Scientific Visualization

• Generally do not start with a 3D model
• Must deal with very large data sets
  – MRI, e.g. $512 \times 512 \times 200 \approx 50$ MB points
  – Visible Human $512 \times 512 \times 1734 \approx 433$ MB points
• Visualize both real-world and simulation data
• User interaction
• Automatic search

Types of Data

• Scalar fields (3D volume of scalars)
  – E.g., x-ray densities (MRI, CT scan)
• Vector fields (3D volume of vectors)
  – E.g., velocities in a wind tunnel
• Tensor fields (3D volume of tensors [matrices])
  – E.g., stresses in a mechanical part [Angel 12.7]
• Static or through time

Meshes

• Function is sampled (given) at $x_i, y_j, 0 \leq i, j \leq n$
• Assume equally spaced

$$f(r, v) = (r(u), v) = \sum_{i=0}^{n} \sum_{j=0}^{n} f(x_i, y_j) \cos \left( \frac{(2x+1)\pi}{2n} \right) \cos \left( \frac{(2y+1)\pi}{2n} \right)$$

where $r(u) = 1/\sqrt{n}$ if $u = 0$, $r(u) = \sqrt{2/n}$ otherwise
• Generate quadrilateral or triangular mesh
• [Asst 1]

Height Field

• Visualizing an explicit function

$$z = f(x, y)$$

• Adding contour curves

$$g(x, y) = c$$

Contour Curves

• Recall: implicit curve $f(x, y) = 0$
• $f(x, y) < 0$ inside, $f(x, y) > 0$ outside
• Here: contour curve at $f(x, y) = c$
• Sample at regular intervals for $x, y$

$$x_j = x_0 + j \Delta x$$
$$y_j = y_0 + j \Delta y$$

• How can we draw the curve?
Marching Squares

- Sample function \( f \) at every grid point \( x_i, y_j \)
- For every point \( f_{ij} = f(x_i, y_j) \) either \( f_{ij} \leq c \) or \( f_{ij} > c \)
- Distinguish those cases for each corner \( x \)
  - White: \( f_{ij} \leq c \)
  - Black: \( f_{ij} > c \)
- Now consider cases for curve
- Assume "smooth"
- Ignore \( f_{ij} = 0 \)

Interpolating Intersections

- Approximate intersection
  - Midpoint between \( x_i, x_{i+1} \) and \( y_j, y_{j+1} \)
  - Better: interpolate
- If \( f_{ij} = a \) is closer to \( c \) than \( b = f_{i+1j} \) then intersection is closer to \( (x_i, y_j) \):
  \[
  \frac{x - x_i}{x_{i+1} - x} = \frac{c - a}{b - c}
  \]
- Analogous calculation for \( y \) direction

Cases for Vertex Labels

- 16 cases for vertex labels
- 4 unique mod. symmetries

Ambiguities of Labelings

- Ambiguous labels
- Different resulting contours
- Resolution by subdivision (where possible)

Marching Squares Examples

- Ovals of Cassini, \( 50 \times 50 \) grid
  \[
  f(x, y) = (x^2 + y^2 + a^2)^2 - 4a^2x^2 - b^4
  \]
  \( a = 0.49, b = 0.5 \)
- Midpoint
- Interpolation
- Contour plot of Honolulu data

Outline

- Height Fields and Contours
- Scalar Fields
- Volume Rendering
- Vector Fields
Scalar Fields
- Volumetric data sets
- Example: tissue density
- Assume again regularly sampled
  \[ x_i = x_0 + i\Delta x \]
  \[ y_j = y_0 + j\Delta y \]
  \[ z_k = z_0 + k\Delta z \]
- Represent as voxels

Isosurfaces
- \( f(x,y,z) \) represents volumetric data set
- Two rendering methods
  - Isosurface rendering
  - Direct volume rendering (use all values [next])
- Isosurface given by \( f(x,y,z) = c \)
- Recall implicit surface \( g(x, y, z) \):
  - \( g(x, y, z) < 0 \) inside
  - \( g(x, y, z) = 0 \) surface
  - \( g(x, y, z) > 0 \) outside
- Generalize right-hand side from 0 to c

Marching Cubes
- Display technique for isosurfaces
- 3D version of marching squares
- 14 cube labelings (after elimination symmetries)

Marching Cube Tessellations
- Generalize marching squares, just more cases
- Interpolate as in 2D
- Ambiguities similar to 2D

Volume Rendering
- Sometimes isosurfaces are unnatural
- Use all voxels and transparency (\( \alpha \)-values)

Surface vs. Volume Rendering
- 3D model of surfaces
- Convert to triangles
- Draw primitives
- Lose or disguise data
- Good for opaque objects
- Scalar field in 3D
- Convert to RGBA values
- Render volume “directly”
- See data as given
- Good for complex objects
Sample Applications

- Medical
  - Computed Tomography (CT)
  - Magnetic Resonance Imaging (MRI)
  - Ultrasound
- Engineering and Science
  - Computational Fluid Dynamic (CFD)
  - Aerodynamic simulations
  - Meteorology
  - Astrophysics

Volume Rendering Pipeline

- Transfer function: from data set to colors and opacities
  - Example: $256 \times 256 \times 64 \times 2 = 4$ MB
  - Example: use colormap (8 bit color, 8 bit opacity)

Transfer Functions

- Transform scalar data values to RGBA values
- Apply to every voxel in volume
- Highly application dependent
- Start from data histogram
- Opacity for emphasis

Transfer Function Example

Mantle Convection

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Volume Ray Casting

- Three volume rendering techniques
  - Volume ray casting
  - Splatting
  - 3D texture mapping
- Ray Casting
  - Integrate color through volume
  - Consider lighting (surfaces?)
  - Use regular x,y,z data grid when possible
  - Finite elements when necessary (e.g., ultrasound)
  - 3D-rasterize geometrical primitives
Accumulating Opacity

• $\alpha = 1.0$ is opaque
• Composity multiple layers according to opacity
• Use local gradient of opacity to detect surfaces for lighting

Trilinear Interpolation

• Interpolate to compute RGBA away from grid
• Nearest neighbor yields blocky images
• Use trilinear interpolation
• 3D generalization of bilinear interpolation

Splatting

• Alternative to ray tracing
• Assign shape to each voxel (e.g., Gaussian)
• Project onto image plane (splat)
• Draw voxels back-to-front
• Composite (\(\alpha\)-blend)

3D Textures

• Alternative to ray tracing, splatting
• Build a 3D texture (including opacity)
• Draw a stack of polygons, back-to-front
• Efficient if supported in graphics hardware
• Few polygons, much texture memory

Example: 3D Textures

Example: 3D Textures
Other Techniques

- Use CSG for cut-away

Acceleration of Volume Rendering

- Basic problem: Huge data sets
- Program for locality (cache)
- Divide into multiple blocks if necessary
  - Example: marching cubes
- Use error measures to stop iteration
- Exploit parallelism

Outline

- Height Fields and Contours
- Scalar Fields
- Volume Rendering
- Vector Fields

Vector Fields

- Visualize vector at each (x,y,z) point
  - Example: velocity field
  - Example: hair
- Hedgehogs
  - Use 3D directed line segments (sample field)
  - Orientation and magnitude determined by vector
- Animation
  - Use for still image
  - Particle systems

Using Glyphs and Streaks

- Glyphs for air flow
- University of Utah

More Flow Examples

- Blood flow in human carotid artery
- Banks and Ferreira
Example: Jet Shockwave

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Summary

• Height Fields and Contours
• Scalar Fields
  – Isosurfaces
  – Marching cubes
• Volume Rendering
  – Volume ray tracing
  – Splatting
  – 3D Textures
• Vector Fields
  – Hedgehogs
  – Animated and interactive visualization

Preview

• Pick up Assignment 6
• Thursday
  – Non-photo-realistic rendering (NPR)
  – Assignment 7 (Ray Tracing) due!
  – Assignment 8 (written) out
• Next Tuesday
  – Guest lecture: Wayne Wooten, Pixar
• Next Thursday
  – Review for final
  – Assignment 8 due