20 Years of Volume Rendering

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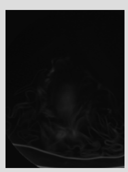
Overview

- Volume data and scanning modalities
- Volume visualization
  - Volume viewing
  - Mapping
  - Volume rendering
    - Direct volume rendering
    - Isosurfacing
- Conclusions

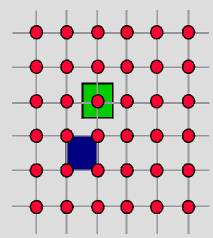
Volume Data

- A spatial sequence of 2D images – slices
- Produced by
  - 3D scanners (tomographs)
    - Different physical background
    - Different and complementary properties
  - Simulation
- Areas of application:
  - Medicine
  - Physics
  - Geology
  - ...
  - Computer (volume) graphics



3D Discrete Space

- 3D grid point (sample):
  P = [x, y, z], x, y, z ∊ Z
- Value at sample P: density
- Voxel:
  - Voronoi neighborhood of P
  - NN interpolation
- Cell:
  - 8 samples
  - higher order interpolation



Volume Data Acquisition

- Different physical configurations
- Example: A CT scanner
  1. One-dimensional X-ray projections
  2. Reconstruction

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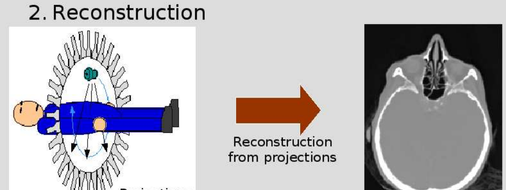
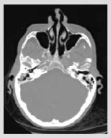


3D Modalities (1)



Computed tomography – CT

- X-ray based
- Consistent scale (Hounsfield units, -1000..3095)
- High spatial resolution (below 1mm^3)

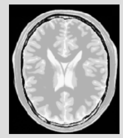
3D Modalities (2)

T1

T2

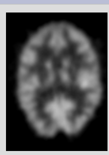
Magnetic Resonance Imaging

- Interaction of hydrogen nuclei with external magnetic field
- Good soft tissue contrast
- Numerous free parameters

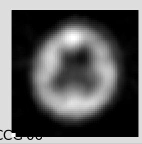


PD

3D Modalities (3)



PET

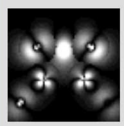


SPECT

Nuclear Imaging – PET, SPECT

- Scanning protocol:
  1. Dopant introduction
  2. Radiation measurement
- Low resolution images
- Shows organ activity

3D Modalities (4)



Simulated electron density

Synthetic data

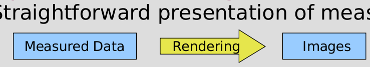
- Physical simulation
- Voxelization
  - Conversion of geometric objects to volumes

Voxelized teapot model

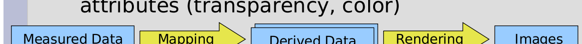
Volume Visualization

Visually perceivable data presentation

- Understanding, not photorealism
- Simple volume viewing
  - Straightforward presentation of measured data

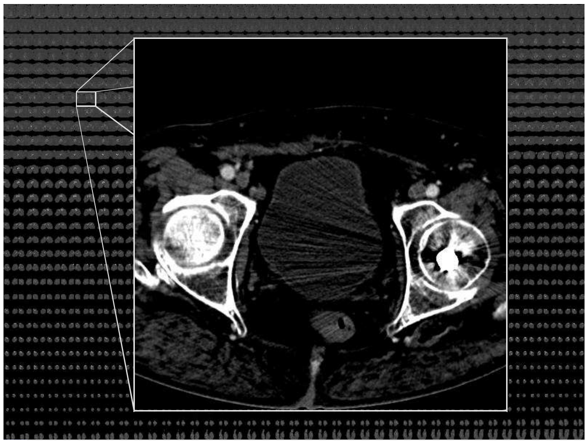


- Mapping techniques
  - Measured densities are mapped to visual attributes (transparency, color)



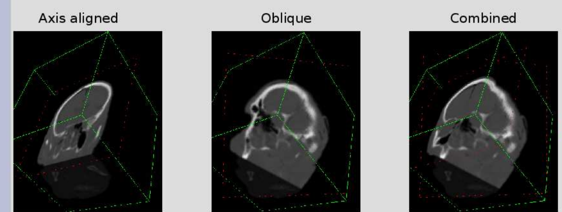
Volume Viewing (1)

Slice-by-slice viewing



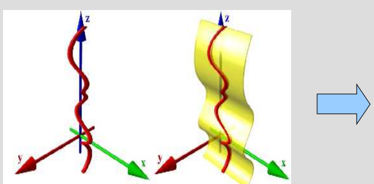
Volume Viewing (2)

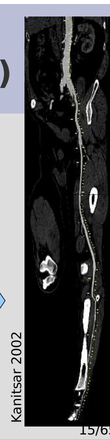
Multiplanar reconstruction
– Definition of new cutplanes



Volume Viewing (3)

Curved planar reconstruction
– Volume cutting along a line



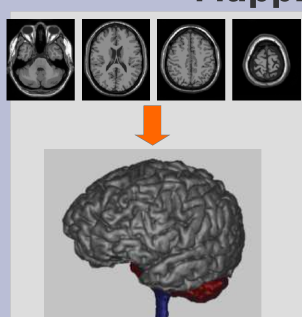


Volume Viewing (4&5)

Reprojection
– Add all values along a viewing ray
– Simulation of X-ray projection

Maximum intensity projection
- Register the brightest value along a viewing ray
- Suitable for thin structures

Volume Visualization by Mapping



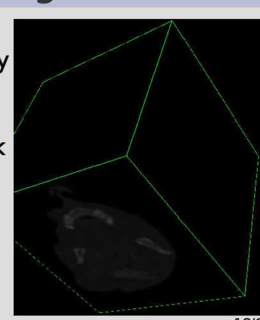
Data Acquisition
CT, MRI, USG, PET, SPECT

Mapping
Visual attributes

Rendering
Surface & Volume Techniques

Why Do We Need Mapping?

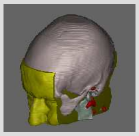
- No visual representation readily exists for 3D data
- Area of interest is occluded by the black background
- We need something to make the background transparent

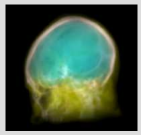


Mapping

- Mapping: Assignment of visual attributes to data:
  - transparency, color, reflectance, surface strength...
- "Area of interest" specification achieved:


Density-based **classification**


Space-based **segmentation**


Combined

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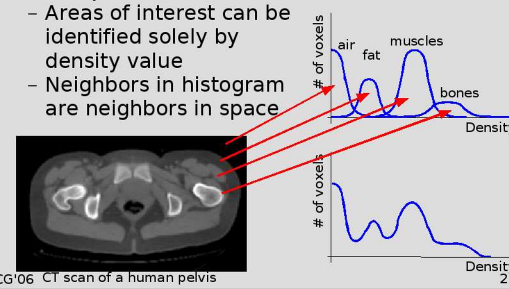
Mapping by Density Classification

- Prerequisites:
  - Areas of interest can be identified solely by density value
  - Neighbors in histogram are neighbors in space



CT scan of a human pelvis

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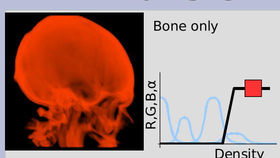
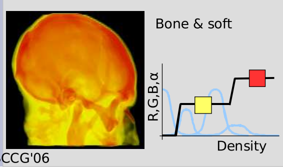
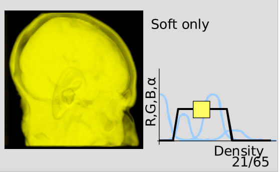
Density Classification by Transfer Functions

$$R,G,B,\alpha = f(density)$$







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TF Design Questions

- How to set TFs to get desired appearance
  - A typical inverse problem
- How to set TFs for unknown data
  - Meaningful TFs reflect data properties
- One possible answer: Design Gallery (Marks 1997)
  - Automatically generated selection of perceptually different images
  - Exhaustive search of the space of all possible Tfs

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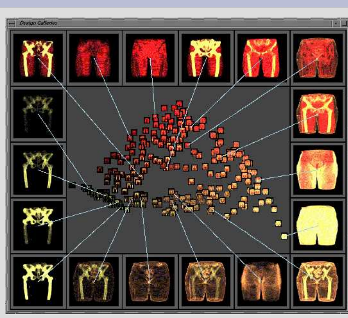
Design Gallery


[Marks 1997]

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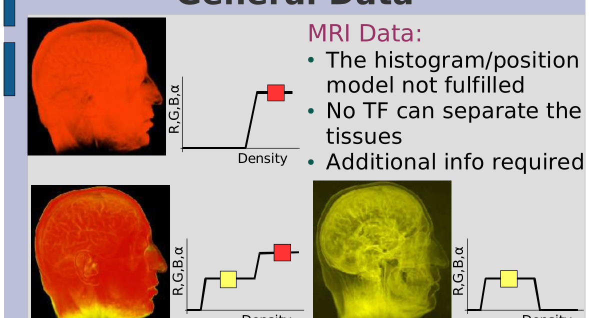
Transfer Functions with General Data

MRI Data:
- The histogram/position model not fulfilled
- No TF can separate the tissues
- Additional info required



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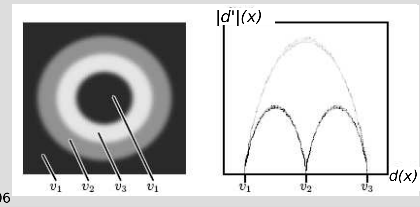
Additional Information for Better Rendering

We need to localize the Tfs

- Partial problem solution by multidimensional TFs:
  - |*d*'| *vs. d* scatterplots
  - LH-histograms
- Full solution by segmentation

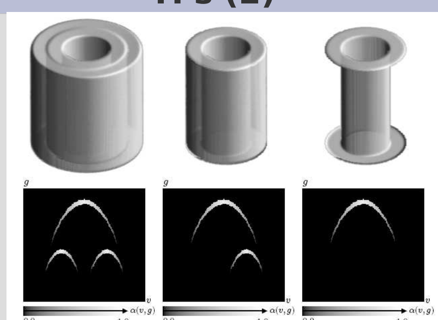
Two- (multi-)dimensional TFs (1)

- TF design paradigm based on |*d*'| *vs. d* scatterplot analysis
- Observation: special arc-shaped of blurred data



[Kindlmann 1998]

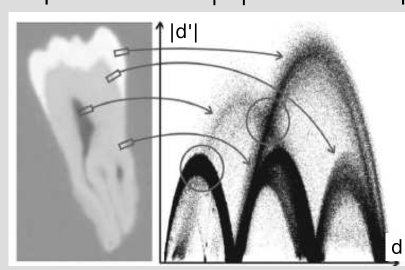
Two- (multi-)dimensional TFs (2)



[Kindlmann 1998]

Two- (multi-)dimensional TFs (3)

- A complex datased: |*d*'| *vs. d* scatterplot

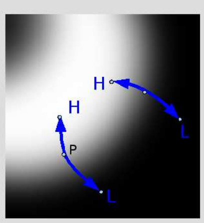


[Šereda 2006]

TF Design by LH-Histograms (1)

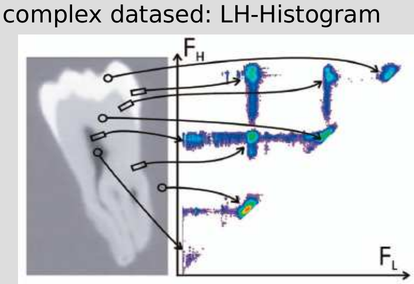
LH-Histogram:

- Downhill and uphill stationary values
- A boundary is represented by a single point



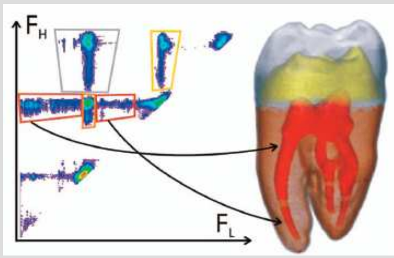
TF Design by LH-Histograms (2)

- A complex datased: LH-Histogram



[Šereda 2006]

TF Design by LH-Histograms (3)



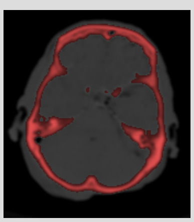
[Šereda 2006]

Mapping by Spatial Segmentation

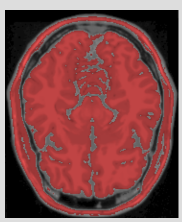
- The process of isolating objects of interest from the rest of the scene (Castleman, 1979)
- Techniques:
  - Gradient-, density- and/or texture-based
  - Fully automatic, semiautomatic, manual
  - See CV & IP literature for more
- Complexity
  - from trivial to hard

Segmentation by Thresholding

- Applicable for data, when density TFs are also OK



CT data: easy by thresholding



MRI data: impossible by thresholding

Volume Data and Segmentation

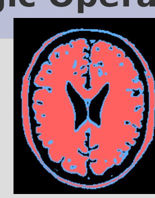
- Large number of anatomically distinct objects
- Variability of object shapes
- Variability of scanner types and parameter settings
- 3D nature of objects
- High demands on segmentation precision
- No universal technique exists

Interactive Segmentation (The ISEG Tool)

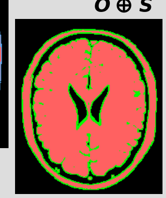
- Anatomic organs are connected and homogeneous:
  - Objects identification by
    - Thresholding
    - Connected component analysis (CCA)
- Objects are sometimes interconnected
  - Objects separation by morphological operations

Morphologic Operations

- Erosion $O \otimes S$
  - Peeling the outer layer off
- Dilation $O \oplus S$
  - Thickening by adding a layer
- Erosion + Dilation $\neq$ Original !!



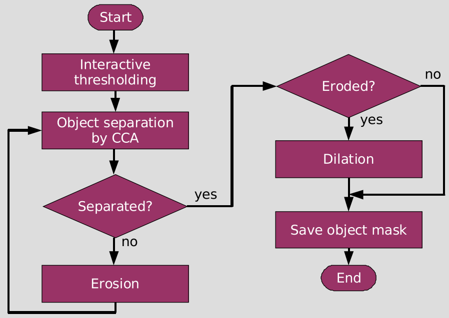
$O \otimes S$



$O \oplus S$

Structuring elements

Iseg Schematic



Iseg Results

MRI head data segmented in various tissues and objects

Head **Skull** **Brain & eyes**

Iseg Results

MRI head data segmented in various tissues and objects

White matter **Cerebellum & ventricles** **Ventricles**

Rendering

Mapping: Summary

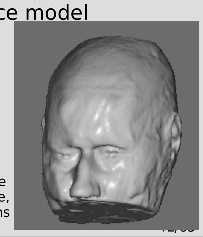
- **Transfer function based:**
  - Color & transparency assigned to voxels
  - Semitransparent volumes
  - Display of volumes
- **Segmentation-based**
  - Unambiguous object definition
  - Color & transparency assigned to objects
  - Display of surfaces

(not used for classification of rendering techniques)

Classification of Rendering Techniques (1)

Based on the basic rendering primitive

- Surface rendering
  - Basic primitive: 2D patches (polygons)
  - Extra data structure: a surface model
  - Decoupling of the model and the data
  - Rendered by standard CG approaches



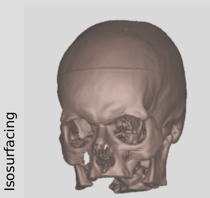
Triangulation by the Marching Cubes technique, approx. 200000 polygons

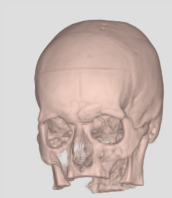
Classification of Rendering Techniques (2)

Volume rendering
- Basic primitive: the voxel itself
- Rendering directly from volume data:
- Two flavors:
  - TF based: Direct volume rendering (DVR)
    - All volume samples potentially contribute to the image
  - Segmentation (object) based: Isosurfacing
    - Only visible surfaces are displayed

DVR vs. Isosurfacing

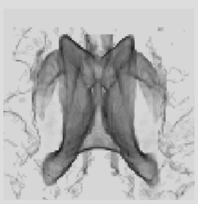
- Rendering algorithms are similar
- Isosurfacing is a limit case of DVRs with special TF and parameter setting


Isosurfacing

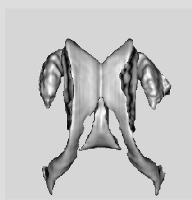

DVR

When to Prefer DVR?

- Low data contrast, weak edges, thin objects

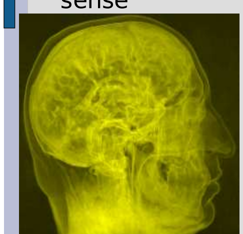

DVR


MRI head data: Ventricles & deep brain structures


Isosurfacing

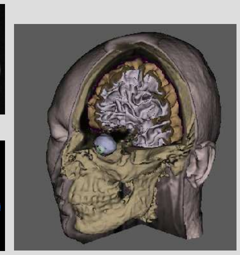
When to Prefer Isosurfacing?

- Numerous & complex objects, TFs make no sense


DVR


MRI data


Object labels


Isosurfacing with cutplanes

DVR Basics

- Simplified light interaction with semi-transparent material (Beer's Law)

$$\frac{dI(t)}{dt} = \rho(t)I(t) - k(t)\rho(t),$$

I(t): Light intensity at the point t
ρ(t): Optical density (attenuation)
k(t): Chromacity
k(t)ρ(t): Light emission rate at t
ρ(t)I(t): Light attenuation at t

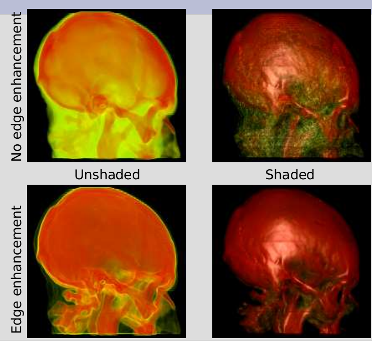
- Numerical evaluation
  - Per-segment compositing by Porter&Duff's operators
  - Front-to-back order
  - Back-to-front order

DVR Techniques (1)

Free/adjustable parameters:

- Transfer functions: $\rho(t)=f_{\rho}(d(t))$
  $k(t)=f_{k}(d(t))$
- Edge accentuation: $\rho(t)\sim|\nabla d(t)|$
- Shading: $s(t)\sim\nabla d(t).\vec{p}$
- Depth cueing
- ...

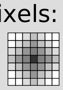
DVR Techniques (2)

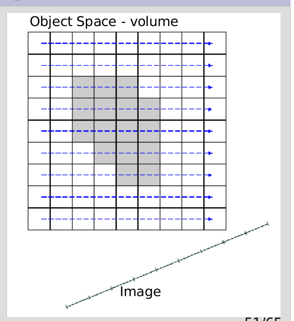


DVR Algorithms

- Object order algorithms (splatting)
  - Projection of samples from volume to image
  - Compositing in image plane
- Image order algorithms
  - Ray casting based
  - Sequence of samples along the ray
  - Compositing along the ray

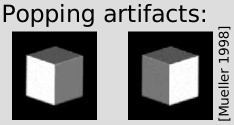
Object Order VR: Splatting (1)

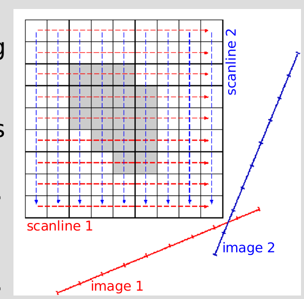
- Samples/voxels are projected (splatted) onto the viewing plane
- Back-to-front of front-to-back order
- One sample projects onto several pixels: footprint 



Object Order VR: Splatting (2)

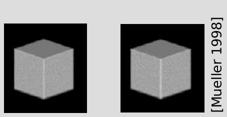
- Traversal order depends on viewing angles
- The most parallel scanline to image is chosen
- Popping artifacts:

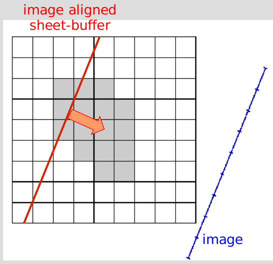




Object Order VR: Splatting (3)

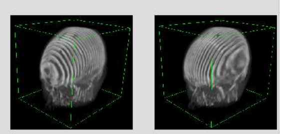
- Image aligned sheet-buffer
- No popping





HW Acceleration by Texture Mapping

- Do the costly part by hardware
- 2D Textures
  - compositing only
  - volume aligned slices
  - three copies of the volume required



- 3D Textures
  - interpolation & compositing
  - image aligned slices
- Shading possible in fragment programs

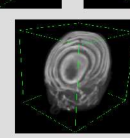
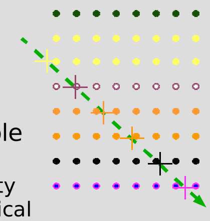


Image Order VR by Ray-Casting

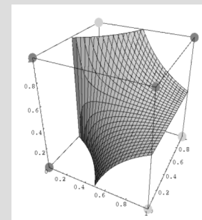
1. Shoot rays from each pixel
2. Define a sequence of samples
3. Accumulate color and opacity along each ray

- CPU and GPU implementations possible
- Acceleration required:
  - Adaptive sampling, empty space skipping, hierarchical subdivision, early termination



Isosurfacing Basics

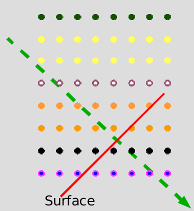
- Isosurface definition by interpolation & thresholding
- Interpolation domain:
  - Original densities
  - Segmentation labels



Interpolation surface within a single cell

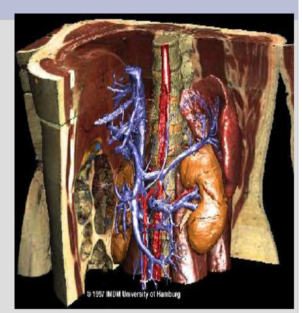
Isosurfacing Basics

- Isosurface definition by interpolation & thresholding
- Interpolation domain:
  - Original densities
  - Segmentation labels
- Algorithms:
  - (First hit) ray tracing
  - Ray/surface intersections by numerical root finding
- CPU and GPU implementations possible
- Acceleration required



Ray Casting Advantages

- Simplicity and flexibility
- Combination of techniques possible:
  - DVR, isosurfacing, MIP, CPR, cutplanes
  - per object definition of techniques and parameters



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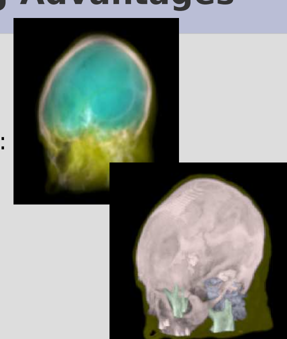

Conclusion

- We have plentiful volume rendering techniques
- We still do not have enough memory
- The computers are still not fast enough
- The doctors still prefer slice-by-slice viewing (but getting better recently...)

And what hapenned 20 (18) years ago?

Two papers were published:

- Drebin, Carpenter, Hanrahan: Volume Rendering (Siggraph)
- Marc Levoy: Display of Surfaces from Volume Data (IEEE CG&A)

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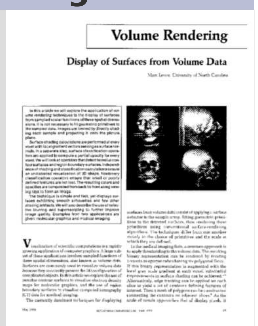
Volume Rendering

Display of Surfaces from Volume Data

Miloš Šrámek