Scientific Visualization

- Generally do not start with a 3D triangle model
- Must deal with very large data sets
  - MRI, e.g. 512 x 512 x 200 = 50MB points
  - Visible Human 512 x 512 x 1734 = 433 MB points
- Visualize both real-world and simulation data
- User interaction
- Automatic search for relevant data

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
- Static or dynamic through time

Visualization

Height Fields and Contours
Scalar Fields
Volume Rendering
Vector Fields

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Height Field

- Visualizing an explicit function
  \[ z = f(x,y) \]
- Adding contour curves
  \[ g(x,y) = c \]

Meshes

- Function is sampled (given) at \( x_i, y_j, 0 \leq i, j \leq n \)
- Assume equally spaced
  \[ x_i = x_0 + i\Delta x \]
  \[ y_j = y_0 + j\Delta y \]
- Generate quadrilateral or triangular mesh
- [Assignment 1]

Contour Curves

- Recall: implicit curve \( f(x,y) = 0 \)
  \[ f(x,y) < 0 \text{ inside, } f(x,y) > 0 \text{ outside} \]
- Here: contour curve at \( f(x,y) = c \)
- Implicit function \( f \) sampled at regular intervals for \( x,y \)
  \[ x_i = x_0 + i\Delta x \]
  \[ y_j = y_0 + j\Delta y \]
- 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”

**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 cases modulo symmetries

**Ambiguities of Labelings**

- Different resulting contours
- Resolution by subdivision (if such higher resolution available / possible)

**Marching Squares Examples**

- Ovals of Cassini, 50 x 50 grid
  \[
  f(x, y) = (x^2 + y^2 + a^2)^2 - 4a^2x^2 - b^4
  \]
  $a = 0.49, b = 0.5$
- 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 of symmetries)

Marching Cube Tessellations

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

Volume Rendering

- Sometimes isosurfaces are unnatural or do not give sufficient information
- 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 it 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: converts input data set to colors and opacities
  - Example input: 256 x 256 x 256 x 8 bytes = 128 MB
  - Convert to 24 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 Heat Convection

**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
- Composite multiple layers according to opacity
- Use local gradient of opacity for enhanced display of boundaries

\[ C_{out} = C_{in} \times \alpha \]
**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**

**Other Techniques**
- Use CSG for cut-aways
Acceleration of Volume Rendering

- Basic problem: Huge data sets
- Must 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 Streaklines

Glyphs for air flow
University of Utah

Glyph = marker (for example, an arrow) used for data visualization

More Flow Examples

Blood flow in human carotid artery

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