Visualization and Virtual Reality in Medicine

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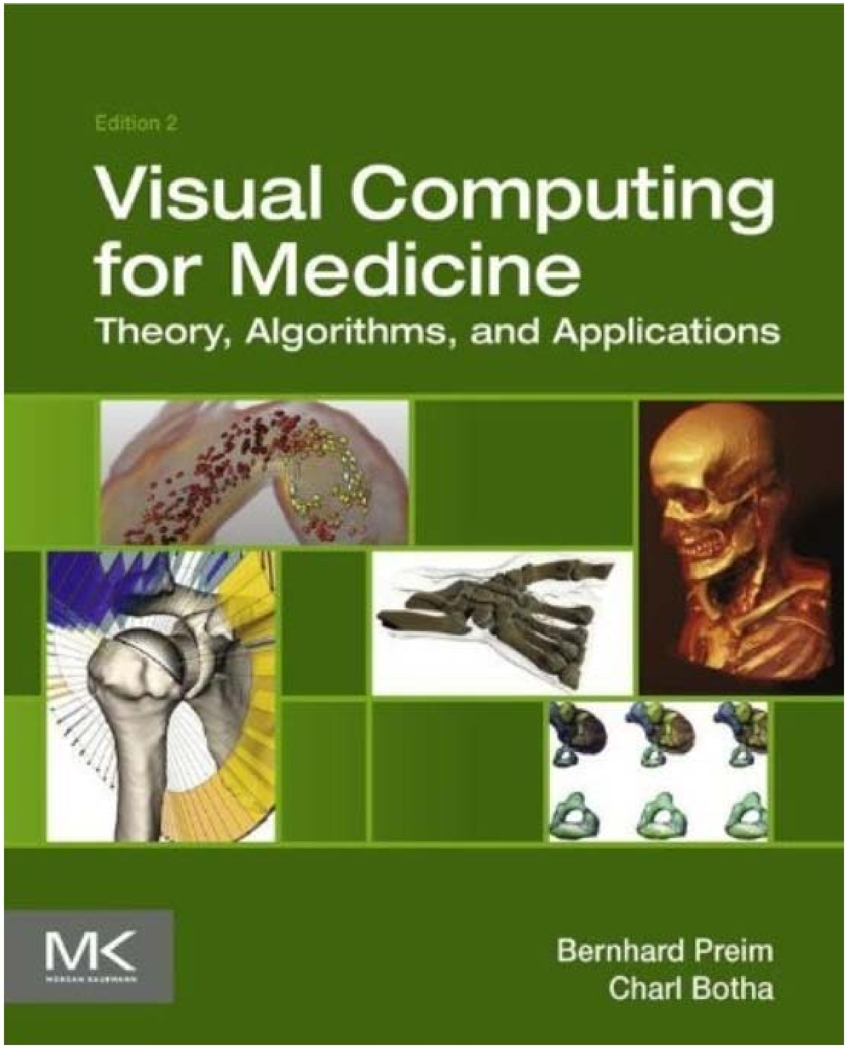
Tutorial Syllabus

Surface Visualization - Marching Cubes and its improvements - Smoothing of surface visualizations	(40 min.)
3D Vessel Visualization	(30 min.)
Labeling Medical Visualizations	(20 min.)
Break	(15 min.)
Direct Volume Visualization - Ray casting and texture-based approaches - Projection methods	(40 min.)
Multifield Medical Visualization	(30 min.)
Virtual Endoscopy	(20 min.)

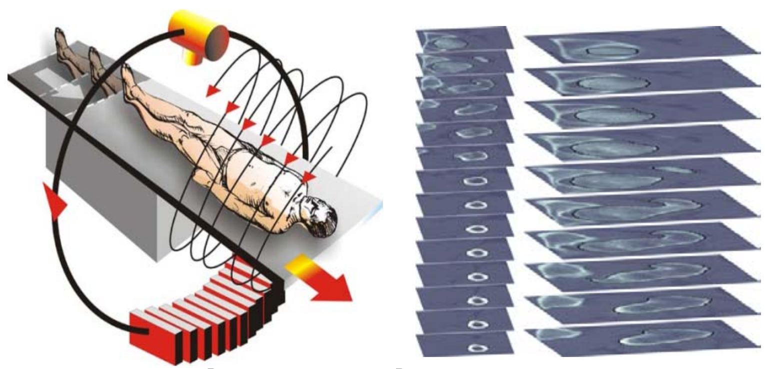


See medvisbook.com, includes tutorial notes and five free online chapters

Medical Data Sets

- Regular data in an orthogonal grid
- Resolution:
  - Anisotropic data sets (layer distance > distance of pixels in the layer)
  - **Characteristic**: CT or MRI data: 512x512 per layer,
    - **80-850 layers, resolution: 12 Bit per layer ,~20-50 Mvoxel**
  - **High-End**: Multi-slice CT: 1024x1024 per layer,
    - **up to 500 layers, ~ 160-400 MVoxel**

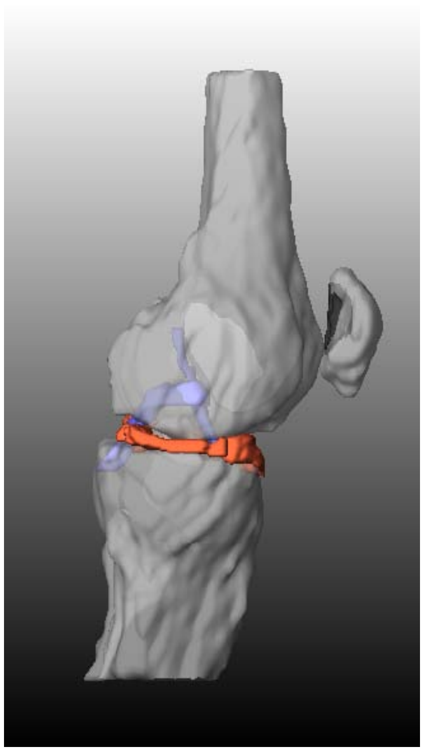
- Less common:
  - PET, SPECT, 3D ultra sound with lower resolution

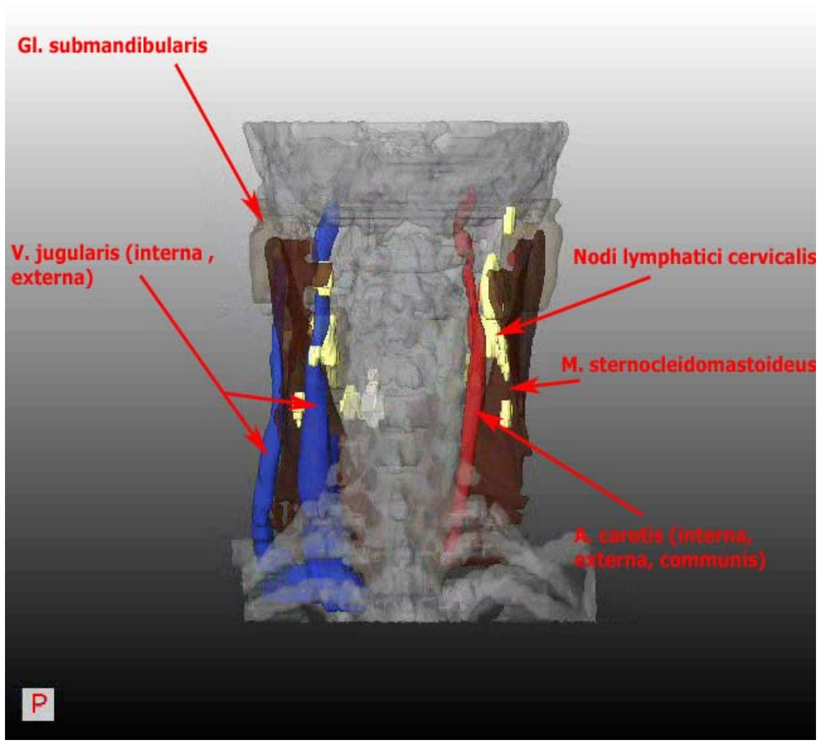


[Kabayim.com]

Surface Visualization

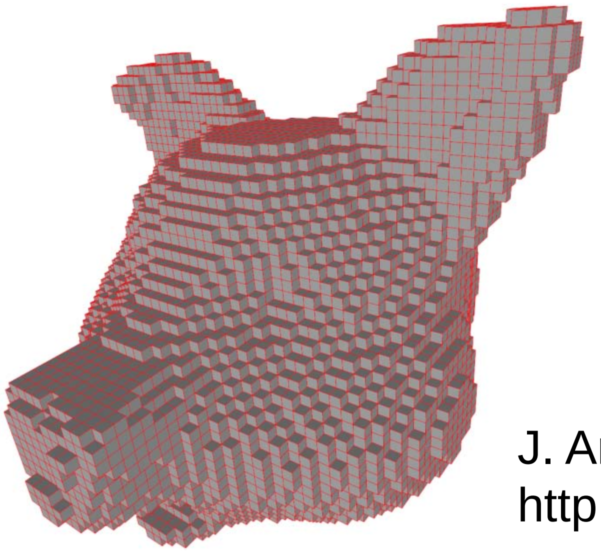
Visualization of isosurfaces and segmentation results





Surface Visualization: Introduction

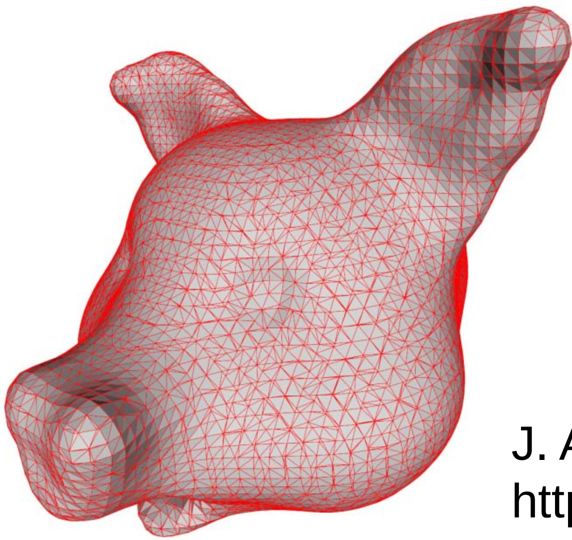
- Assumption:
  - Relevant structures are segmented.
  - Segmentation is model-based (Snakes, …), with “classical“ procedures (Region Growing, Watershed, …), or manually
  - Segmentation result is binary represented at the voxel plane (1 for the foreground, 0 for the background).
- Visualization: 1st idea: presentation of the voxels (“Cuberille“ approach, Herman & Liu 1979)



J. Andreas Bærentzen
http://www2.imm.dtu.dk/~jab/

Surface Visualization: Introduction

- Visualization, better idea:
  - linear interpolation, depiction on a polygonal surface (isosurface for the value 0.5)
  - definition of intersection between voxel edges and isoline, triangulation, definition of normals for shading
  - rendering by using the graphics hardware



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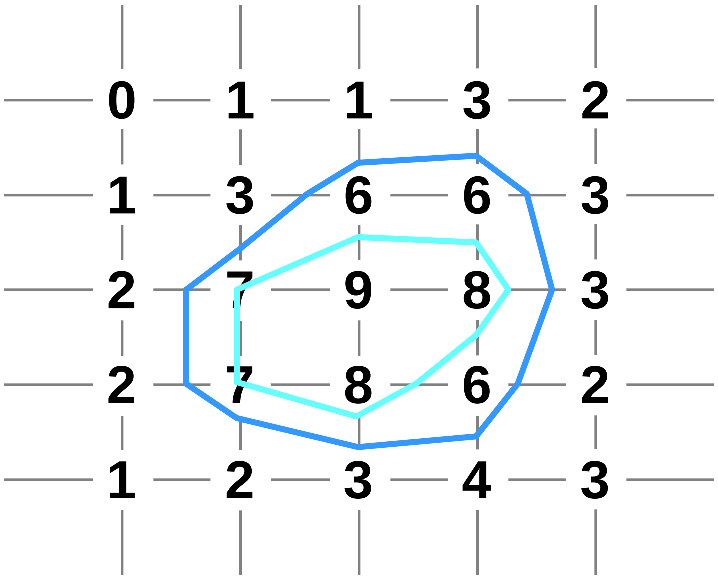
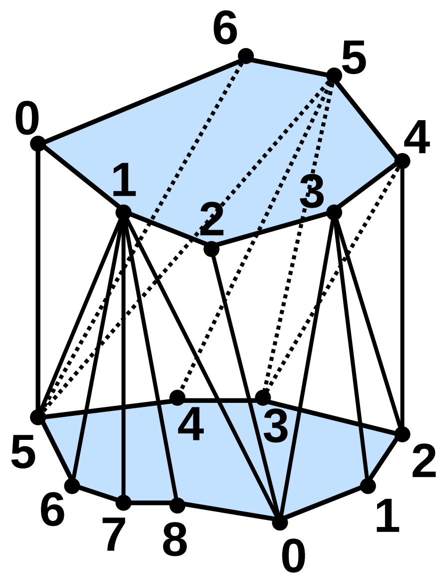
http://www2.imm.dtu.dk/~jab/

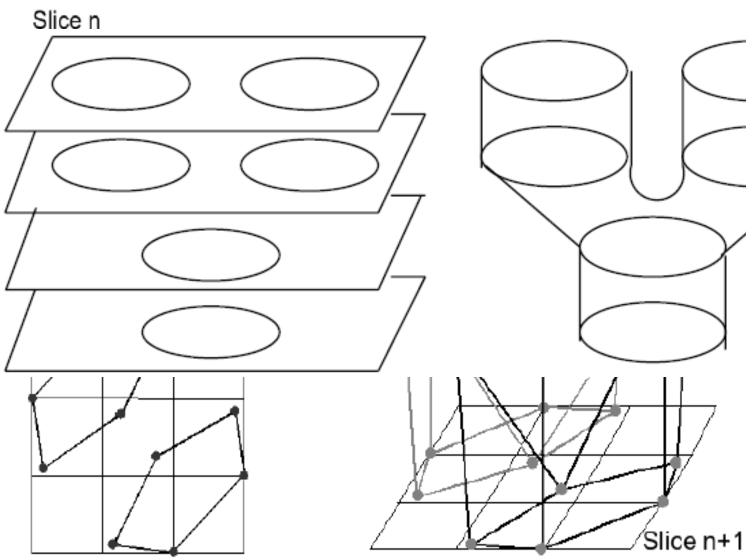
- How can this be realized?
  - Follow the outlines: very difficult in 3D, many case distinctions
  - Locally independent inspection of the cells. Determine how the cell is cut from the surface.
    - ➢ **basic idea of Marching Cubes (patented in 1985, published in 1987)**





From Contours in slices to Surfaces

- Which problems need to be solved?
  - *Correspondence:* Which contour of one slice belongs to a contour at the next slice
  - *Triangulation (Tiling):* C_1 and C_2 be corresponding contours. How shall these contours be connected through triangle nets?
  - *Branching problem:* If the number of contours in one slice S_n is different to the number of contours in the neighbor slice S_{n+1}.

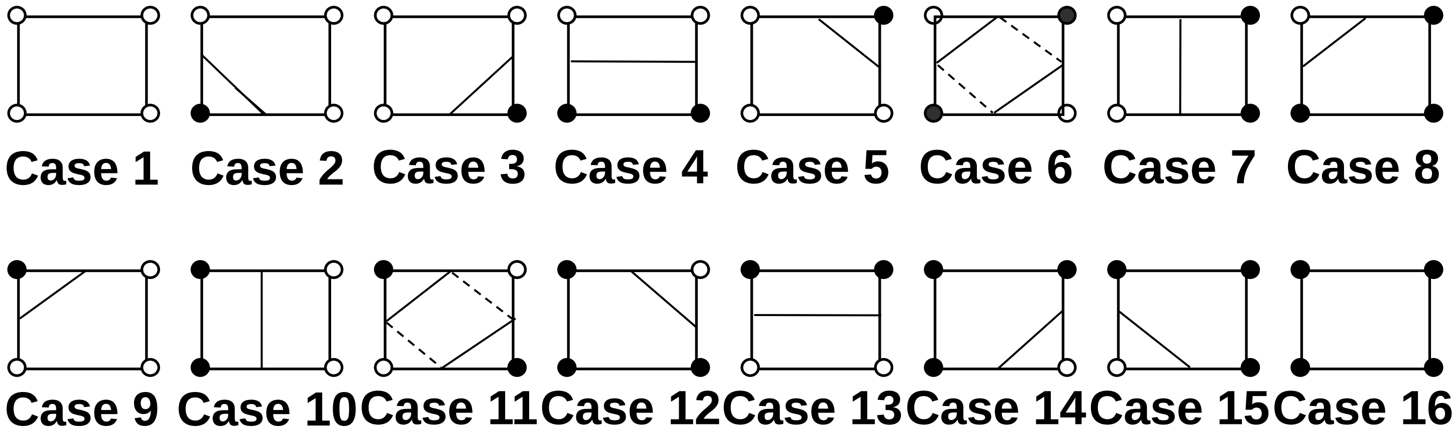


„Surfaces from Contours“, Meyers et al. (1992)

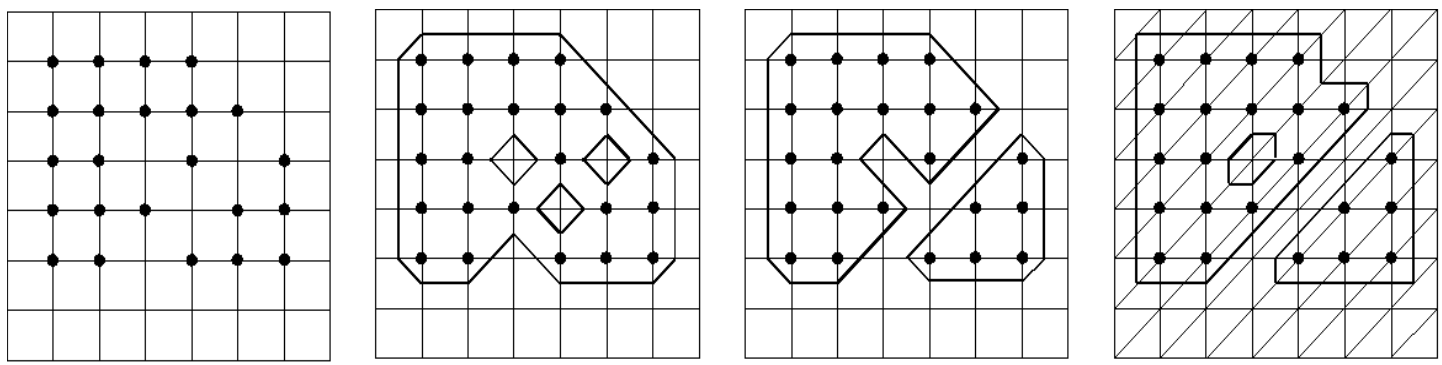
From Contours in slices to Surfaces

- *Correspondence problem:* Comes up, if the following applies:
  - The contours in slice S_n and S_{n+1} belonging to the same object do not overlap, and the number of contours belonging to one object is > 1 in S_n and/or S_{n+1}.
- What does Marching Cubes?
  - An overlapping of contours in neighbored slices is assumed.
  - Limit of this assumption? In case of a large slice distance or thin objects which proceed diagonal to the slices.
  - If the requirements are not fulfilled, separate surfaces are generated.
- In such cases, correct solutions are complex.
  - Interpolation of intermediate slices often helps.

- Consideration of the 2D case (Marching Squares). Isoline for iso=0.5.



- Ambiguities:

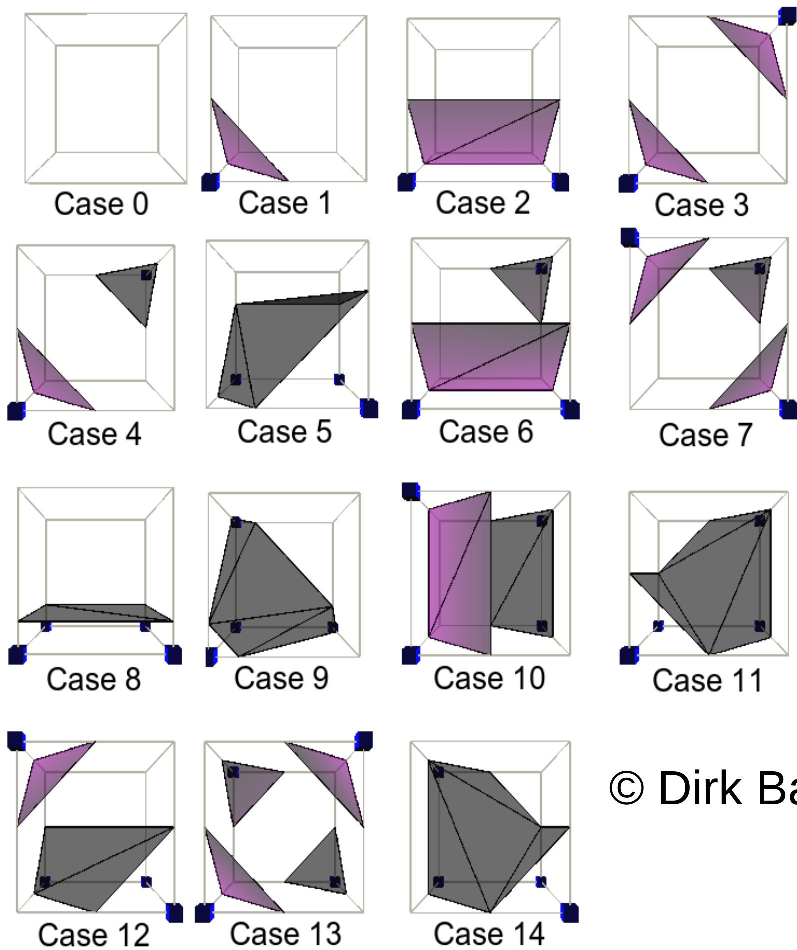


© Dirk Bartz

Surface Visualization: Marching Cubes

- Extension to 3D:
  - there are 15 topologically different cases of how a cell can proceed through a surface.

- Procedure (rough):
  - determine the case for each cell.
  - determine the triangles if the cell is cut.

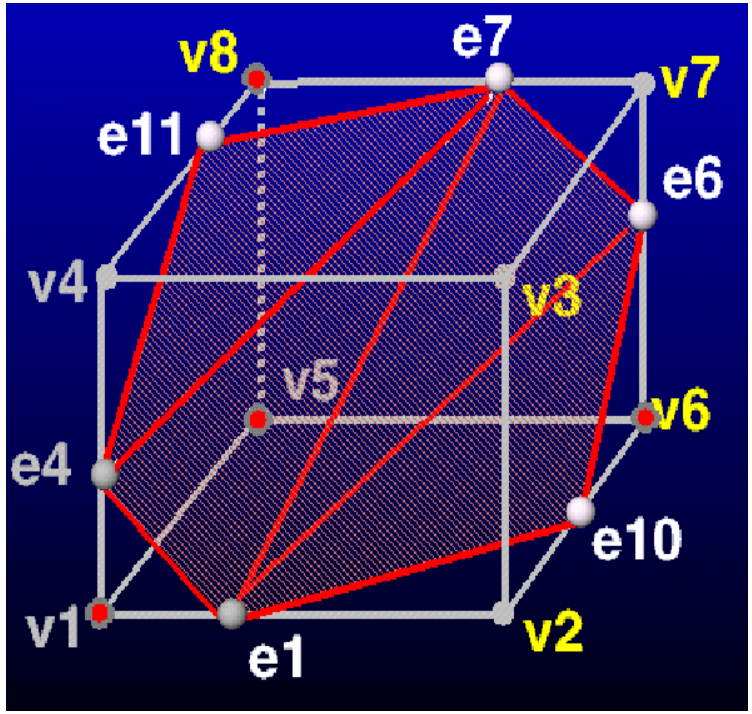


Surface Visualization: Marching Cubes

- Marching Cubes
  - Purpose: transfer of the voxels of a volume with a given value into a triangulation net (Lorensen et al. [1987])

- Procedure:
  1. Consider cells from 4 voxels of the slice S_n and 4 voxels of the slice S_{n+1}
  2. Check which vertices have values above the threshold value, create an index
  3. Determine the involved edges
  4. Determination of points at these edges through linear interpolation
  5. Connection of these points to create triangles

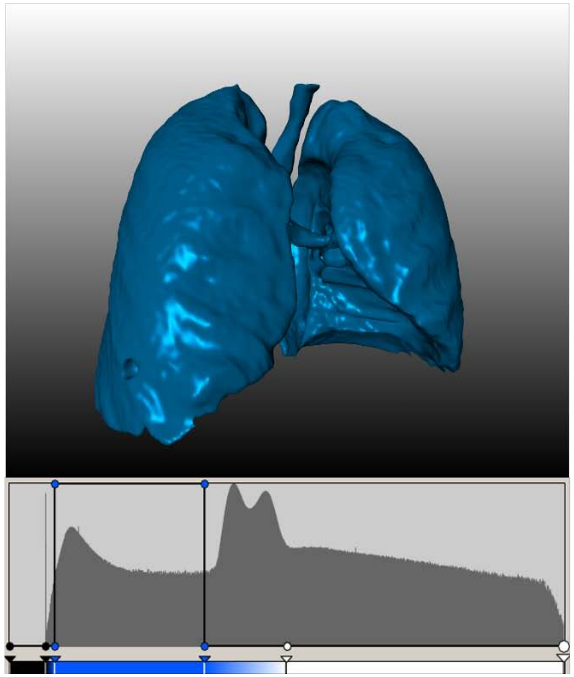
- Marching Cubes
  - Step 2:
    - v1, v5, v6, v8 – above,
    - v2, v3, v4, v7 – below
    - Index: 1000 1101
  - Step 4: Linear interpolation
    - Example: determination of e1 to the edge (v1; v2)
      - e1 = v1 + (isoval – f(v1)) / (f(v2) - f(v1)) * (v2 –v1)
  - Step 5: Triangles
    - (e4, e7, e11) (e1, e7, e4)
    - (e1, e6, e7) (e1, e10, e6)

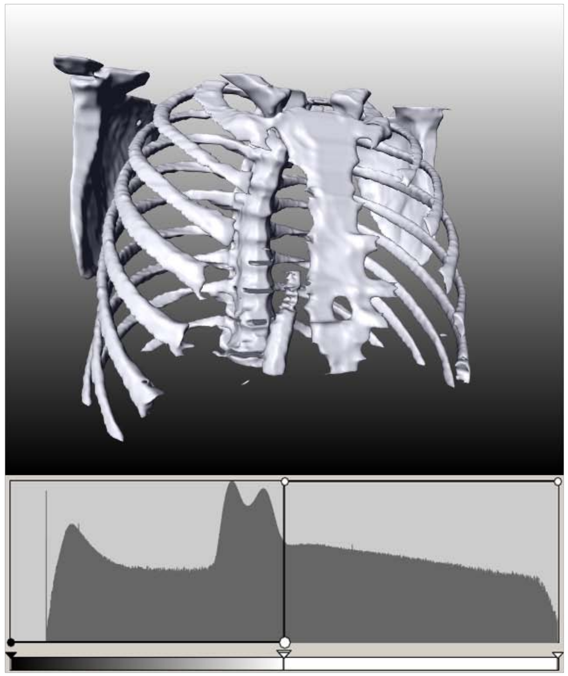


© Alexandre Telea

Marching Cubes and its Improvements

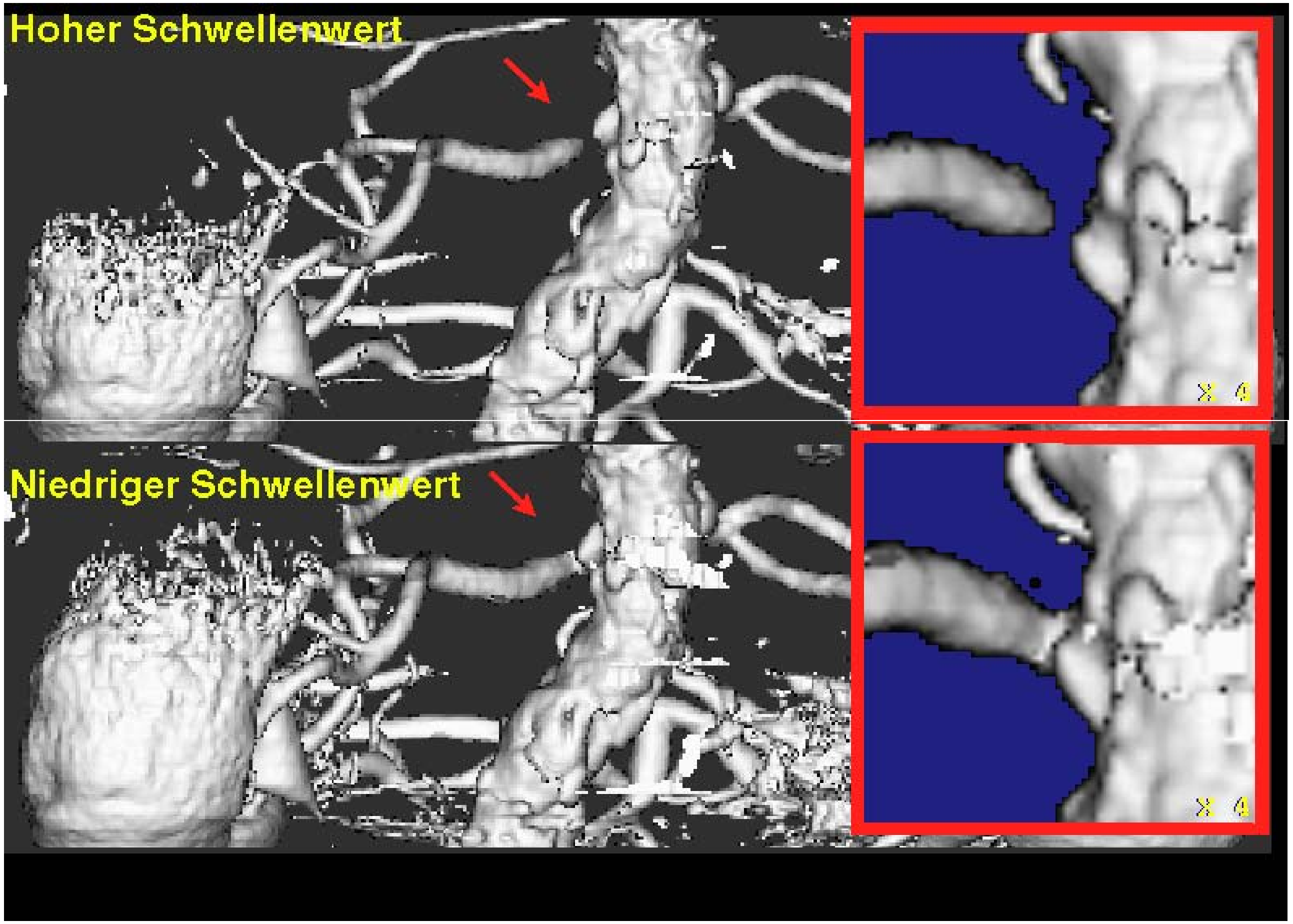
Marching Cubes may also be applied to original data.
Challenge: threshold detection





Histogram depiction of CT thorax data sets for selection of threshold values. In the left image: an interval is specified.

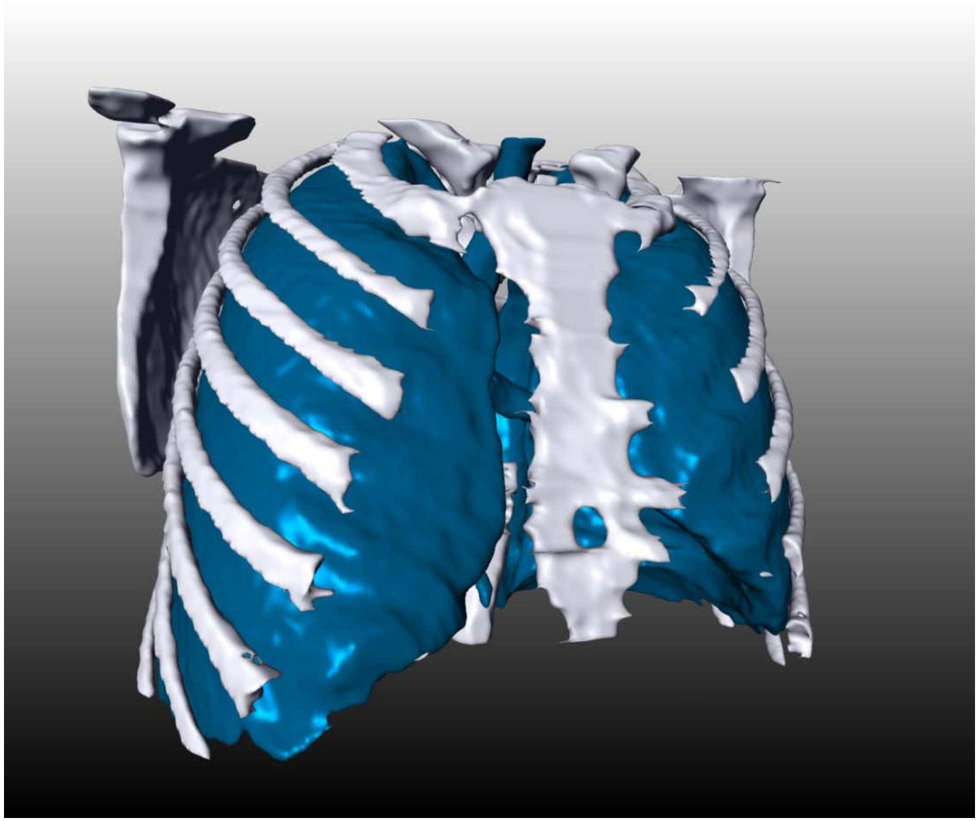
Marching Cubes and its Improvements

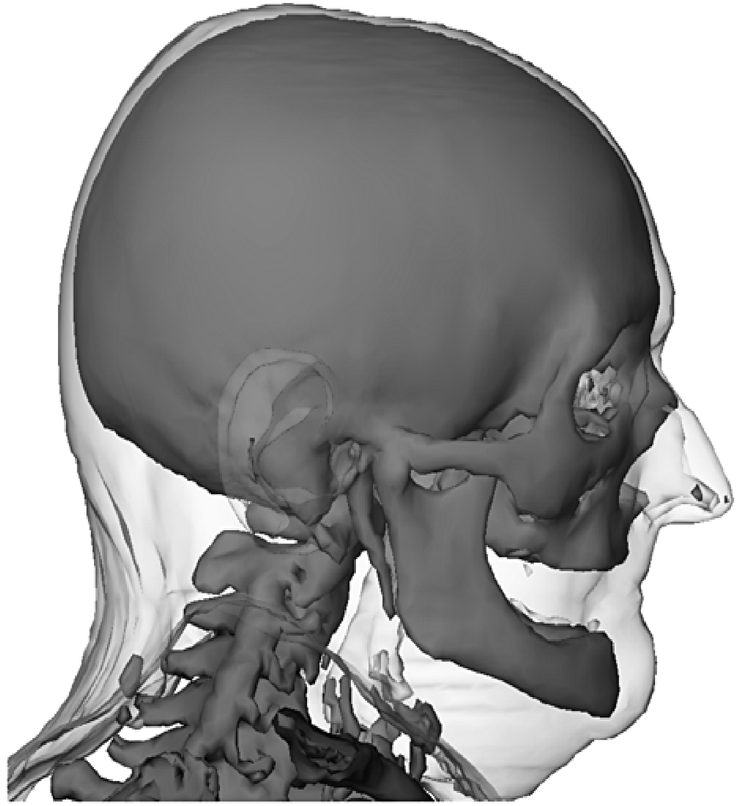


Sensitivity: Small changes of the threshold (isovalue) may severely affect the resulting surface and the diagnostic consequences

(Courtesy of Hoen-Oh Shin, Medical School Hannover)

Marching Cubes and its Improvements





- Simultaneous display of several surfaces. Right: outer surface is semi-transparent (gradient-weighted opacity).

Surface Visualization: Marching Cubes

- What is important about Marching Cubes?
  - Very simple
  - Compared to Cuberille: Better depiction through linear interpolation
    - **But:** Viewers are also sensitive for discontinuities of the first and second derivative
  - Ambiguities and inconsistencies, no treatment of the correspondence problem, no optimal solution for the tiling problem
  - Relatively precise, but improvable (only interpolation along the edges)
  - Relatively fast procedure
    - **But:** A lot of time is spent on cells which do not contribute to the surface
  - Fast rendering

Surface Visualization: Marching Cubes

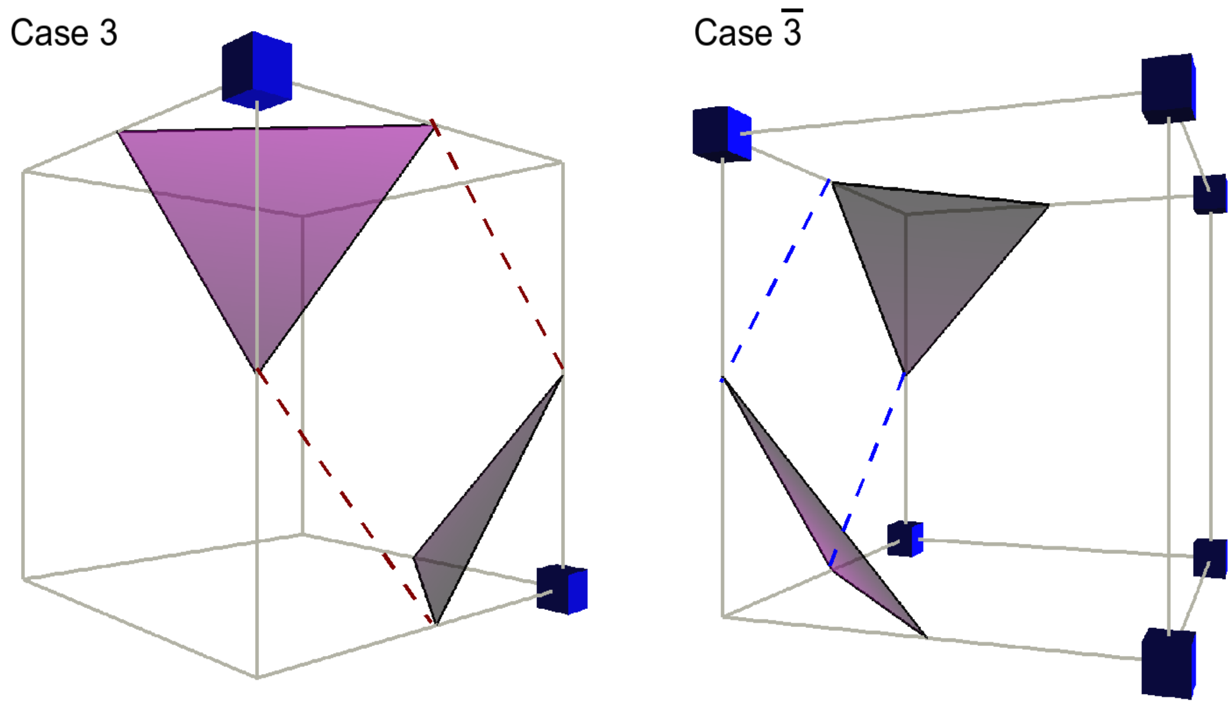
- Quality problems through linear interpolation and Gouraud shading

Virtual bronchoscopy

© Dirk Bartz

Surface Visualization: Marching Cubes

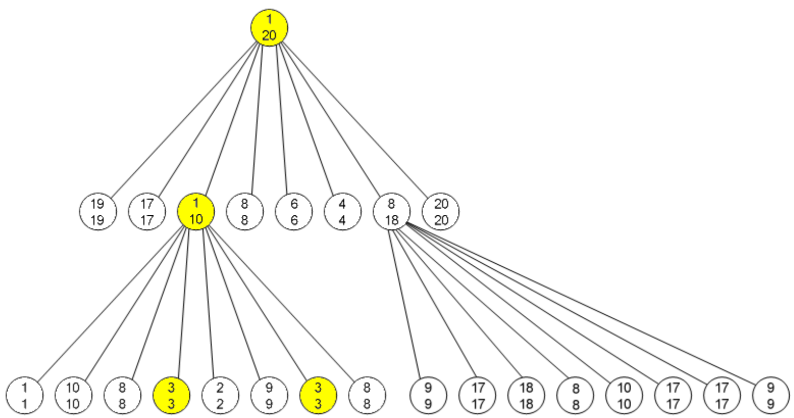
- Holes in the surface arise, if, for the neighboring cells,…
  - the decision is made to divide the intersections and …
  - the decision is made to connect them in the second cell.



Surface Visualization: Marching Cubes

- How can this inconsistency be corrected?
  - Interpolation of points at the shared face. The state of this point (above/below) is decisive (Nielsen, Hamann [1991])
  - Decomposition of the cells into tetrahedrons (Shirley, Tuchman [1990])

- How can Marching Cubes be accelerated?
  - Fast recognition of areas that are not affected by the surface.
  - Representation of the scene through hierarchic data structures, e.g., min-max-octrees (Wilhelms, van Gelder [1992])



Source:
http://de.wikipedia.org
/wiki/Octree

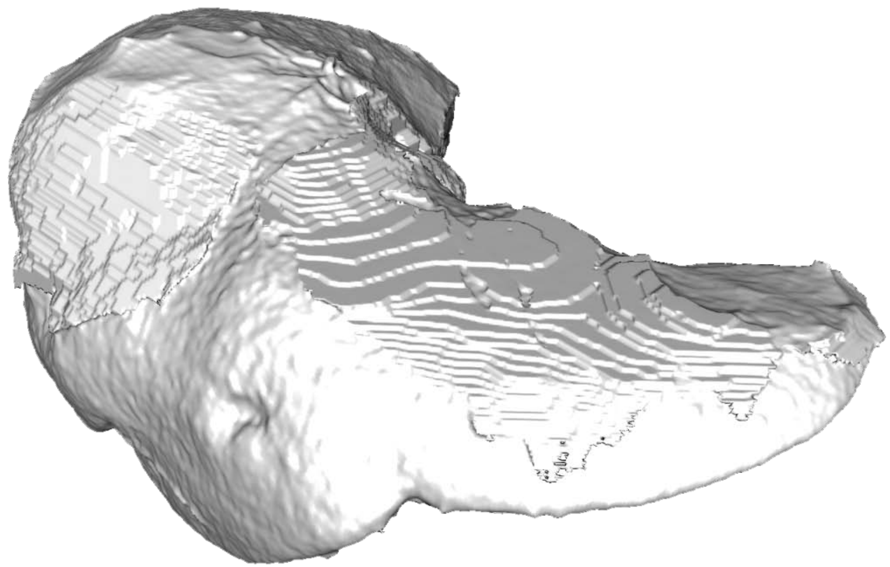
Surface Visualization: Smoothing and Noise Reduction

- Problem:
  - Generation of surface models from segmentation results leads to artifacts, especially in case of strongly anisotropic data

MRI data

3D

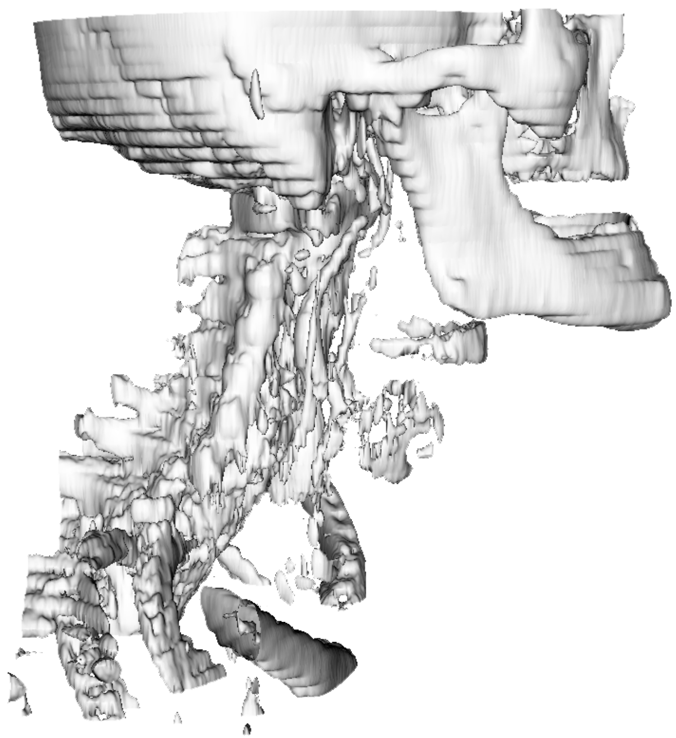
Photo



Liver from almost isotropic CT data

Surface Visualization: Smoothing and Noise Reduction

- **Problem**: Development of many small surfaces which represent artifacts
- **Purpose**: Restriction of the extraction to the largest surface (or a given amount of surfaces)
- **Method**: Connected Component Analysis (according to Schroeder et al.[1998])
- VTK: vtkConnectivityFilter



Surface Visualization: Smoothing and Noise Reduction

- Algorithm Connected Component Analysis:

  While there are cells which are not “visited”,

  - Start with any cell z and mark it as „visited“.

  - Initialise the component k

  While there is a cell z_n adjacent to z which contributes to the surface and has not been “visited“ yet:

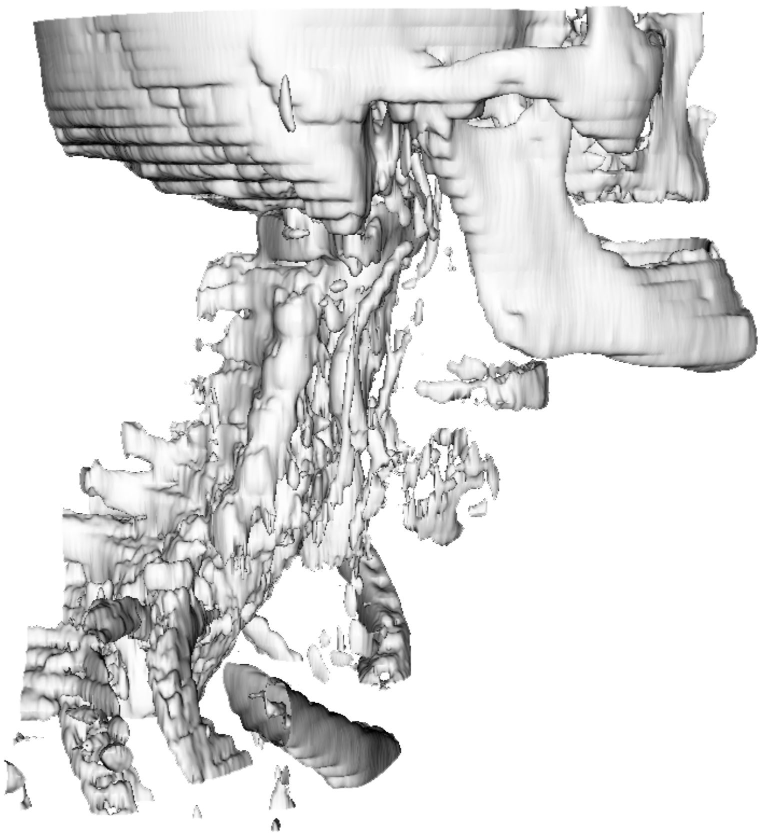
  - add z_n to the component k and mark it as “visited“.

  Repeat recursively as long as there are still neighboring cells which have not been visited

- Result: all connected components
- Selection of the largest (n) component(s) according to the surface area or length of the object contour

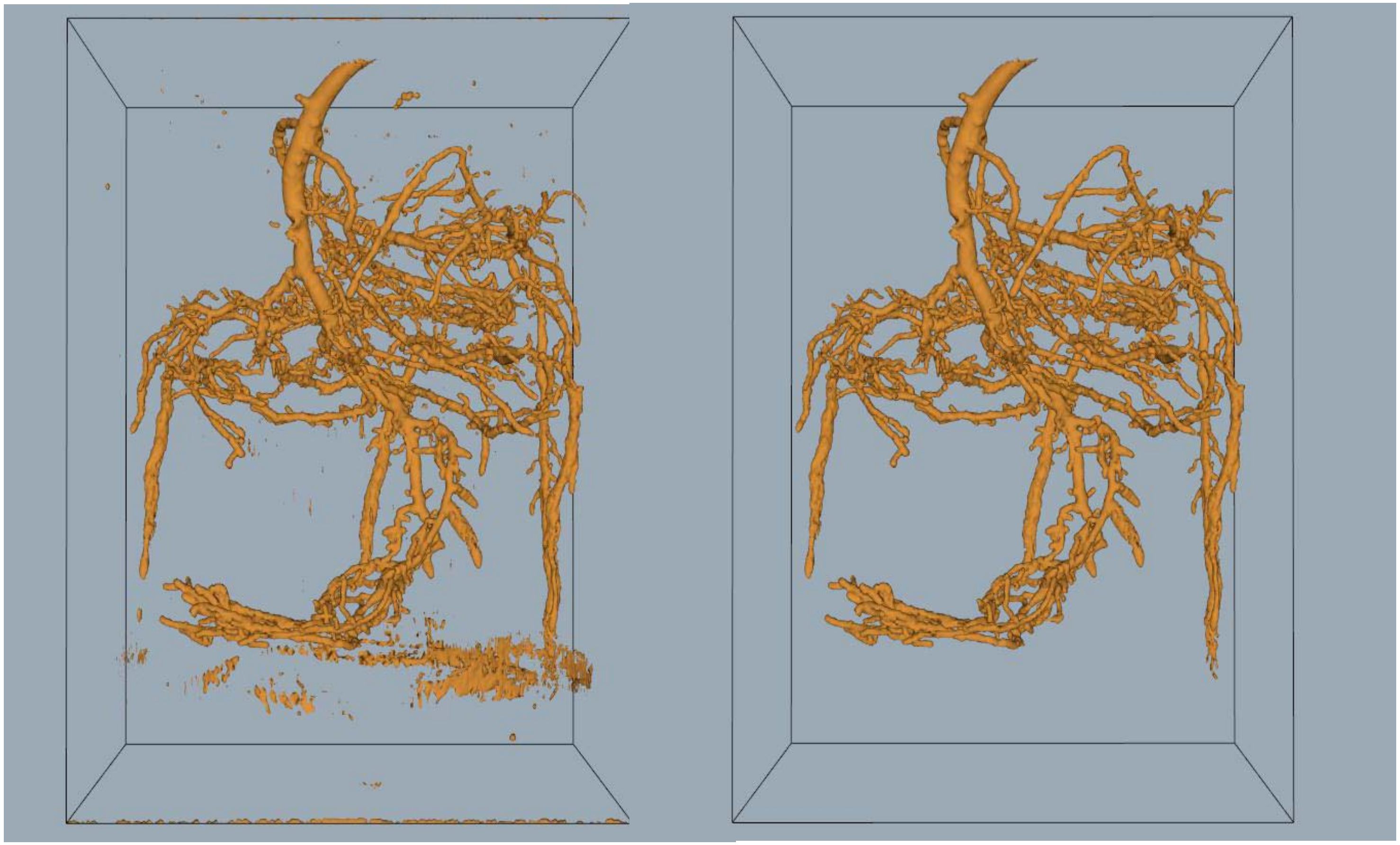
Surface Visualization: Smoothing and Noise Reduction

- Connected Component Analysis. Display of the largest component.



Surface Visualization: Smoothing and Noise Reduction

- Connected Component Analysis. Display of the largest component.



Digitalized photograph of a pine root (Source: Schroeder et al. [1998])

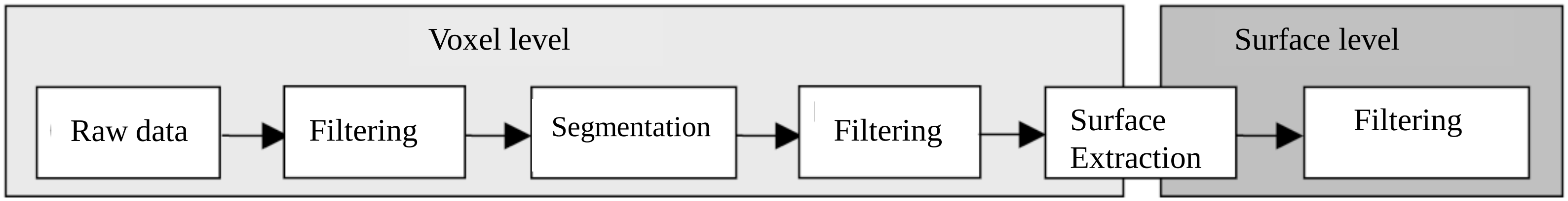
Surface Visualization: Smoothing and Noise Reduction

- General practice:
  - Interpolation of intermediate slices
  - “Manual“ smoothing
  - e.g., in vtk (vtkSmoothPolyDataFilter), itk, 3D Studio, Amira
- Disadvantages
  - complex trial-and-error process
  - not reproduceable, not standardized
  - only visual control

Surface Visualization: Smoothing and Noise Reduction

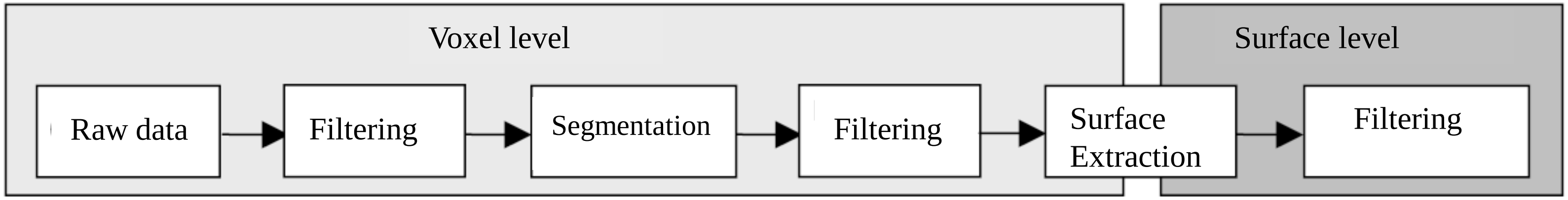
- Long-term goal:
  - Pipeline of algorithms for the post-processing of segmentation results (e.g., closure of holes), surface generation and subsequent smoothing
- Adaptation of the respective procedures to
  - the class of anatomic structure (e.g., tumor, organ, …)
  - imaging or segmentation parameters (e.g., slice distance, model-based segmentation)

Extraction of surfaces



Surface Visualization: Smoothing and Noise Reduction

- Smoothing of the segmentation result through smoothing filters (e.g., Gauss) or morphologic methods



0	0	0	0	0	0	0
0	0	0	100	100	100	0
0	100	100	100	100	100	0
0	100	100	100	100	100	0
0	0	0	100	100	100	0
0	0	0	0	0	0	0

→

0	6	26	33	33	26	6
20	33	54	66	66	54	26
33	66	66	100	100	66	33
33	66	66	100	100	66	33
20	33	54	66	66	54	26
0	6	26	33	33	26	6

Source: Neubauer et al., IEEE Visualization 2004

- First of all, erosion and modification:

$$v = v_2 - (v_2 - v_1) * \frac{1}{3}$$

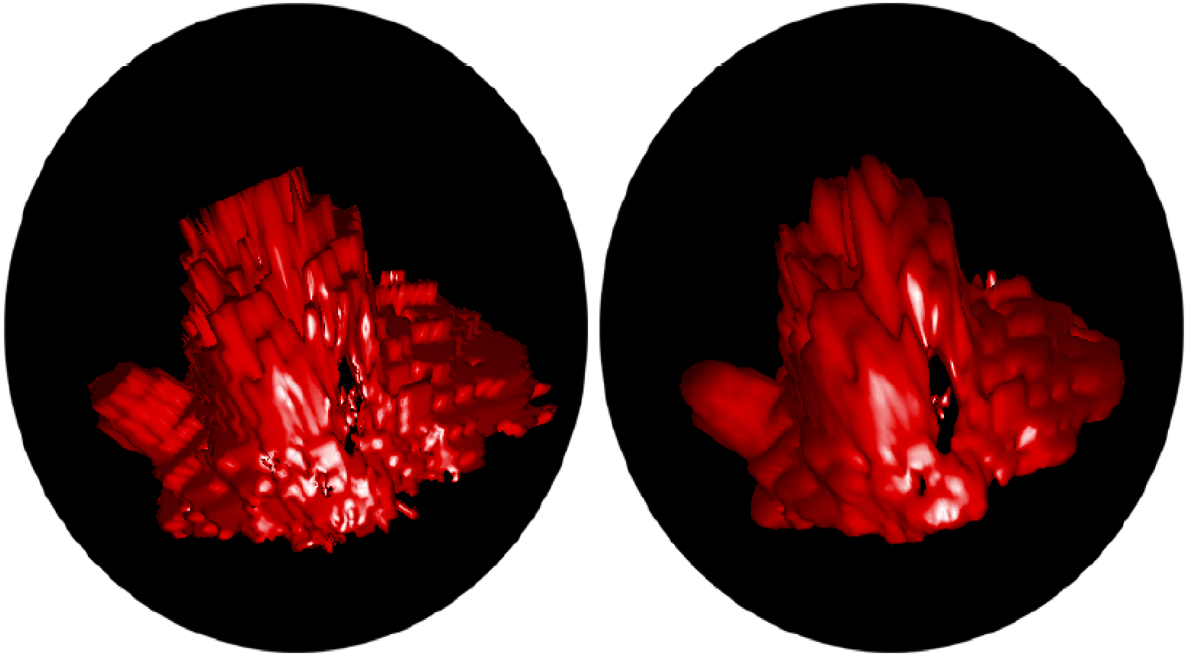
- Afterwards, twice dilatation and modification:

$$v = v_{ref} - (v_2 - v_1) * \frac{d}{3}$$

- d Eucl. Distance, v_ref = 50

Surface Visualization: Smoothing and Noise Reduction

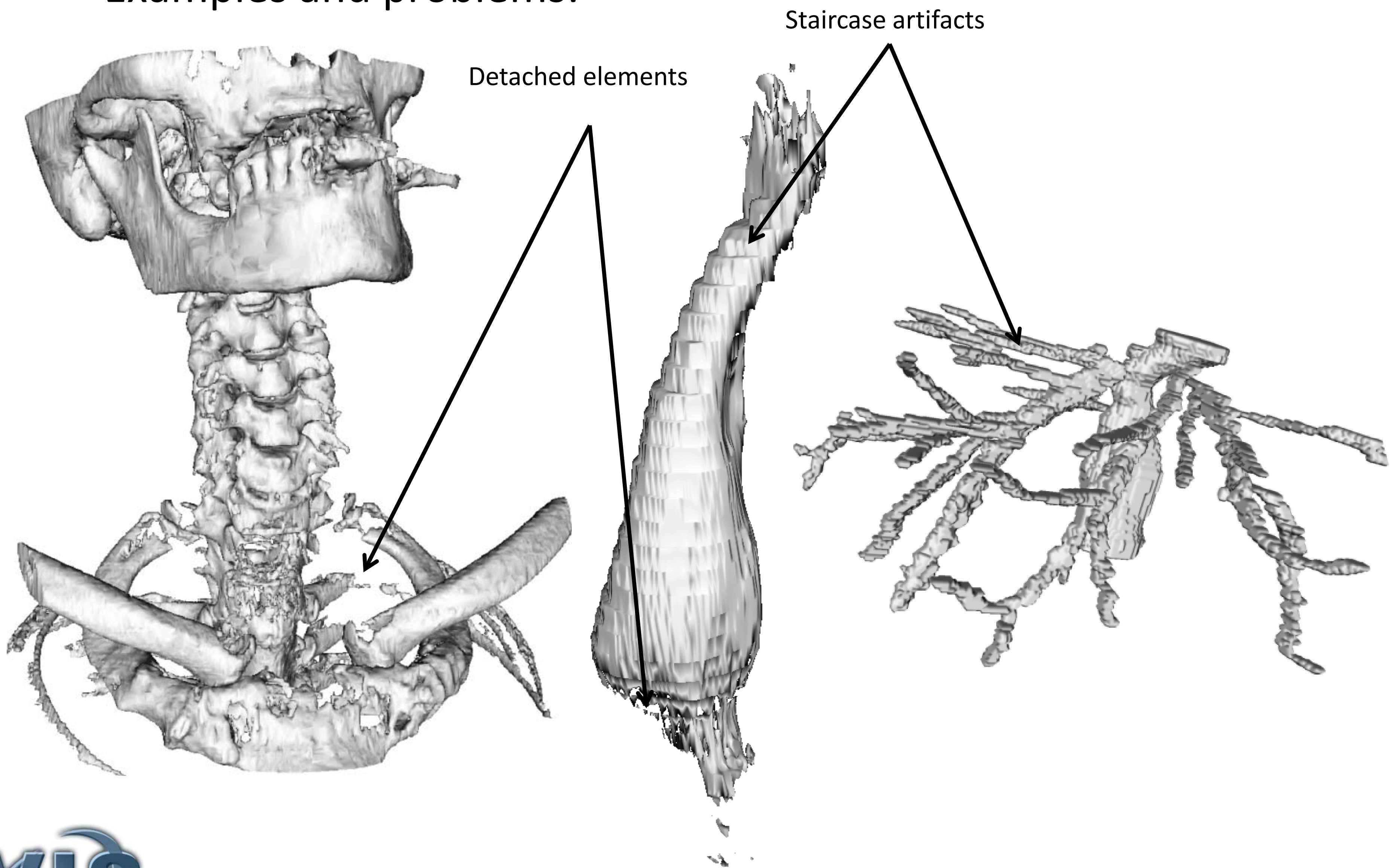
- Smoothing of the segmentation result through morphological methods



Source: Neubauer et al., IEEE Visualization 2004

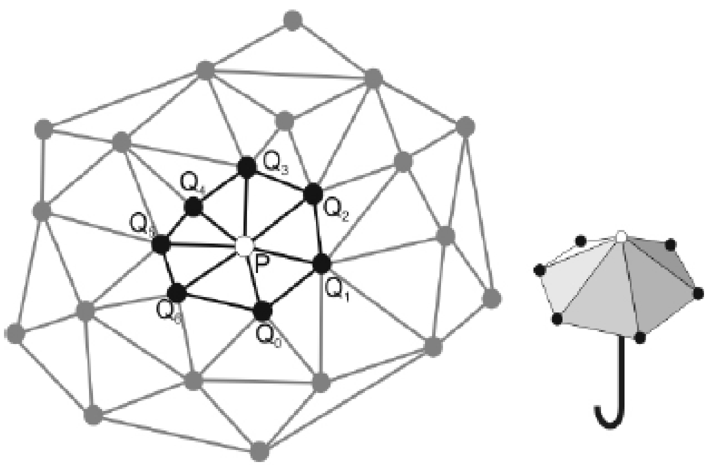
Smoothing of Polygonal Surfaces

- Examples and problems:

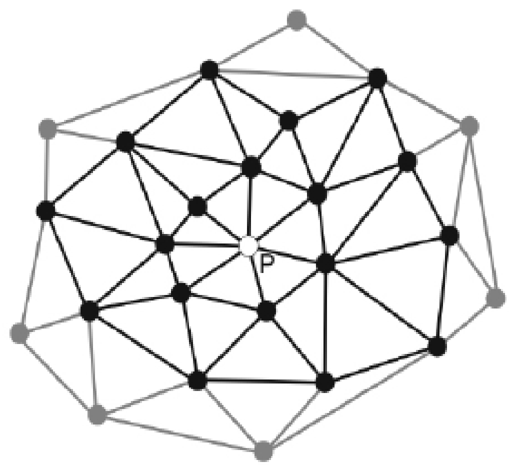


Smoothing of Polygonal Surfaces

- Iterate over all vertices and replace each vertex through a weighted average from its former value and the vertices from the neighborhood
- Which neighborhood?
  - vertices in a specific distance (Euclidean distance)
  - vertices which are connected to the current vertex (directly or through a path of length n) (topological distance)
  - Typical: vertices in the topological distance of 1 or 2



Direct, 1st order neighbors

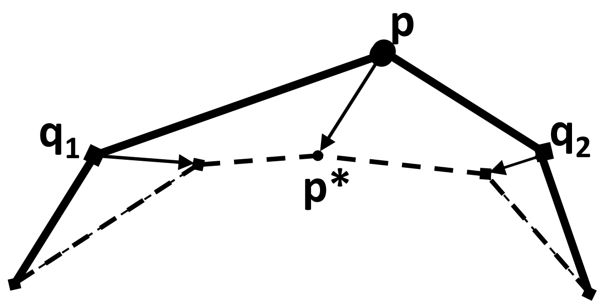


2nd order neighbors

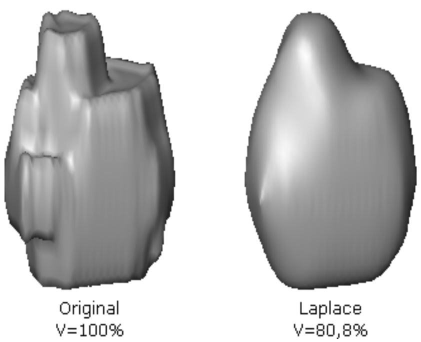
Smoothing of Polygonal Surfaces: Laplace Smoothing

- Considers the points q_i in the topological distance of 1
- Parameter: smoothing factor α and number of iterations

$$p' = p + \frac{\alpha}{n} \sum_{i=0}^{n-1} (q_i - p)$$



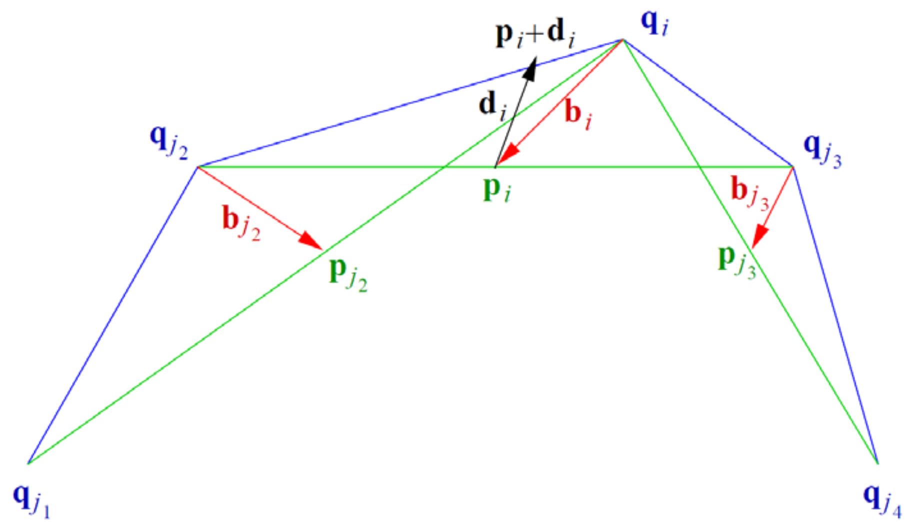
- Simple, fast realization (e.g., in vtkSmoothPolyDataFilter)
- Causes strong (uncontrolled) shrinkage and the favored smoothness is often only achieved through total smoothing of minor features



smoothing with α = 0.5 and 20 iterations

Smoothing: Laplace Smoothing with Correction

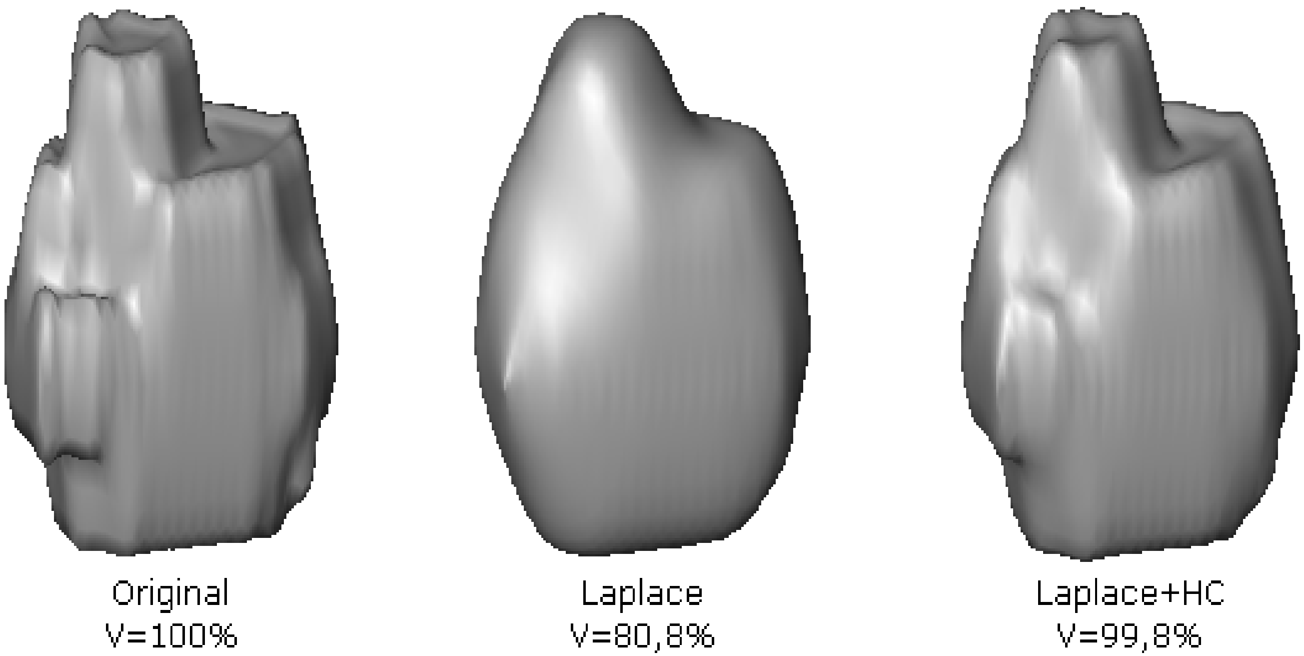
- Correction to maintain the volume
- In each step, modified nodes are shifted back about a certain value (the average of all shiftings in the considered surrounding)
- Additional parameters:
  - How strong is the shifting in direction to the original point?
  - How is the shifting of the neighbors considered?



Example: Laplace+HC

Source: Vollmer et al., Eurographics 1999

Smoothing: Laplace Smoothing with Correction



Literature: Vollmer et al., „Improved Laplacian Smoothing of Noisy Surface Meshes“, Eurographics, 1999

Smoothing: Low-pass Filtering

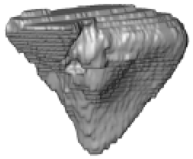
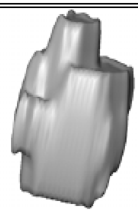
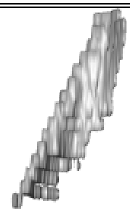
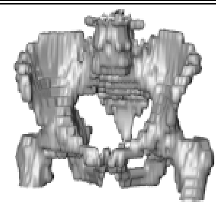
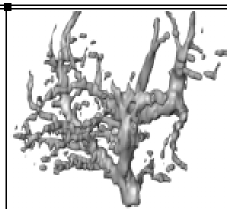
- Alternating implementation of two filters similar to Laplace with different factors α and μ

$$p' = p + \lambda \sum_{i=0}^{n-1} w_i (q_i - p)$$

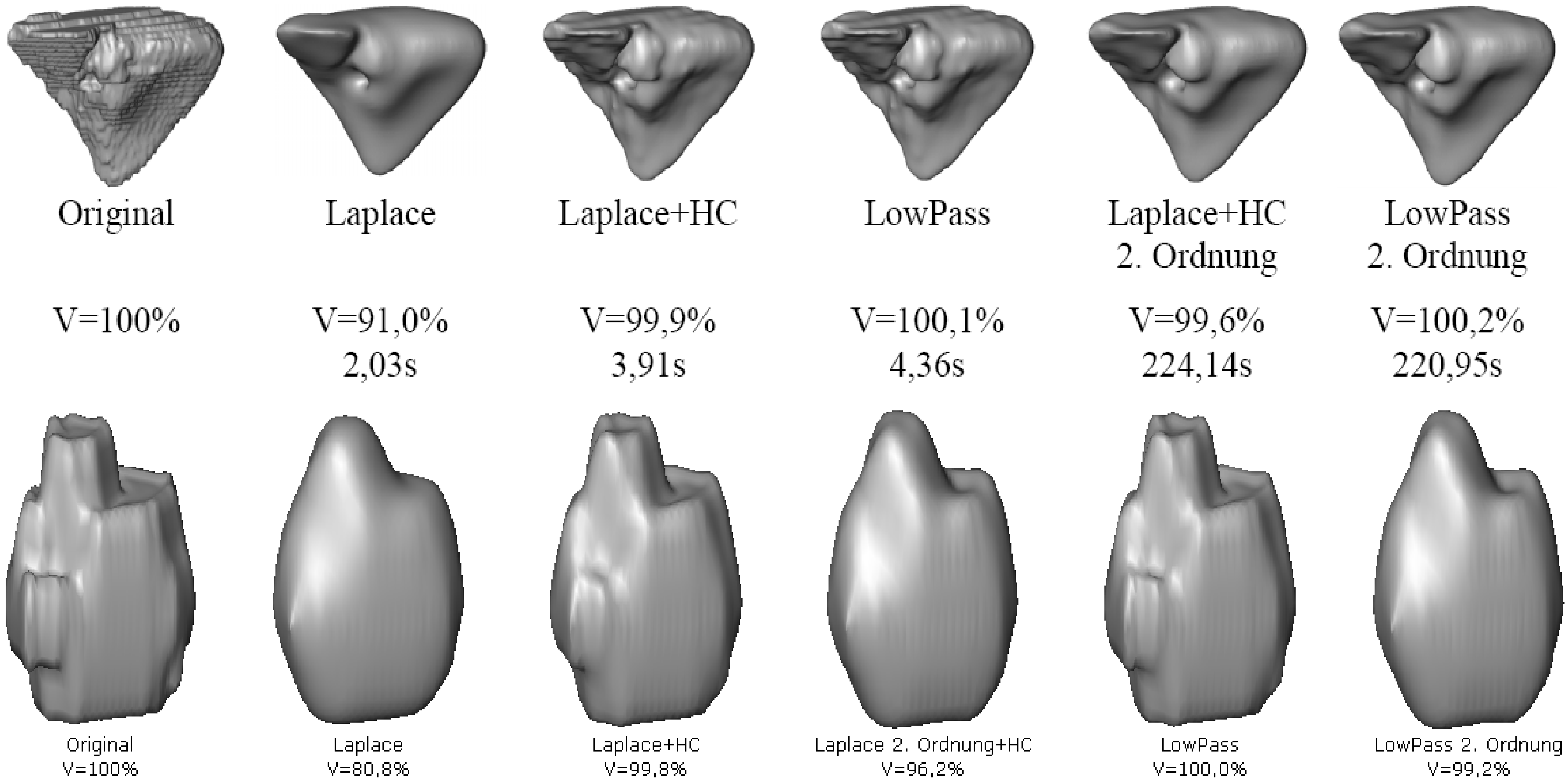
- Selection of μ: a bit smaller than α
- Default: - μ = -1.02 α (Taubin, 1995)

Smoothing: Comparison of Elementary Methods

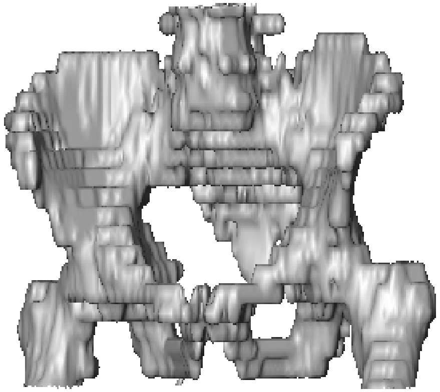
- Criteria: Quality, volume preservation
- Methods/parameters:
  - Laplace, Laplace with correction, Low-pass
  - Different iteration steps: 5, 10, 20, 50
  - Different weighting factors: 0.05, 0.1, 0.3, 0.5, 0.7, 0.9
  - Different neighborhood: 1, 2 (topological)

	 Leber	 Lymphknoten	 Kopfwendemuskel	 Beckenknochen	 Gefäßbaum	 Halsschlagader
Faces	37.148	3.412	9.616	53.930	23.236	1.956
Vertices	18.576	1.708	4.804	27.211	11.820	982
Voxel	1.696.250	1.664	101.035	430.318	96.807	16.404

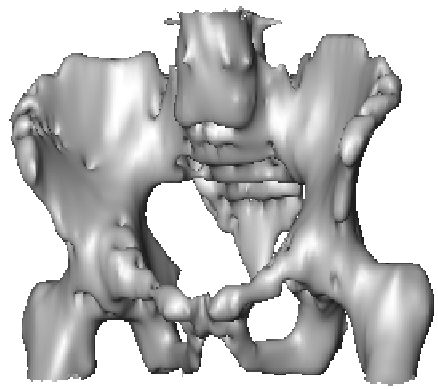
Smoothing: Comparison of Methods



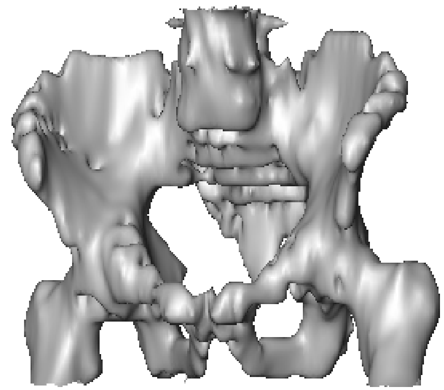
- All images with smoothing factor 0.5 and 10 iterations



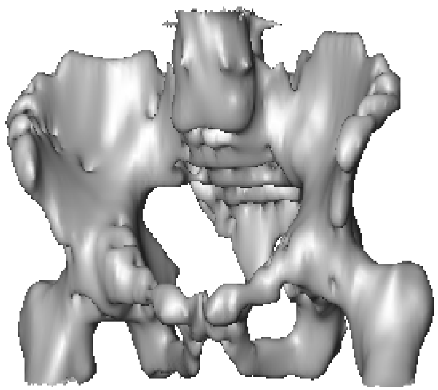
Original
V=100%



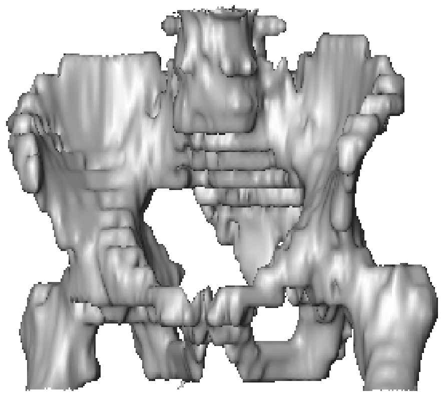
Laplace
V=94,2%



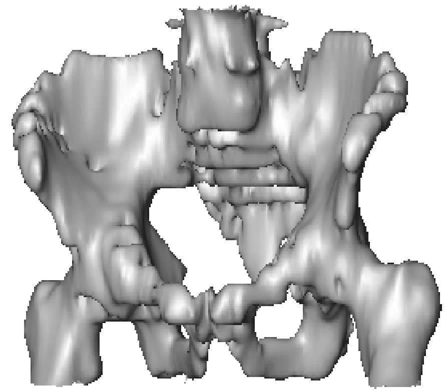
Laplace+HC
V=99,7%



Laplace 2. Ordnung+HC
V=98,9%



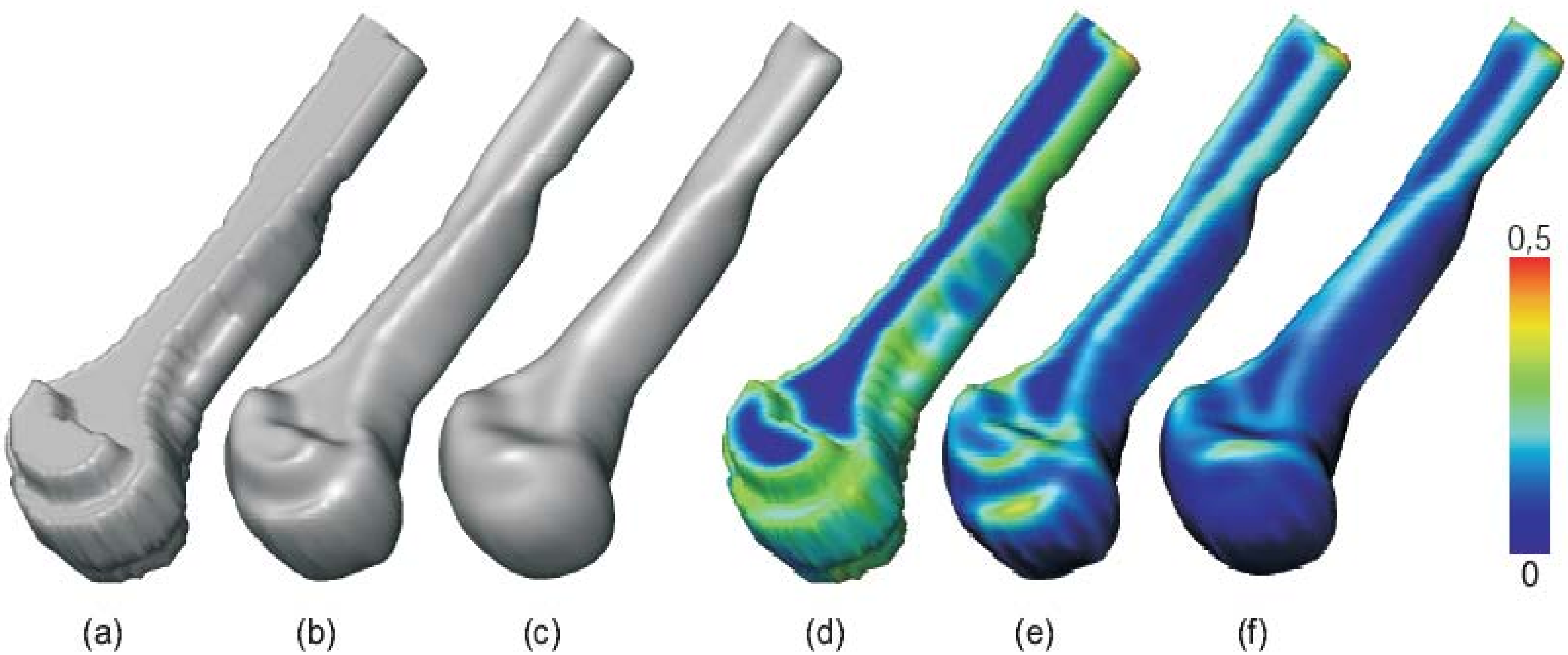
LowPass
V=100,4%



LowPass 2. Ordnung
V=100,1%

Smoothing of Surfaces: Comparison of Methods

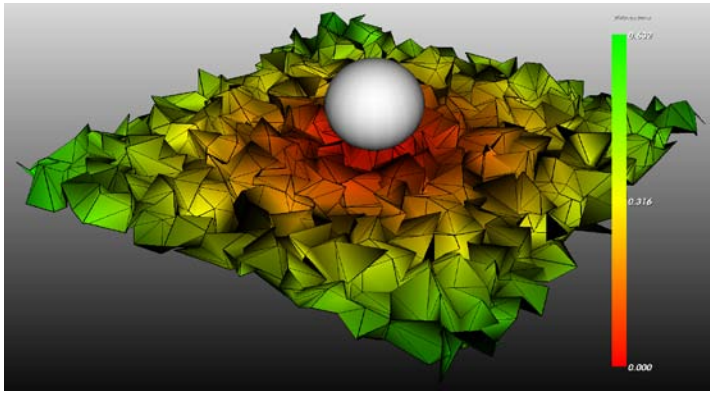
- Original, low-pass filtering with one neighborhood and extended neighborhood as well as the corresponding curvature values.



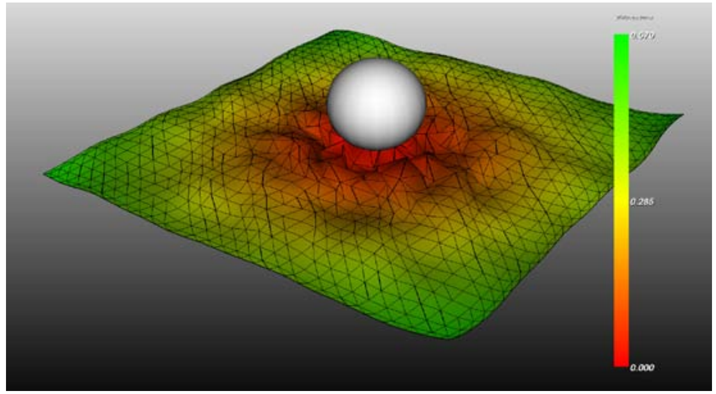
Smoothing of Polygonal Surfaces: Recommendations

- A low-pass filter is the best solution for all object classes.
- For smaller objects
  - Topological neighborhood of the size 2, 20-50 iterations, weighting: 0.7
- For flat or larger objects, especially with poblem points:
  - Topological neighborhood: 1, approx. 20 iterations
- For elongated, branching objects:
  - No really good filter (→ Vessel Visualization part will provide appropriate methods)
  - Low-pass filter with topological neighborhood of 1, weighting factor: 0.5 and 10 iterations

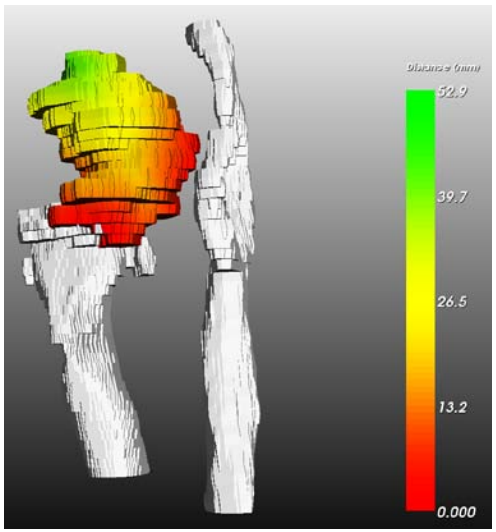
Distance-Aware Smoothing. Restrict smoothing where it affects distance measurements



Original model



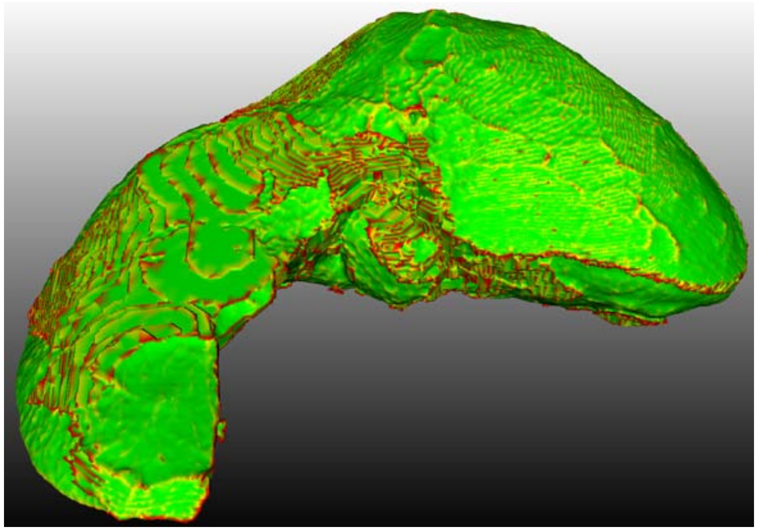
Distance-Aware Laplace

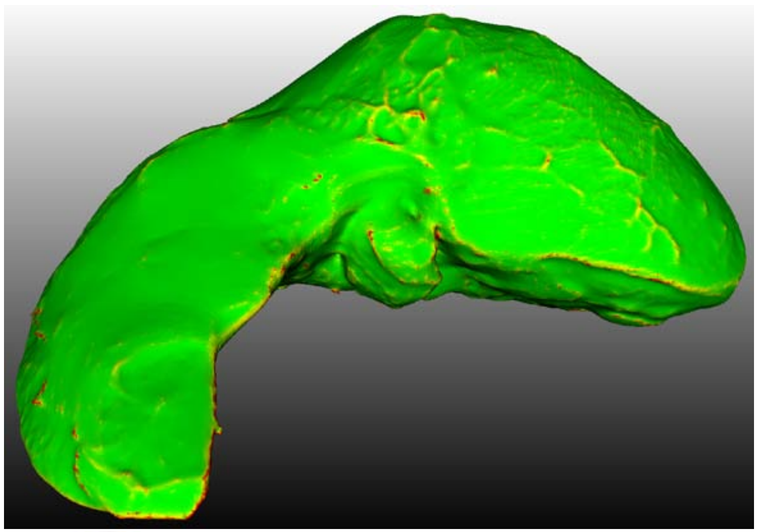


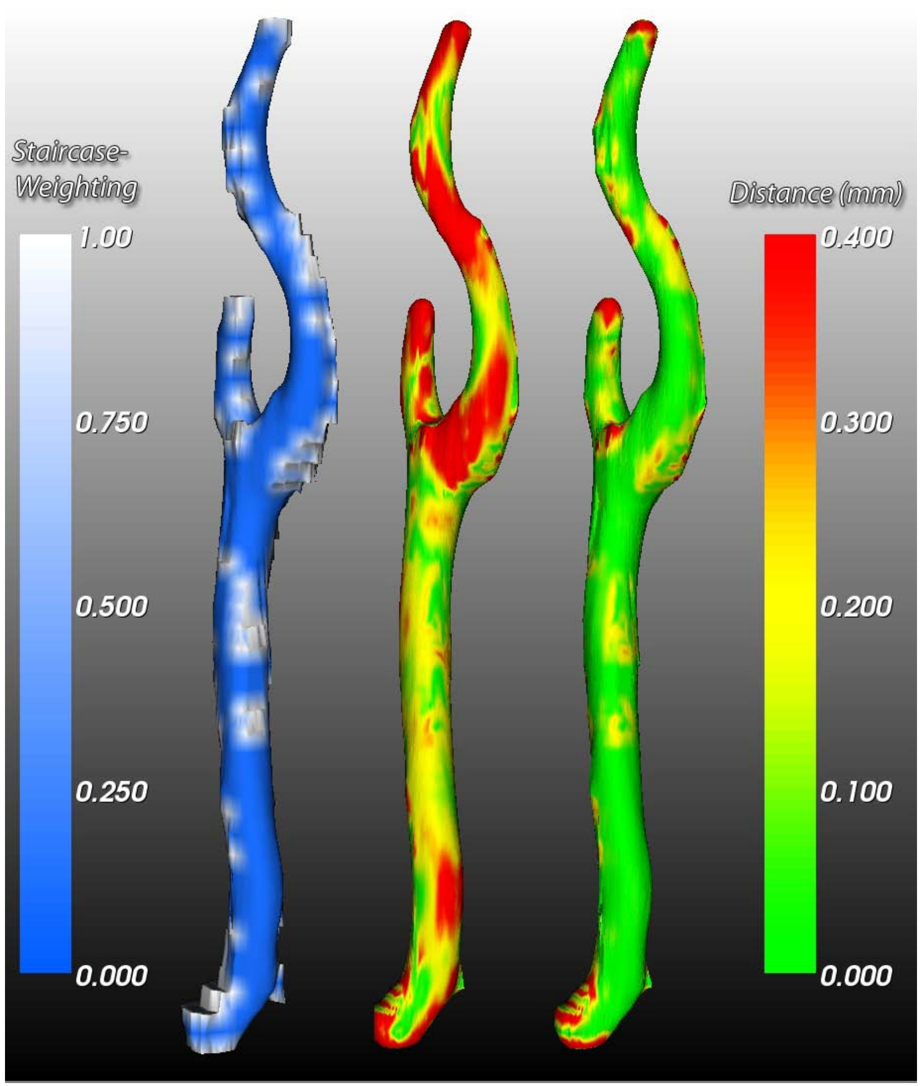
Source: [Mönch, 2010]

Smoothing of Polygonal Surfaces: Advanced Methods

- Smoothing is restricted to staircase regions

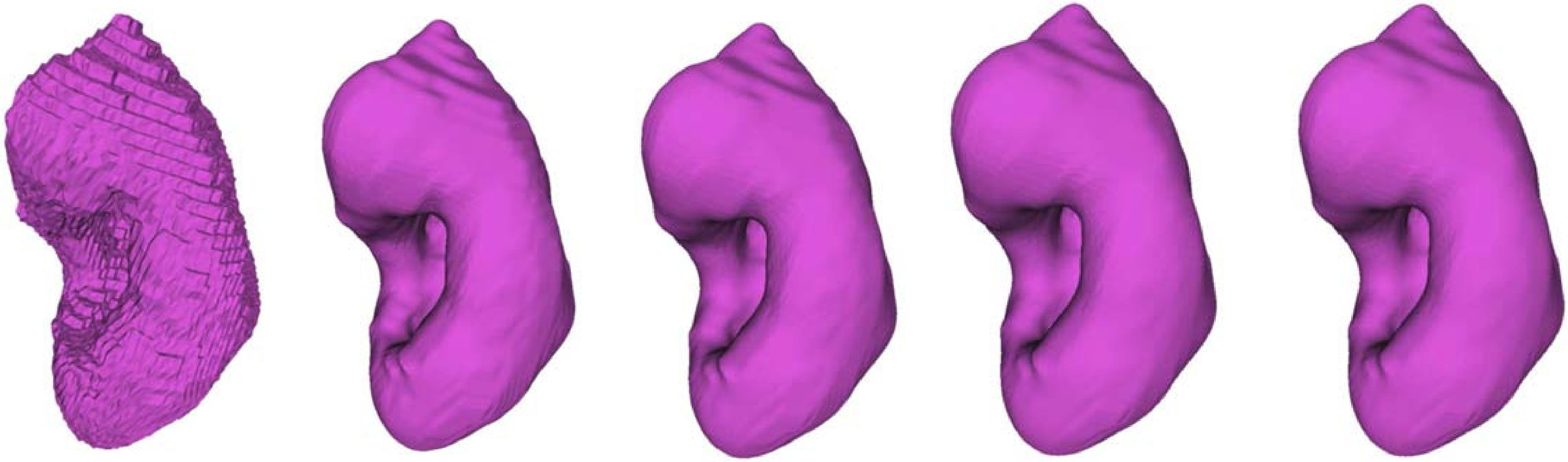






Source: [Mönch, 2011]

Smoothing of Polygonal Surfaces: Advanced Methods



(From: [Wei, 2015])

- Iterative staircase-aware smoothing (left original surface, second to fifth image: number of iterations is increasing).

Summary

- Surface visualization is essential to show vascular surfaces, skeletal structures and segmented objects
- With a carefully selected isovalue, it may be applied to the original data
- Surface models are used for visualization, biomedical simulation and rapid prototyping (some additional req.s)
- In all applications, smooth and accurate models are desired.
- Smoothness is achieved with local filters that are applied iteratively.
- Advanced methods detect staircasiness and other contextual information to adapt the amount of smoothing.

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