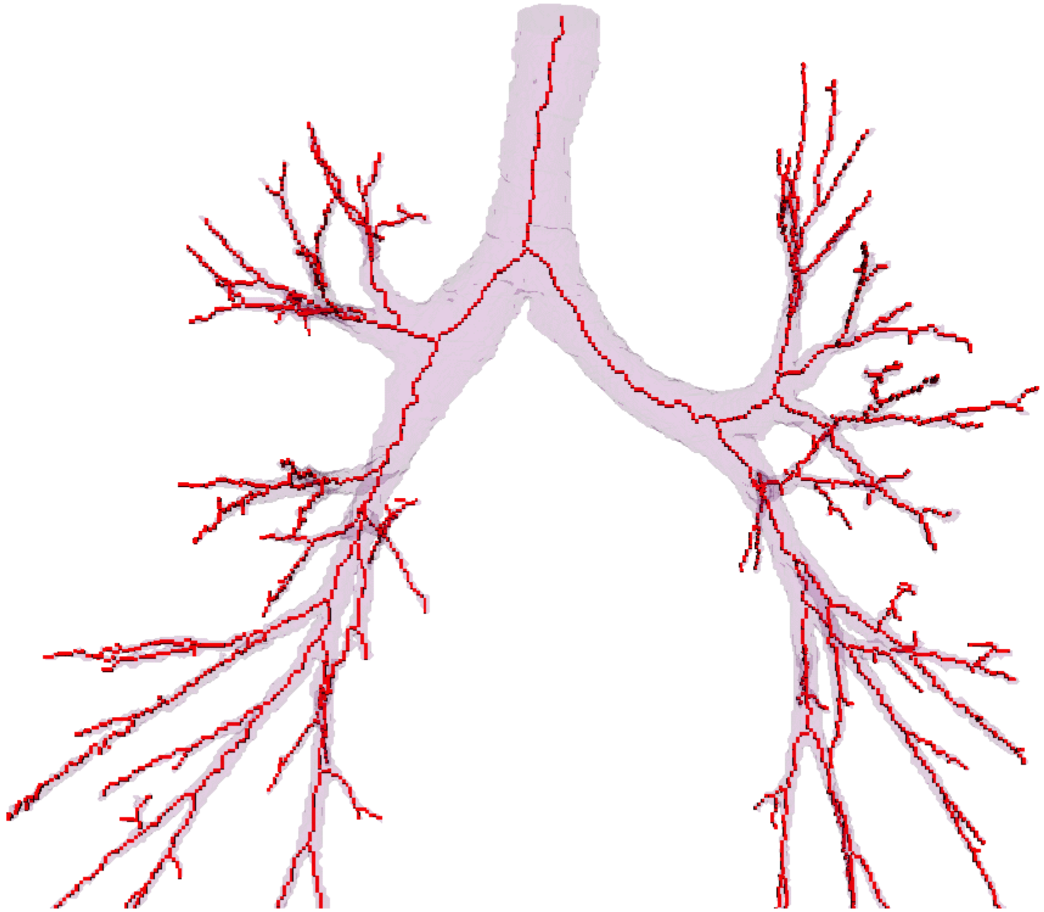
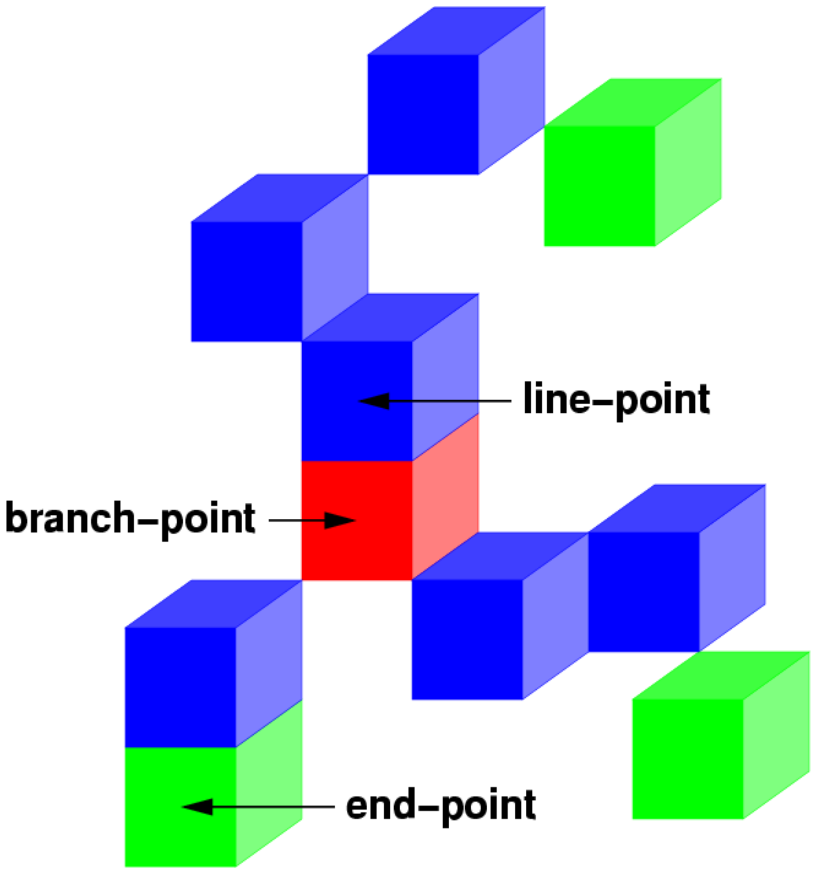
Skeleton-like shape features in 3D



centerline

Skeleton-like shape features in 3D



centerline

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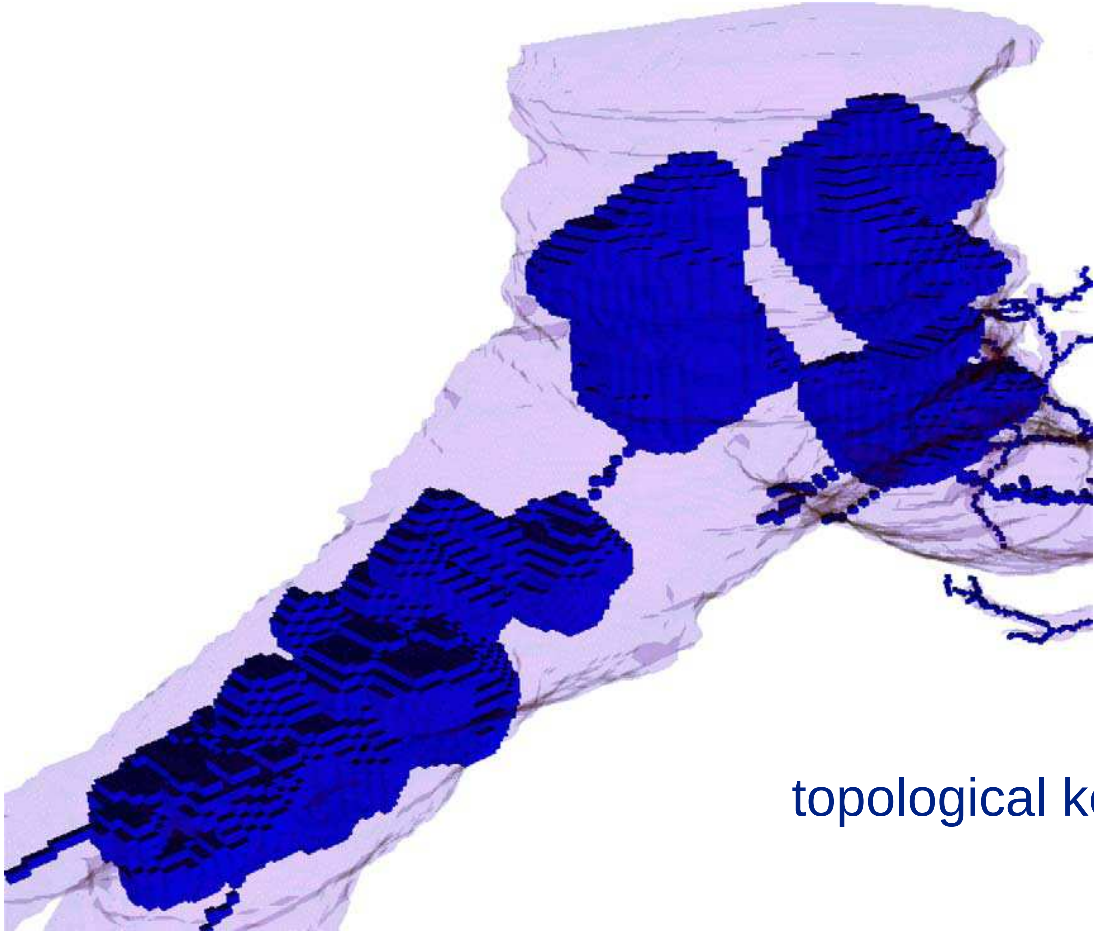
Skeleton-like shape features in 3D



topological kernel

Skeletonization techniques

- Distance-based
- Voronoi-based
- **thinning**

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Thinning

Matryoshka:
Russian nesting wooden doll

original object

reduced structure

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Thinning algorithms

repeat

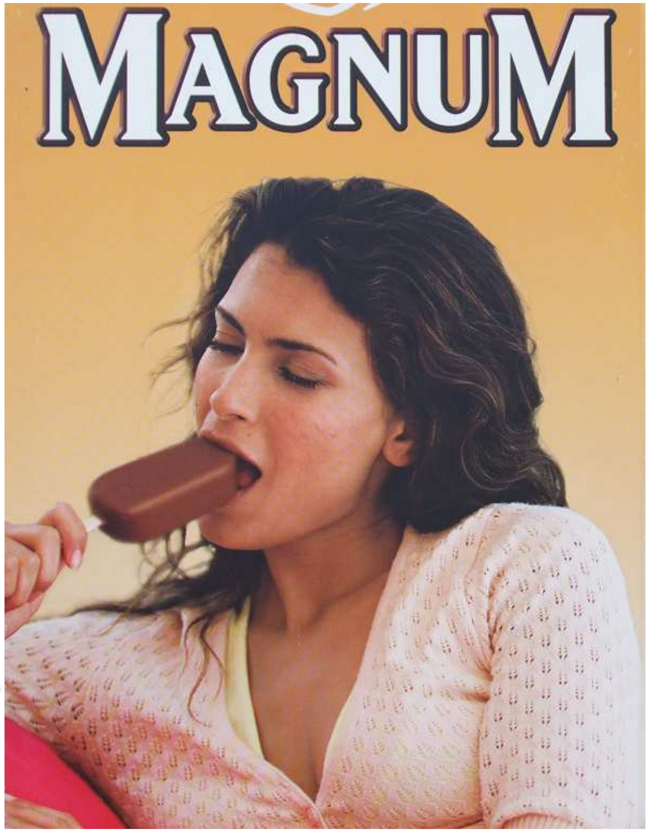
remove „*deletable*" points
from the actual binary image } one iteration step

until no points are deleted

degrees of freedom:

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

Thinning



sequential and parallel approaches

Topology preservation in 2D

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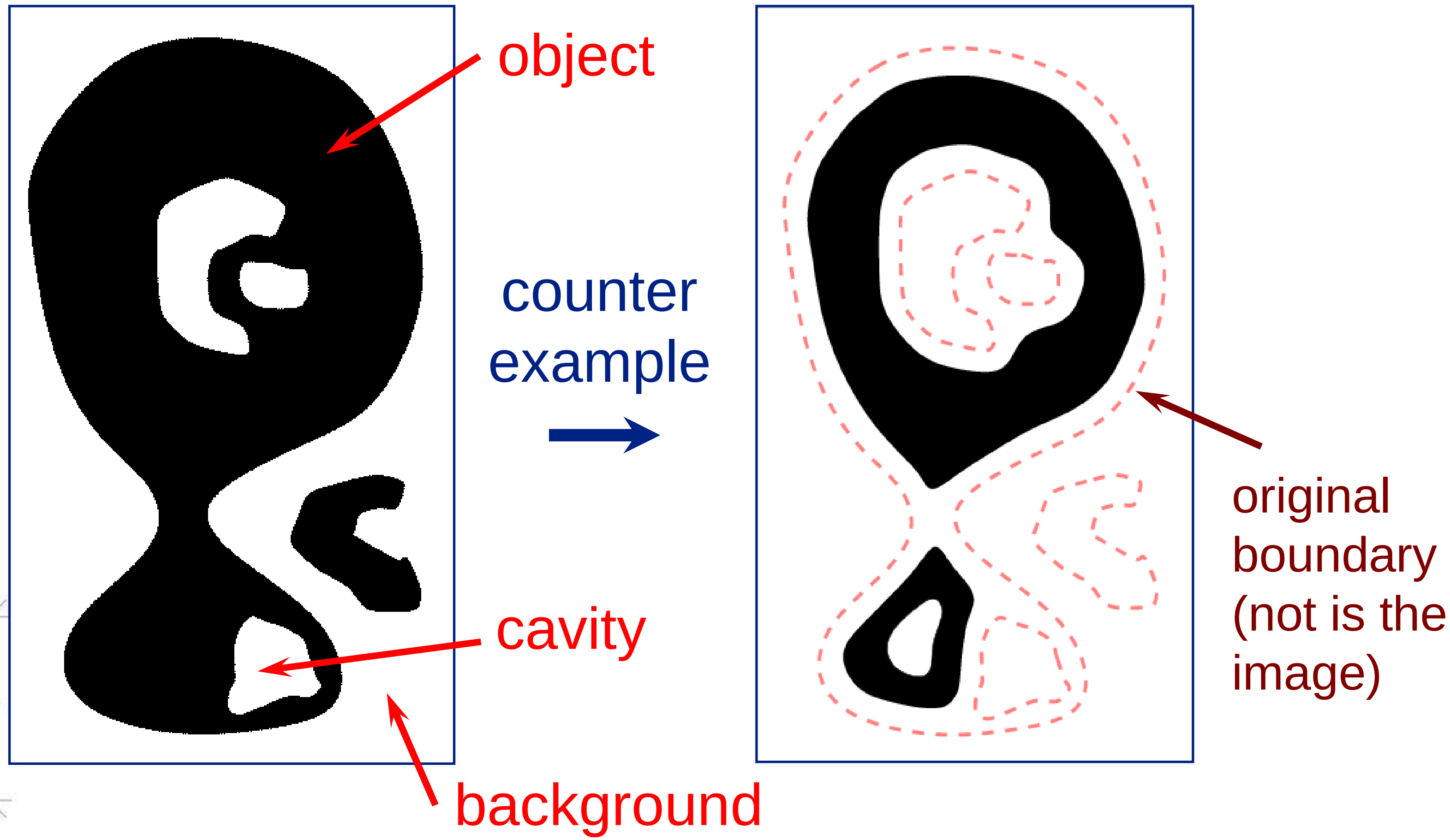
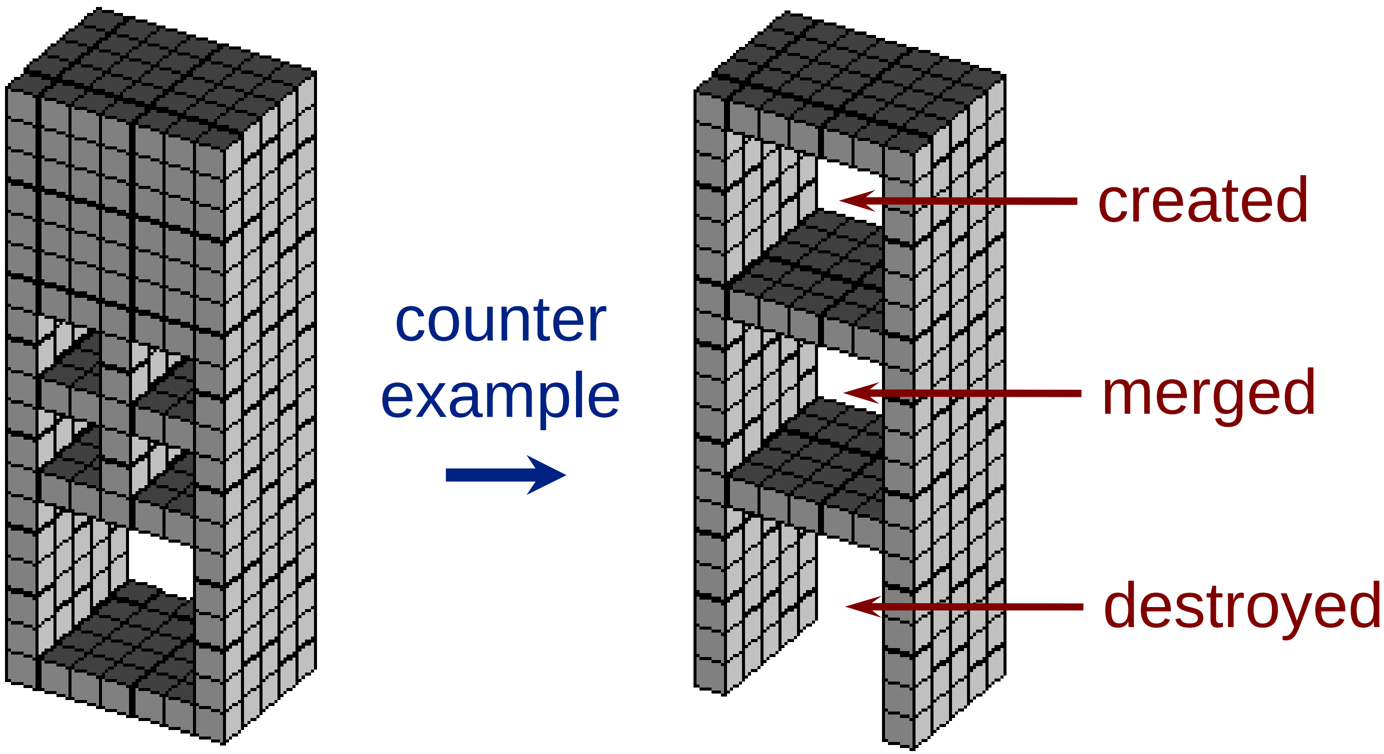
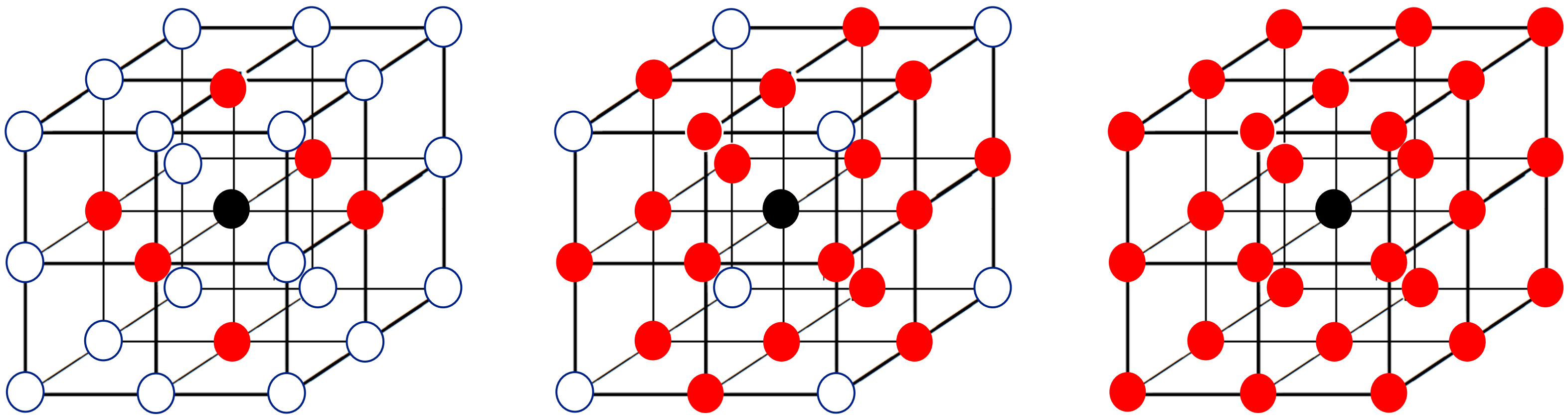


Topology preservation in 3D



Some concepts

Adjacency relations in Z^3



6-adjacency 18-adjacency 26-adjacency

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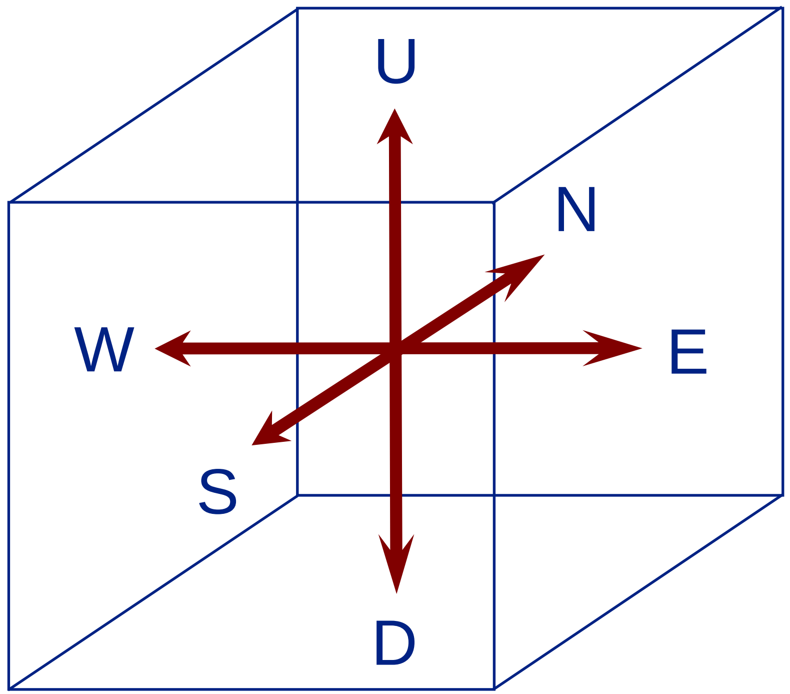
Some concepts

(26,6) **binary digital picture**: ($\boldsymbol{Z}^3$, 26, 6, $\boldsymbol{B}$)

- $\boldsymbol{p} \in \boldsymbol{Z}^3$: point/voxel
- $\boldsymbol{B}$: set of black/object points
  $\boldsymbol{Z}^3 \setminus \boldsymbol{B}$: set of white points
- **object** : maximal 26-connected set of black points
- **background**, **cavity** : maximal 6-connected set of white points

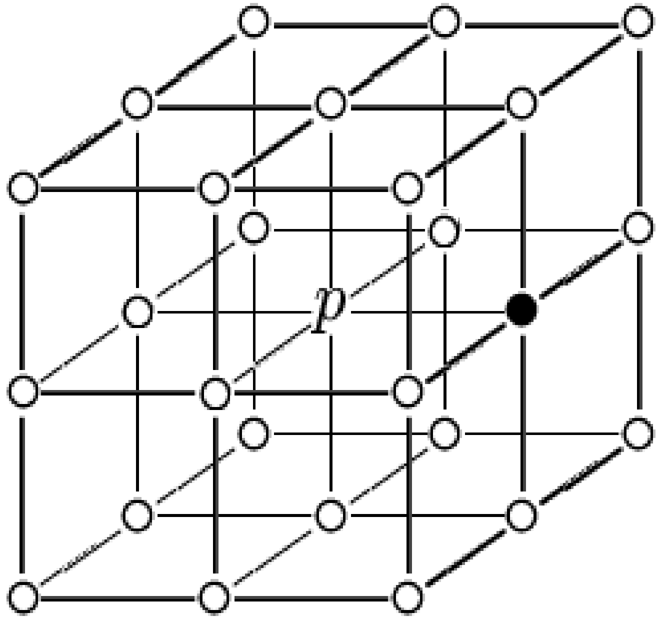
Some concepts



main directions in 3D

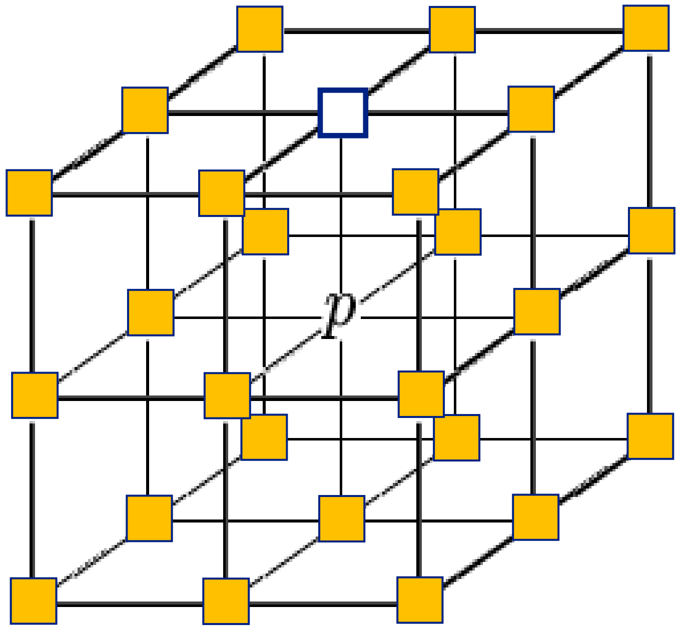
Some concepts

black point *p* is a **line-end point**
if it is adjacent to just one black point



Some concepts

black point *p* is a **border point** if it is 6-adjacent to at least one white point

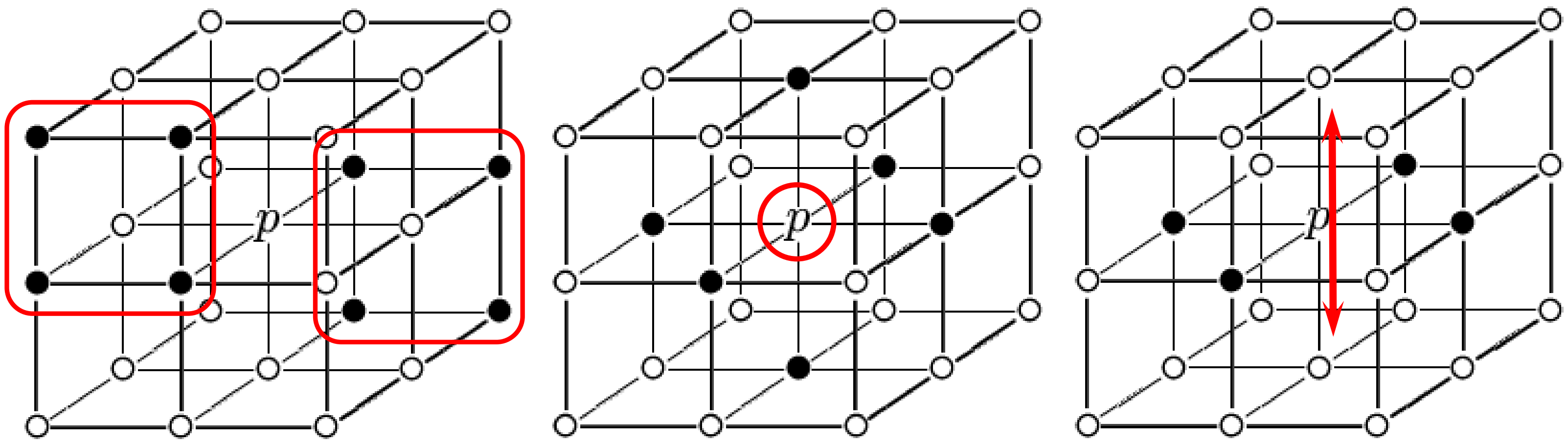


don't care (either 0 or 1)

border point of type U

Some concepts

A black point is **<u>simple</u>** if its deletion preserves the topology of the picture.
Examples of ***non***-simple points in 3D pictures:



splitting an object creating a cavity creating a hole

Some concepts

*Simple*ness is a local property:
It depends on the 3x3x3 neighborhood
of the point in question.

↓

It can be decided by using a precalculated
LUT (look-up table) of size 8 Mbyte.

A 3D sequential curve-thinning algorithm

Palágyi et al. (2006)

K. Palágyi, J. Tschirren, E.A. Hoffman, M. Sonka:
Quantitative analysis of pulmonary airway tree structures,
Computers in Biology and Medicine 36, 974-996, 2006.

A 3D sequential curve-thinning algorithm

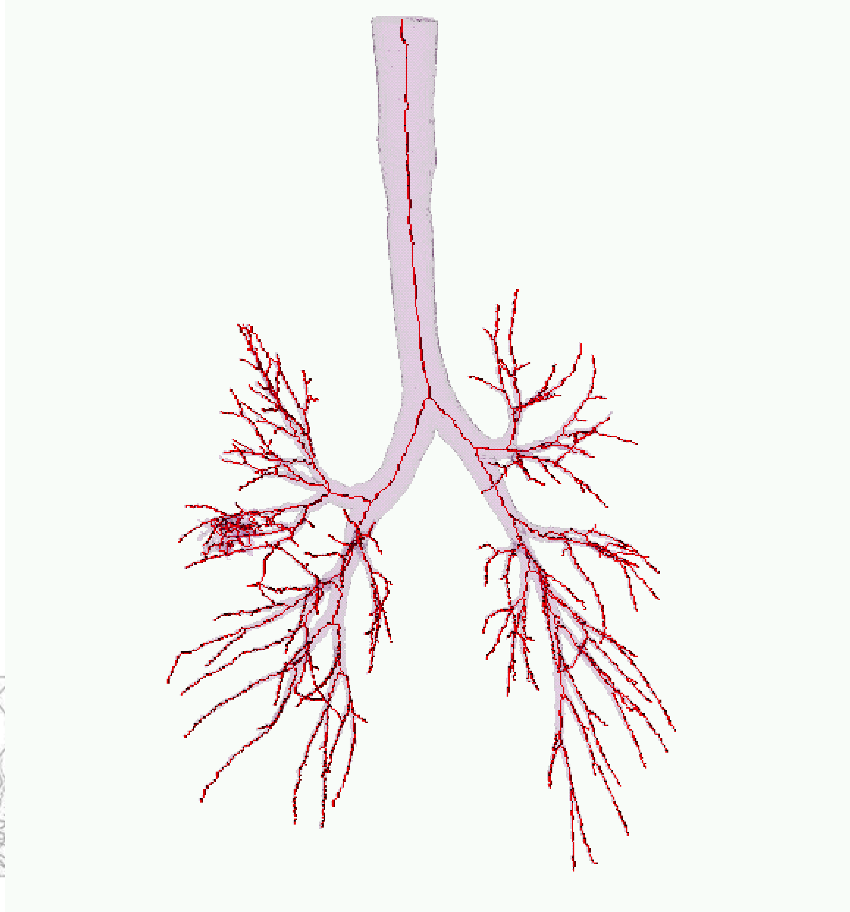
repeat
foreach direction d in {U,N,E,S,W,D} **do**
mark black point p if it is a
- *border* point of type d,
- *not line-end* point, and
- *simple* point

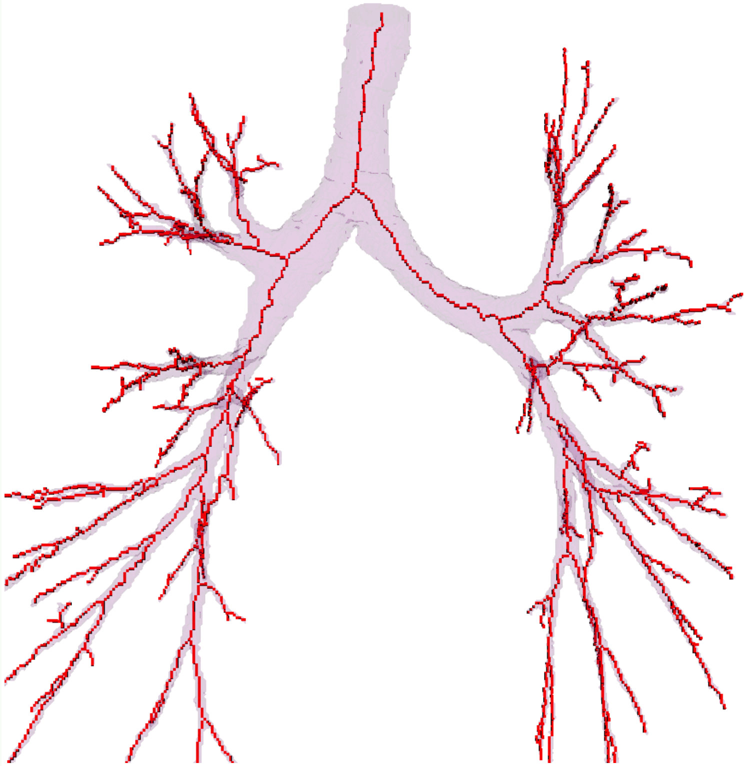
for each marked point q **do**
delete q if it is
- not a *line-end* point, and
- *simple* point in the actual picture

until no points are deleted

Palágyi et al. (*2006*)

A 3D sequential curve-thinning algorithm





Palágyi et al. (*2006*)

A 3D parallel curve-thinning algorithm

Palágyi & Kuba (1998)

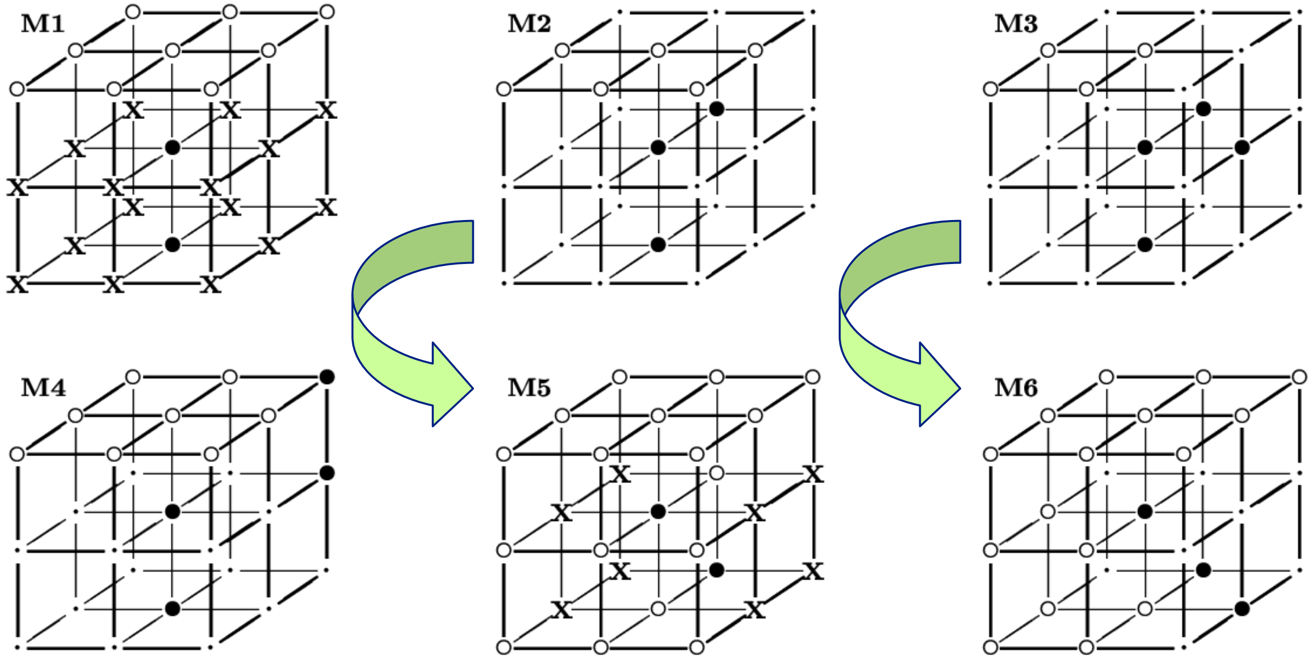
K. Palágyi, A. Kuba:
A 3D 6-subiteration thinning algorithm for extracting medial lines,
Pattern Recognition Letters 19, 613-627, 1998.

A 3D parallel curve-thinning algorithm

repeat
  foreach direction d in {U,N,E,S,W,D} **do**
    simultaneous deletion of black points that satisfy the deletion conditions assigned to deletion direction d
until no points are deleted

Palágyi & Kuba (*1998*)

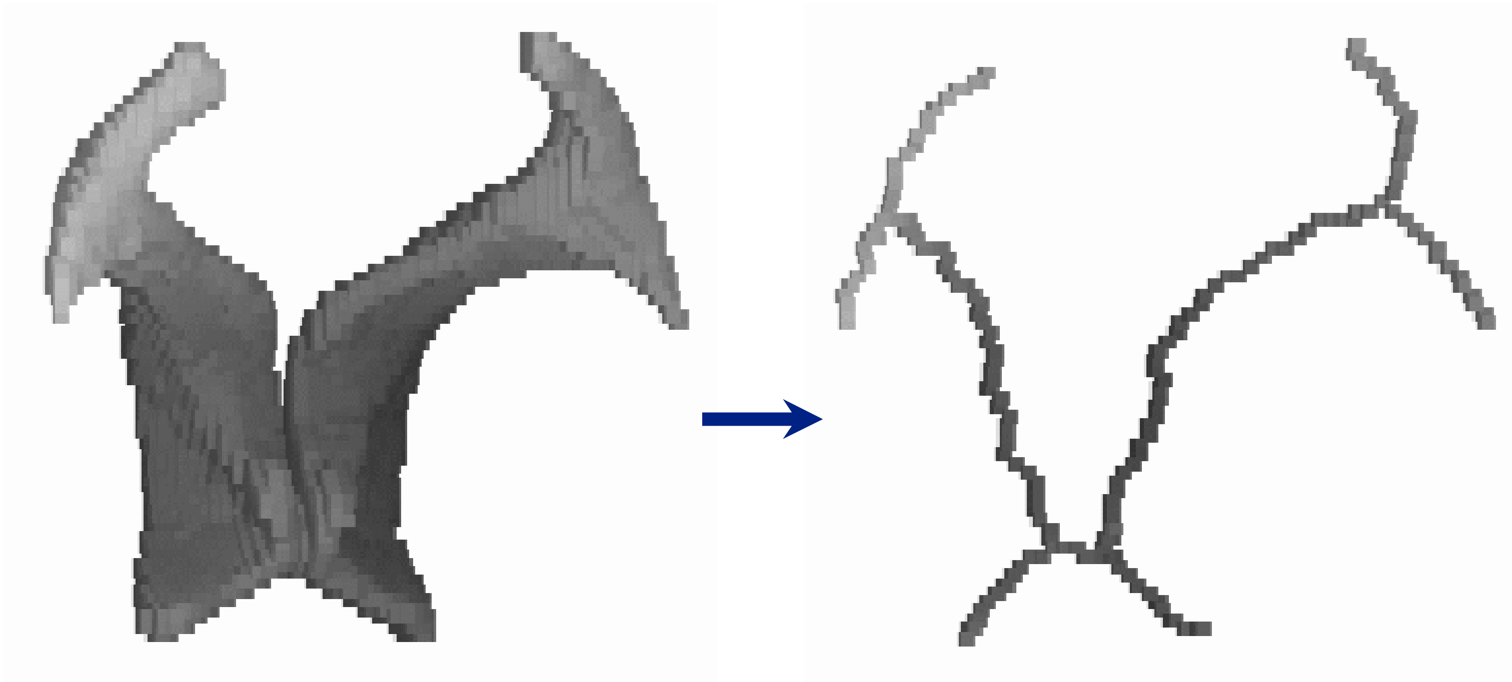
A 3D parallel curve-thinning algorithm



deletion conditions assigned to direction d=U given by a set of matching templates

Palágyi & Kuba (*1998*)

A 3D parallel curve-thinning algorithm



Palágyi & Kuba (1998)

Validating conventional parallel thinning algorithms

Theorem (*C.M. Ma, 1994; T.Y. Kong, 1995*)

A parallel reduction operator is topology preserving for (26,6) pictures if all of the following conditions hold:

1. Only simple points are deleted.
2. For any two, three, or four mutually 18-adjacent points are deleted, these points form a simple set.
3. No object containing mutually 26-adjacent points is deleted completely.

Validating conventional parallel thinning algorithms

parallel reduction

↓

sufficient conditions for topology preservation

↓

correct
(Y/N)

Constructing a new family of parallel thinning algorithms

Palágyi, Németh, Kardos (2012)

K. Palágyi, G. Németh, P. Kardos:
Topology Preserving Parallel 3D Thinning Algorithms,
in V.E. Brimkov, R.P. Barneva (eds.):
Digital Geometry Algorithms. Theoretical Foundations and Applications to Computational Imaging,
Springer, 165-188, 2012.

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Constructing a new family of parallel thinning algorithms

Theorem

Let T be a parallel reduction operator. Let p be any black point in any picture such that point p is deleted by T. Operator T is topology preserving for (26,6) pictures if all of the following conditions hold:

1. Point p is simple.
2. If point p is an element of any set of simple points Q containing two, three, or four mutually 18-adjacent simple points, then Q is a simple set or point p is not the smallest element of Q.
3. Point p is not the smallest element of any object containing mutually 26-adjacent but not mutually 18-adjacent points.

Palágyi, Németh, Kardos (2012)

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Constructing a new family of parallel thinning algorithms

parallel thinning strategies

geometrical contrains

→ new sufficient conditions for topology preservation → topologically correct thinning algorithms

Palágyi, Németh, Kardos (2012)

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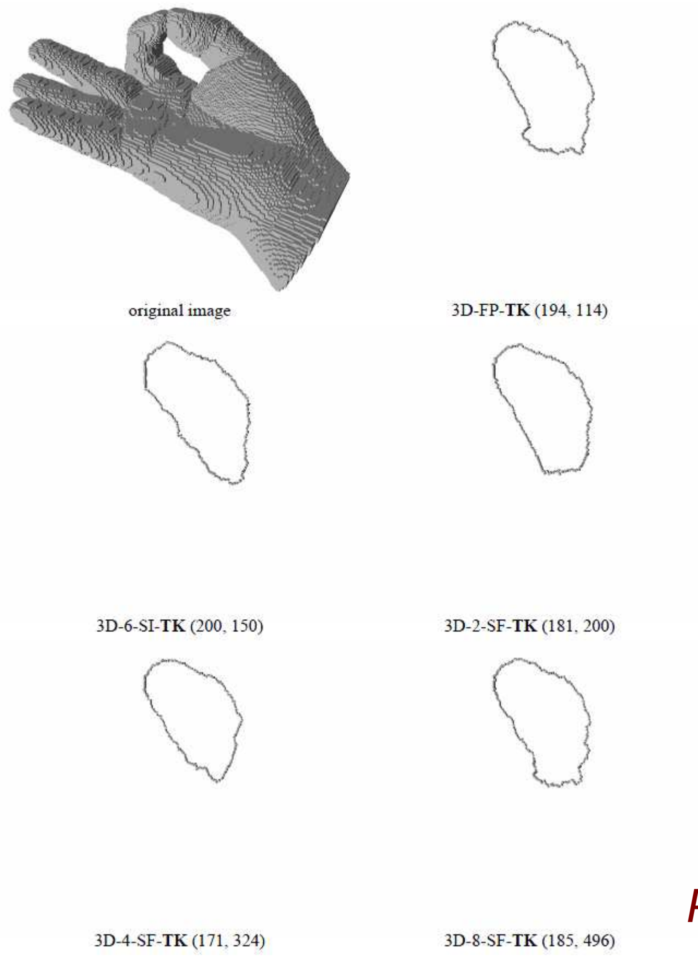
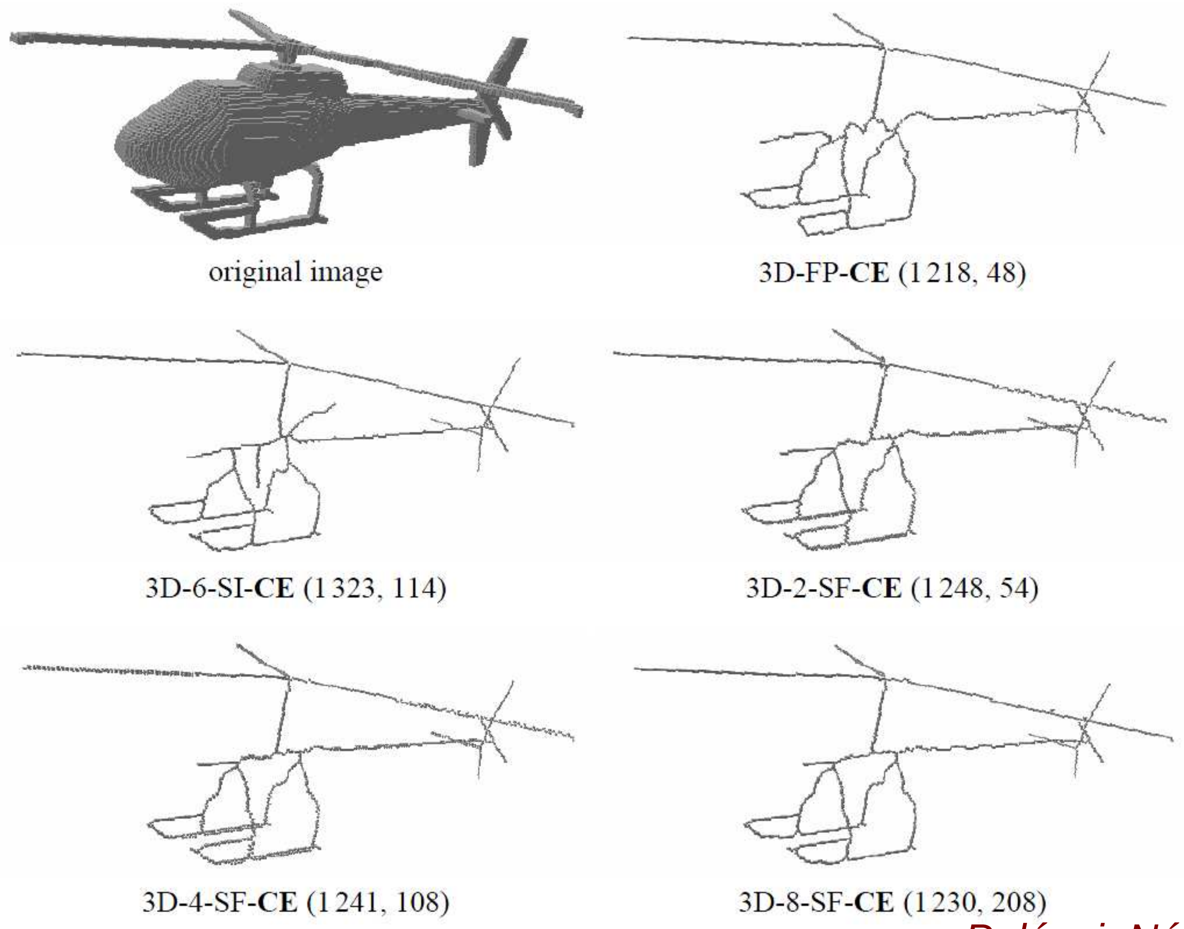
Constructing a new family of parallel thinning algorithms



topological kernels produced by five parallel 3D thinning algorithms

Palágyi, Németh, Kardos (2012)

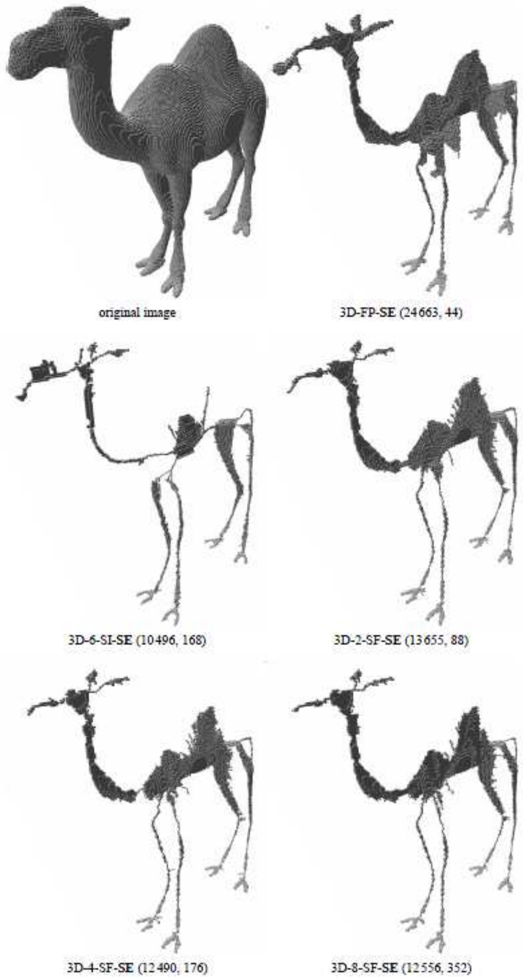
Constructing a new family of parallel thinning algorithms



centerlines produced by five parallel 3D thinning algorithms

Palágyi, Németh, Kardos (2012)

Constructing a new family of parallel thinning algorithms



medial surfaces produced by five parallel 3D thinning algorithms

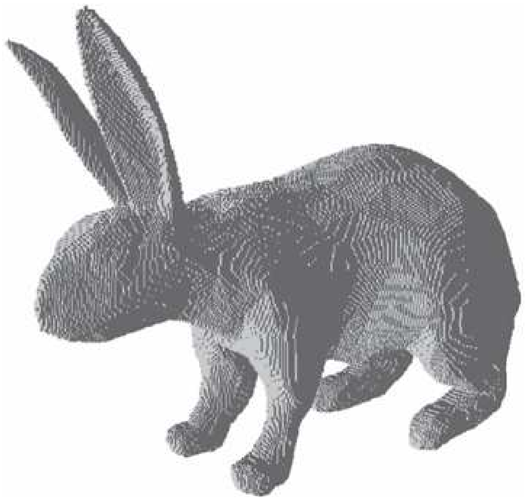
Palágyi, Németh, Kardos (2012)

Thinning combined with iteration-by-iteration smoothing

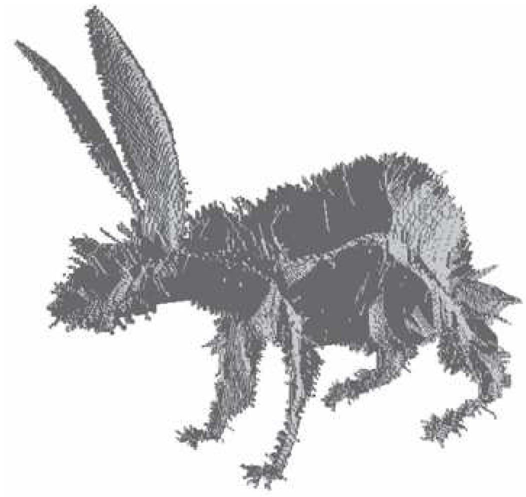
Németh, Kardos, Palágyi (2011)

G. Németh, P. Kardos, K. Palágyi:
Thinning combined with iteration-by-iteration smoothing for 3D binary images,
Graphical Models 73, 335–345, 2011.

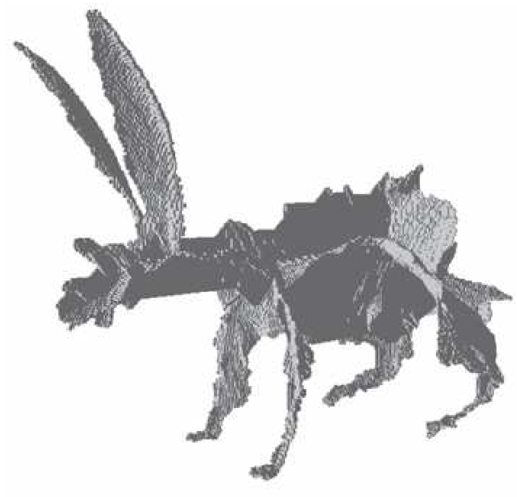
Thinning combined with iteration-by-iteration smoothing



original image



medial surface produced by Gong & Bertrand (1990)



medial surface produced by Gong & Bertrand (1990) with iteration-level smoothing

Németh, Kardos, Palágyi (2011)

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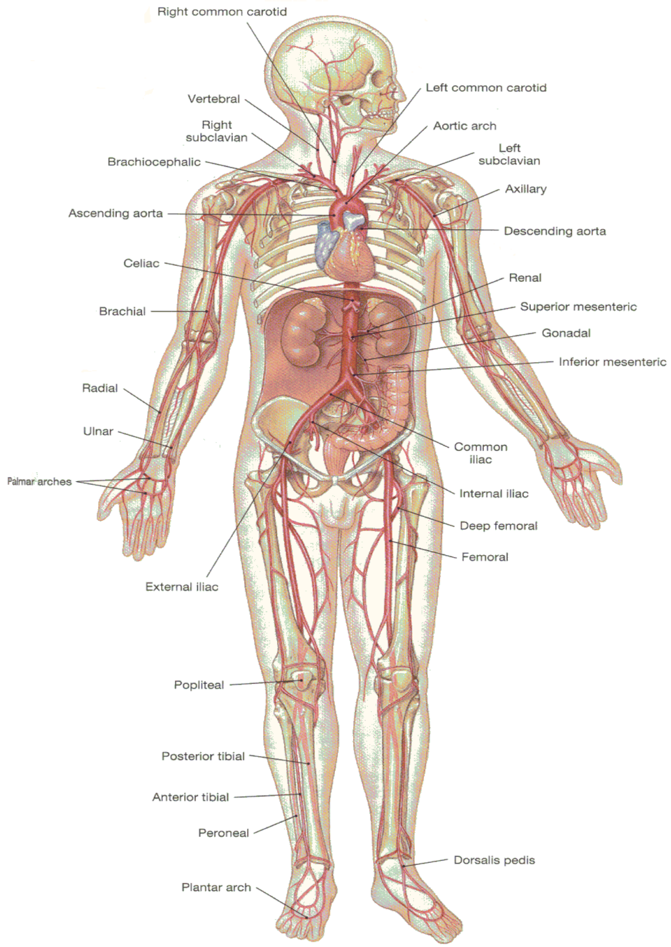
Medical applications

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).



Cooperation with Medical University Graz

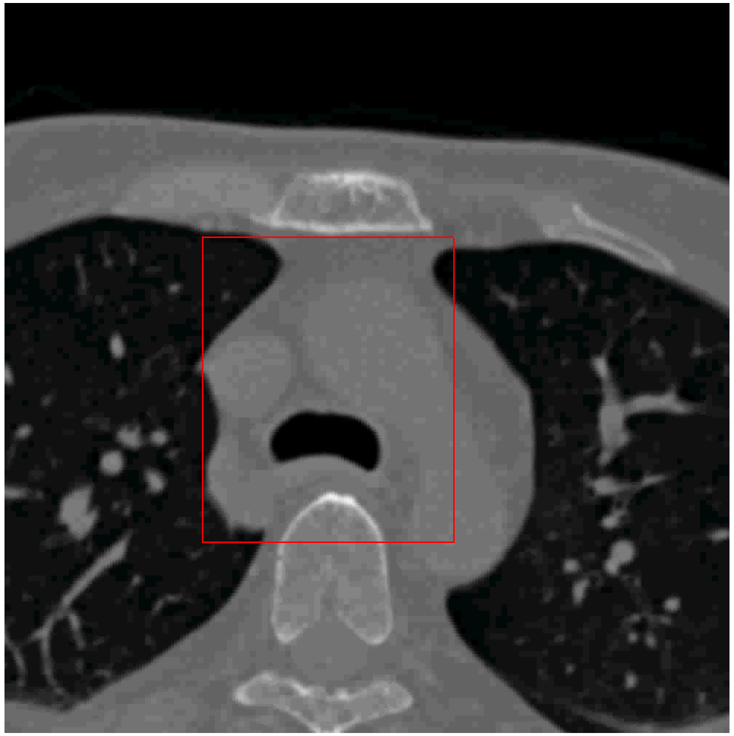
- assessment of laryngotracheal stenosis
- assessment of infrarenal aortic aneurysm
- unravelling the colon

Medical University of Graz

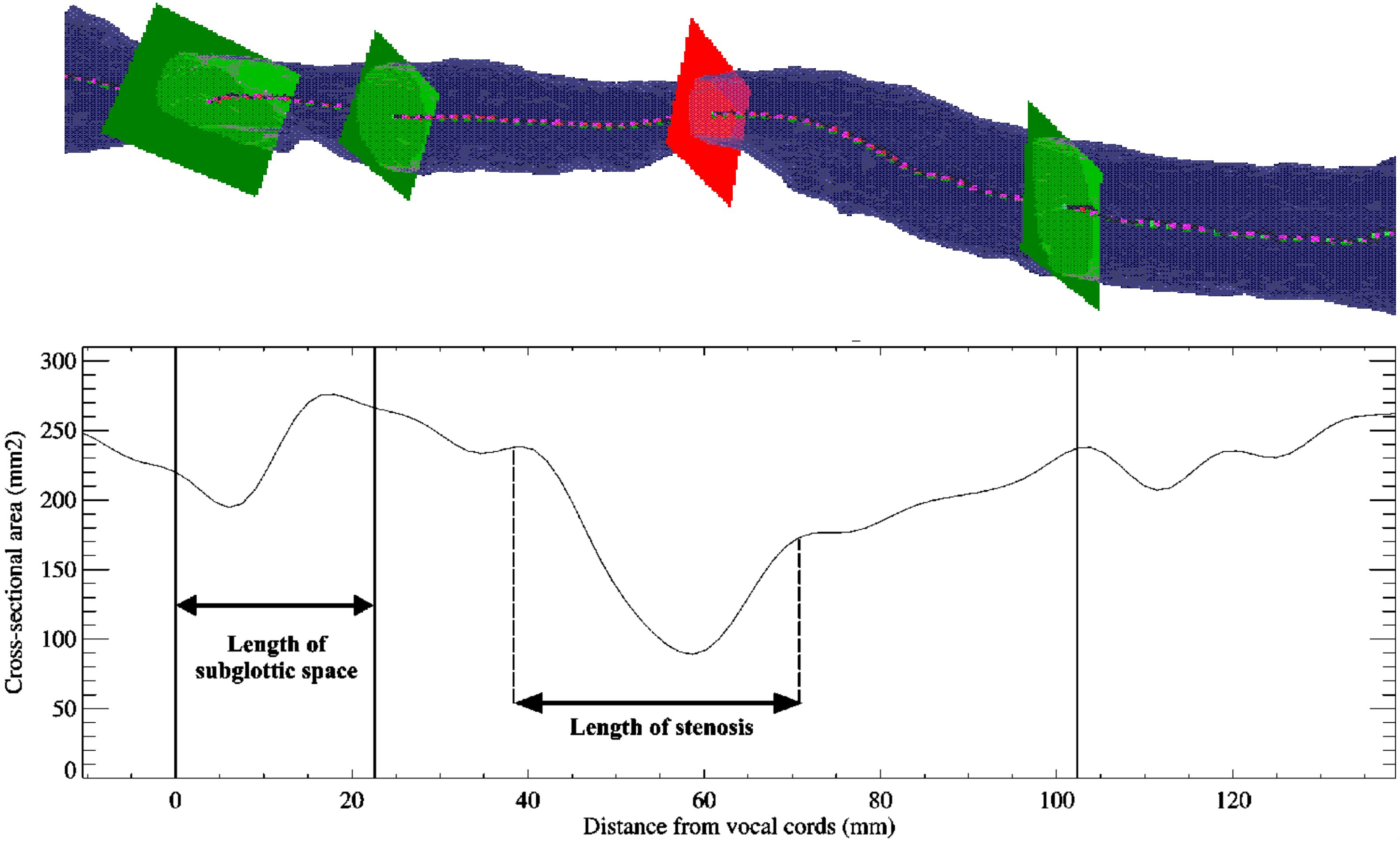
E. Sorantin et al.

Assessment of laryngotracheal stenosis

- Data from multirow detector spiral CT
- Laryngo-Tracheal Tract (LTT) segmentation based on based on fuzzy connectedness
- LTT centerline extraction by 3D curve-thinning
- Diameter estimation based on the LTT cross-sectional profile along the centerline



Assessment of laryngotracheal stenosis



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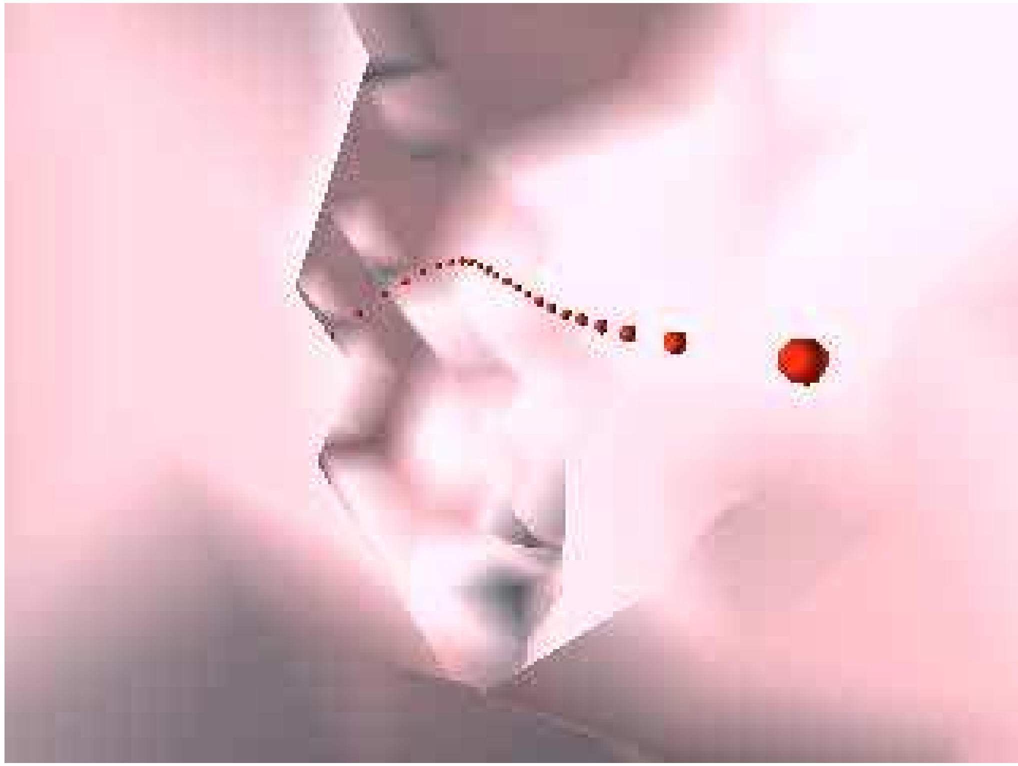
Virtual colonoscopy



Some publications

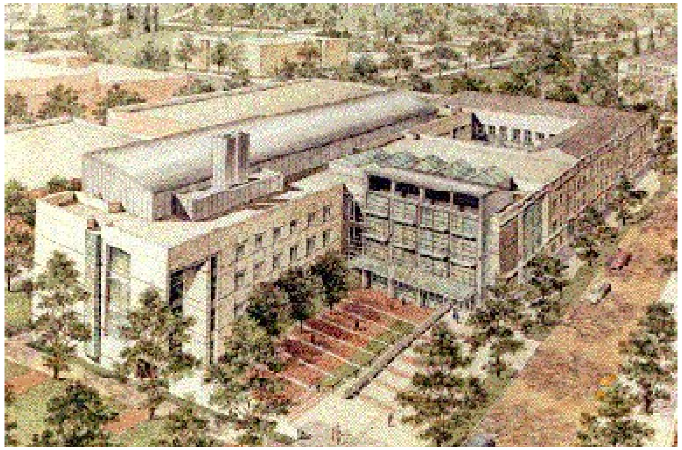
- E. Sorantin, Cs. Halmai, B. Erdôhelyi, K. Palágyi, L.G. Nyúl, L. K. Ollé, B. Geiger, F. Lindbichler, G. Friedrich, K. Kiesler: **Spiral-CT-based assessment of tracheal stenoses using 3-D-skeletonization**, *IEEE Transactions on Medical Imaging* 21, pp. 263-273, 2002.
- E. Sorantin, D. Mohadjer, L.G. Nyúl, K. Palágyi, F. Lindbichler, B. Geiger: **New advances for imaging of laryngotracheal stenosis by post processing of spiral-CT data**, in W. Hruby (ed.) *Digital (R)Evolution in Radiology - Bridging the Future of Health Care*, Springer, pp. 297-308, 2006.
- E. Sorantin, E. Balogh, A. Vilanova i Bartrolí, K. Palágyi, L.G. Nyúl, F. Lindbichler, A. Ruppert: **Virtual dissection of the colon based of spiral CT data**, in E. Neri, D. Caramella, C. Bartolozzi (eds.) *Image Processing in Radiology – Current Applications*, Springer, pp. 257-268, 2008.

Cooperation with The University of Iowa

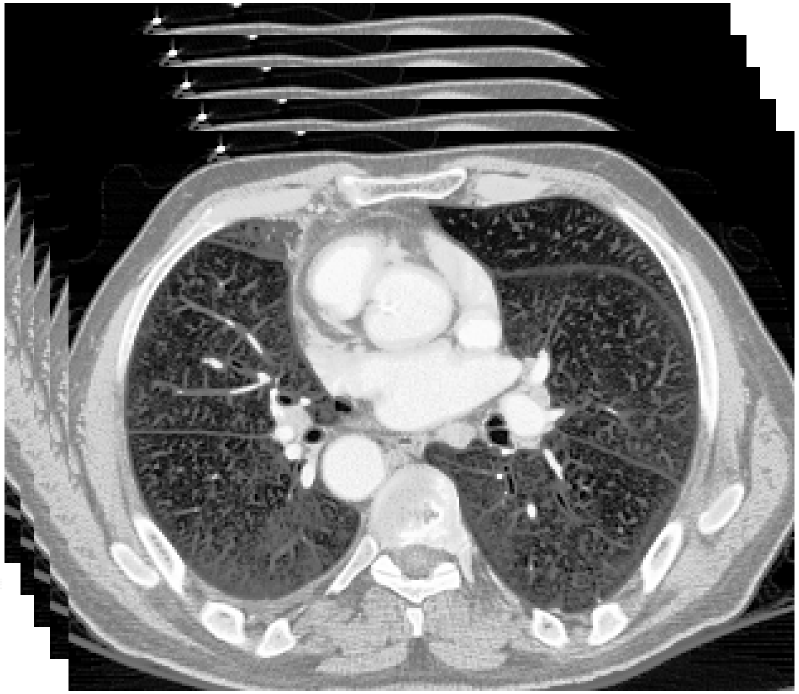
Quantitative analysis of pulmonary airway trees

THE UNIVERSITY OF IOWA

The University of Iowa
College of Engineering Imaging Group



Quantitative analysis of pulmonary airway trees



Multi-detector
Row Spiral CT

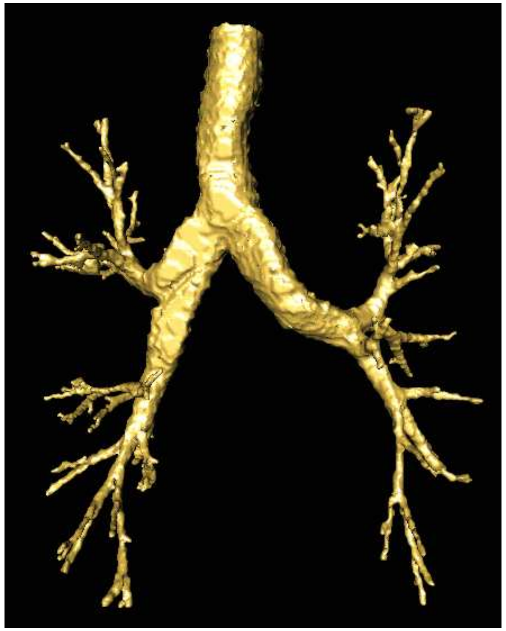
512 x 512 voxels

500 – 600 slices

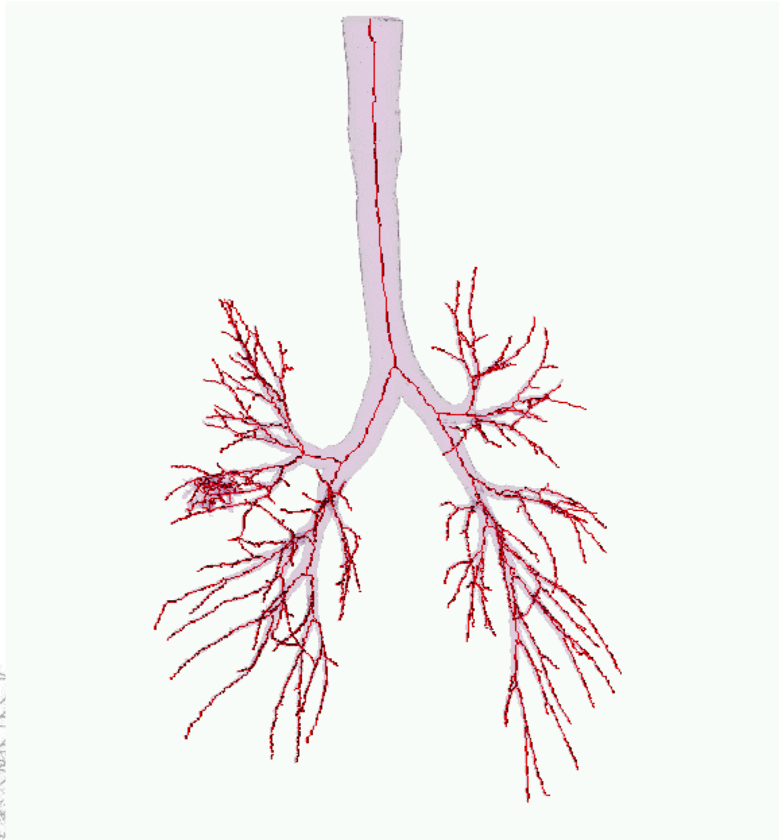
0.65 x 0.65 x 0.6 mm^3
(almost isotropic)

Quantitative analysis of pulmonary airway trees

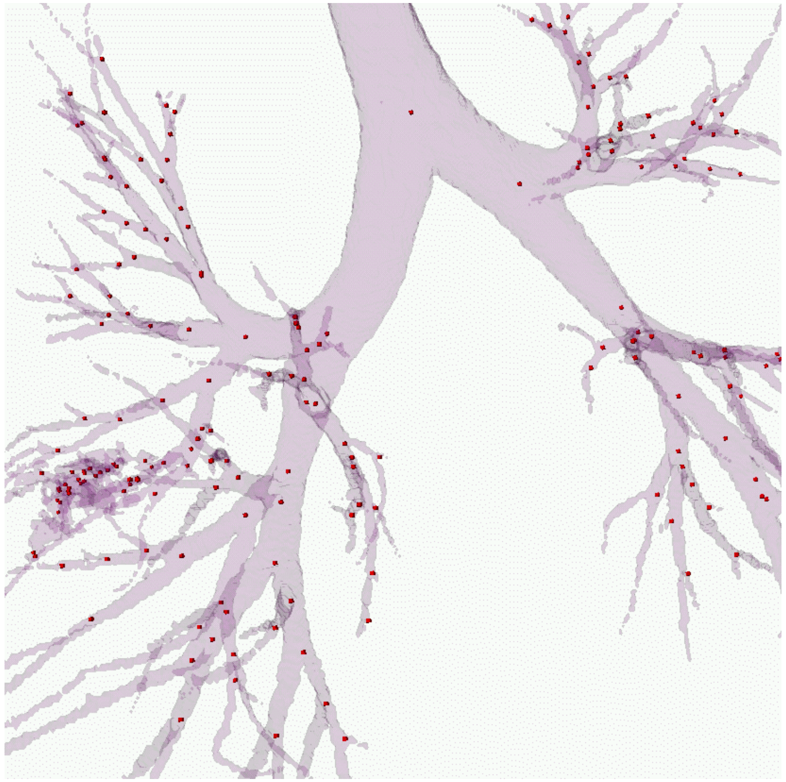
lung segmentation



Quantitative analysis of pulmonary airway trees

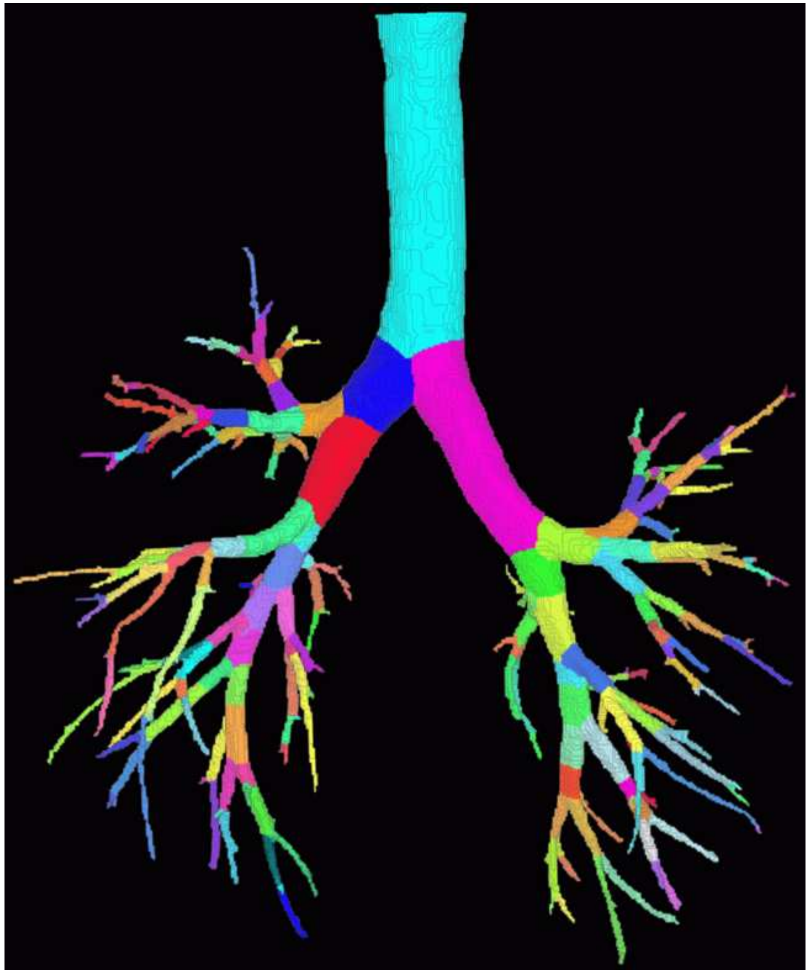


centerline



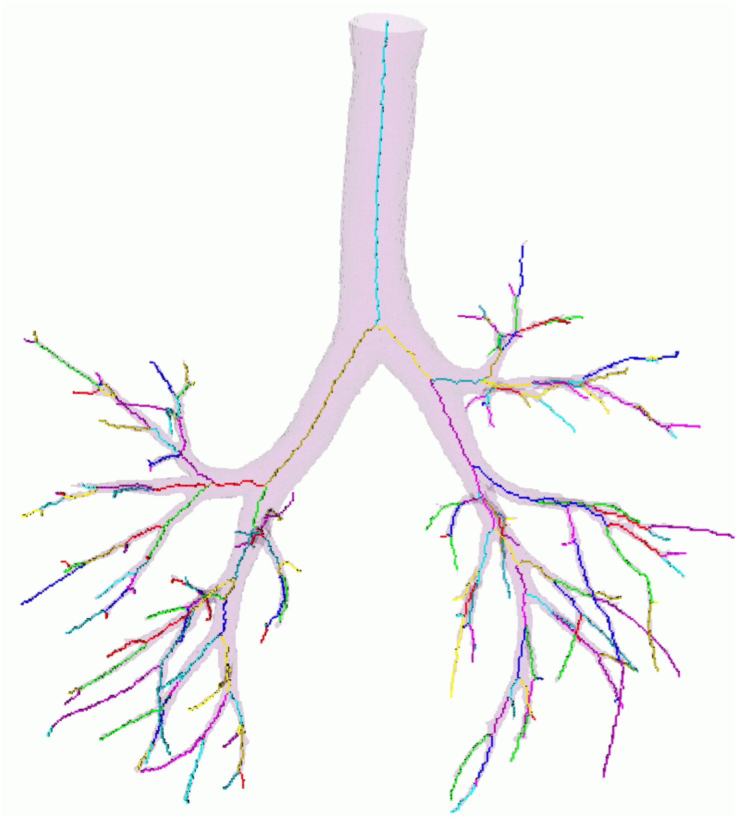
identified branch-points

Quantitative analysis of pulmonary airway trees

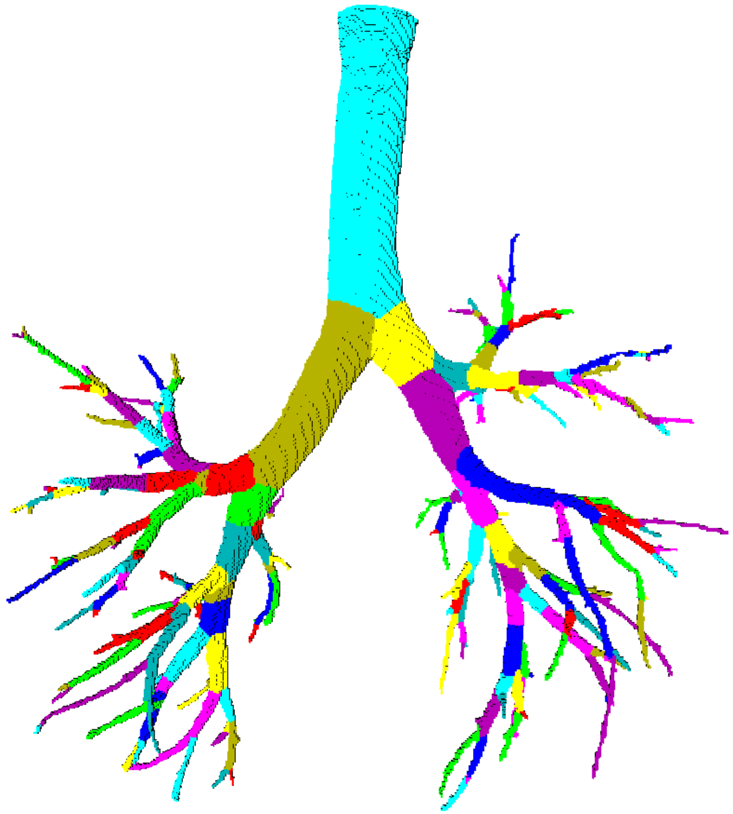


branch partitioning

Quantitative analysis of pulmonary airway trees



centerline labeling



label propagation

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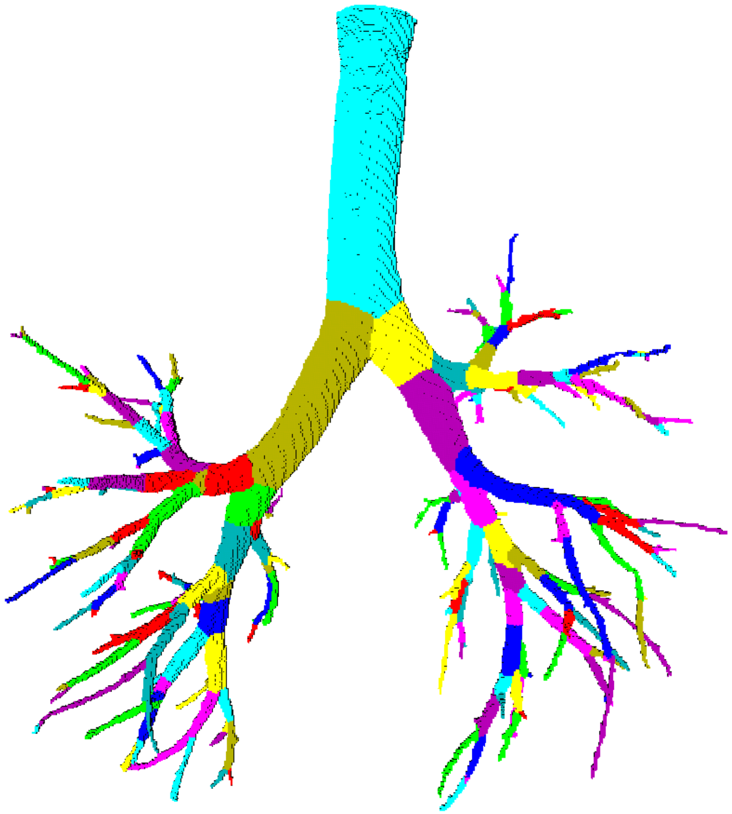
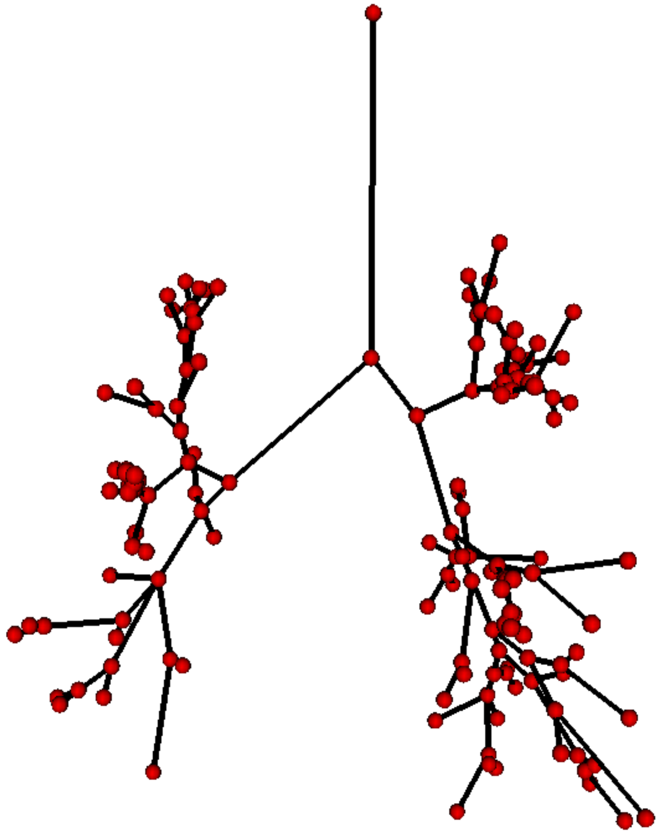
Quantitative analysis of pulmonary airway trees



labeled tree



formal tree (in XML)

Quantitative analysis of pulmonary airway trees

Quantitative indices for tree branches

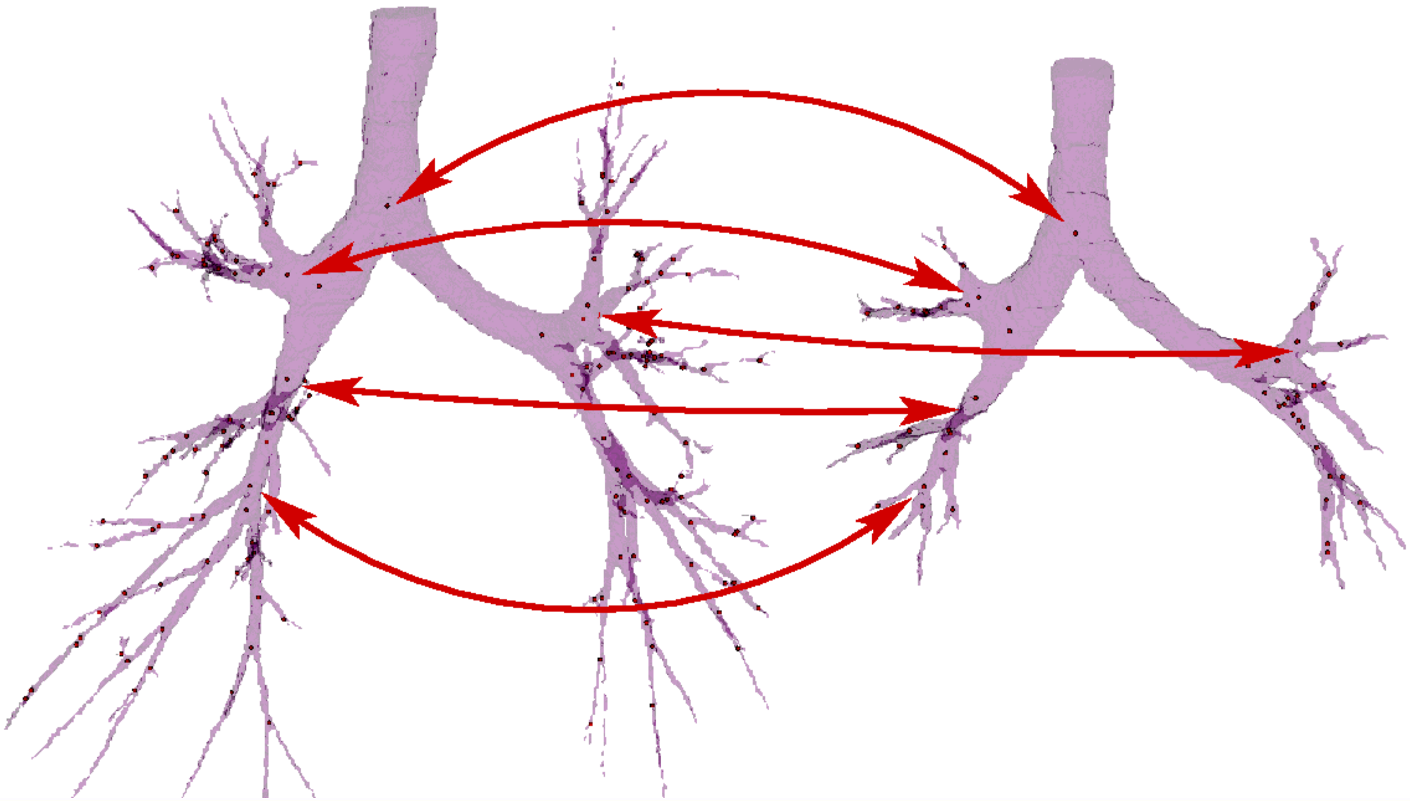
- length (Euclidean distance between the parent and the child branch points)
- volume (volume of all voxels belonging to the branch)
- surface area (surface area of all boundary voxels belonging to the branch)
- average diameter (assuming cylindric segments)

Quantitative analysis of pulmonary airway trees

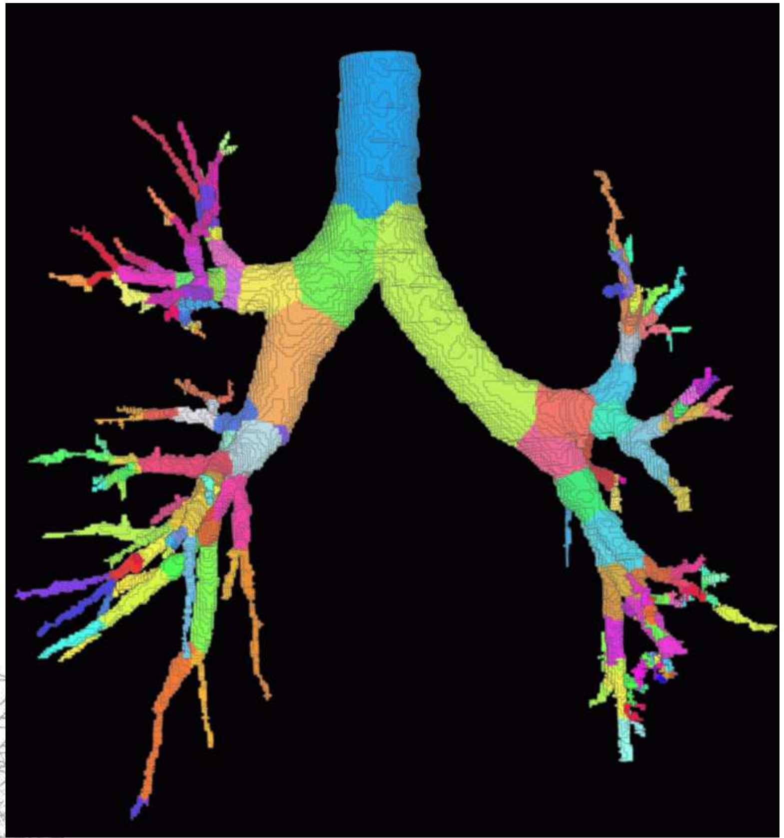
- The automated method for skeletonization, branch-point identification and quantitative analysis of tubular tree structures is robust, efficient, and highly reproducible
- The method was validated in computer and physical phantoms and in vivo CT scans of human lungs.
- The validation studies demonstrated high reproducibility of derived quantitative indices of the tubular structures (p<<0.001).

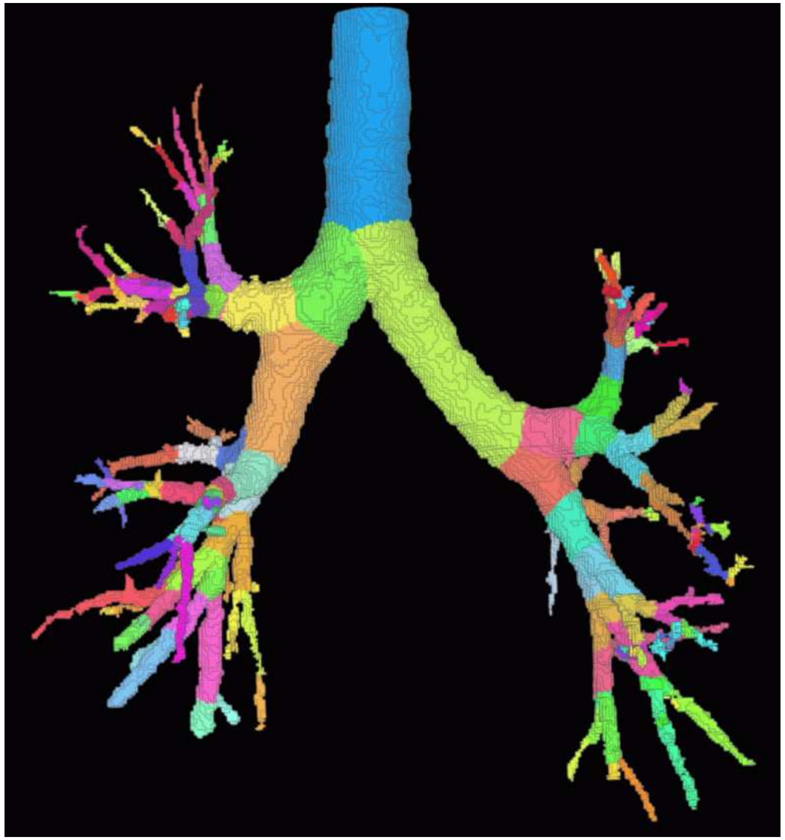
Tree matching

based on identified branch-points in the centerlines

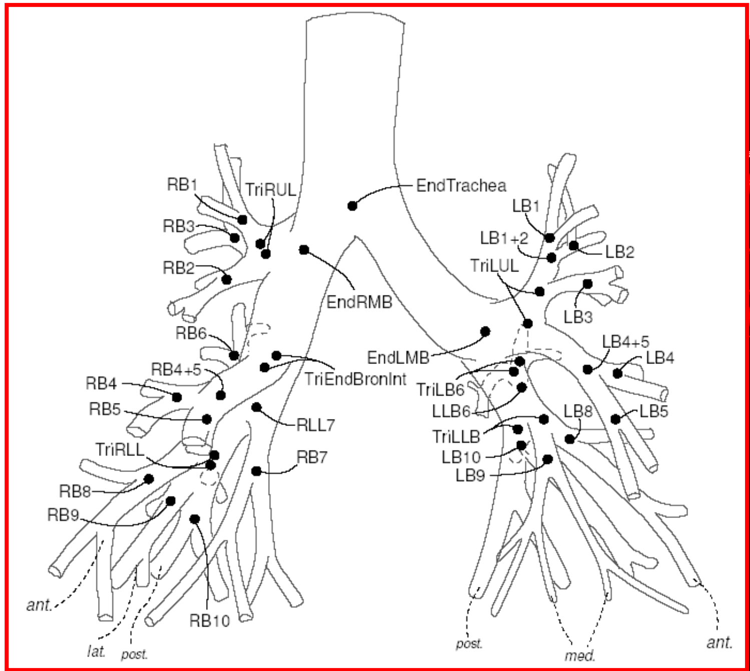


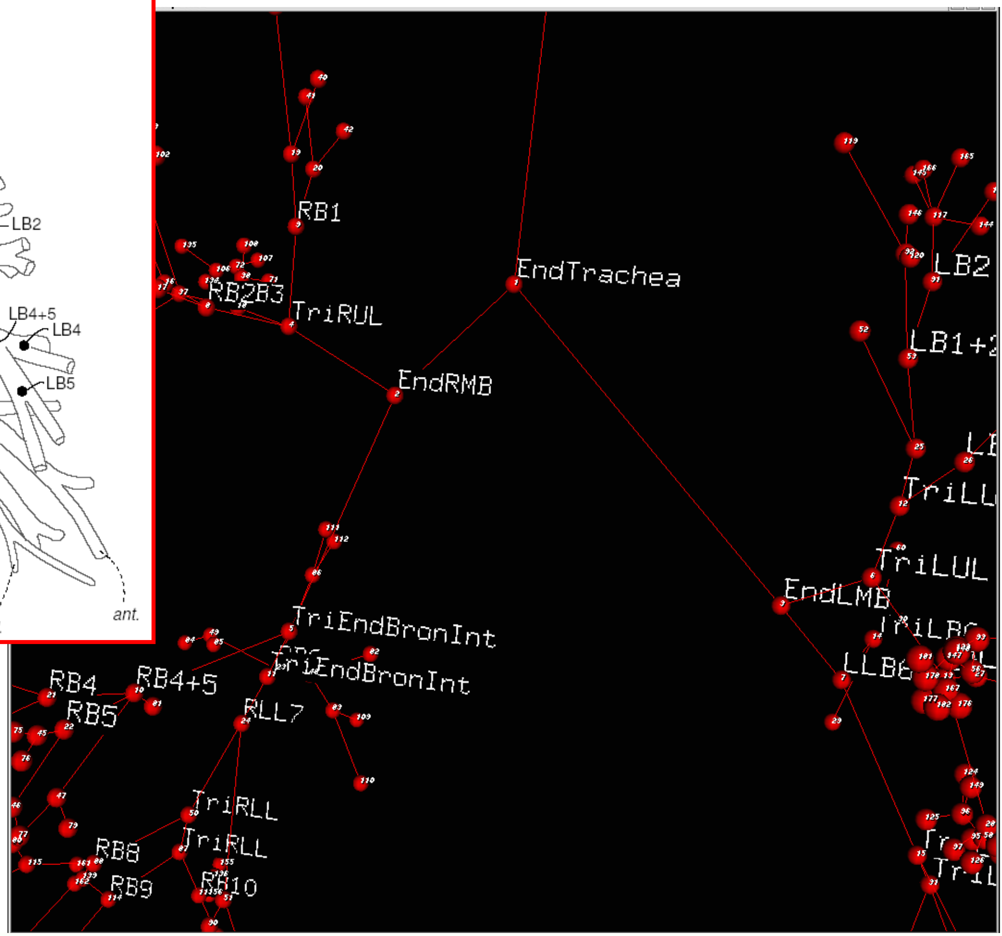
Tree matching


functional residual capacity (FLC)


total lung capacity (TLC)

Anatomical labeling





Some publications

- K. Palágyi, J. Tschirren, M. Sonka:
Quantitative analysis of intrathoracic airway trees: methods and validation, in *Proc. 18th Int. Conf. Information Processing in Medical Imaging, IPMI 2003, Ambleside, UK,* LNCS 2732, Springer, pp. 222-233, 2003.
- J. Tschirren, G. McLennan, K. Palágyi, E.A. Hoffman, M. Sonka:
Matching and anatomical labeling of human airway tree, *IEEE Transactions on Medical Imaging* 24, pp. 1540-1547, 2005.
- K. Palágyi, J. Tschirren, E.A. Hoffman, M. Sonka:
Quantitative analysis of pulmonary airway tree structures, *Computers in Biology and Medicine* 36, pp. 974-996, 2006.

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