Realtime Computer Graphics on GPUs

Scientific Visualization

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Volumetric Data

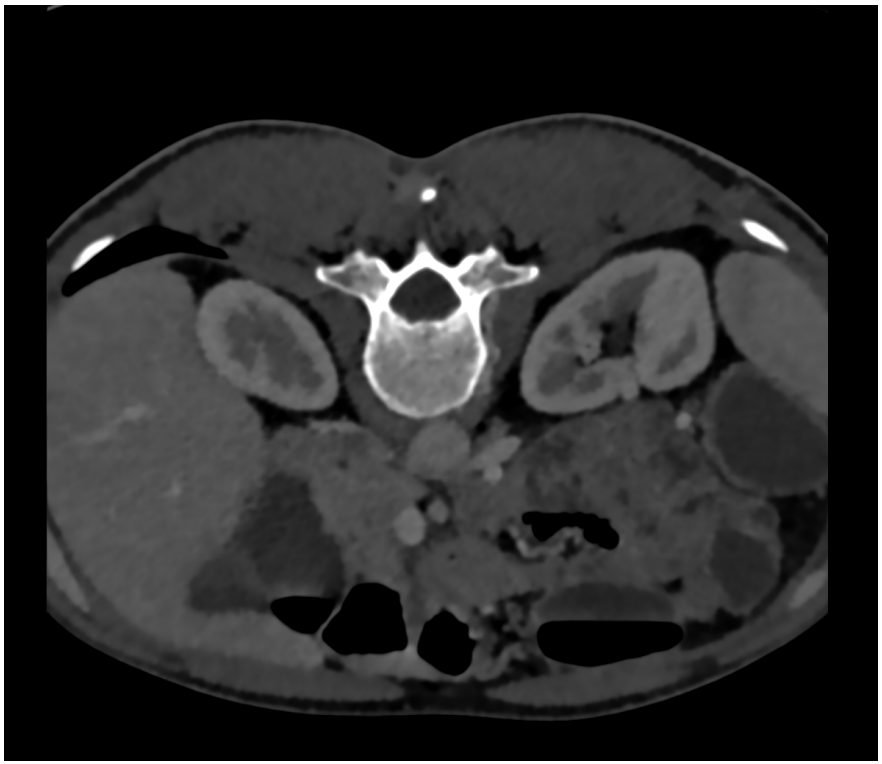
Data Source

- Computed tomography (CT)
- Magnetic resonance (MRI)
- Confocal laser scanning microscopy
- Ultrasonic imaging
- Cryo-electron tomography
- Positron emission tomography (PET)
- ...

Data Representation

- Regular, 3-dimensional grid of samples (voxels)
  - Scalar values – density, absorption coefficients, event counting
  - Vectors
  - Color
- 3D texture:
  - Trilinear filtering
  - Easy *slicing* in general direction
- 2D texture:
  - Set of textures
  - Texture atlas
  - Manual filtering in Z-direction

2D Slices



Direct Volume Rendering

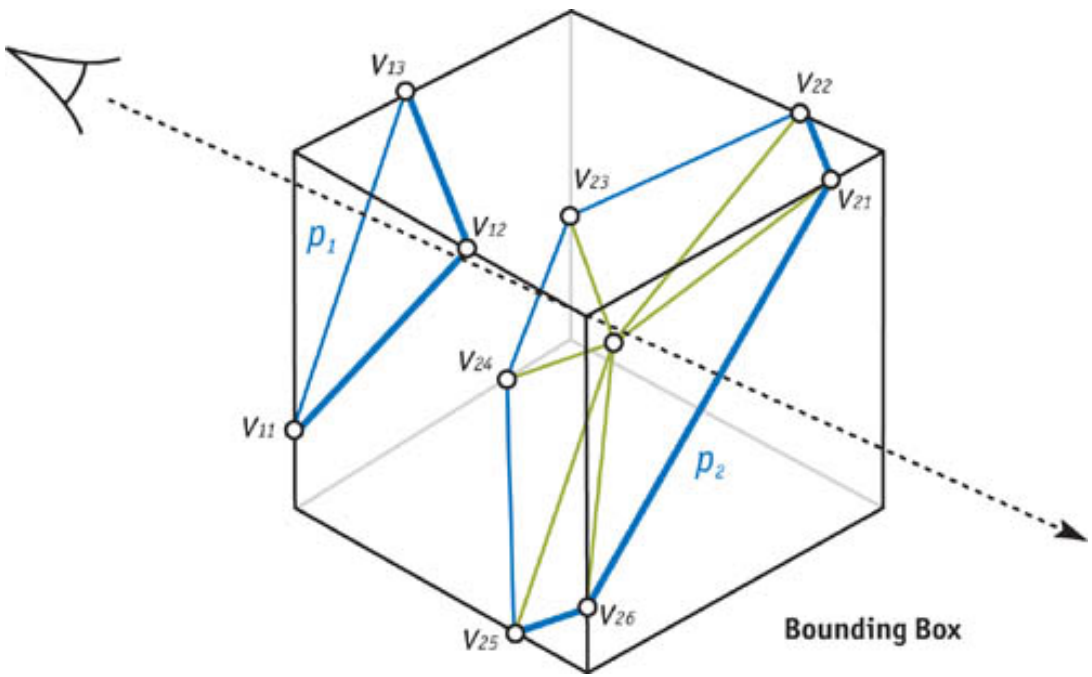
Volume Rendering Integral

$$I(D) = I_0 e^{-\int_{s_0}^{D} \kappa(t)dt} + \int_{s_0}^{D} q(s) e^{-\int_{s}^{D} \kappa(t)dt} ds$$

- entry point s_0
- exit point D (camera position)
- emission at a point q
- I_0 initial intensity s_0 (light emmitance of the background),
- κ is absorption coefficient.

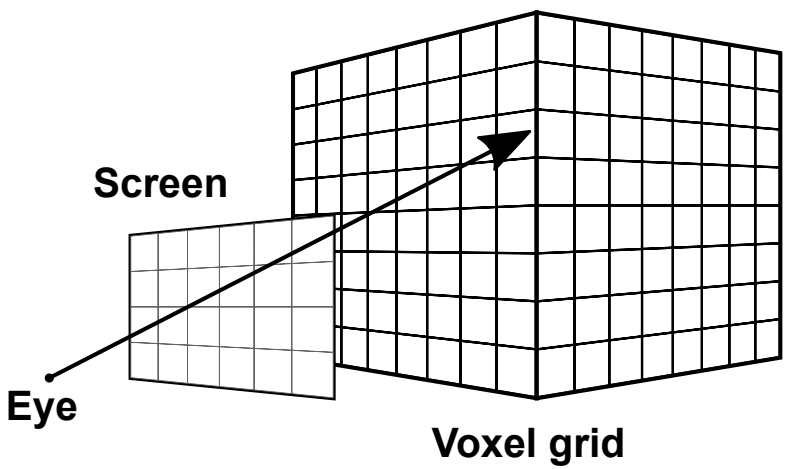
VIEWPORT ALIGNED SLICES

- Generate proxy geometry
  - Viewport aligned slices (billboards)
  - Limited by volume bounding box – limit fragment count
  - Convex – easy to triangulate
- Enable framebuffer blending
  - Color attachment with float precision



RAY-CASTING

- Generate rays from camera through each pixel
  - Fragments generated by rendering bounding volume
- Discrete samples along the ray
- Numerical computation of the rendering integral



Volume Compositing Schemes

- In Direct Volume Rendering, *compositing* accumulates color and opacity along the viewing ray.
- Two main compositing orders:
  - **Front-to-back**: processes samples from the eye toward the volume.
  - **Back-to-front**: processes samples from deep in the volume toward the eye.

Compositing Equations

Color premultiplied by alpha

Front-to-Back Compositing:

$$\begin{aligned} C_{dst} &\leftarrow C_{dst} + (1 - \alpha_{dst})C_{src} \\ \alpha_{dst} &\leftarrow \alpha_{dst} + (1 - \alpha_{dst})\alpha_{src} \end{aligned}$$

- Supports *early ray termination* when $\alpha_{dst} \approx 1$.

Back-to-Front Compositing (painter's algorithm):

$$C_{dst} \leftarrow (1 - \alpha_{src})C_{dst} + C_{src}$$

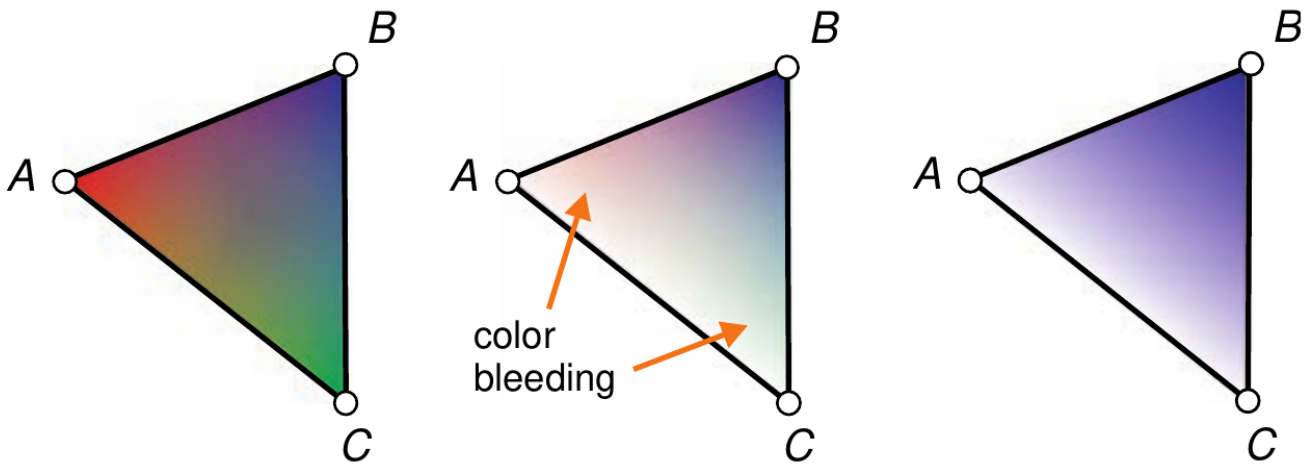
- Doesn't allow early termination.

Opacity from Absorption (based on distance):

$$\alpha_i = 1 - e^{-\kappa_i \Delta s}$$

COLOR BLEEDING

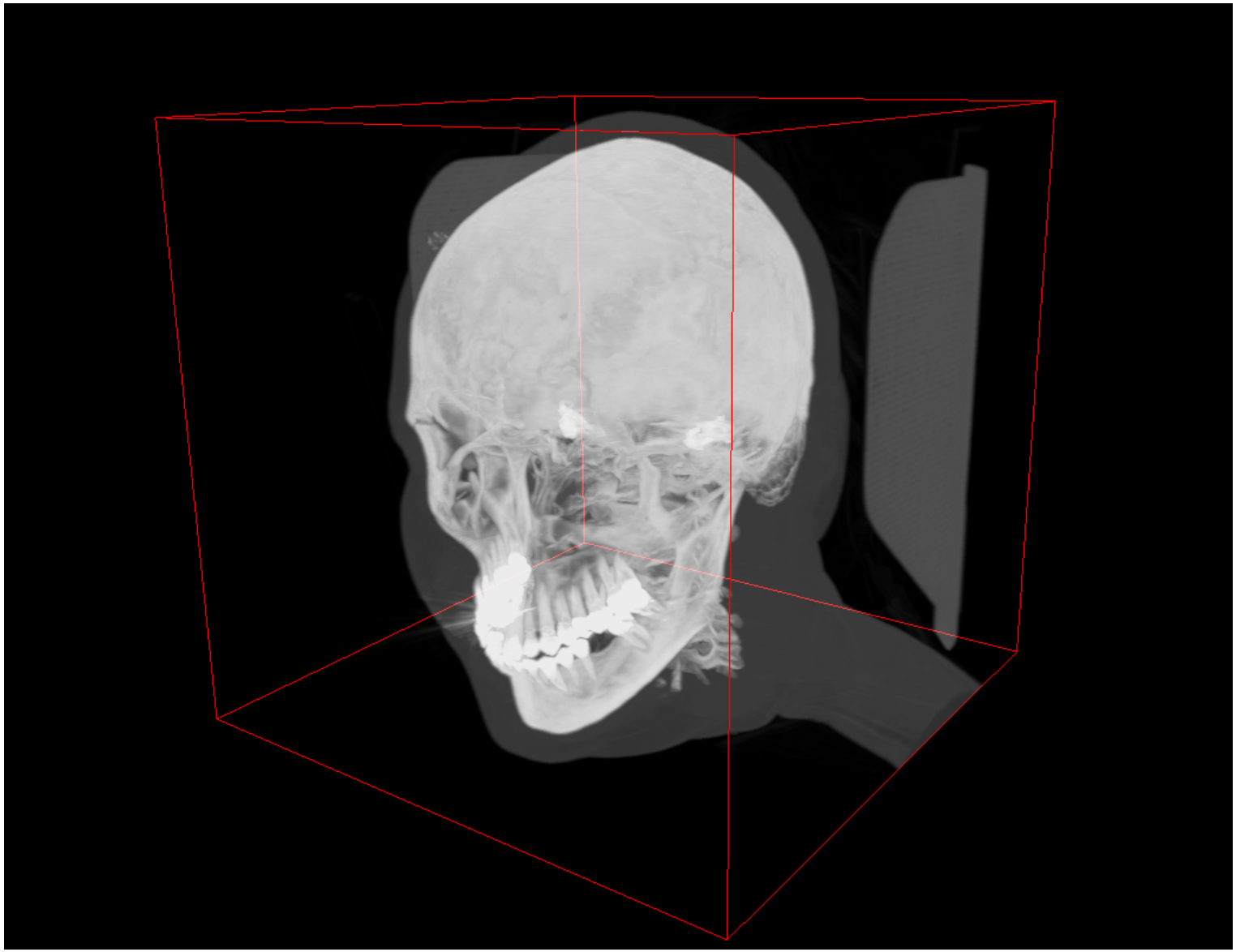
Interpolation with/without premultiplied alpha



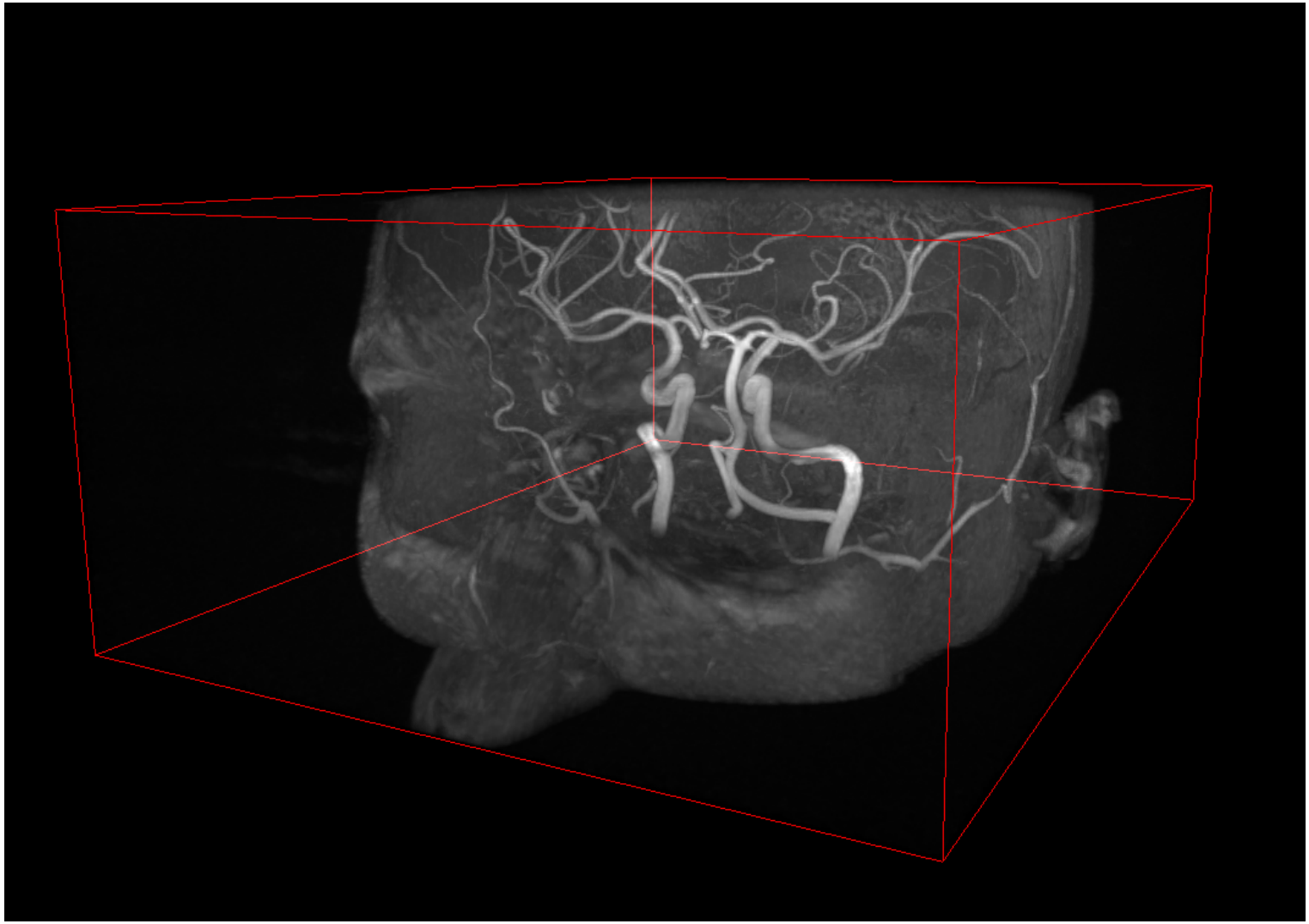
Maximum Intensity Projection

- Uses maximum value found along the ray.
- Bad sense of depth.

Maximum Intensity Projection

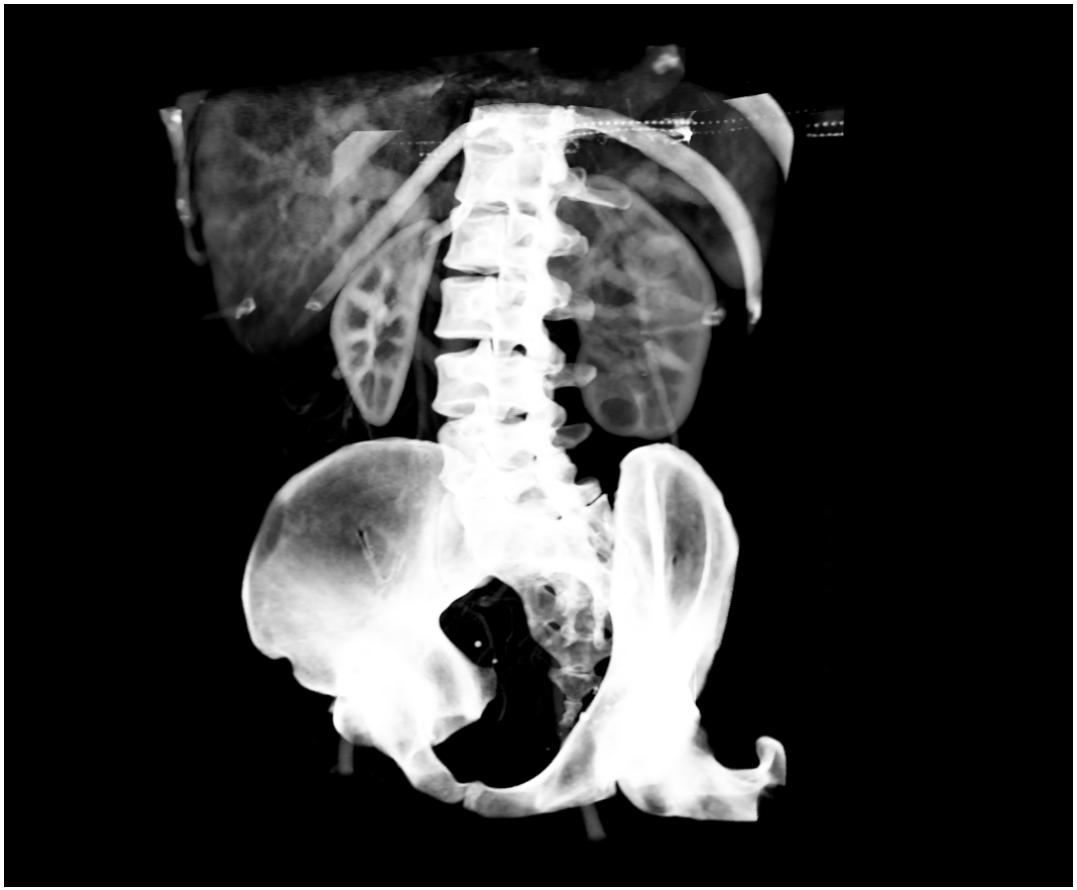


Maximum Intensity Projection



Direct Volume Rendering

- Use values stored in voxels (color, density)
- Simple contrast/lightness adjustments



Combined Geometry Rendering

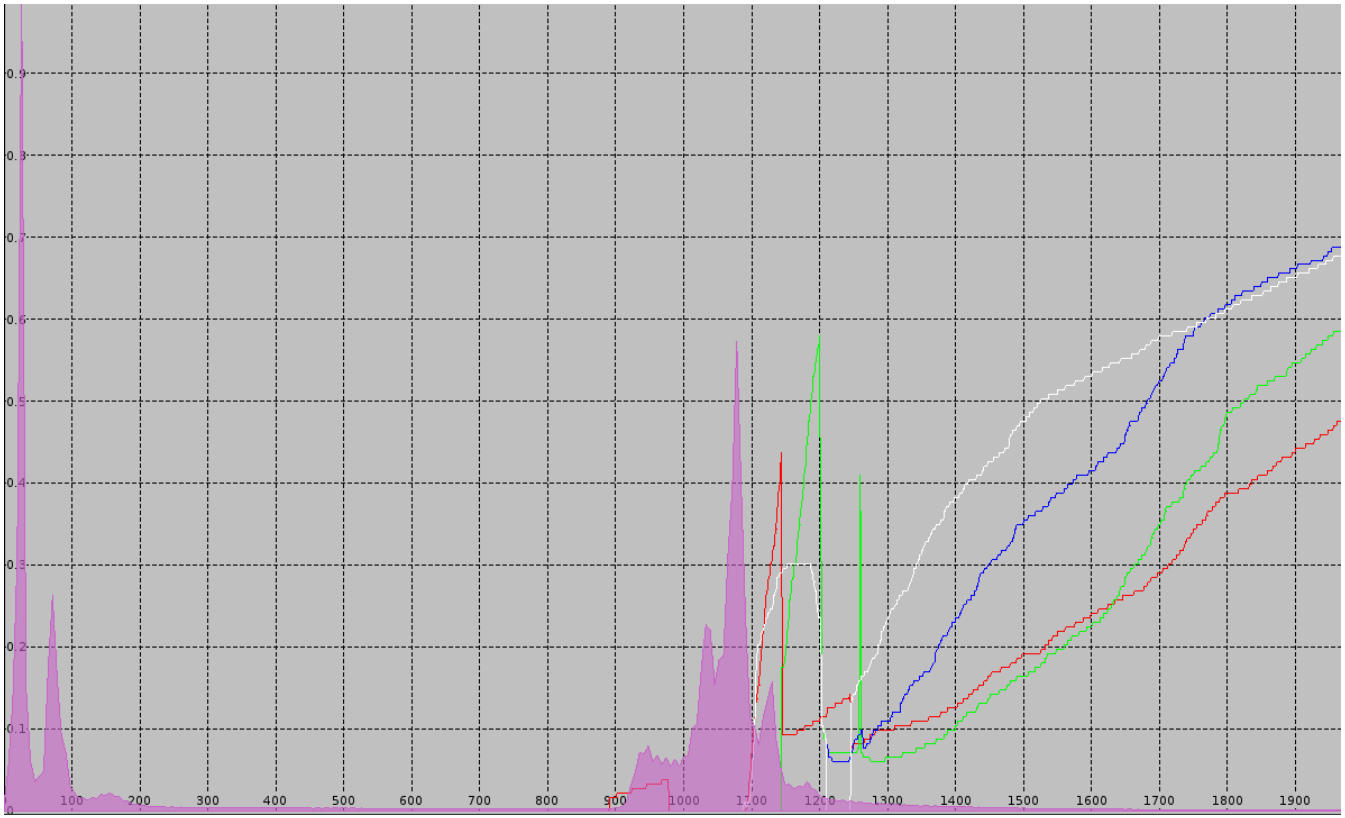
- Opaque geometry
  - Rendered before volume
  - Rays terminated by value in z-buffer
- Transparent geometry
  - Checking for geometry/ray intersections during ray traversal
  - Color computed together with volume sampling

Transfer Functions

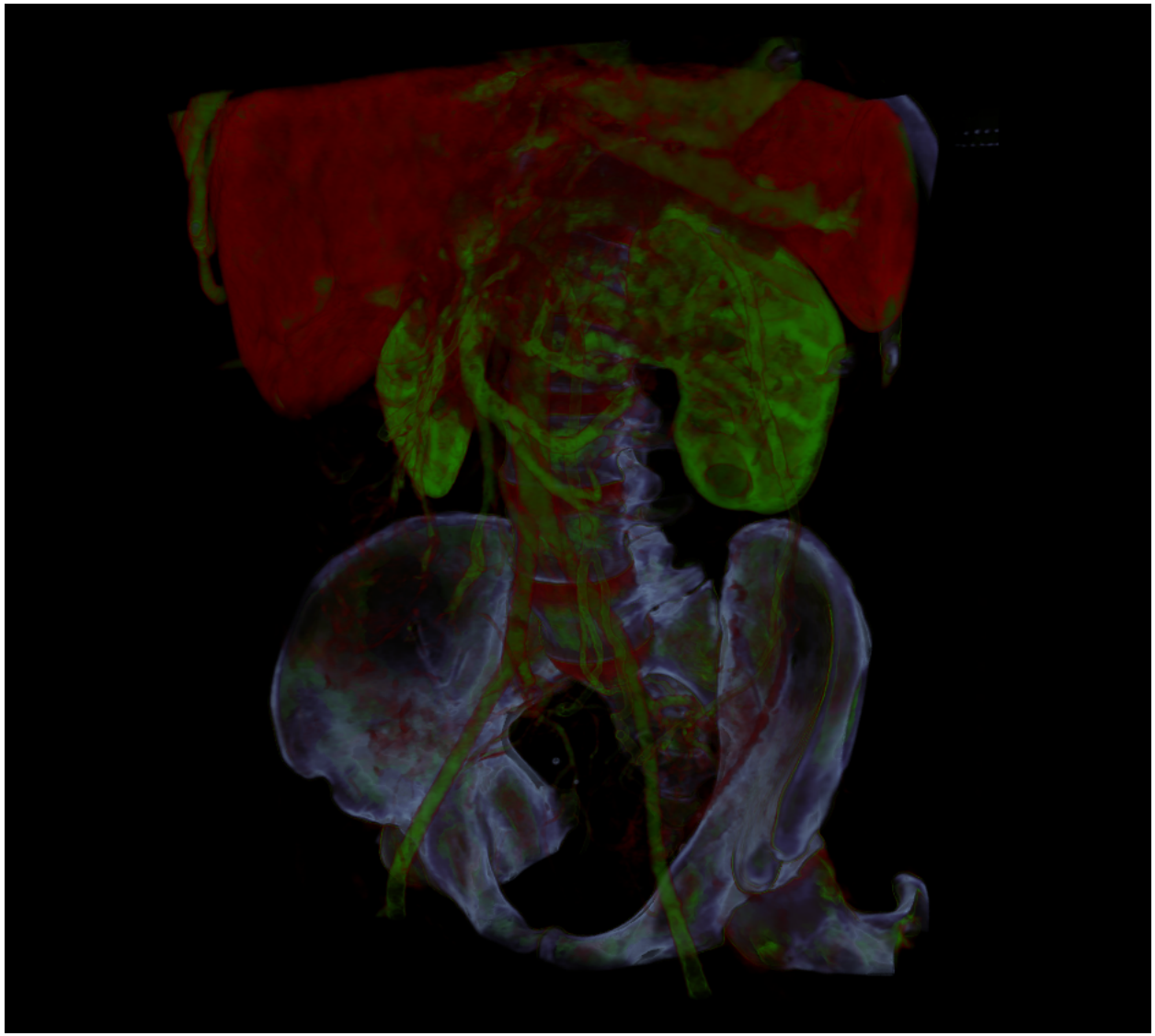
1D Transfer Functions

- Runtime fuzzy classification
- Transfer function $g(v) : R \rightarrow R^4$
- Ray sample: $g(f(\mathbf{x}))$
- Maps scalar value to RGBA color.
- Implementation:
  - 1D RGBA texture with interpolation
  - Final sample color – access TF texture

Histogram + 1D TF



1D Transfer Functions



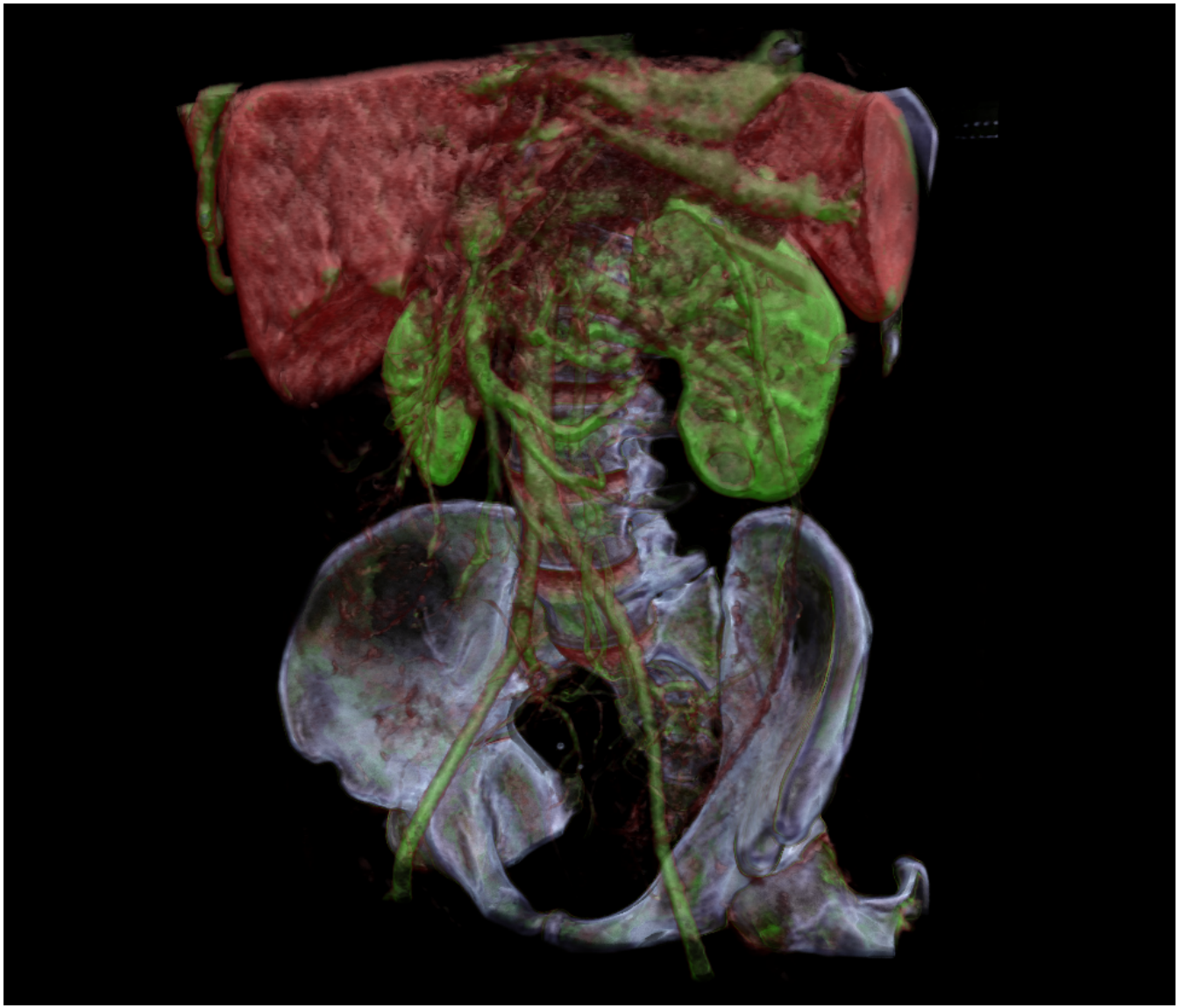
GRADIENT

- $\nabla f(\mathbf{x}) = \left(\frac{\partial f(\mathbf{x})}{\partial x_1}, \frac{\partial f(\mathbf{x})}{\partial x_2}, \frac{\partial f(\mathbf{x})}{\partial x_3} \right)$
- Direction of the greatest rate of increase.
- Magnitude is the slope of the graph.
- Directional derivative: $\frac{\partial f(\mathbf{x})}{\partial \mathbf{v}} = \nabla f(\mathbf{x}) \cdot \mathbf{v}$
  - Can be computed on the fly
  - Symmetric differences

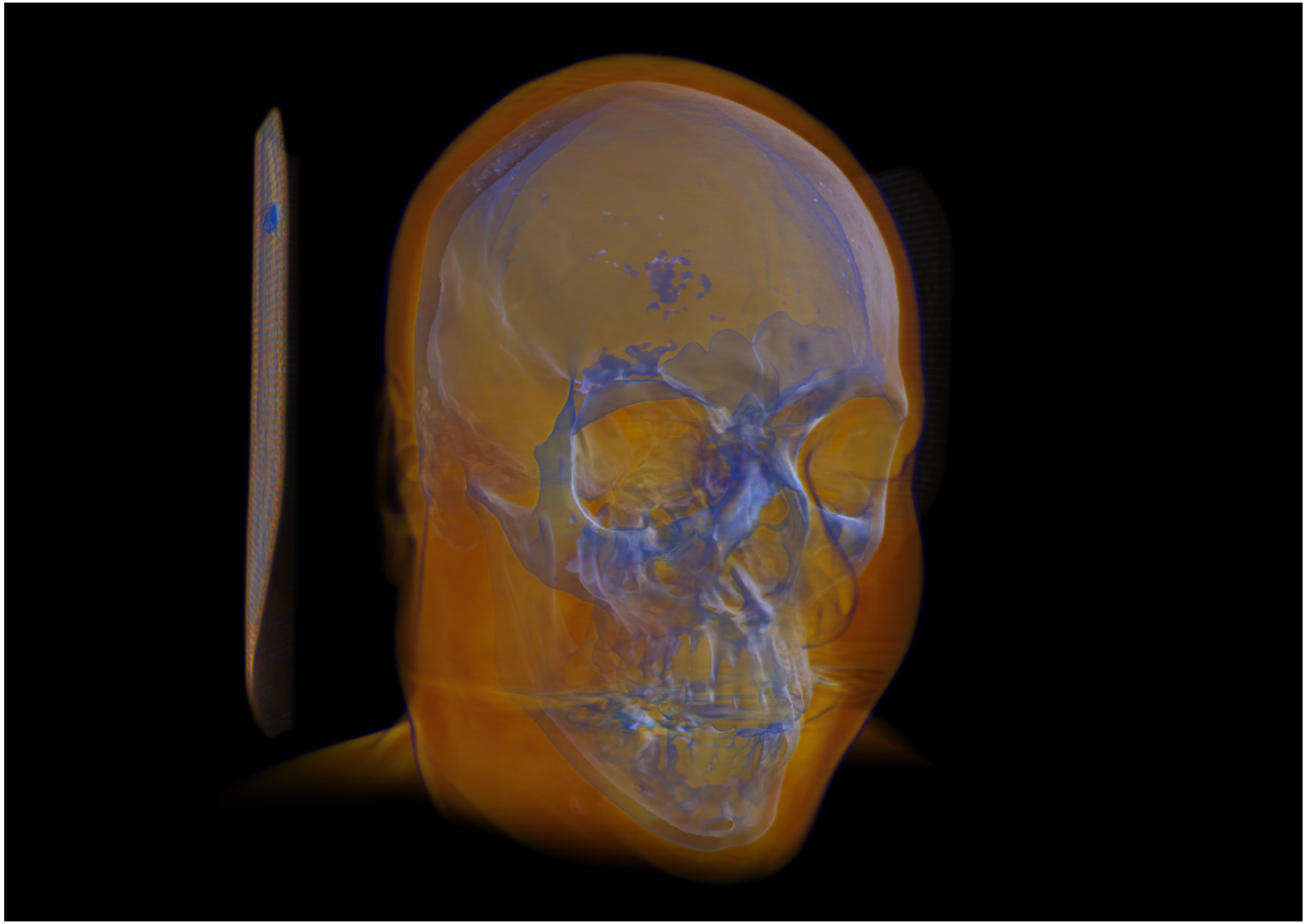
1D Transfer Functions + Light

- Better surface shape perception.
- Compute shading for opaque regions (α channel over some threshold)
- Normalized gradient as surface normal.

1D Transfer Functions + Light

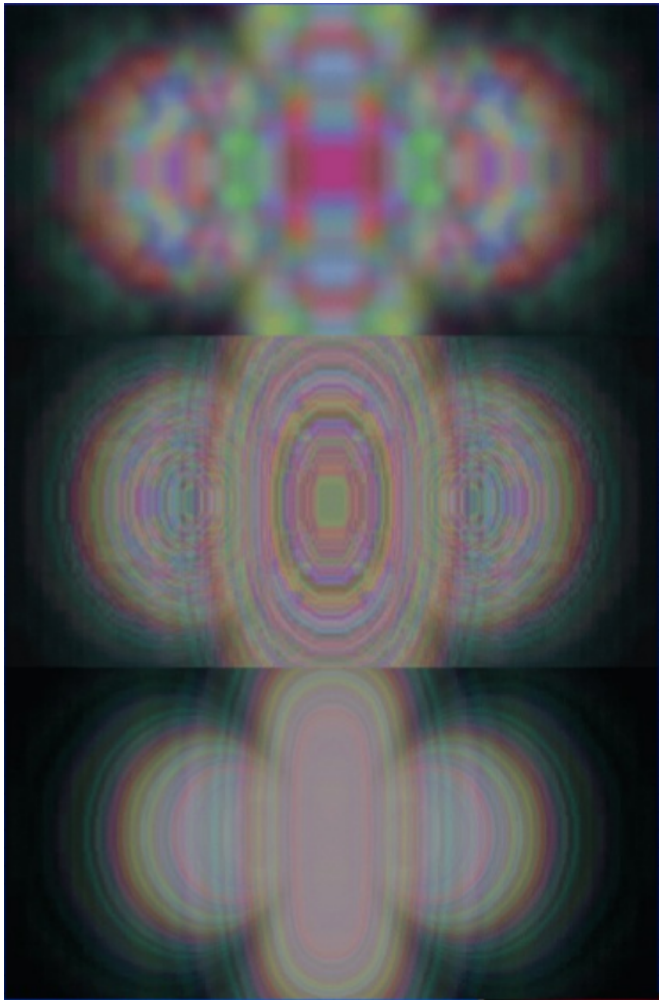


1D Transfer Functions



POST-CLASSIFICATION VS. PRE-CLASSIFICATION

- Pre-classification
  - TF applied before rendering
  - Interpolating already mapped data
- Post-classification
  - TF applied on the fly
  - Mapping interpolated input
- TF pre-integration
  - More precise integratal computation
  - Precompute integrals for each possible segment (start, end values)



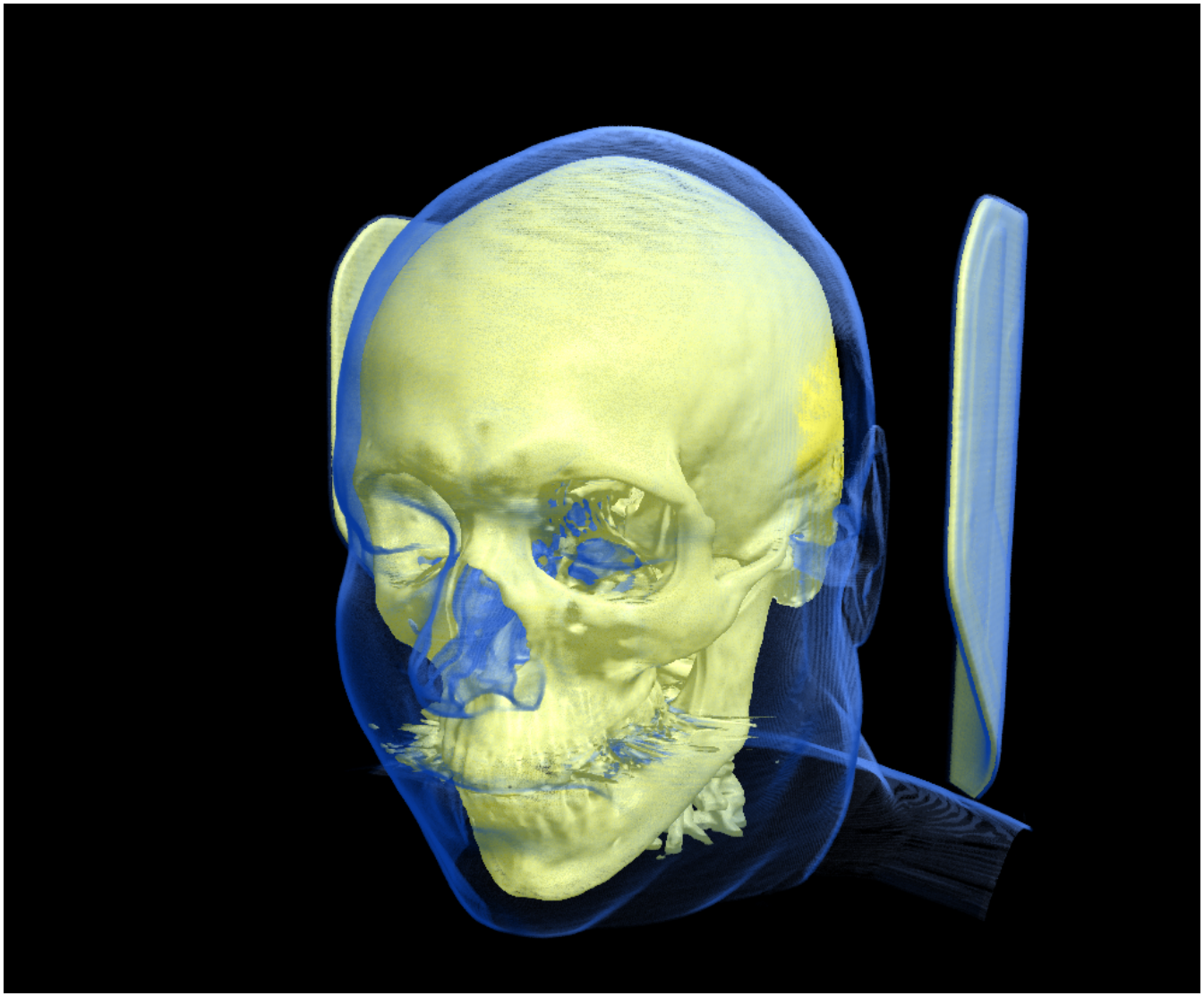
2D Transfer Functions

- Transfer function $h(v_1, v_2) : R^2 \rightarrow R^4$
- Ray sample: $h(f(\mathbf{x}), g(\mathbf{x}))$
- Maps two dimensional vector to RGBA color.
- Where we get the second dimension?.
  - Dual source CTs
  - Gradient magnitude ...

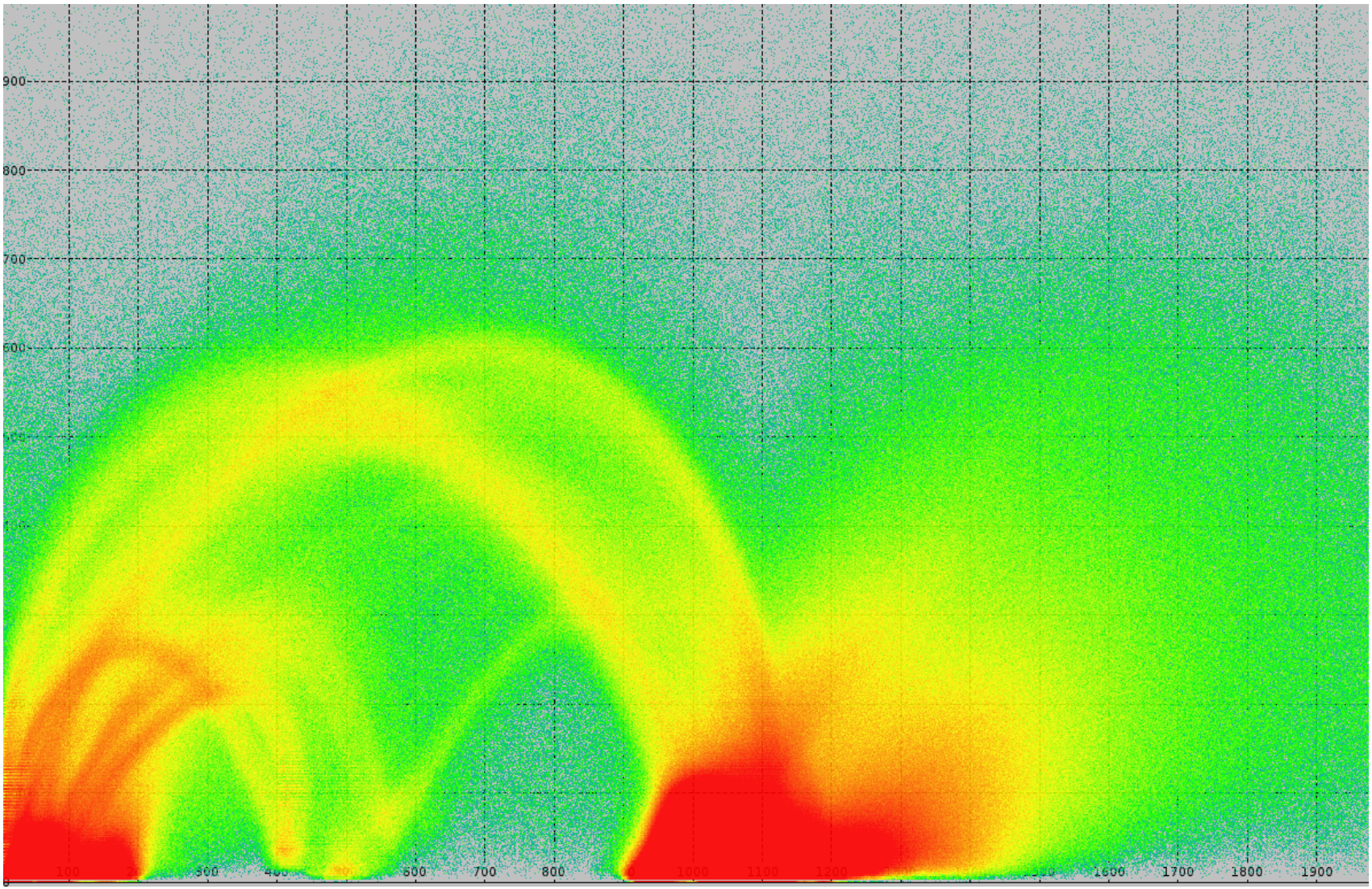
Gradient Magnitude

- Can be computed on the fly.
- Ability to separate borders from homogeneous regions.

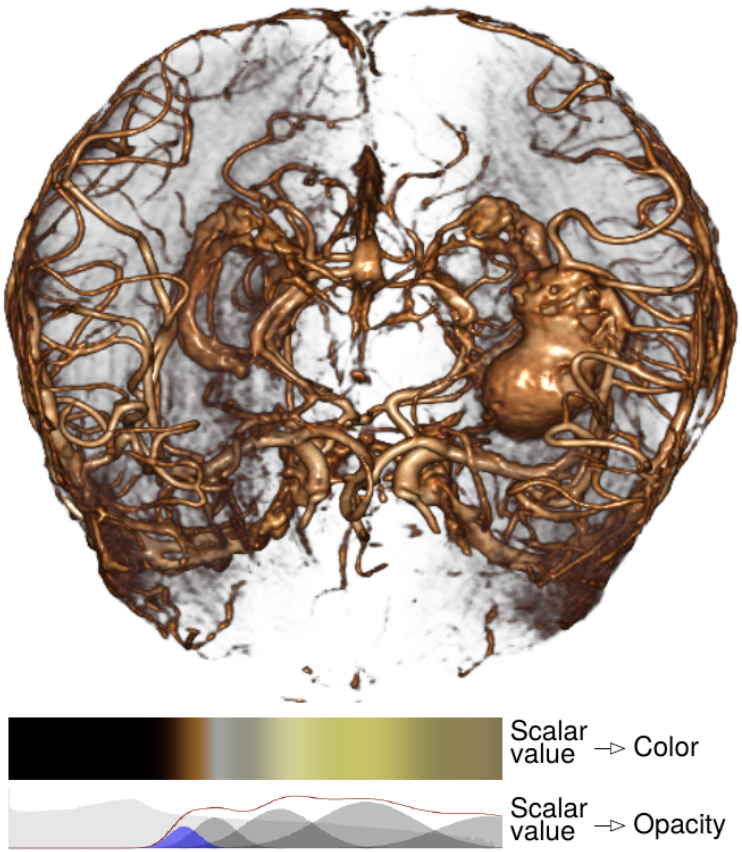
Gradient Magnitude

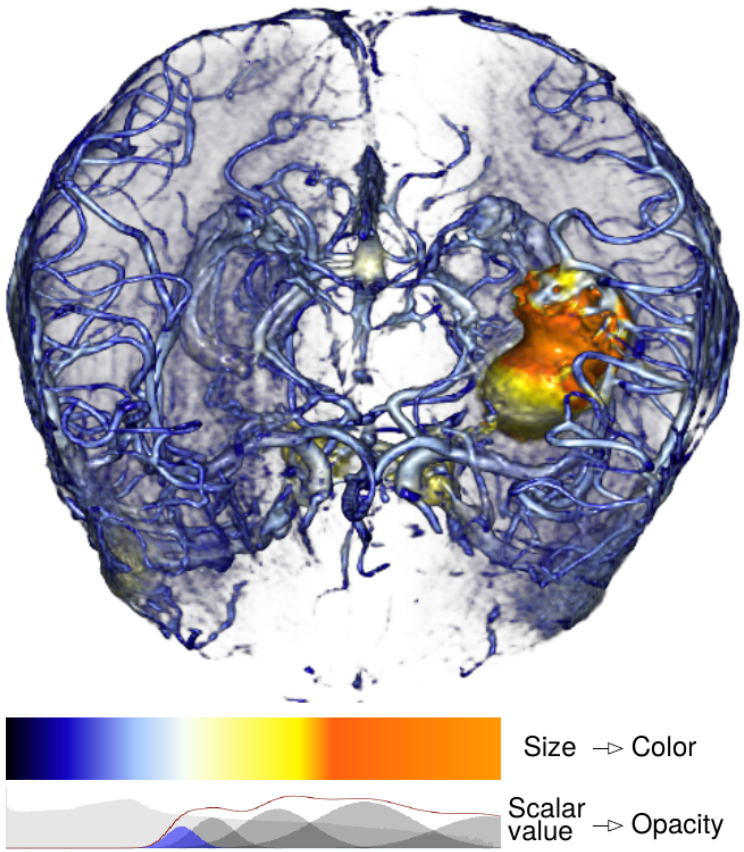


Scatter Plot

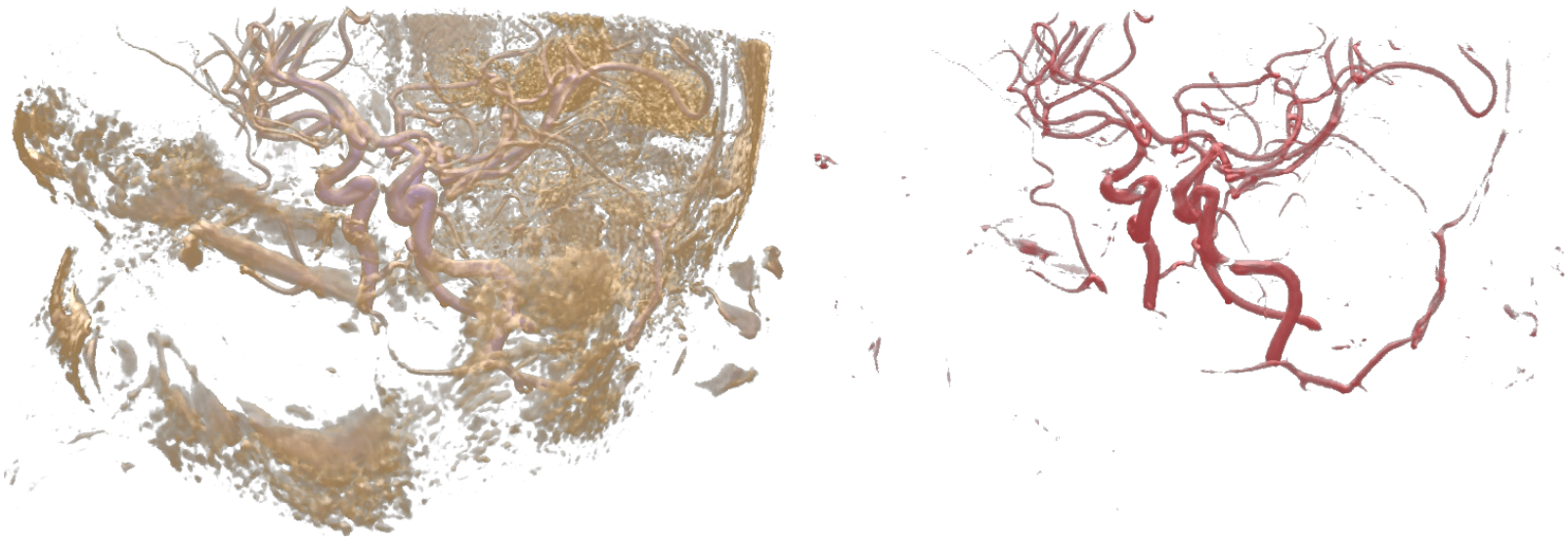


Size-based Transfer Functions





Shape Oriented Transfer Functions



Improvements

LIGHTING

- Self shadowing
- Material modeling
- Light scattering
- ...

JITTERING

- Uniform ray sampling – alias
- Hide behind noise:
  - Randomly shift ray origins, along view direction
  - Pregenerated random texture

SPEEDUP TECHNIQUES

- Early termination
  - Do not sample data behind opaque sections
- Empty space skipping
  - Large sparse data
  - Multiresolution
  - Skip sections without important data
  - Must be recomputed when TF changes

Isosurfaces

Polygonal Mesh

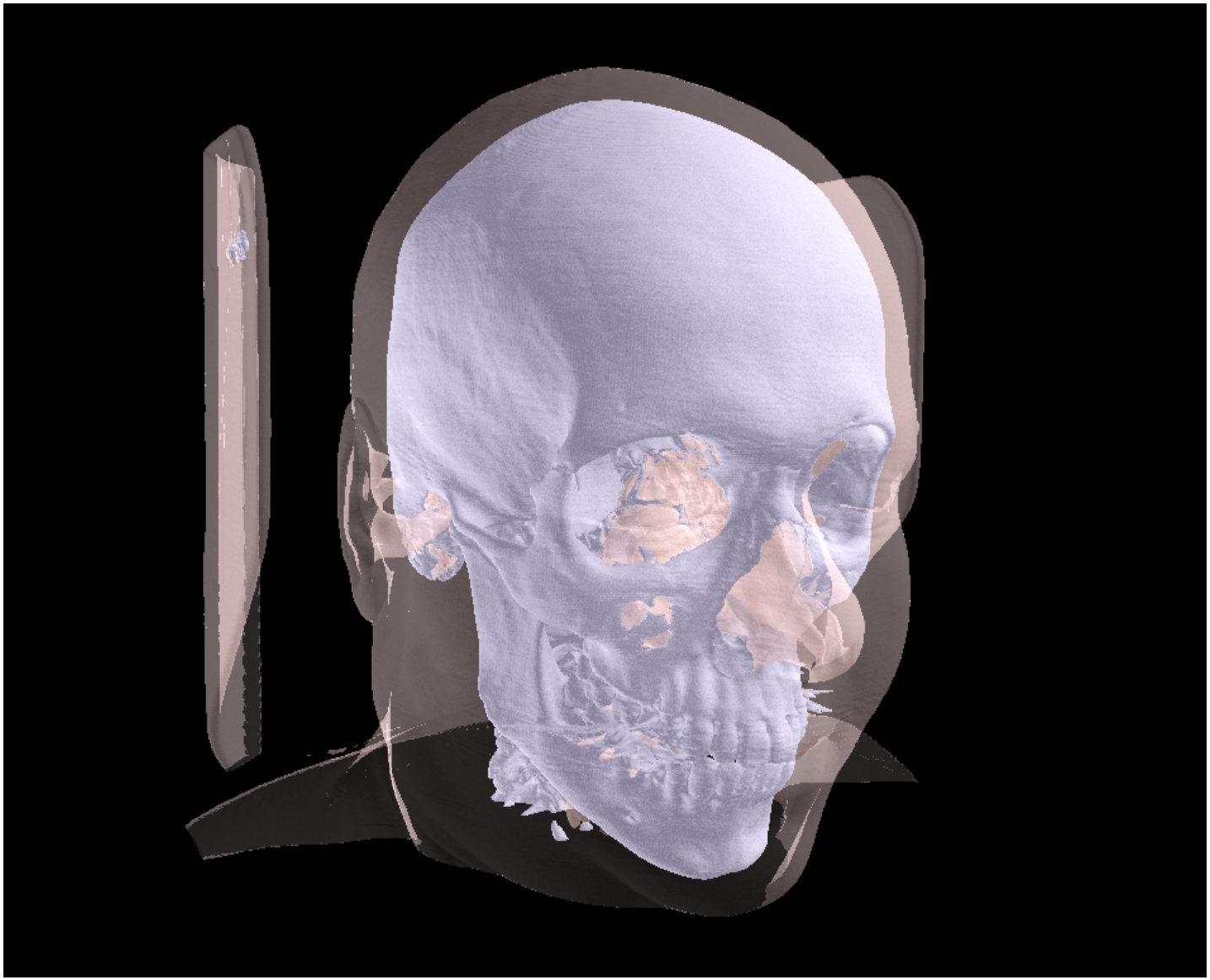
- Polygonal mesh representing level set
- Volume preprocessing:
  - Cuberille (+filtering)
  - Marching cubes, tetrahedra, ...
- Use normal rasterization pipeline for rendering

Realtime Isosurface Construction

- Ray-casting
  - Search for isovalue crossings
  - Fine search in subintervals for intersection point
  - Gradient for surface normal

ISO-SURFACES

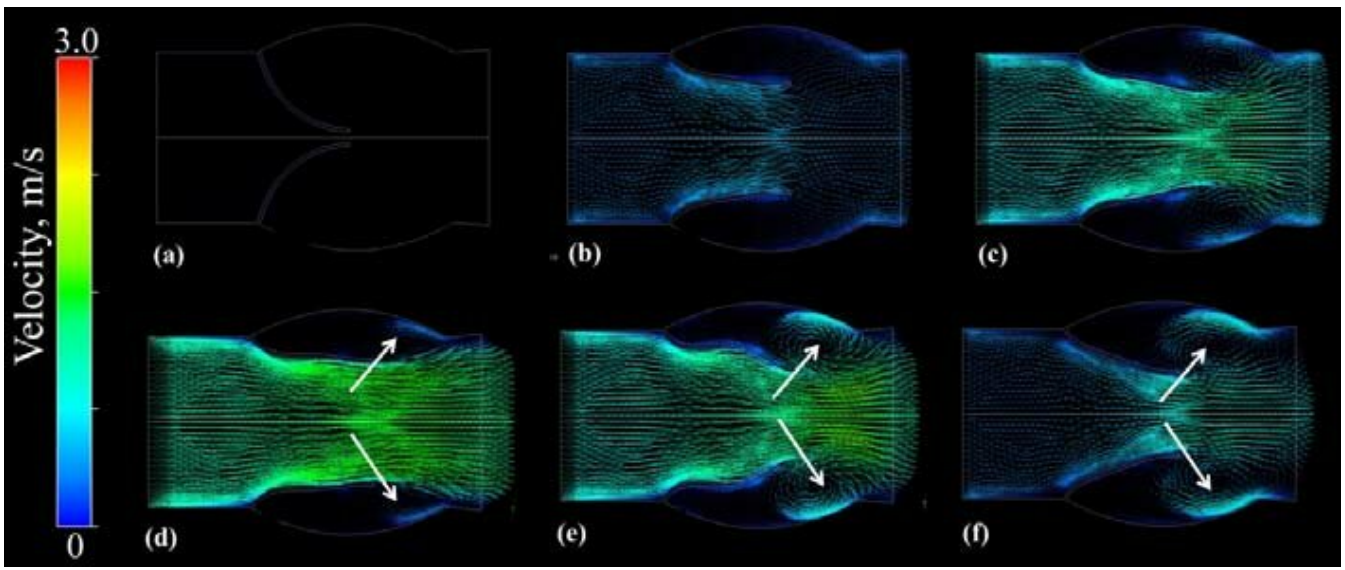
ISO-SURFACES



Vector Fields

Data Source

- Physical simulations:
  - Fluid dynamics
  - Particle simulations
  - Electromagnetic fields (Maxwell)



Numerical Integration

- Simulate motion under vector field influence
- Numerical integration
  - Euler method – low numerical stability, fast
  - Higher order Runge-Kutta methods

Differential Operators

- $\nabla = \frac{\partial}{\partial x}\frac{\partial}{\partial y}\frac{\partial}{\partial z}$
- Gradient
  - $\nabla f(\mathbf{x}) = \left(\frac{\partial f(\mathbf{x})}{\partial x_1}, \frac{\partial f(\mathbf{x})}{\partial x_2}, \frac{\partial f(\mathbf{x})}{\partial x_3}\right)$
- Divergence
  - $\nabla \cdot \mathbf{F} = \frac{\partial \mathbf{F}_x}{\partial x} + \frac{\partial \mathbf{F}_y}{\partial y} + \frac{\partial \mathbf{F}_z}{\partial z}$
- Curl
  - $\nabla \times \mathbf{F} = \left(\frac{\partial \mathbf{F}_z}{\partial y} - \frac{\partial \mathbf{F}_y}{\partial z}, \frac{\partial \mathbf{F}_x}{\partial z} - \frac{\partial \mathbf{F}_z}{\partial x}, \frac{\partial \mathbf{F}_y}{\partial x} - \frac{\partial \mathbf{F}_x}{\partial y}\right)$

Glyphs, Icons, Probes

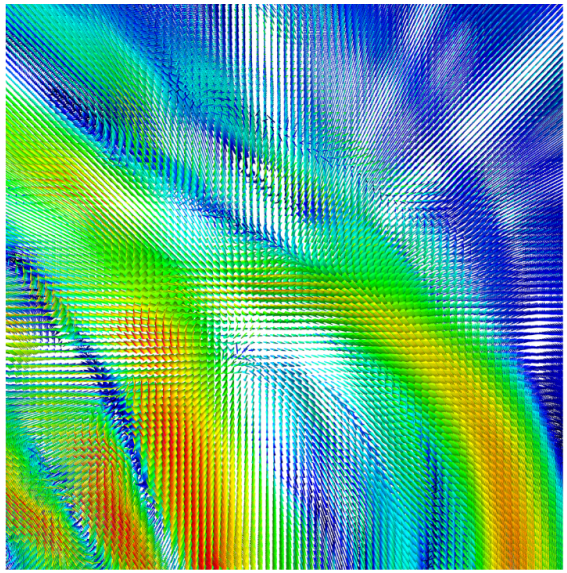
- Sample vector field:
  - Arrows
  - Lines
  - Balls, ellipsoids
  - Ribons
- Other characteristics represented by shape, color
- To prevent clutter:
  - Importance sampling
  - Slice-probe through vector field

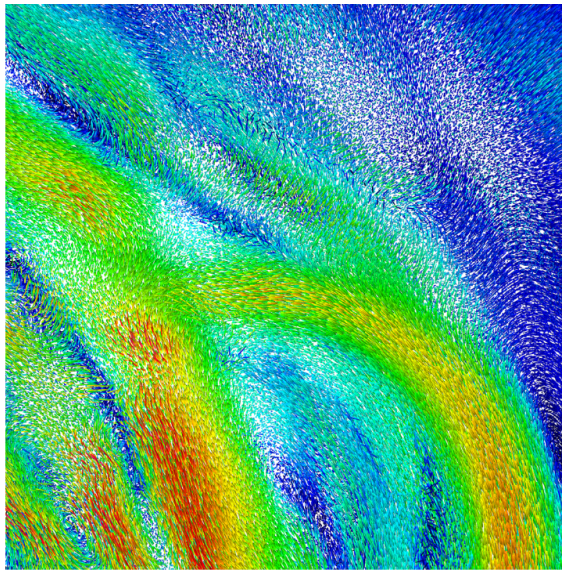
Rendering Glyphs

- Large number of similar geometries
- Instanced rendering
  - Impostors for complicated geometries
- Geometry shader:
  - From point samples generate glyph geometry

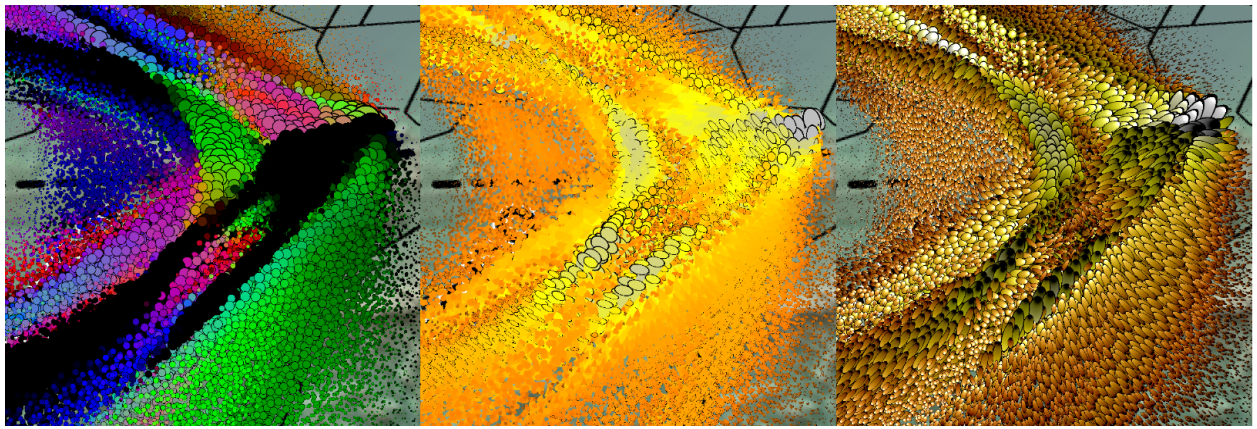
Glyph Examples

- Sampling jitter



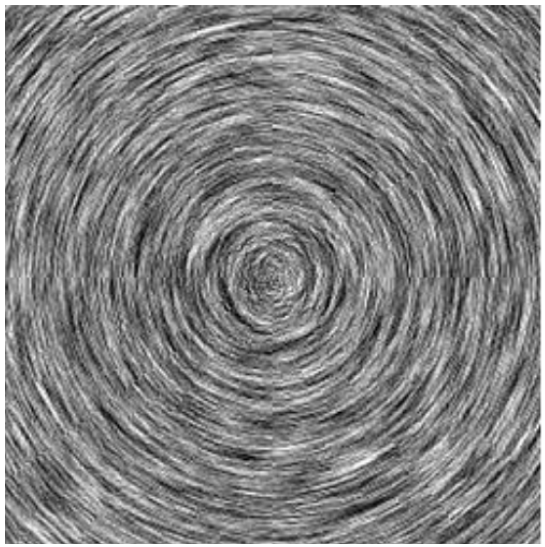


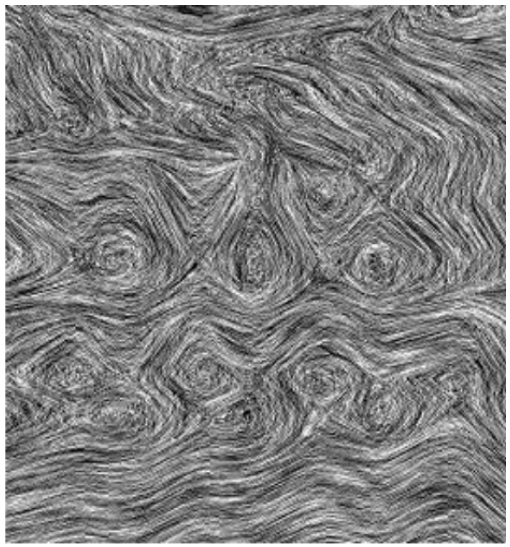
- Different shading



Line Integral Convolution

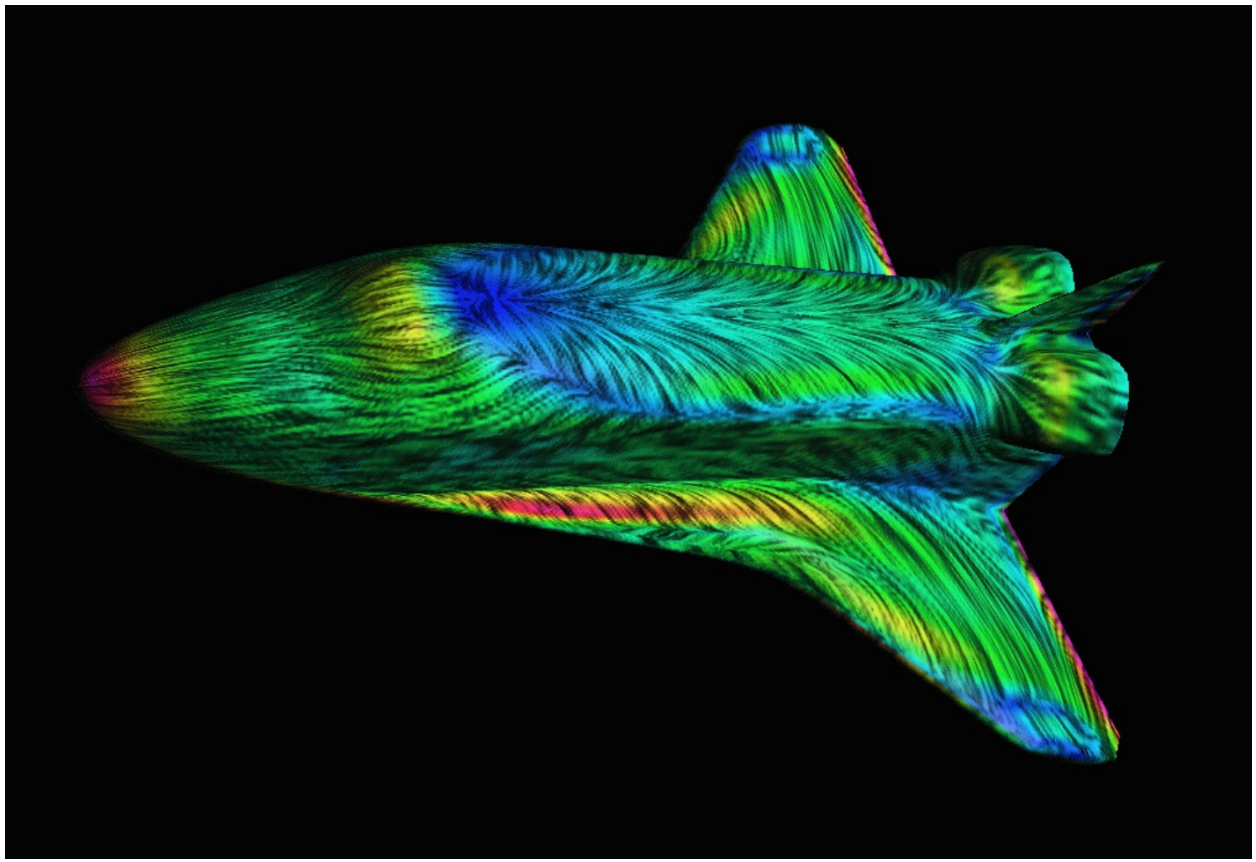
- Underlying texture blurred along vector directions
  - Multiple texture accesses in fragment shader – integration





LIC on Surface

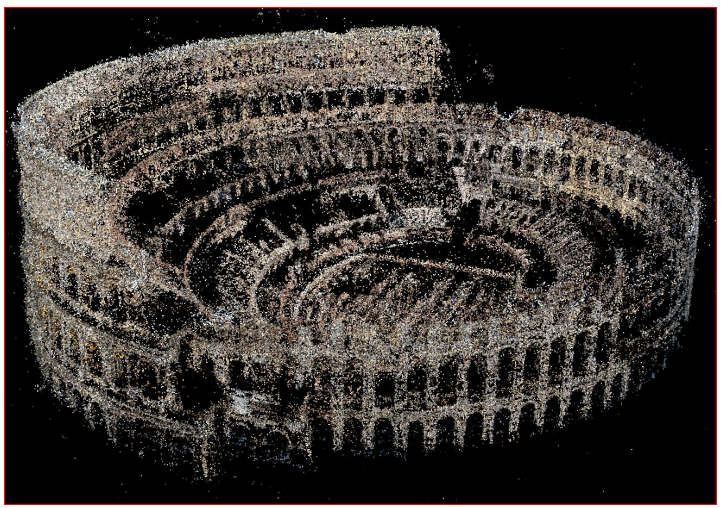
- Compute in object fragment shader



Point Clouds

Data Source

- Surface points:
  - 3D scanner output
  - Scene reconstruction:
    - Stereo cameras
    - Camera + depth sensor (Kinect)
    - Single moving camera
- Random spatial samples:
  - Unstructured vector field
  - Unstructured volume



Point Cloud Rendering

- Glyph for each point
  - Colored/textured facets
- Glyph for group of points
  - Size, shape – properties of point group

Volume Rendering

- Unstructured volume samples:
  - Datastructure for fast queries (octree, . . .)
  - Ray sample – weighted average of points in certain radius
- Surface reconstruction:
  - Distance field
  - Isosurface rendering