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 → Vol → Data Value → TF → Color And Opacity

  Domain √ Vol Range/TF Domain

  Range
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

\[ \alpha \rightarrow v \]

\[ \alpha \rightarrow v \]

\[ \alpha \rightarrow v \]

\[ \alpha \rightarrow v \]
Volumes Consisting of Materials

Grey-Level Histogram

Data value

Num voxels

Material 1

Material 2

Material 3
Finding edges: easy in image

“Where’s the edge?”

Result: edge pixels
Transfer function Unintuitive

\[ v = f(x) \]

"Here's the edge"
TFs as feature detection

$v = f(x)$

“here’s the edge!”

Domain of the transfer function does not include position

$v = f(x)$

$v_0$

“here’s the edge!”
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
TF Tools

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

1. Manually edit graph of transfer function
2. Enforces learning by experience
3. Get better with practice
4. Can make terrific images

William Schroeder, Lisa Sobierajski Avila, and Ken Martin; Transfer Function Bake-off Vis ’00
2. Spatial Feature Detection
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 $f_1(x_i)$
  - Shading
    - Voxel colors $c_1(x_i)$
  - Classification
    - Voxel opacities $\alpha(x_i)$
  - Shaded, segmented volume $[c_1(x_i), \alpha(x_i)]$
  - Resampling and compositing (raycasting, splatting, etc.)
- Image pixels $C_1(u_i)$

Volume Illustration Rendering Pipeline
- Volume values $f_1(x_i)$
  - Transfer function
  - Volume Illustration
    - Color modification
    - Opacity modification
  - Final volume sample $[c_2(x_i), \alpha(x_i)]$
- Image pixels $C_2(u_i)$

Feature Enhancement
- Boundary, silhouette enhancement
- Depth and Orientation Cues
- Halos, depth cueing

Thanks to Penny Rheingans and David Ebert
Volume Illustration

Silhouettes

Halos

Blurs distinction between transfer functions and feature detection
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
Contour Spectrum

The contour spectrum allows the development of an adaptive ability to separate *interesting* isovalues from the others.
The contour spectrum allows the development of an adaptive ability to separate *interesting* isovalues from the others.
“Semi-Automatic ...”

Reasoning:

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

⇒ Make 3D histograms of value, 1\textsuperscript{st}, 2\textsuperscript{nd} deriv.

By (1) **inspecting** and (2) algorithmically **analyzing** histogram volume, we can create transfer functions
Derivative relationships

Edges at maximum of 1\textsuperscript{st} derivative or zero-crossing of 2\textsuperscript{nd}
(1) Scatterplots

Project histogram volume to 2D scatterplots

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

Detected 4 distinct boundaries between 4 materials

- Pulp
- Background
- Dentine
- Enamel

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

Color transfer function
(2) Analysis

Volume Graphics Distance Map

\[(x, y, z)\]

3D position

\[d\]

Signed distance to boundary

New Distance Map!

\[0 \quad V \quad 255\]

data value

4. Data-Centric
(2) New Distance Maps

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

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

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

2. Whole process

Automatically generated from histogram volume

distance function:

\[ d(v) \]

data value:

\[ v \]

Opacity function:

\[ \alpha(v) \]

Created by user

boundary emphasis function:

\[ b(x) \]
Results: CT Head
Results: Tooth

Boundary emphasis function simple to set

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

• Basic Transfer Functions:

Space → Vol Range/TF Domain

Vol Range/TF Domain → Value + Grad Mag

Value + Grad Mag → Color And Opacity

Range
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 $K_1$ and $K_2$: 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, 1\textsuperscript{st}, 2\textsuperscript{nd} derivative)
- “Paint” into the transfer function domain