



CS 247 – Scientific Visualization

Lecture 16: Volume Rendering, Pt. 3

Markus Hadwiger, KAUST

Reading Assignment #9 (until Apr 12)



Read (required):

- Paper:

Markus Hadwiger, Ali K. Al-Awami, Johanna Beyer, Marco Agus, and Hanspeter Pfister

SparseLeap: Efficient Empty Space Skipping for Large-Scale Volume Rendering, IEEE Scientific Visualization 2017

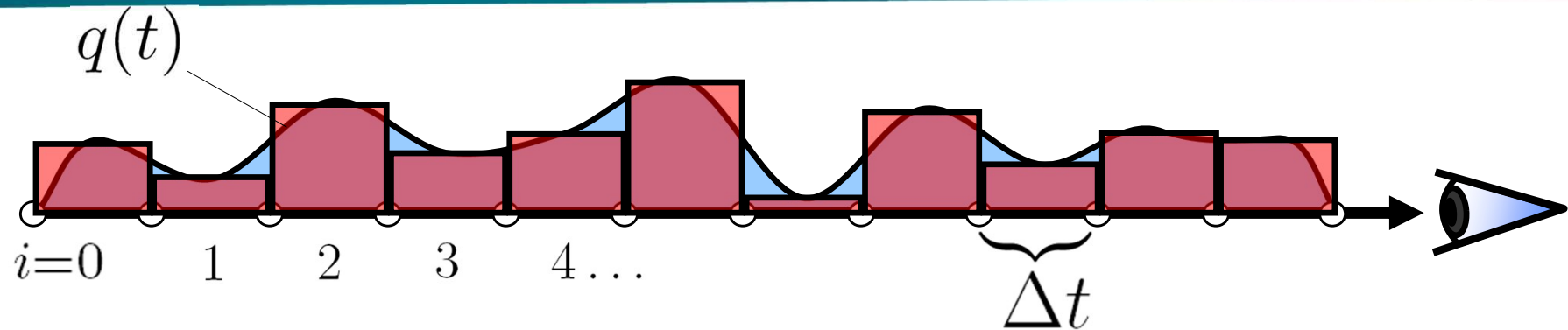
http://vccvisualization.org/publications/2017_hadwiger_sparseleap.pdf

http://vccvisualization.org/publications/2017_hadwiger_sparseleap.mp4

Read (optional):

- Real-Time Volume Graphics, Chapter 6
(Global Volume Illumination)

Volume Rendering Integral: Numerical Solution



Note: we just changed the convention from $i=0$ is at the front of the volume (previous slides) to $i=0$ is at the back of the volume !

can be computed iteratively/recursively:

$$C'_i = C_i + (1 - A_i)C'_{i-1}$$

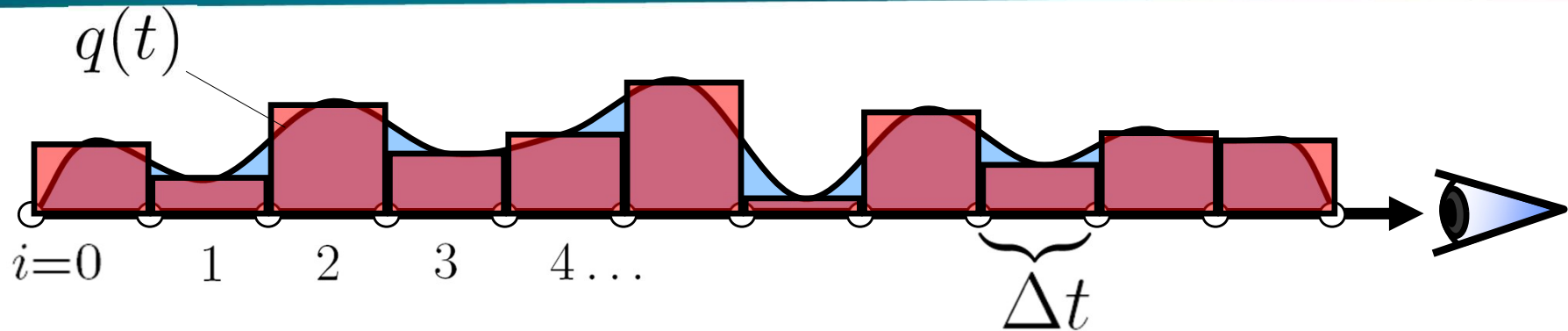
Radiant energy
observed at position i

Radiant energy
emitted at position i

Absorption at
position i

Radiant energy
observed at position $i-1$

Volume Rendering Integral: Numerical Solution



**Back-to-front
compositing**

$$C'_i = C_i + (1 - A_i)C'_{i-1}$$

iterate from $i=0$ (back) to $i=\max$ (front): i increases

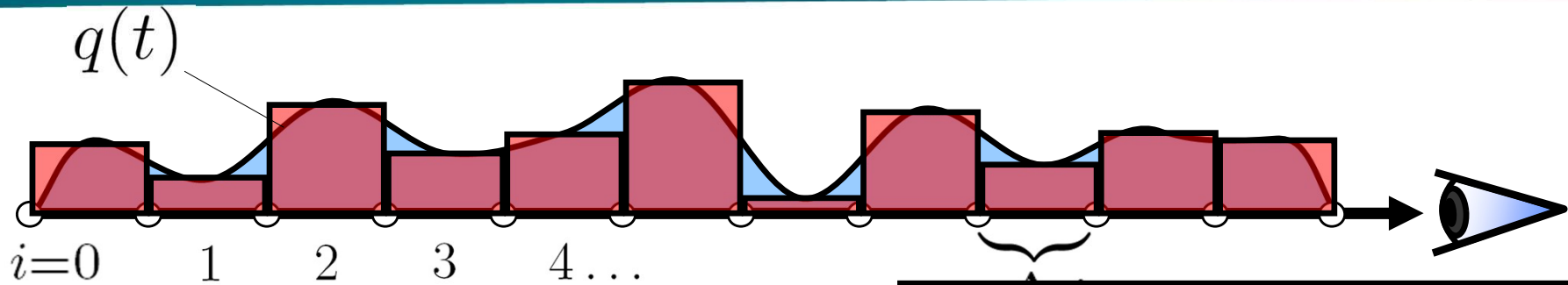
**Front-to-back
compositing**

$$C'_i = C'_{i+1} + (1 - A'_{i+1})C_i$$

$$A'_i = A'_{i+1} + (1 - A'_{i+1})A_i$$

iterate from $i=\max$ (front) to $i=0$ (back) : i decreases

Volume Rendering Integral: Numerical Solution



**Back-to-front
compositing**

$$C'_i = C_i + (1 - A'_i)C'_i$$

iterate from $i=\max$ (front) to $i=0$ (back)

Early Ray Termination:
Stop the calculation when

$$A'_i \approx 1$$

**Front-to-back
compositing**

$$C'_i = C'_{i+1} + (1 - A'_{i+1})C_i$$

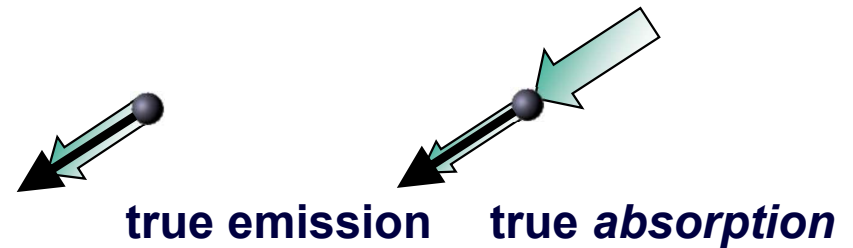
$$A'_i = A'_{i+1} + (1 - A'_{i+1})A_i$$

iterate from $i=\max$ (front) to $i=0$ (back) : i decreases

Volume Rendering Integral



Volume rendering integral
for *Emission Absorption* model



$$I(s) = I(s_0) e^{-\tau(s_0, s)} + \int_{s_0}^s q(\tilde{s}) e^{-\tau(\tilde{s}, s)} d\tilde{s}$$

$$\tau(s_1, s_2) = \int_{s_1}^{s_2} \kappa(s) ds.$$

Iterative/recursive numerical solutions:

Back-to-front compositing

$$C'_i = C_i + (1 - A_i)C'_{i-1}$$

Front-to-back compositing

$$C'_i = C'_{i+1} + (1 - A'_{i+1})C_i$$
$$A'_i = A'_{i+1} + (1 - A'_{i+1})A_i$$

here, all colors are *associated colors*!

Opacity Correction

Opacity Correction



Simple compositing only works as far as the opacity values are correct... and they depend on the sample distance!

$$T_i = e^{-\int_{s_i}^{s_i+\Delta t} \kappa(t) dt} \approx e^{-\kappa(s_i)\Delta t} = e^{-\kappa_i\Delta t}$$

$$A_i = 1 - e^{-\kappa_i\Delta t} \quad \tilde{T}_i = T_i^{\left(\frac{\Delta \tilde{t}}{\Delta t}\right)}$$

$$\tilde{A}_i = 1 - (1 - A_i)^{\left(\frac{\Delta \tilde{t}}{\Delta t}\right)}$$

opacity correction formula

Beware that usually this is done for each different scalar value (every transfer function entry), not actually at spatial positions/intervals i

Associated Colors



Associated (or “opacity-weighted” colors) are often used in compositing equations

Every color is *pre-multiplied* by its corresponding opacity

$$\begin{pmatrix} \mathbf{R} \\ \mathbf{G} \\ \mathbf{B} \\ \mathbf{A} \end{pmatrix} \rightarrow \begin{pmatrix} \mathbf{R} * \mathbf{A} \\ \mathbf{G} * \mathbf{A} \\ \mathbf{B} * \mathbf{A} \\ \mathbf{A} \end{pmatrix}$$

Our compositing equations assume associated colors!

Important: **After opacity-correction, all associated colors must be updated!**
(or combined/multiplied correctly on-the-fly!)

Associated Colors in Volume Rendering



Standard emission-absorption optical model

- Only one kind of particle: the same particles that absorb light, emit light
- Aha! Therefore lower absorption means lower emission as well

Light observed from (in front of) segment i (without any light behind it):

$$C_i = \frac{q_i}{\kappa_i} \left(1 - e^{-\kappa_i \Delta t} \right) = \hat{C}_i A_i$$

$$q_i := \hat{C}_i \kappa_i$$

$$A_i := 1 - e^{-\kappa_i \Delta t}$$

$$\lim_{\kappa_i \rightarrow 0} q_i \frac{(1 - e^{-\kappa_i \Delta t})}{\kappa_i} = \lim_{\kappa_i \rightarrow 0} \hat{C}_i (1 - e^{-\kappa_i \Delta t}) = 0$$

$$\lim_{\kappa_i \rightarrow \infty} q_i \frac{(1 - e^{-\kappa_i \Delta t})}{\kappa_i} = \lim_{\kappa_i \rightarrow \infty} \hat{C}_i (1 - e^{-\kappa_i \Delta t}) = \hat{C}_i$$

Associated Colors in Volume Rendering



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$$\lim_{\kappa_i \rightarrow \infty} q_i \frac{(1 - e^{-\kappa_i \Delta t})}{\kappa_i} = \lim_{\kappa_i \rightarrow \infty} \hat{C}_i (1 - e^{-\kappa_i \Delta t}) = C_i$$

Implementation

Implementation



Ray setup

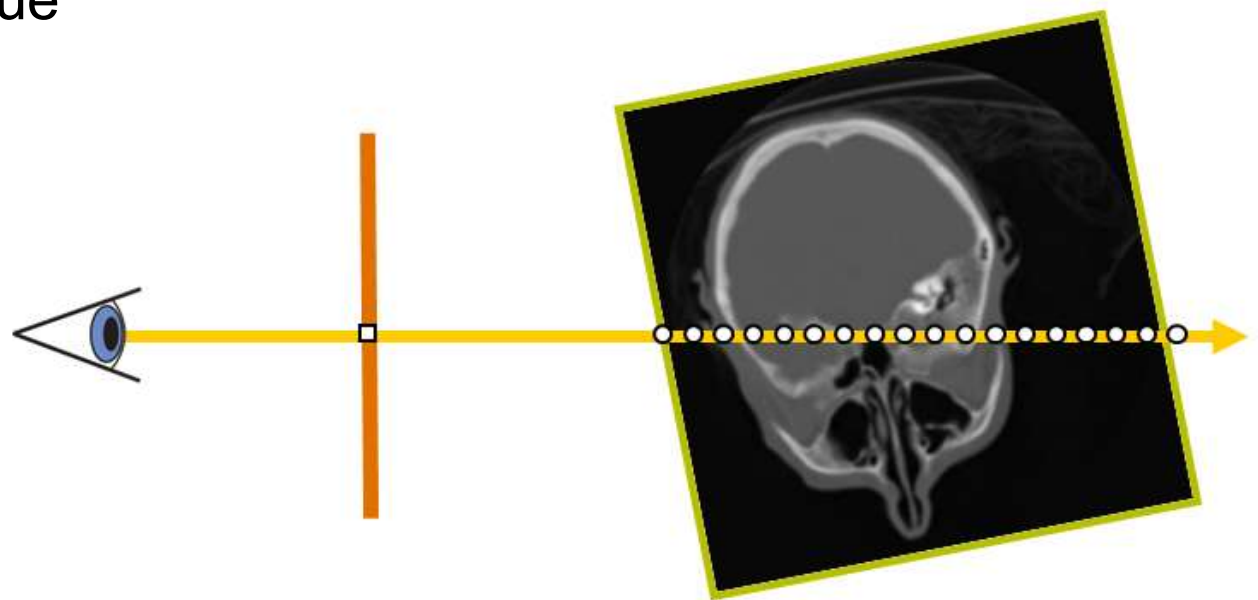
Loop over ray

Resample scalar value

Classification

Shading

Compositing



Implementation



Ray setup

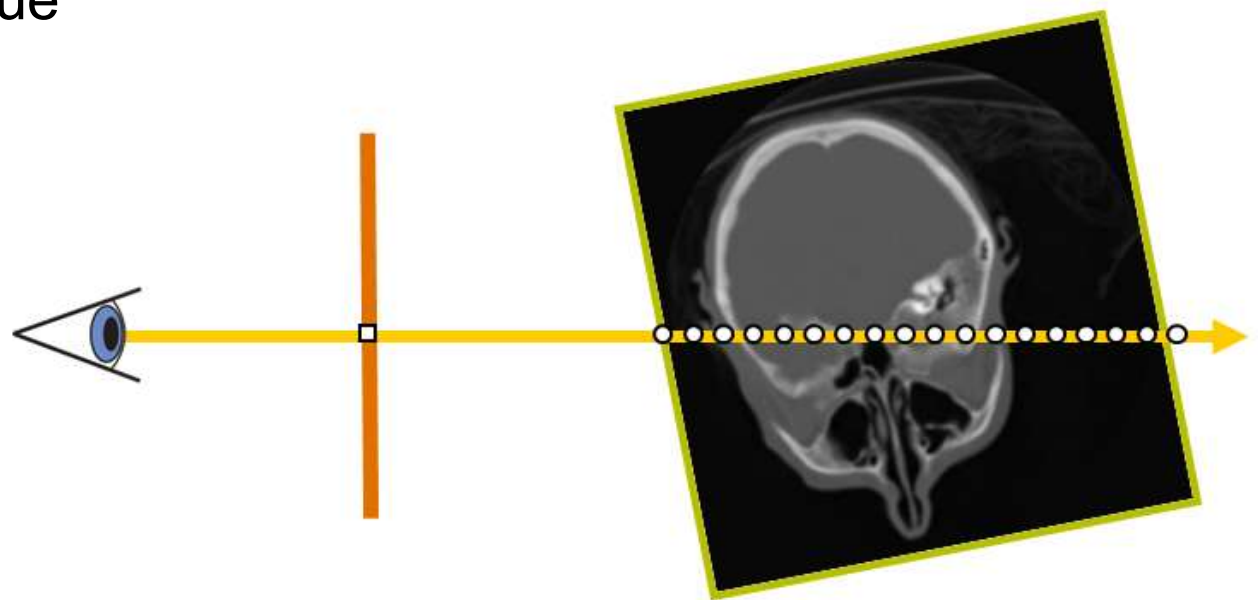
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Ray Setup

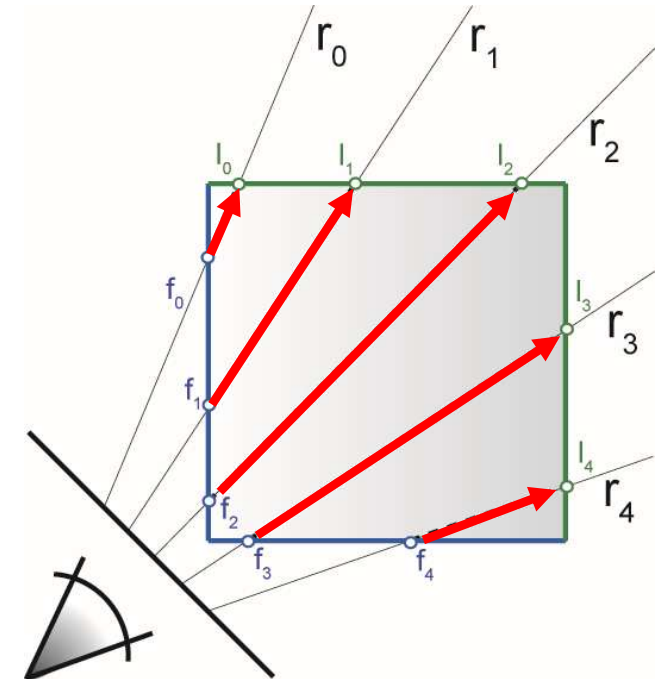


Two main approaches:

- Procedural ray/box intersection [Röttger et al., 2003], [Green, 2004]
- Rasterize bounding box [Krüger and Westermann, 2003]

Some possibilities

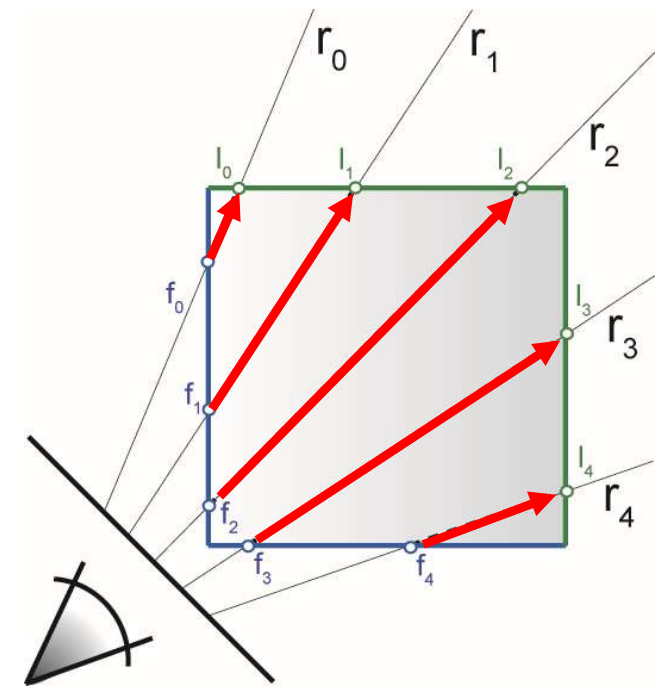
- Ray start position and exit check
- Ray start position and exit position
- Ray start position and direction vector



Procedural Ray Setup/Termination



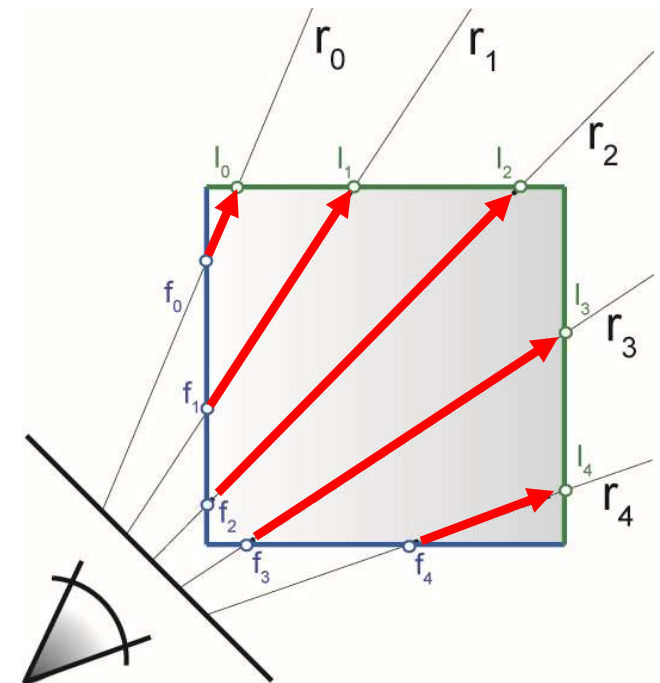
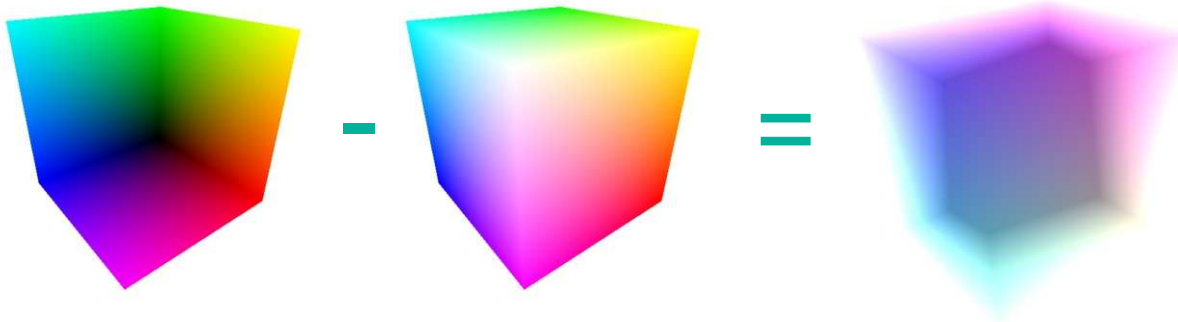
- Everything handled in the fragment shader / CUDA kernel
- Procedural ray / bounding box intersection
- Ray is given by camera position and volume entry position
- Exit criterion needed
- Pro: simple and self-contained
- Con: full computational load per-pixel/fragment



Rasterization-Based Ray Setup



- Fragment == ray
- Need ray start pos, direction vector
- Rasterize bounding box

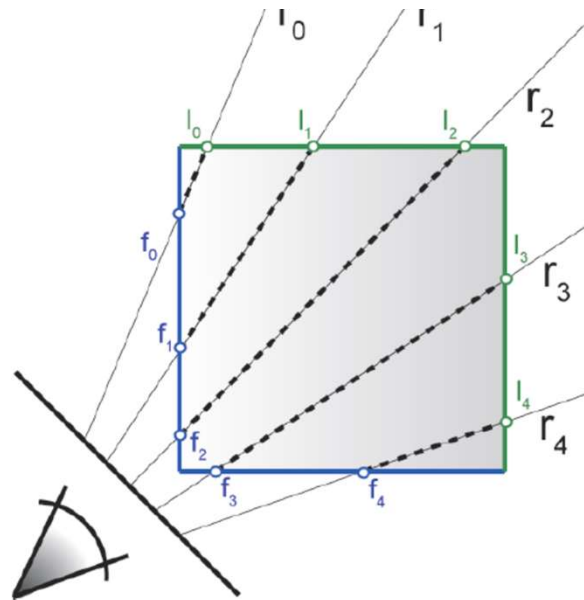
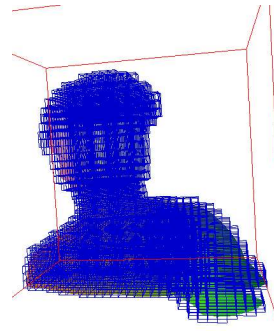
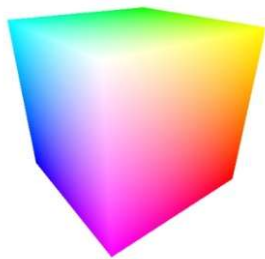


- Identical for orthogonal and perspective projection!

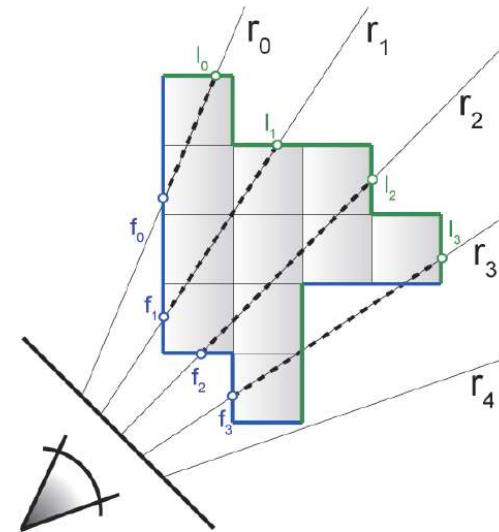
Object-Order Empty Space Skipping



Modify initial rasterization step



rasterize bounding box

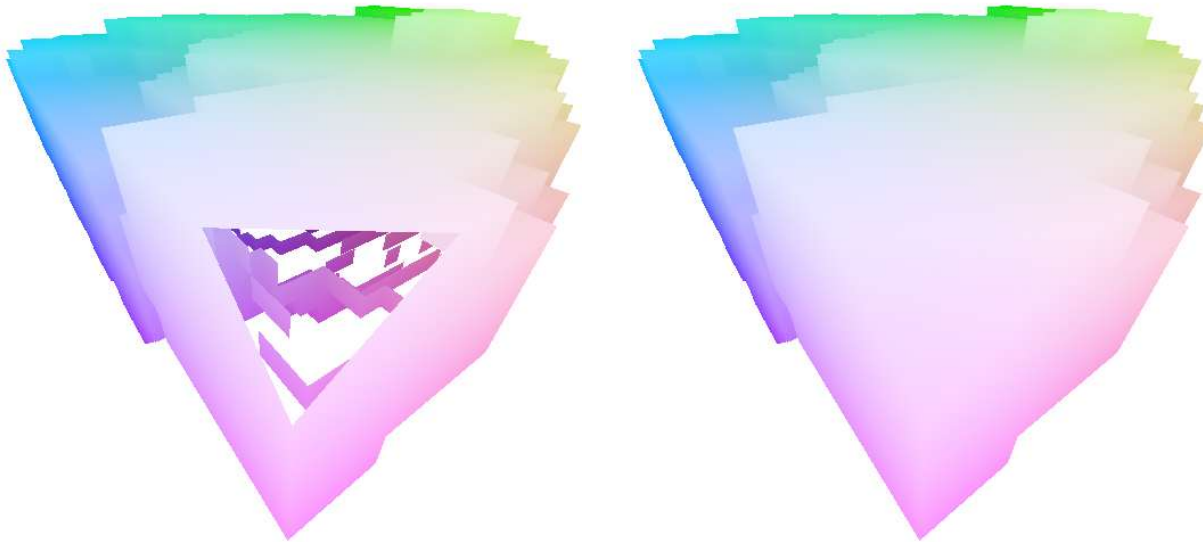


rasterize "tight" bounding geometry

Moving Into The Volume

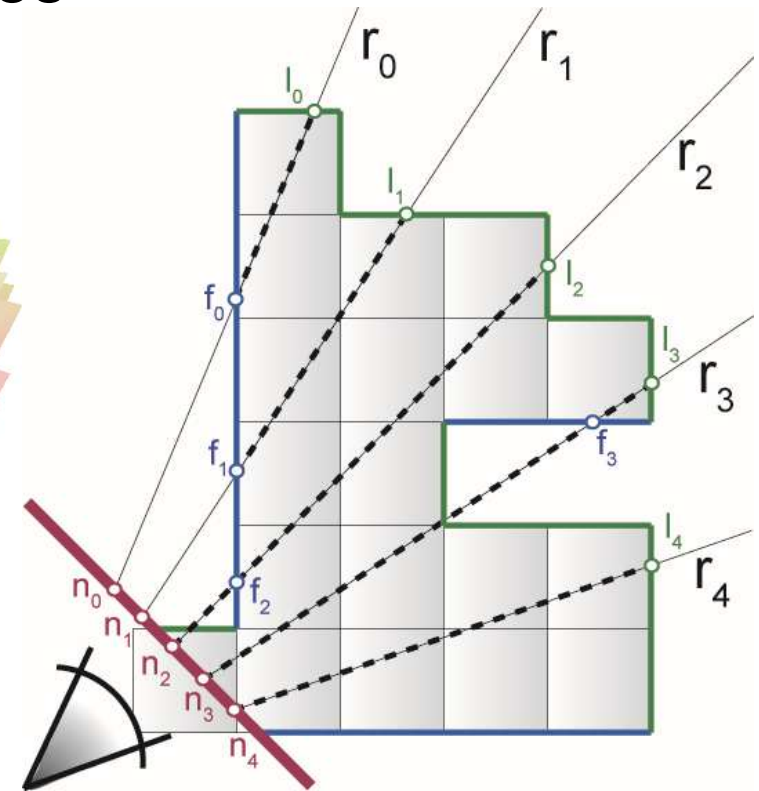


Near clipping plane clips into front faces



Fill in holes with near clipping plane

Can use depth buffer [Scharsach et al., 2006]



Implementation



Ray setup

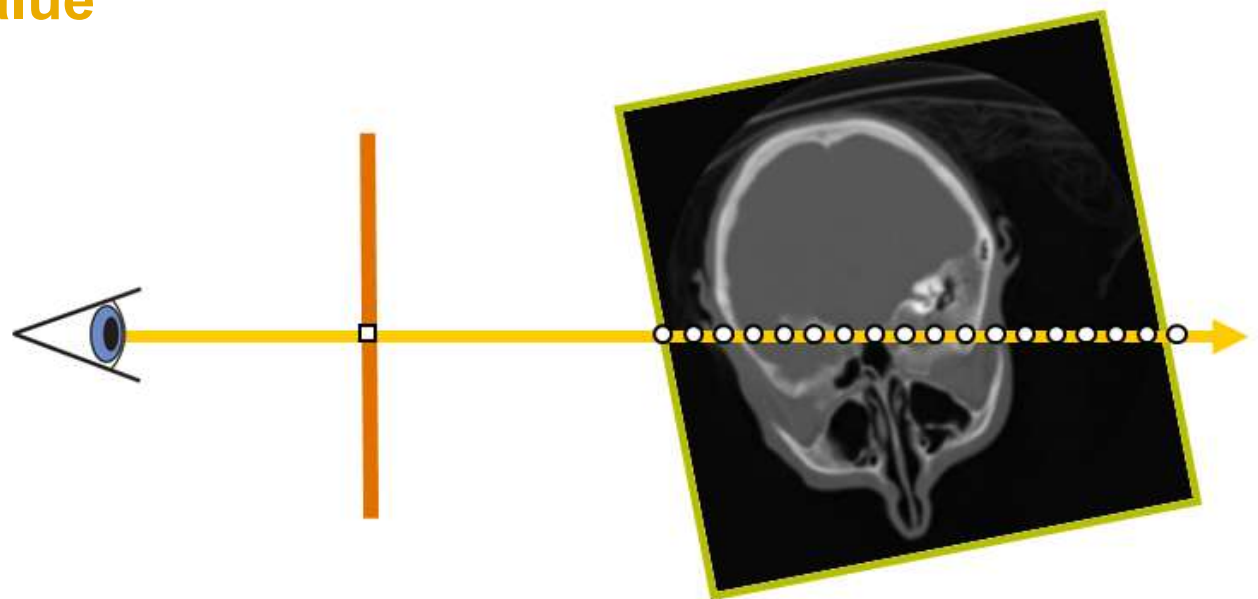
Loop over ray

Resample scalar value

Classification

Shading

Compositing



Classification – Transfer Functions



During Classification the user defines the “**look**” of the data.

- Which parts are transparent?
- Which parts have what color?



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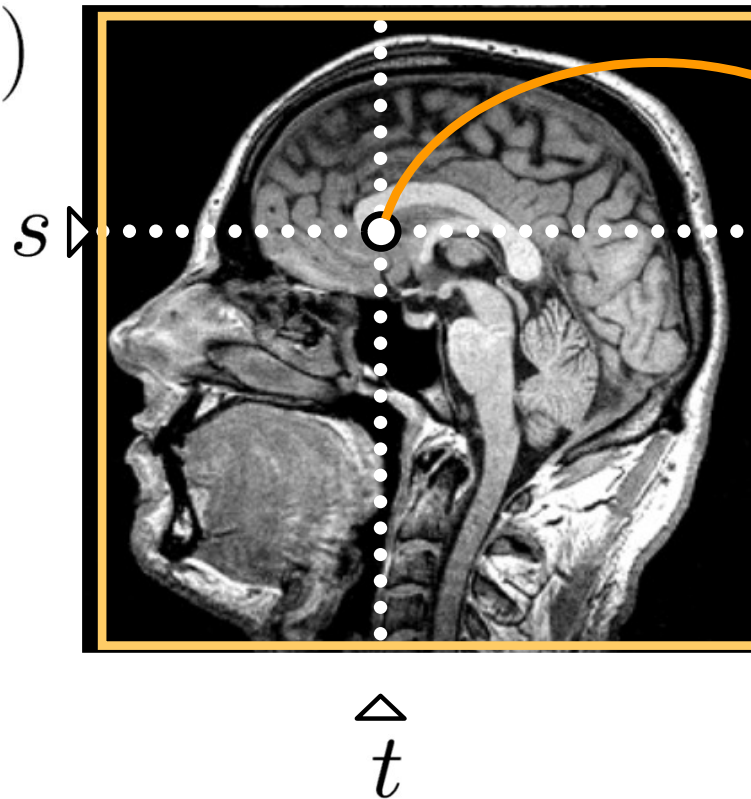
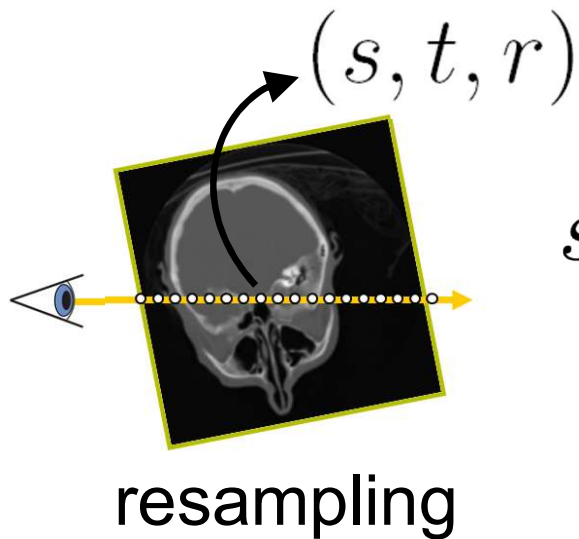
The user defines a ***transfer function***.



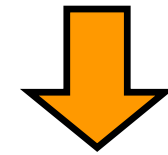
1D Transfer Functions



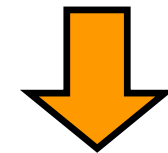
texture = scalar field



scalar value S



$T(S)$

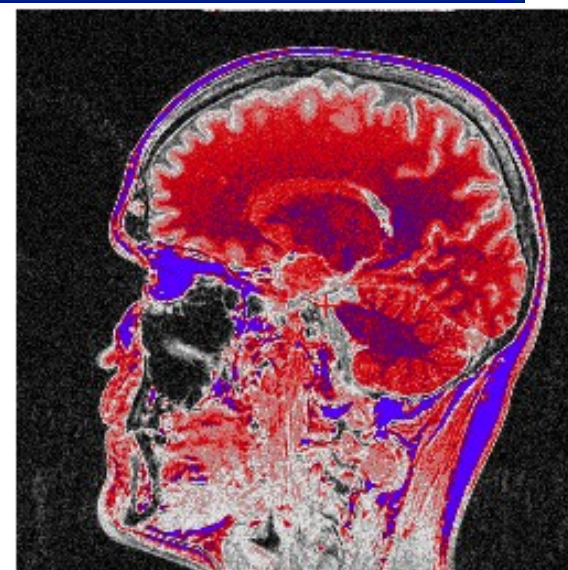
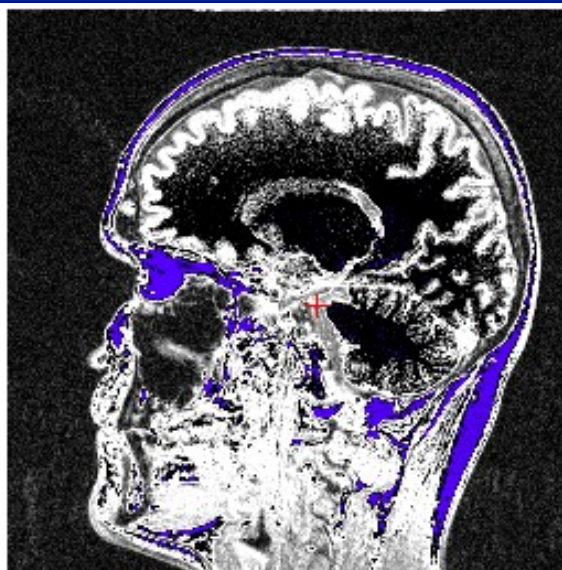
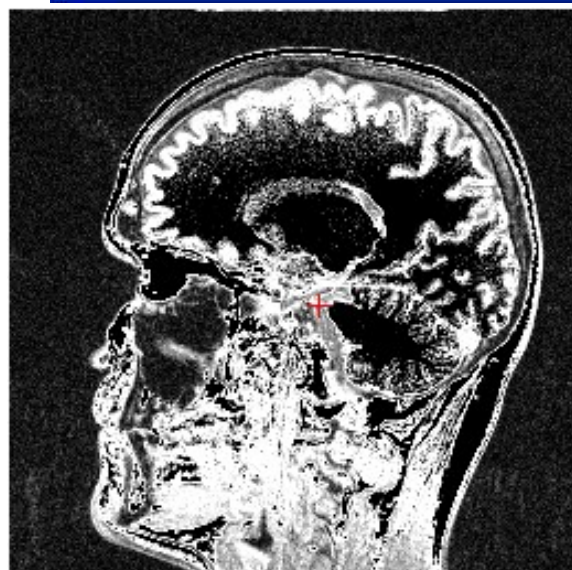
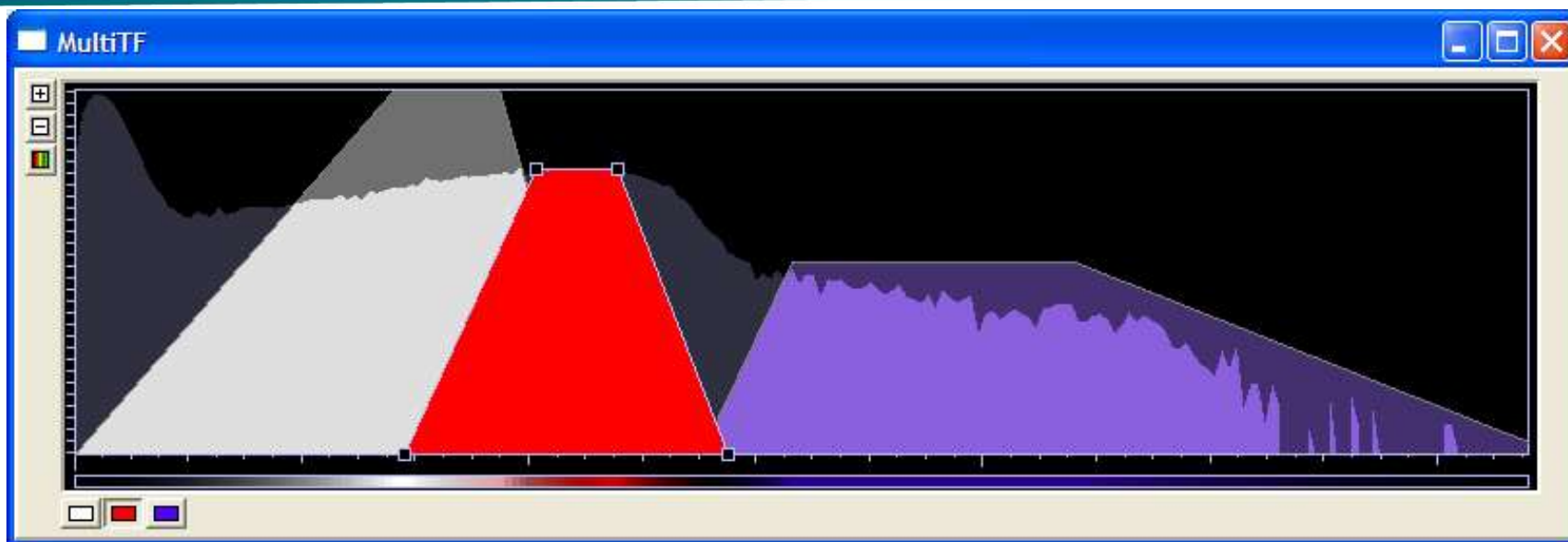


RGBA

transferfunction texture = [Emission RGB, Absorption A]



1D Transfer Functions



Applying Transfer Function: Cg Example



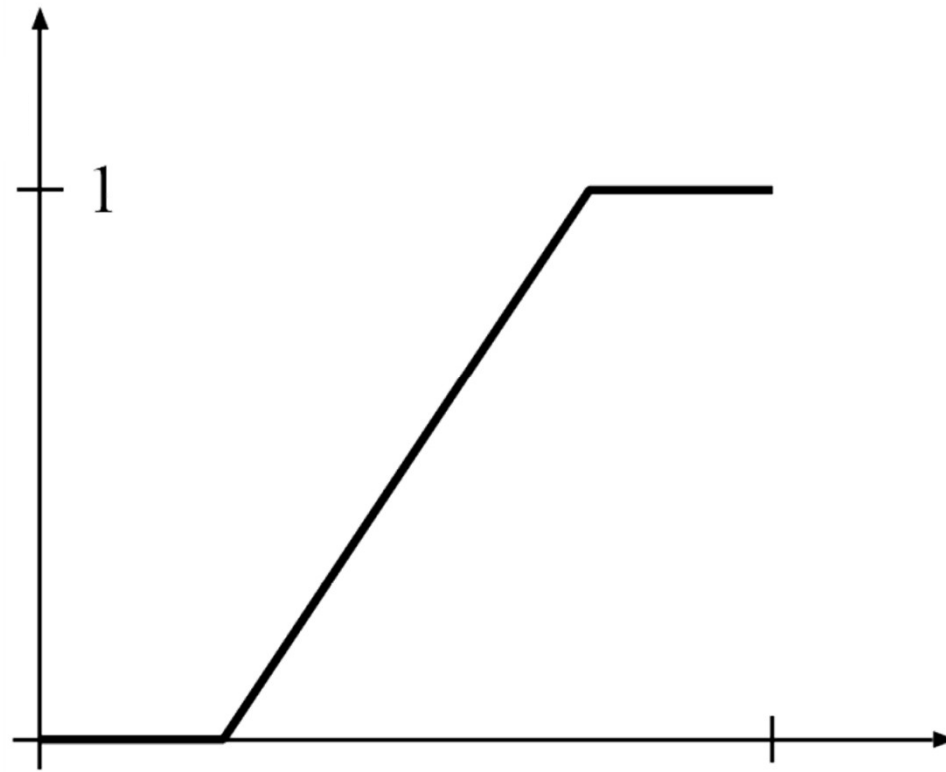
```
// Cg fragment program for post-classification
// using 3D textures
float4 main (float3 texUV : TEXCOORD0,
             uniform sampler3D volume_texture,
             uniform sampler1D transfer_function) :
    COLOR
{
    float index = tex3D(volume_texture, texUV);
    float4 result = tex1D(transfer_function, index);
    return result;
}
```

Windowing Transfer Function



Map input scalar range to output intensity range

- Select scalar range of interest
- Adjust contrast



Implementation



Ray setup

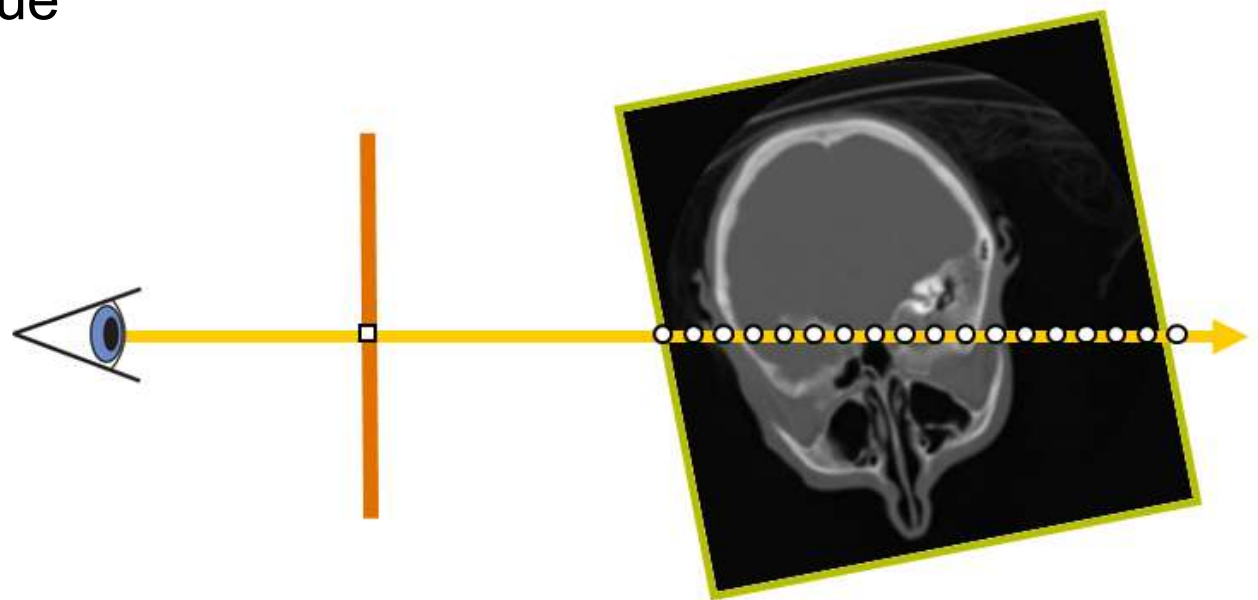
Loop over ray

Resample scalar value

Classification

Shading

Compositing

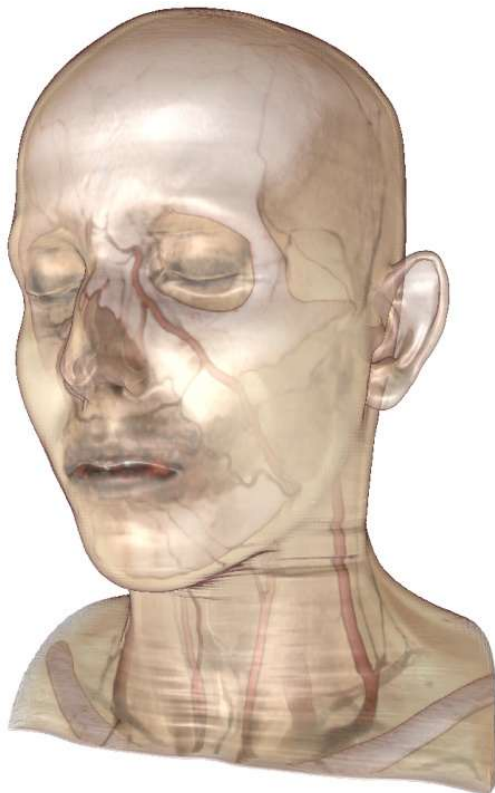


Volume Shading



Local illumination vs. global illumination

- Gradient-based or gradient-less
- Shadows, (multiple) scattering, ...



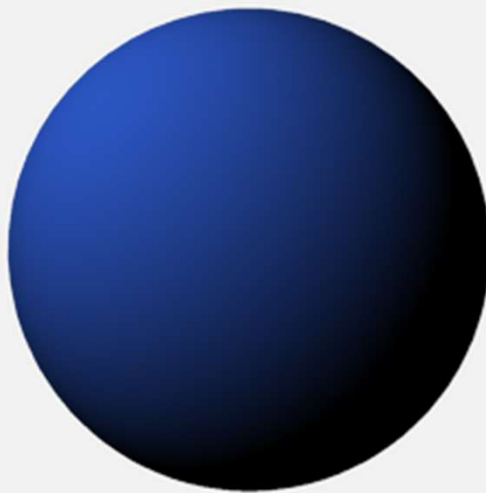
Local Illumination Model: Phong Lighting Model



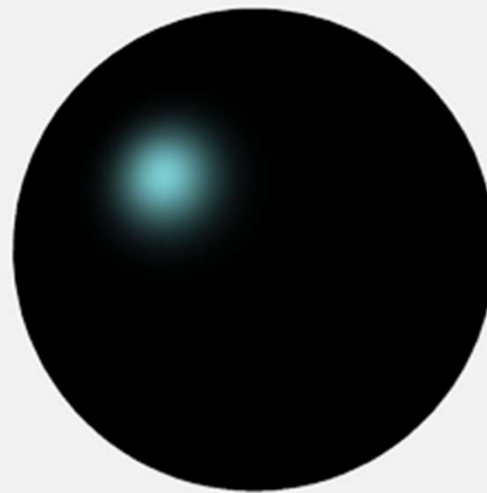
$$\mathbf{I}_{\text{Phong}} = \mathbf{I}_{\text{ambient}} + \mathbf{I}_{\text{diffuse}} + \mathbf{I}_{\text{specular}}$$



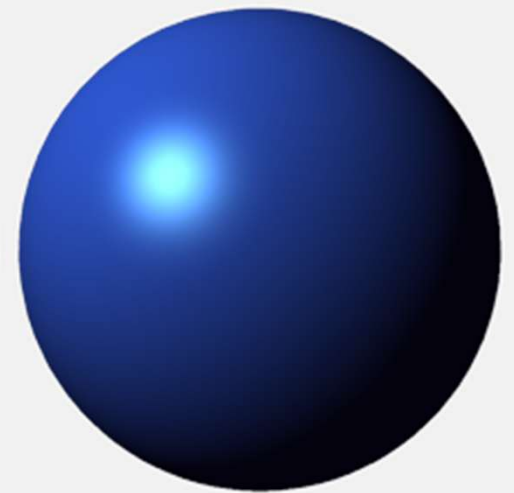
Ambient



Diffuse



Specular



Combined

On-the-fly Gradient Estimation



$$\nabla f(x, y, z) \approx \frac{1}{2h} \begin{pmatrix} f(x + h, y, z) - f(x - h, y, z) \\ f(x, y + h, z) - f(x, y - h, z) \\ f(x, y, z + h) - f(x, y, z - h) \end{pmatrix}$$

```
float3 sample1, sample2;  
// six texture samples for the gradient  
sample1.x = tex3D(texture,uvw-half3(DELTA,0.0,0.0)).x;  
sample2.x = tex3D(texture,uvw+half3(DELTA,0.0,0.0)).x;  
sample1.y = tex3D(texture,uvw-half3(0.0,DELTA,0.0)).x;  
sample2.y = tex3D(texture,uvw+half3(0.0,DELTA,0.0)).x;  
sample1.z = tex3D(texture,uvw-half3(0.0,0.0,DELTA)).x;  
sample2.z = tex3D(texture,uvw+half3(0.0,0.0,DELTA)).x;  
// central difference and normalization  
float3 N = normalize(sample2-sample1);
```

On-The-Fly Gradients



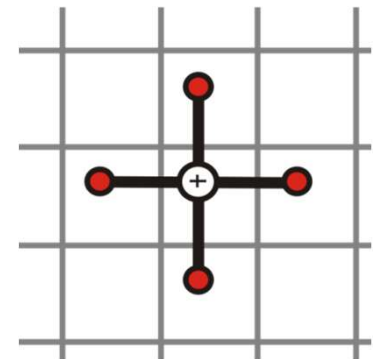
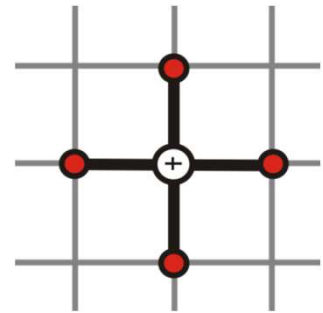
Reduce texture memory consumption!

Central differences before and after linear interpolation of values at grid points yield the same results

Caveat: texture filter precision

Filter kernel methods are expensive, but:

Tri-cubic B-spline kernels can be used in real-time (e.g., GPU Gems 2 Chapter “Fast Third-Order Filtering”)



Implementation



Ray setup

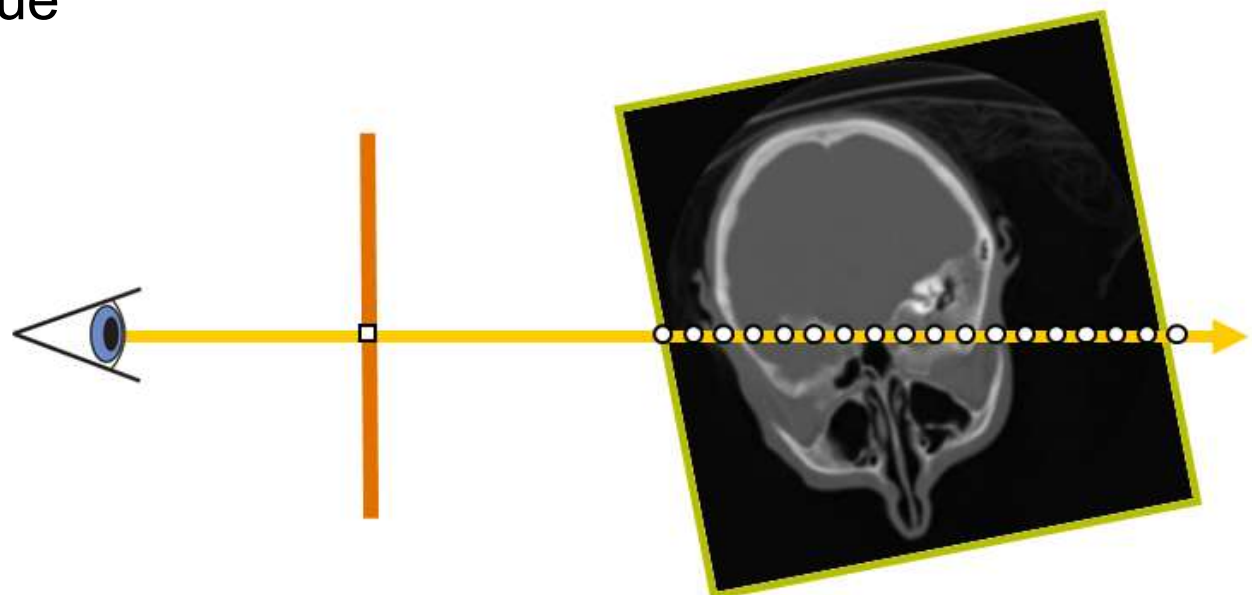
Loop over ray

Resample scalar value

Classification

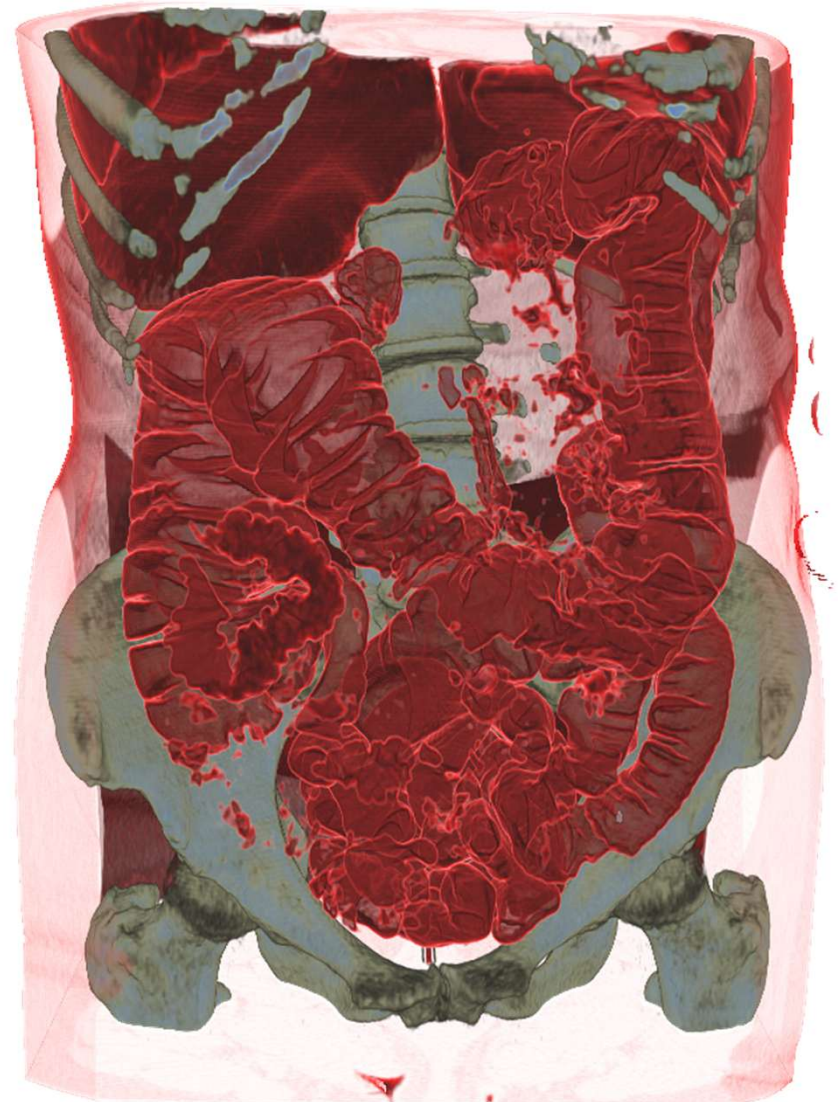
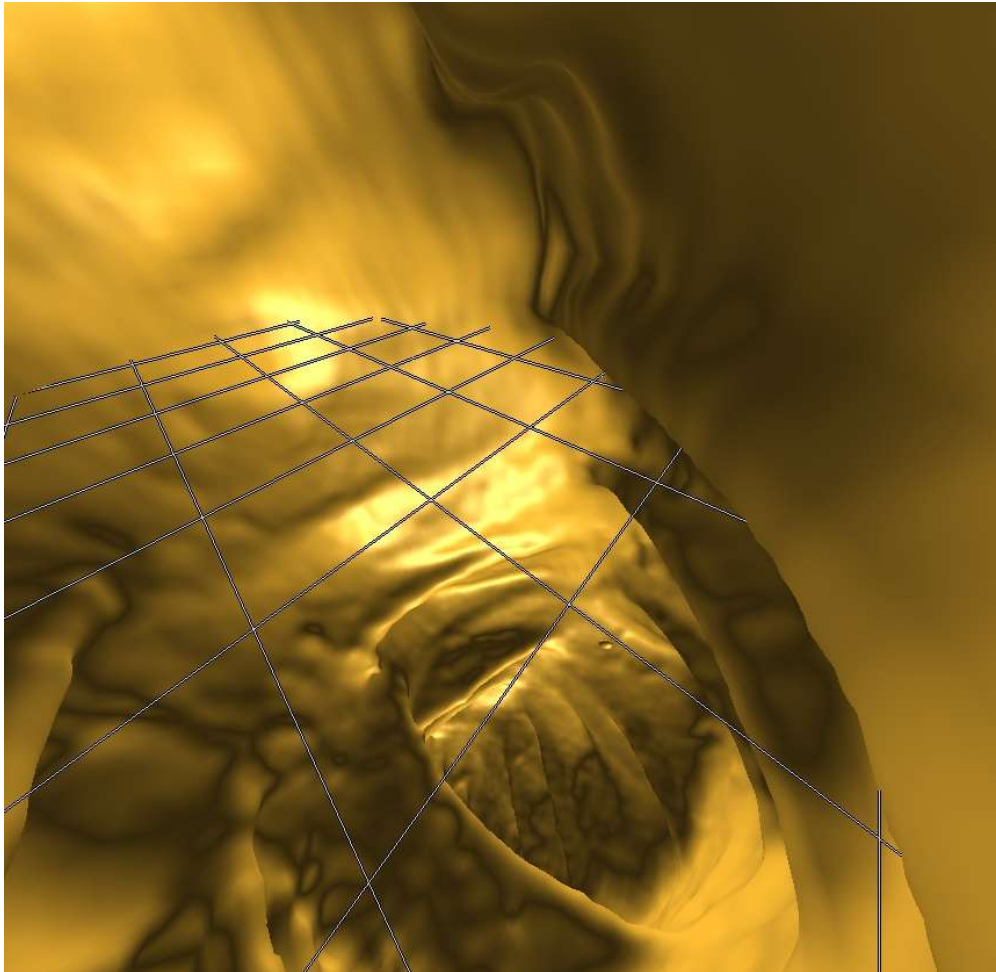
Shading

Compositing

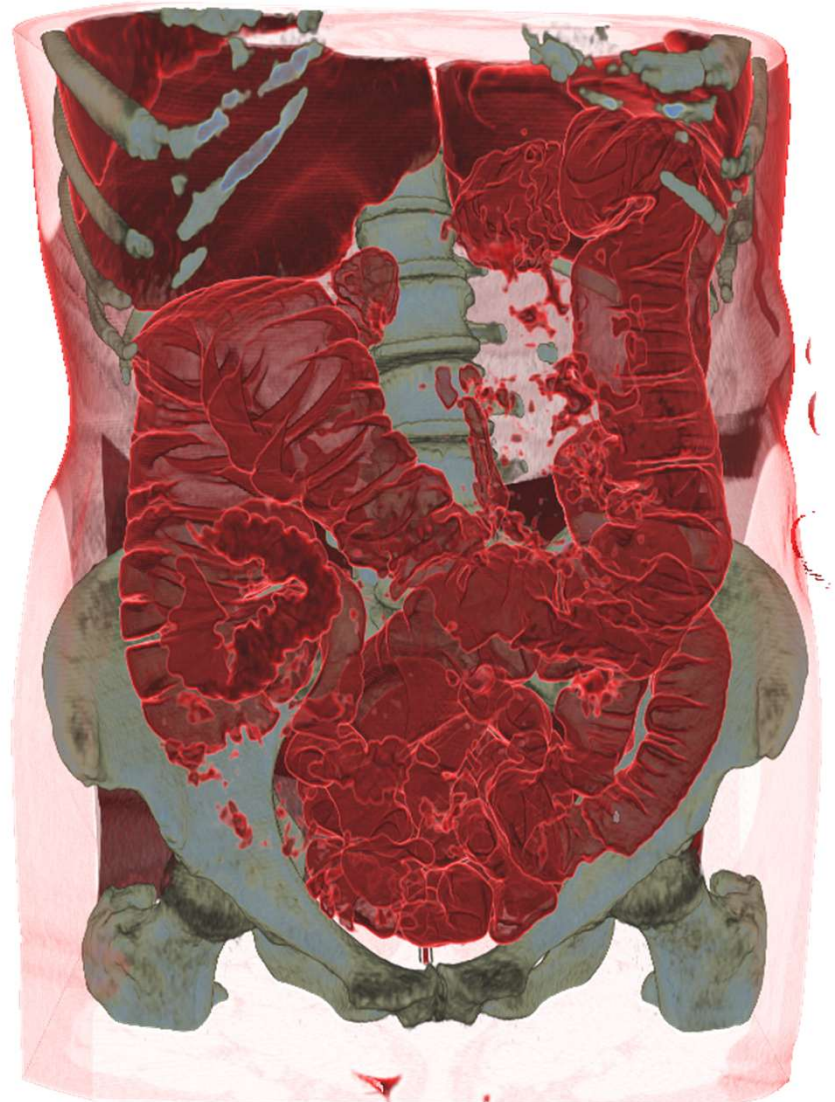


$$C'_i = C'_{i+1} + (1 - A'_{i+1})C_i$$
$$A'_i = A'_{i+1} + (1 - A'_{i+1})A_i$$

Compositing



Compositing



Fragment Shader

- Rasterize front faces of volume bounding box
- Texcoords are volume position in [0,1]
- Subtract camera position
- Repeatedly check for exit of bounding box

```
// Cg fragment shader code for single-pass ray casting
float4 main(VS_OUTPUT IN, float4 TexCoord0 : TEXCOORD0,
            uniform sampler3D SamplerDataVolume,
            uniform sampler1D SamplerTransferFunction,
            uniform float3 camera,
            uniform float stepsize,
            uniform float3 volExtentMin,
            uniform float3 volExtentMax
            ) : COLOR
{
    float4 value;
    float scalar;
    // Initialize accumulated color and opacity
    float4 dst = float4(0,0,0,0);
    // Determine volume entry position
    float3 position = TexCoord0.xyz;
    // Compute ray direction
    float3 direction = TexCoord0.xyz - camera;
    direction = normalize(direction);
    // Loop for ray traversal
    for (int i = 0; i < 200; i++) // Some large number
    {
        // Data access to scalar value in 3D volume texture
        value = tex3D(SamplerDataVolume, position);
        scalar = value.a;
        // Apply transfer function
        float4 src = tex1D(SamplerTransferFunction, scalar);
        // Front-to-back compositing
        dst = (1.0-dst.a) * src + dst;
        // Advance ray position along ray direction
        position = position + direction * stepsize;
        // Ray termination: Test if outside volume ...
        float3 temp1 = sign(position - volExtentMin);
        float3 temp2 = sign(volExtentMax - position);
        float inside = dot(temp1, temp2);
        // ... and exit loop
        if (inside < 3.0)
            break;
    }
    return dst;
}
```

CUDA Kernel

- Image-based ray setup
 - Ray start image
 - Direction image
- Ray-cast loop
 - Sample volume
 - Accumulate color and opacity
- Terminate
- Store output

```
__global__  
void RayCastCUDAKernel( float *d_output_buffer, float *d_startpos_buffer, float *d_direction_buffer )  
{  
    // output pixel coordinates  
    dword screencoord_x = __umul24( blockIdx.x, blockDim.x ) + threadIdx.x;  
    dword screencoord_y = __umul24( blockIdx.y, blockDim.y ) + threadIdx.y;  
  
    // target pixel (RGBA-tuple) index  
    dword screencoord_indx = ( __umul24( screencoord_y, cu_screensize.x ) + screencoord_x ) * 4;  
  
    // get direction vector and ray start  
    float4 dir_vec = d_direction_buffer[ screencoord_indx ];  
    float4 startpos = d_startpos_buffer[ screencoord_indx ];  
  
    // ray-casting loop  
    float4 color = make_float4( 0.0f );  
    float poscount = 0.0f;  
    for ( int i = 0; i < 8192; i++ ) {  
  
        // next sample position in volume space  
        float3 samplepos = dir_vec * poscount + startpos;  
        poscount += cu_sampling_distance;  
  
        // fetch density  
        float tex_density = tex3D( cu_volume_texture, samplepos.x, samplepos.y, samplepos.z );  
  
        // apply transfer function  
        float4 col_classified = tex1D( cu_transfer_function_texture, tex_density );  
  
        // compute (1-previous.a)*tf.a  
        float prev_alpha = -color.w * col_classified.w + col_classified.w;  
  
        // composite color and alpha  
        color.xyz = prev_alpha * col_classified.xyz + color.xyz;  
        color.w += prev_alpha;  
  
        // break if ray terminates (behind exit position or alpha threshold reached)  
        if ( ( poscount > dir_vec.w ) || ( color.w > 0.98f ) ) {  
            break;  
        }  
    }  
  
    // store output color and opacity  
    d_output_buffer[ screencoord_indx ] = __saturatef( color );  
}
```

Thank you.

Thanks for material

- Helwig Hauser
- Eduard Gröller
- Daniel Weiskopf
- Torsten Möller
- Ronny Peikert
- Philipp Muigg
- Christof Rezk-Salama