Transfer Functions for Direct Volume Rendering
Introduction

Transfer functions make volume data visible by mapping data values to optical properties
Transfer Functions (TFs)

Simple (usual) case: Map data value \( f \) to color and opacity

Shading, Compositing…

Human Tooth CT
Math Terminology

• Basic Transfer Functions:

Space → Data Value → TF Domain → Vol Range/TF Domain → Color And Opacity

What and Why
What else in range?

• “Optical Properties”: Anything that can be composited with a standard graphics operator ("over")
  – **Opacity**: “opacity functions”
    • Most important
  – **Color**
    • Can help distinguish features
  – Emittance
  – Phong parameters ($k_a$, $k_d$, $k_s$)
  – Index of refraction
Setting Transfer Function: Hard

\[ \alpha \]

\[ \alpha \]

\[ \alpha \]

\[ \alpha \]
Volumes Consisting of Materials

So the task is to reveal the boundaries of different materials

Recall the tooth example!
Volumes Consisting of Materials

So the task is to reveal the boundaries of different materials

Grey-Level Histogram

In reality, the values at material boundaries are blurred due to the precision limit
Finding edges: easy in image

“Where’s the edge?”

Result: edge pixels

Recall the gradient calculation!
Transfer function **Unintuitive**

\[ v = f(x) \]

Opacity transfer function

**No spatial content!!!!**

Recall the gradient calculation!
TFs as feature detection

\[ v = f(x) \]

“here’s the edge (in space)!”

Domain of the transfer function does not include position

Data Value

Domain

\[ v = f(x) \]

“here’s the edge in data range \( x \)”
TFs as feature detection

$v = f(x)$

“here’s the edge (in space)!”

$TF$

Domain of the transfer function does not include position

Note that this $v_0$ may correspond to places other than edges!!!!
Now we have seen the challenge of transfer function design, let us see some strategies of addressing this challenge.

But before that, let us see some general guideline for transfer function design.
Tools for TFs

• Make good renderings easier to come by
• Make space of TFs less confusing
• Remove excess “flexibility”
• Provide one or more of:
  – Information
  – Guidance
  – Semi-automation
  – Automation
Tools for TFs

• Make good renderings easier to come by
• Make space of TFs less confusing
• Remove excess “flexibility”
• Provide one or more of:
  – Information
  – Guidance (for Semi-automation)
  – Semi-automation (more popular)
  – Automation (Machine learning!)
TF Tools

1. Trial and Error (manual)
2. Spatial Feature Detection
3. Image-Centric
4. Data-Centric
1. **Manually** edit graph of transfer function
2. Enforces learning by experience
3. Get better with practice
4. Can make terrific images
1. Trial and Error

1. Manually edit graph of transfer function
2. Enforces learning by experience
3. Get better with practice
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Control points selected by the user!
In VTK

**An example color transfer function**

```python
volumeColor = vtk.vtkColorTransferFunction()
volumeColor.AddRGBPoint(0, 0.0, 0.0, 0.0)
volumeColor.AddRGBPoint(500, 1.0, 0.5, 0.3)
volumeColor.AddRGBPoint(1000, 1.0, 0.5, 0.3)
volumeColor.AddRGBPoint(1150, 1.0, 1.0, 0.9)
```

**An example opacity transfer function**

```python
volumeScalarOpacity = vtk.vtkPiecewiseFunction()
volumeScalarOpacity.AddPoint(0, 0.00)
volumeScalarOpacity.AddPoint(500, 0.15)  # Skin is more transparent
volumeScalarOpacity.AddPoint(1000, 0.15)
volumeScalarOpacity.AddPoint(1150, 0.85)  # Bone get the highest opacity
```
1. Trial and Error (manual)
2. Spatial Feature Detection
3. Image-Centric
4. Data-Centric
2. Spatial Feature Detection

Transform TF specification to **feature detection in the spatial domain**

- extremely flexible
- different parameter space
- *not exactly transfer functions* ...

1. Fang, Biddlecome, Tuceryan (Vis ‘98)  
   “Image-based Transfer Function Design...”

2. Rheingans, Ebert (Vis ’00, TVCG July ’01)  
   “Volume Illustration: Non-photorealistic...”

3. Hladuvka, Gröller (VisSym ’01) “Salient Representation of Volume Data”
Volume Illustration

Traditional Volume Rendering Pipeline

- Volume values \( f_i(x_i) \)
- Shading
  - Voxel colors \( c_\lambda(x_i) \)
- Classification
  - Voxel opacities \( \alpha(x_i) \)
- Resampling and compositing (raycasting, splatting, etc.)
- Shaded, segmented volume \([c_\lambda(x_i), \alpha(x_i)]\)
- Image pixels \( C_\lambda(u_i) \)

Volume Illustration Rendering Pipeline

- Volume Rendering
  - Transfer function
- Volume Illustration
  - Color modification
- Volume Illustration
  - Opacity modification
- Final volume sample \([c_\lambda(x_i), \alpha(x_i)]\)
- Image pixels \( C_\lambda(u_i) \)

Feature Enhancement

- Boundary, silhouette enhancement

Depth and Orientation Cues

- Halos, depth cueing

Thanks to Penny Rheingans and David Ebert
Silhouettes  Halos
Volume Illustration

Traditional

Boundary and silhouette
TF Tools

1. Trial and Error (manual)
2. Spatial Feature Detection
3. Image-Centric
4. Data-Centric
3. Image-centric

Specify TFs via the resulting renderings

- **Genetic Algorithms** ("Generation of Transfer Functions with Stochastic Search Techniques", He, Hong, et al.: Vis ’96)
- **Design Galleries** (Marks, Andalman, Beardsley, et al.: SIGGRAPH ’97; Pfister: Transfer Function Bake-off Vis ’00)
- **Thumbnail Graphs + Spreadsheets** ("A Graph Based Interface...", Patten, Ma: Graphics Interface ’98; “Image Graphs...", Ma: Vis ’99; Spreadsheets for Vis: Vis ’00, TVCG July ’01)
TF Tools

1. Trial and Error (manual)
2. Spatial Feature Detection
3. Image-Centric
4. Data-Centric
5. Others
4. Data-centric

Specify TF by **analyzing** volume data itself

1. **Salient Isovalues:**
   - Contour Spectrum (Bajaj, Pascucci, Schikore: Vis ’97)
   - Statistical Signatures (“Salient Iso-Surface Detection Through Model-Independent Statistical Signatures”, Tenginaki, Lee, Machiraju: Vis ’01)
   - Other computational methods (“Fast Detection of Meaningful Isosurfaces for Volume Data Visualization”, Pekar, Wiemker, Hempel: Vis ’01)

2. “Semi-Automatic Generation of Transfer Functions for Direct Volume Rendering” (Kindlmann, Durkin: VolVis ’98; Kindlmann MS Thesis ’99; Transfer Function Bake-Off Panel: Vis ‘00)
Salient Isovalues

What are the “best” isovalues for extracting the main structures in a volume dataset?

Contour Spectrum (Bajaj, Pascucci, Schikore: Vis ’97; Transfer Function Bake-Off: Vis ’00)

- Efficient computation of isosurface metrics
  - Area, enclosed volume, gradient surface integral, etc.
- Efficient connected-component topological analysis
- Interface itself concisely summarizes data
The contour spectrum allows the development of an adaptive ability to separate *interesting* isovalues from the others.
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Contour Spectrum

Any issue with the contour spectrum???
“Semi-Automatic ...”

Reasoning:

- *TFs are volume-position invariant*
- Histograms "project out (lose)" position
- *Interested in boundaries between materials*
“Semi-Automatic ...”

Reasoning:
• **TFs are volume-position invariant**
• Histograms “**project out (lose)**” position
• *Interested in boundaries between materials*
• Boundaries characterized by derivatives
“Semi-Automatic …”

Reasoning:

- **TFs are volume-position invariant**
- Histograms “**project out (lose)**” position
- **Interested in boundaries between materials**
- Boundaries characterized by derivatives

\[\rightarrow \text{Make 3D histograms of value, } 1^\text{st}, 2^\text{nd} \text{ deriv.}\]

By (1) **inspecting** and (2) **algorithmically analyzing** histogram volume of the function and its derivatives, we can create transfer functions.
Derivative relationships

Edges at maximum of 1\textsuperscript{st} derivative or zero-crossing of 2\textsuperscript{nd} derivative
4. Data-Centric

Scatterplots to find boundaries

Project histogram volume to 2D scatterplots

- Visual summary
- Interpreted for TF guidance
- No reliance on boundary model at this stage
Example: 2D transfer function for Tooth Data

Detected 4 distinct boundaries between 4 materials

\[ d(v,g) \]

White regions in color mapped 2D distance function plot are boundary centers

- Pulp
- Background
- Dentine
- Enamel

Color transfer function
Opacity Transfer Function: Analysis

Volume Graphics Distance Map

\[(x, y, z)\]

3D position

\(d\) Signed distance to boundary

New Distance Map in data range!

0 255

\(V\) data value
Opacity Transfer Function: New Distance Map

- Supports 2D distance map:
  \[ d(v, g); \quad g = \text{gradient magnitude} \]
- Produced automatically from histogram volume via boundary model
Opacity Transfer Function: Whole Process

Automatically generated from histogram volume

\[ x = d(v) \]

distance function:

data value: \( v \)

opacity function:

\[ \alpha(v) = b(d(v)) \]

opacity:

\[ a = b(x) \]

boundary emphasis function:

4. Data-Centric
Results: CT Head
Results: Tooth

Boundary emphasis function simple to set

\[ a(v) = b(d(v)) \]
Math Terminology

• Basic Transfer Functions:

Space → Vol Domain → Value + Grad Mag → TF Domain → Color And Opacity
2D Opacity Functions

Mostly accurate isolation of all material boundaries
2D Opacity Functions
Organization

1. Trial and Error (manual)
2. Spatial Feature Detection
3. Image-Centric
4. Data-Centric
5. Others
Curvature

“Curvature-Based Transfer Functions for Direct Volume Rendering”, Hladuvka, König, Gröller: SCCG ’00

- Uses 2D space of $\kappa_1$ and $\kappa_2$: principal curvatures of isosurface at a given point
- Graphically indicates aspects of local shape
- Specification is simple
Different Interaction

“Interactive Volume Rendering Using Multi-Dimensional Transfer Functions and Direct Manipulation Widgets” Kniss, Kindlmann, Hansen: Vis ’01

- Make things opaque by pointing at them
- Uses 3D transfer functions (value, 1st, 2nd derivative)
- “Paint” into the transfer function domain