

CS 247 – Scientific Visualization

Lecture 16: Volume Rendering, Pt. 3 [preview]

Markus Hadwiger, KAUST



Reading Assignment #9 (until Mar 28)

Read (required):

- Real-Time Volume Graphics, Chapter 4.5 – 4.8
- Paper:

Jens Krüger and Rüdiger Westermann,
Acceleration Techniques for GPU-based Volume Rendering,
IEEE Visualization 2003,
<http://dl.acm.org/citation.cfm?id=1081482>



Quiz #2: Mar 23

Organization

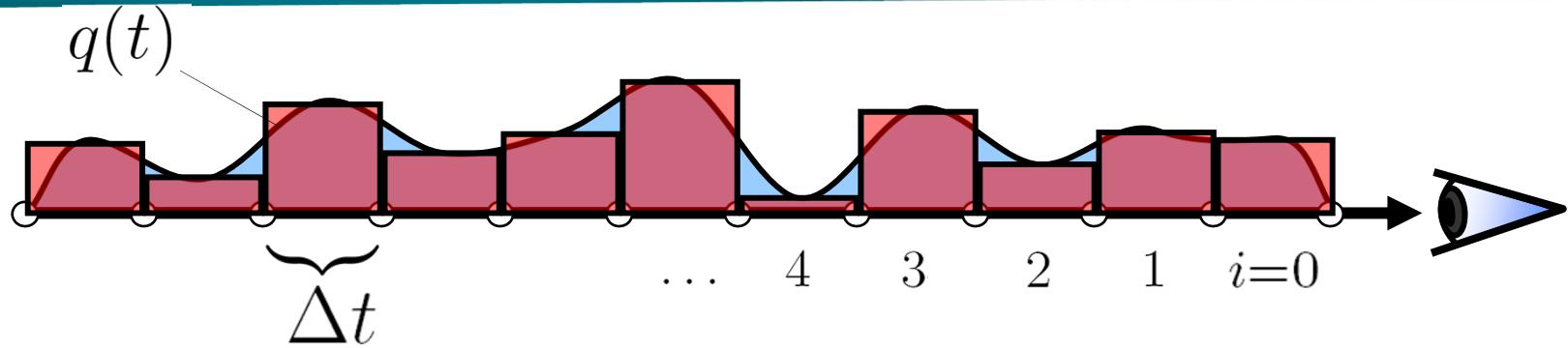
- First 30 min of lecture
- No material (book, notes, ...) allowed

Content of questions

- Lectures (both actual lectures and slides)
- Reading assignments (except optional ones)
- Programming assignments (algorithms, methods)
- Solve short practical examples

Volume Visualization

Volume Rendering Integral: Numerical Solution



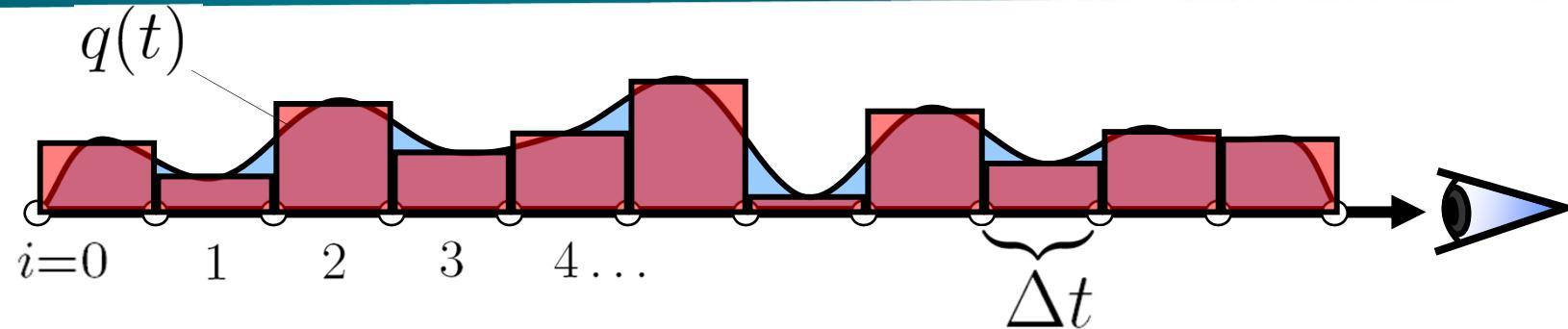
$$e^{-\tilde{\tau}(0,t)} = \prod_{i=0}^{\lfloor t/\Delta t \rfloor} (1 - A_i)$$

$$q(t) \approx C_i = c(i \cdot \Delta t) \Delta t$$

$$\tilde{C} = \sum_{i=0}^{\lfloor T/\Delta t \rfloor} C_i \prod_{j=0}^{i-1} (1 - A_j)$$

can be computed recursively/iteratively!

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

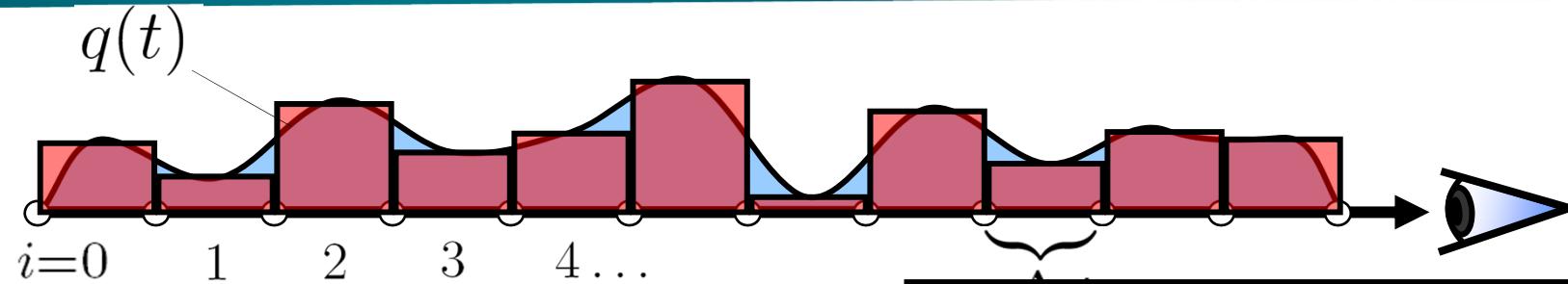
**Front-to-back
compositing**

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

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

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 $i=0$ (back)

Early Ray Termination:
Stop the calculation when

$$A'_i \approx 1$$

**Front-to-back
compositing**

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

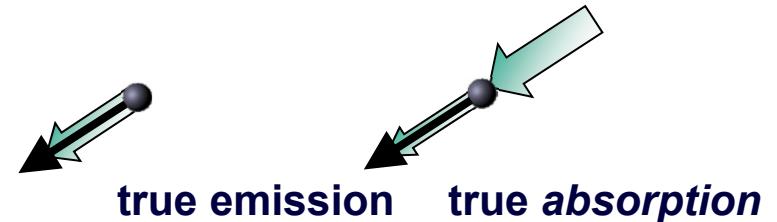
$$A'_i = A'_{i+1} + (1 - A'_{i+1}) A_i$$

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

Volume Rendering Integral Summary



Volume rendering integral
for *Emission Absorption* model



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

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!

VoVis: Implementation

Implementation



Ray setup

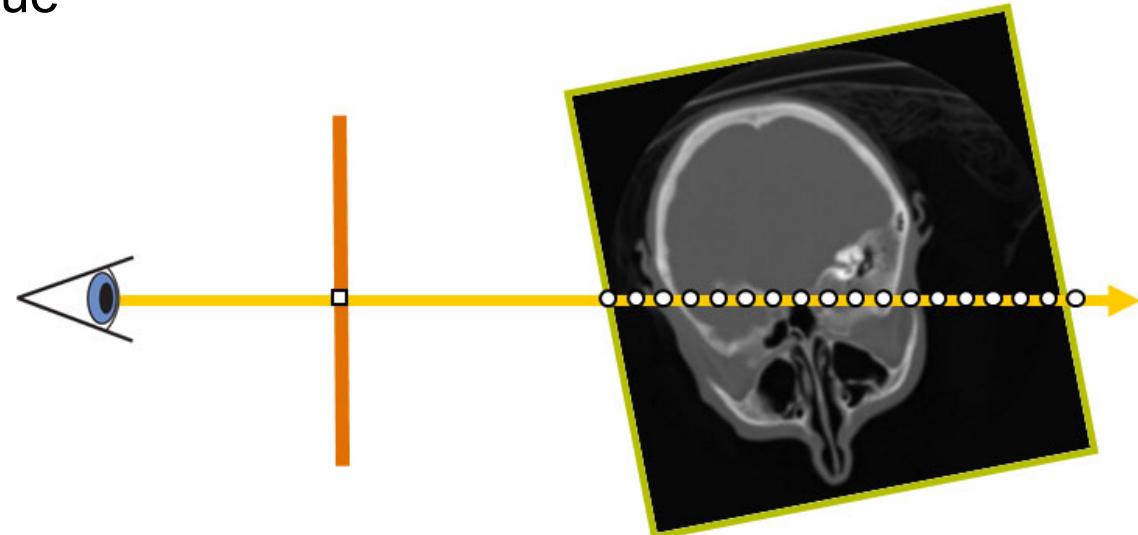
Loop over ray

 Resample scalar value

 Classification

 Shading

 Compositing



Implementation



Ray setup

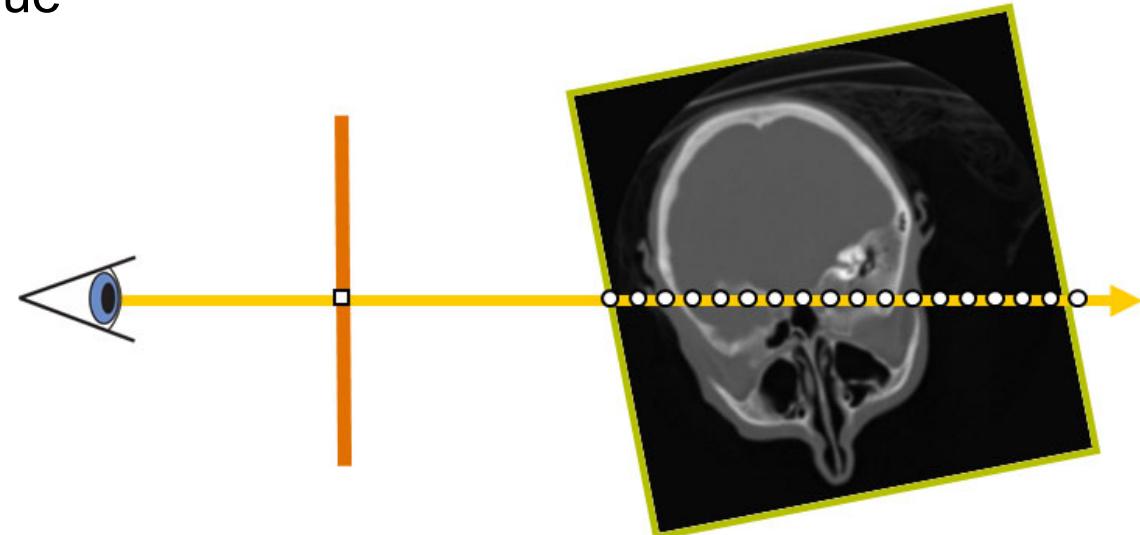
Loop over ray

Resample scalar value

Classification

Shading

Compositing



Ray Setup

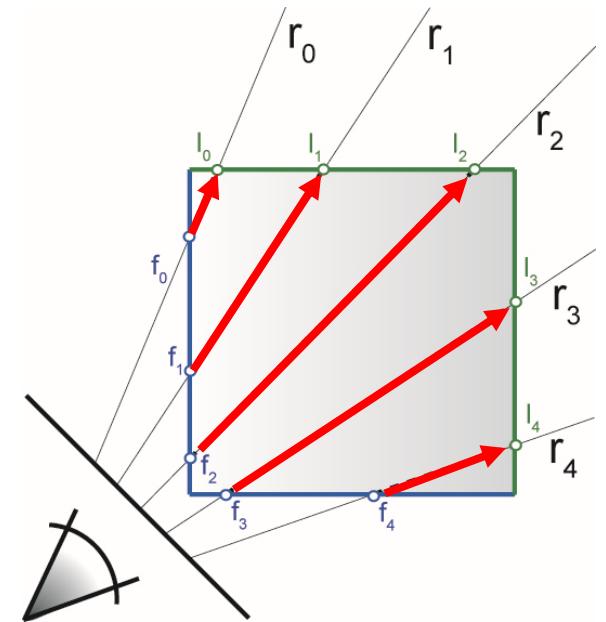


Two main approaches:

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

Some possibilities

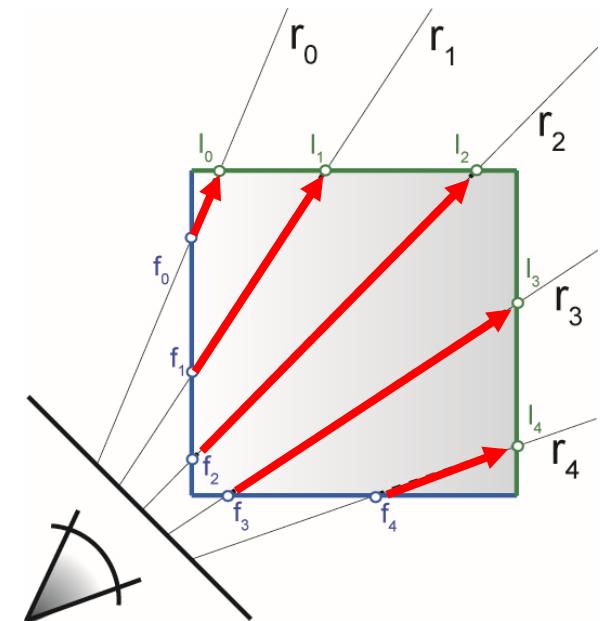
- Ray start position and exit check
- Ray start position and exit position
- Ray start position and direction vector



Procedural Ray Setup/Termination



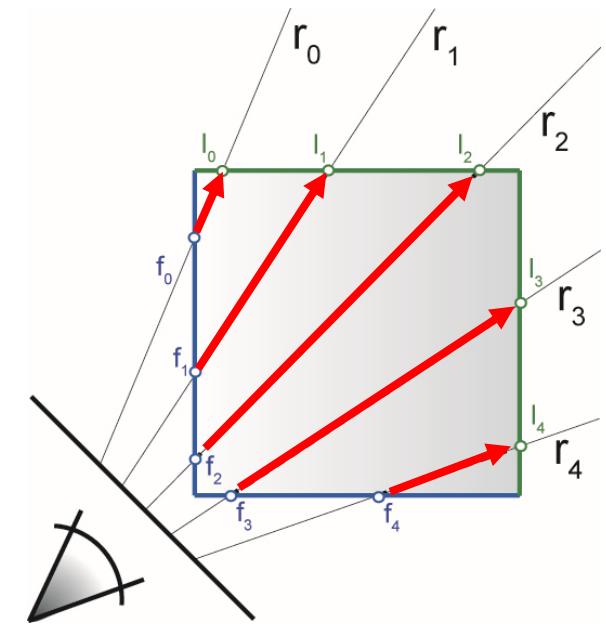
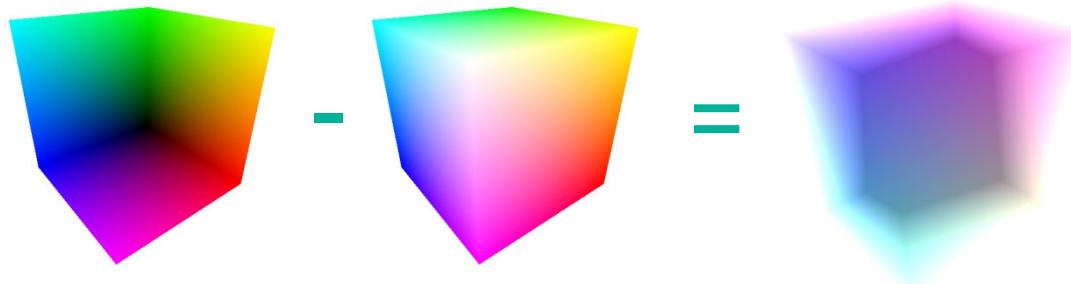
- Everything handled in the fragment shader / CUDA kernel
- Procedural ray / bounding box intersection
- Ray is given by camera position and volume entry position
- Exit criterion needed
- Pro: simple and self-contained
- Con: full computational load per-pixel/fragment



Rasterization-Based Ray Setup



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

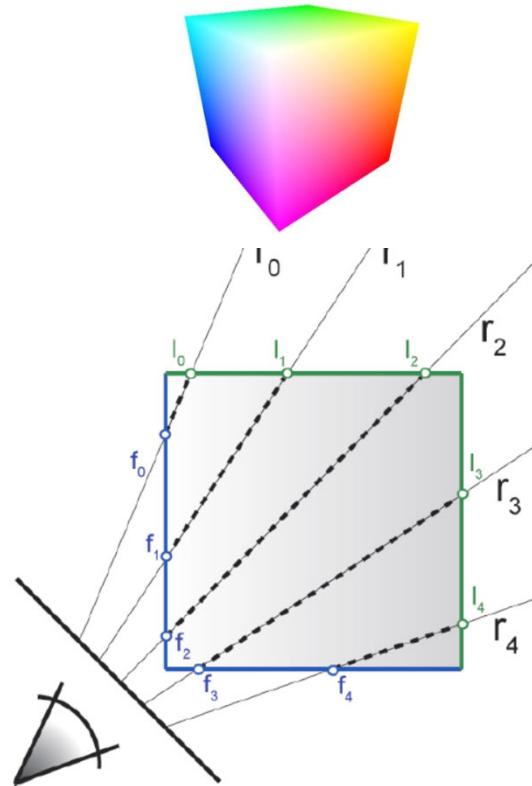


- Identical for orthogonal and perspective projection!

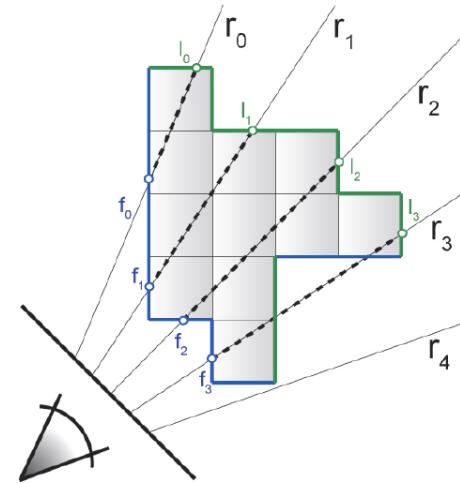
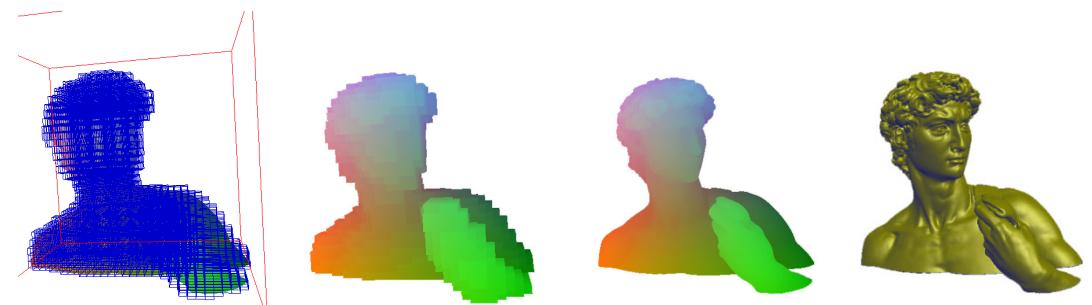
Object-Order Empty Space Skipping



Modify initial rasterization step



rasterize bounding box

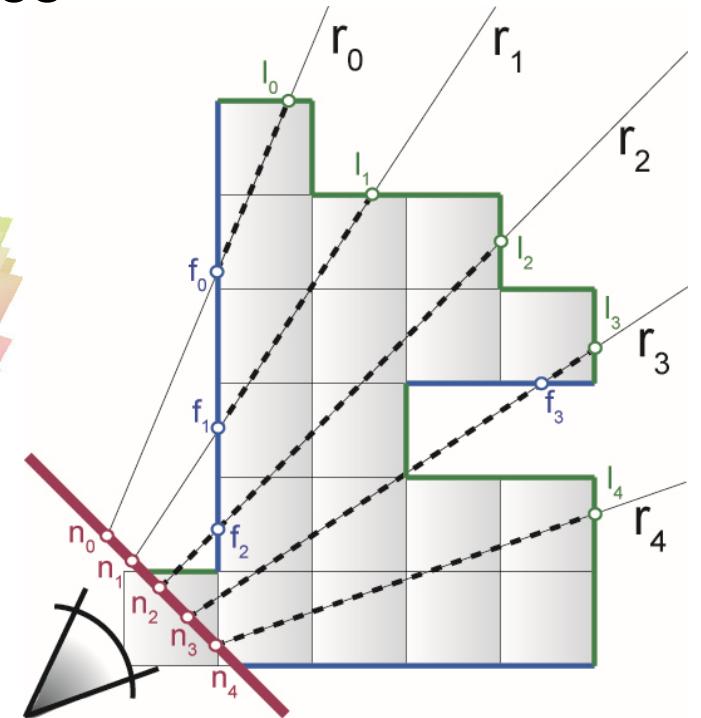
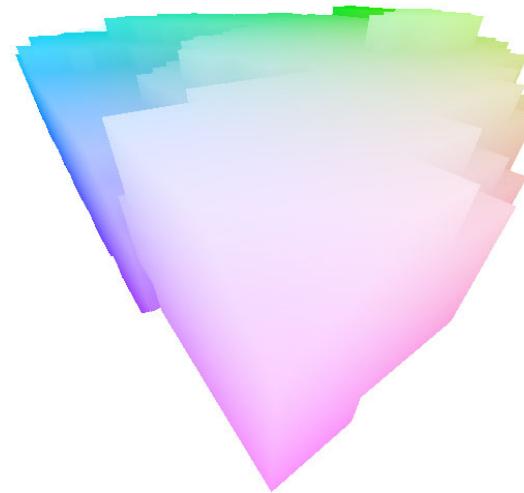


rasterize “tight” bounding geometry

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

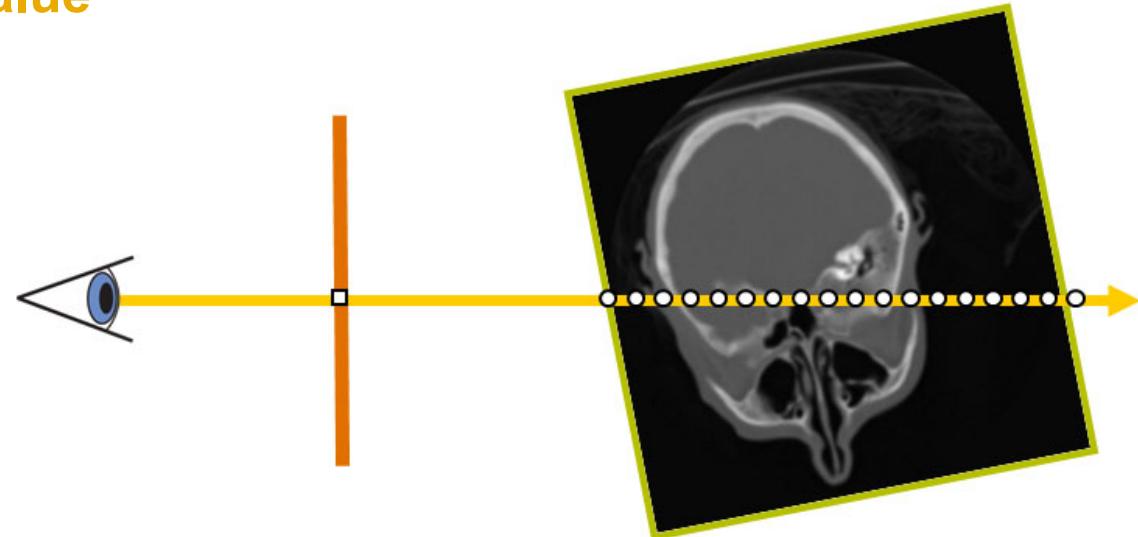
Loop over ray

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?



Classification – Transfer Functions



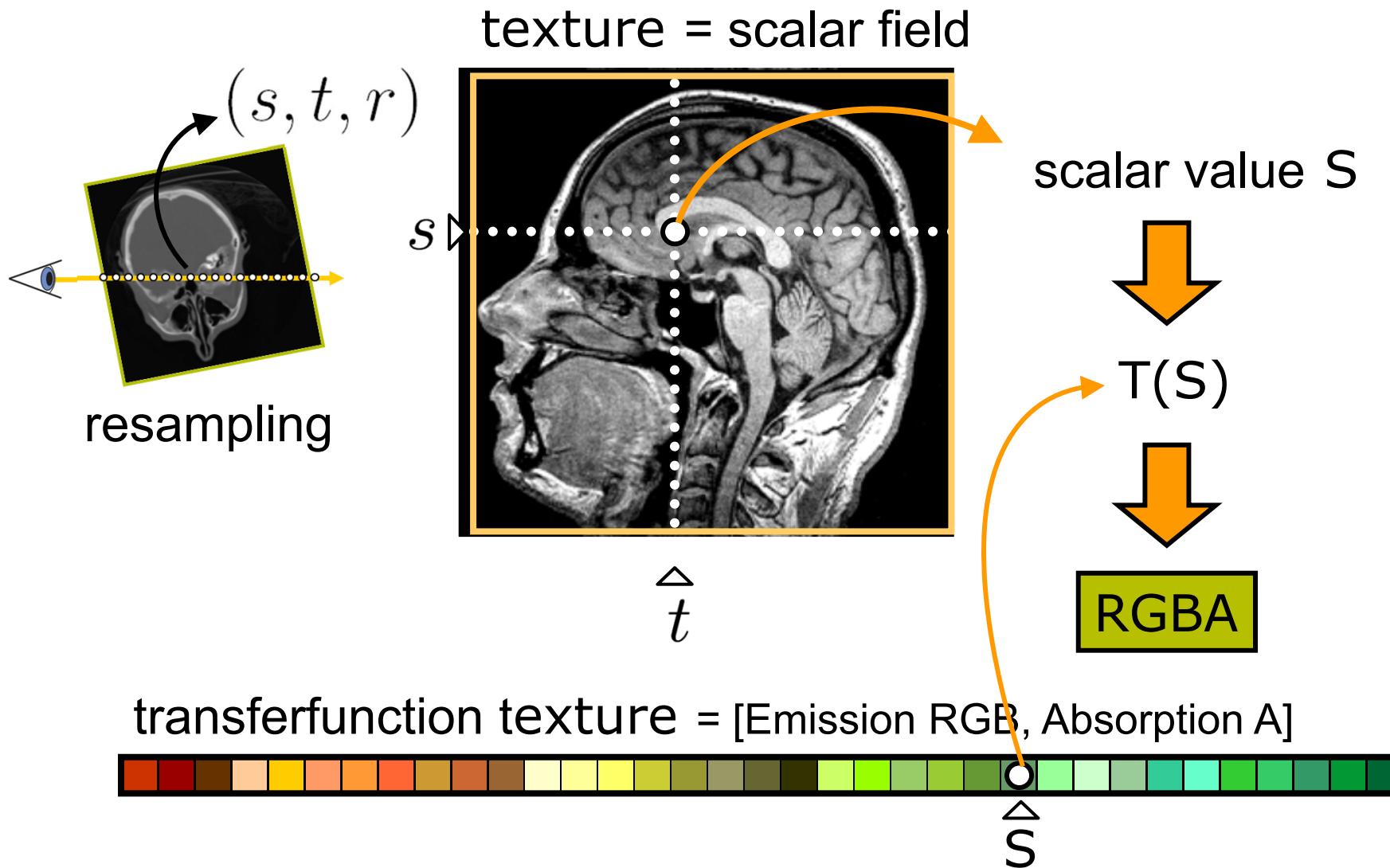
During Classification the user defines the “*look*“ of the data.

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

The user defines a *transfer function*.

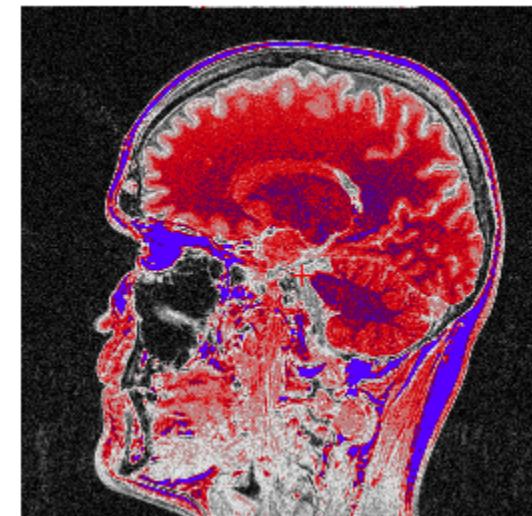
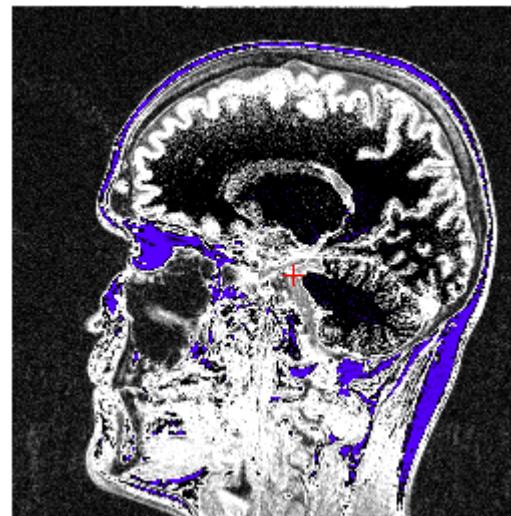
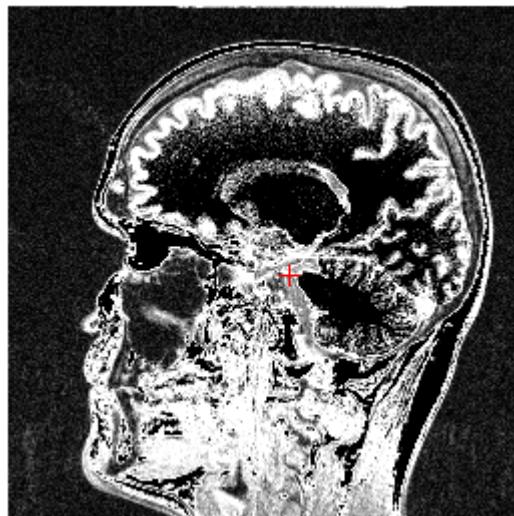
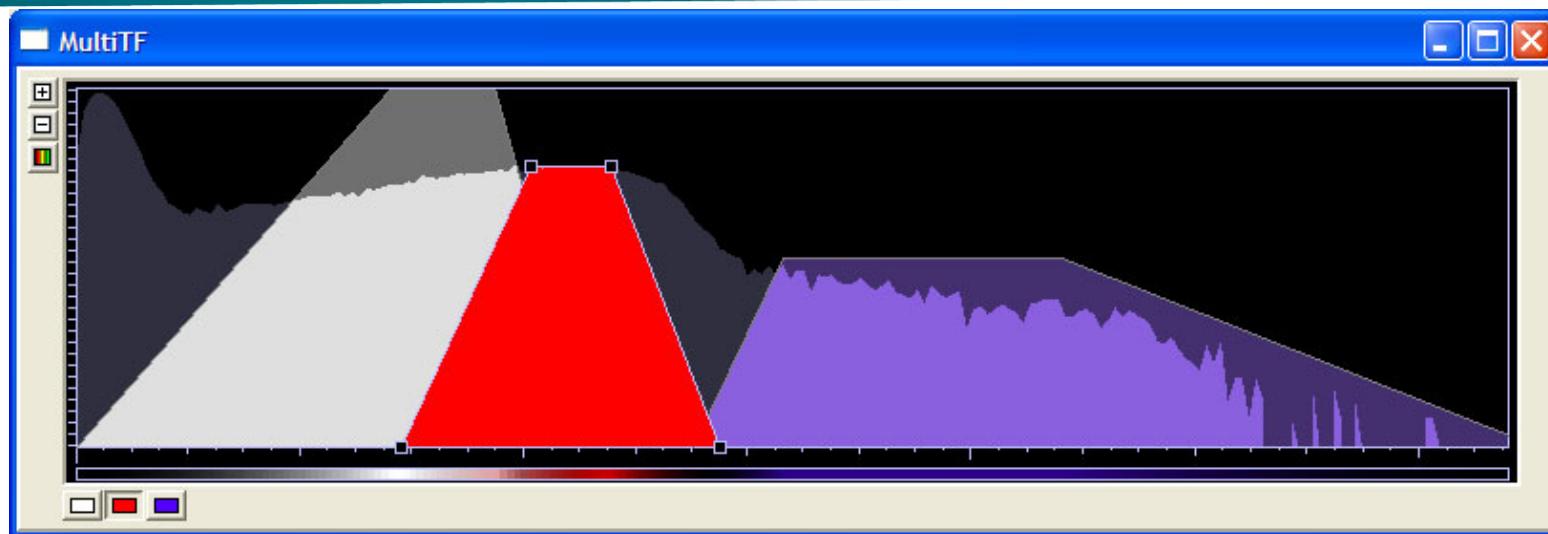


1D Transfer Functions





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

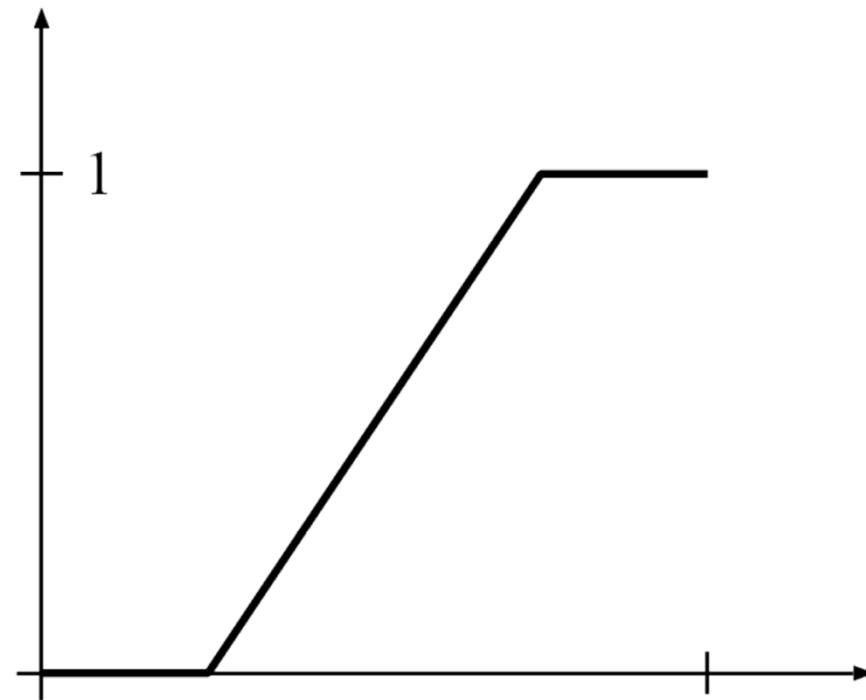
{
    float index = tex3D(volume_texture, texUV);
    float4 result = tex1D(transfer_function, index);
    return result;
}
```



Windowing Transfer Function

Map input scalar range to output intensity range

- Select scalar range of interest
- Adjust contrast



Implementation



Ray setup

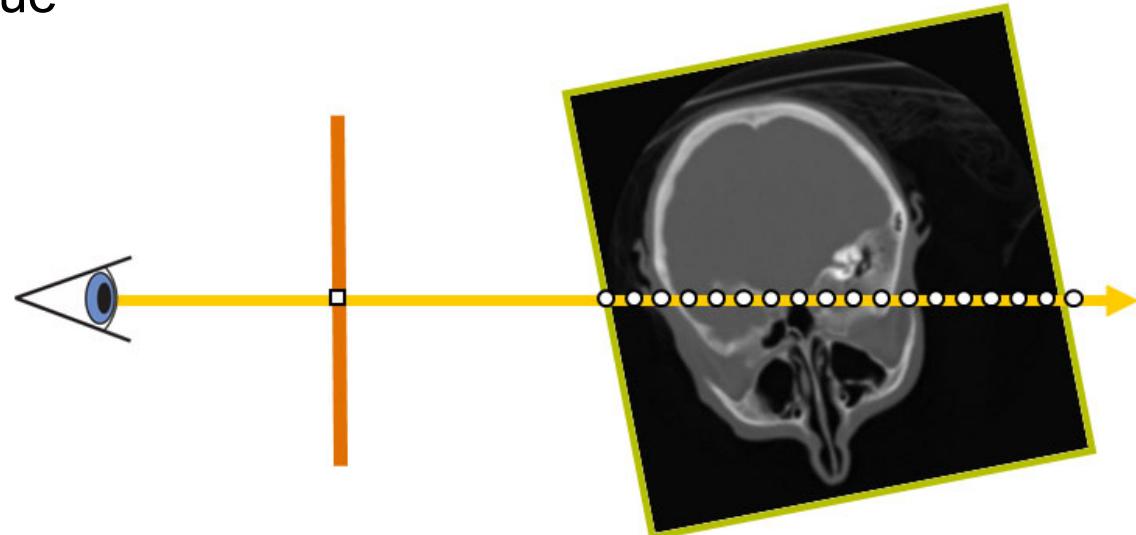
Loop over ray

Resample scalar value

Classification

Shading

Compositing





Volume Shading

Local illumination vs. global illumination

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



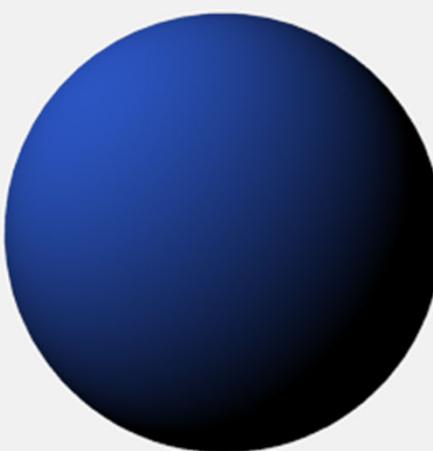
Local Illumination Model: Phong Lighting Model



$$I_{\text{Phong}} = I_{\text{ambient}} + I_{\text{diffuse}} + I_{\text{specular}}$$



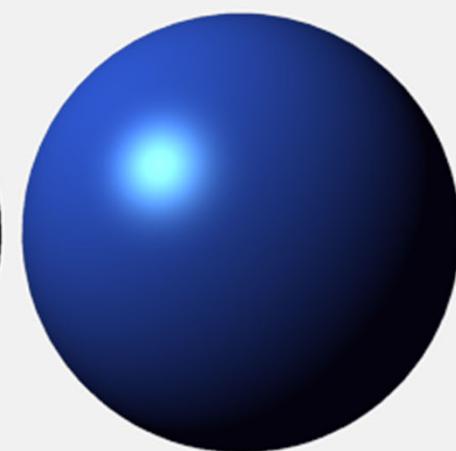
Ambient



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



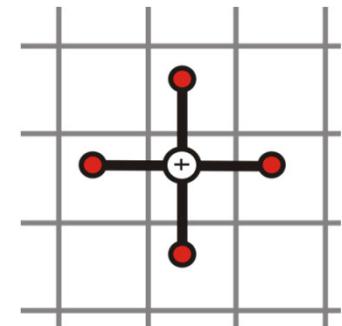
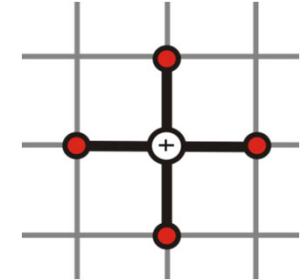
Reduce texture memory consumption!

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

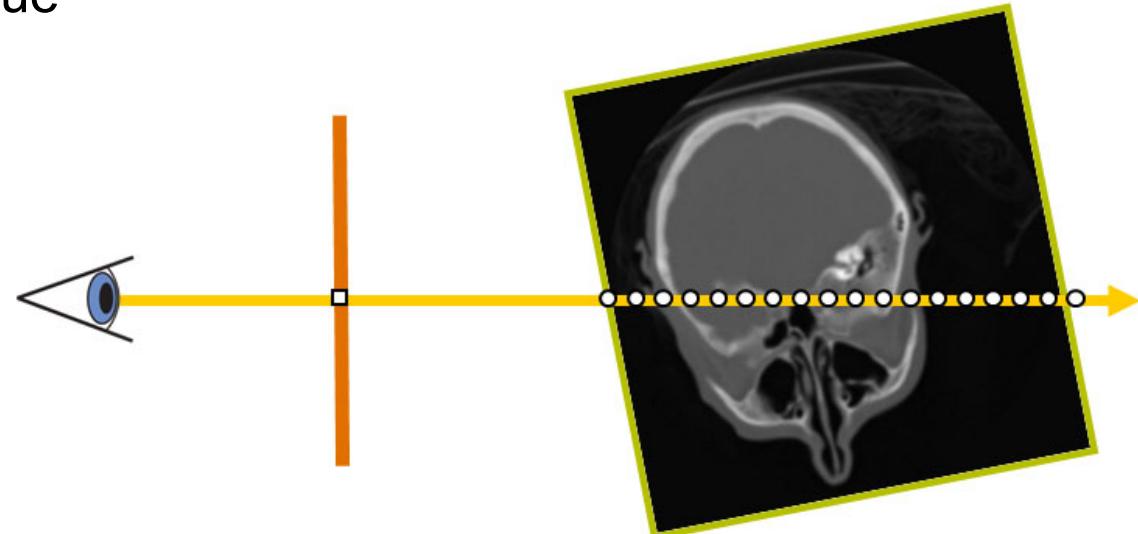
Loop over ray

Resample scalar value

Classification

Shading

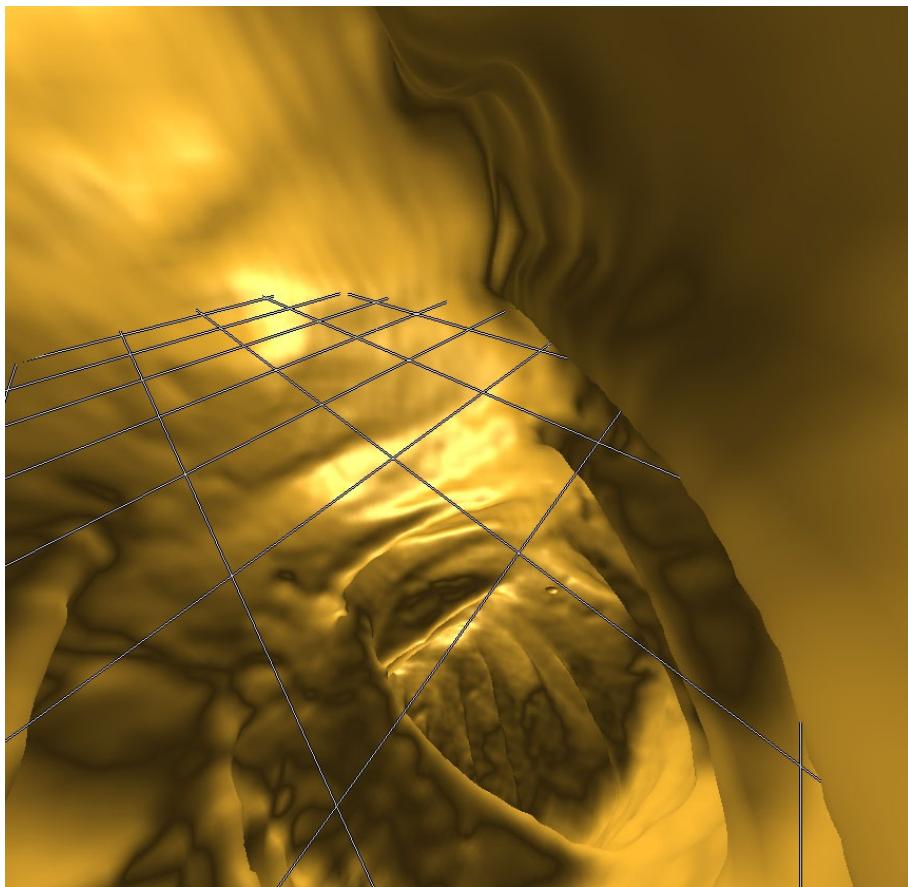
Compositing



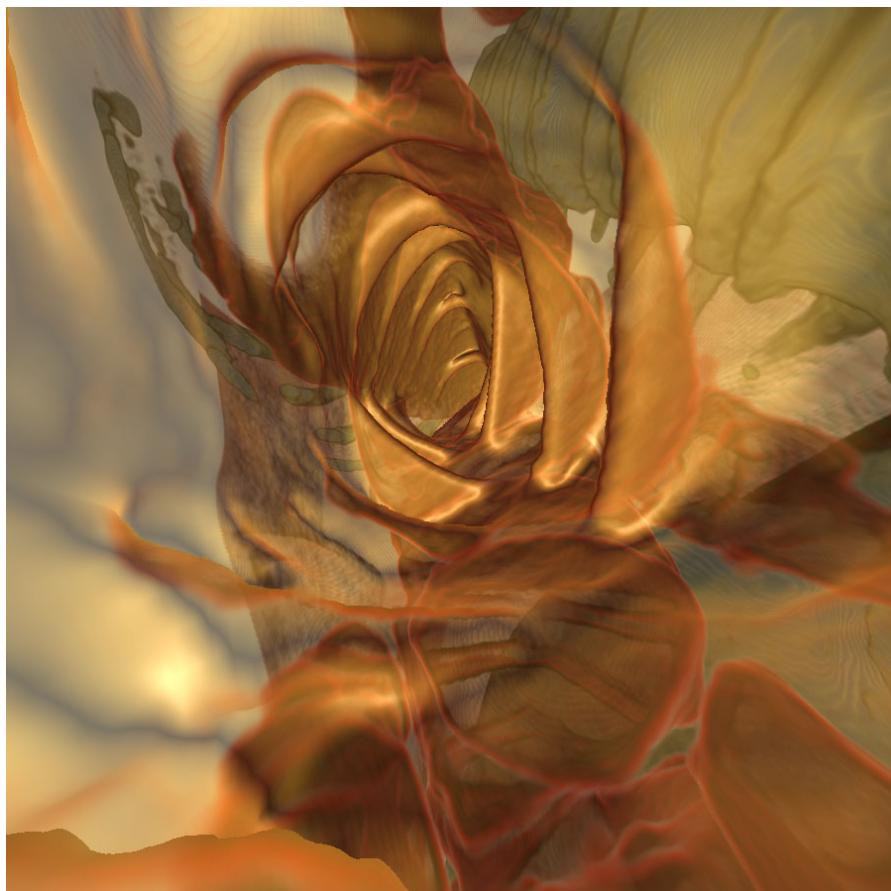
$$C'_i = C'_{i+1} + (1 - A'_{i+1})C_i$$

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

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_idx = ( __umul24( screencoord_y, cu_screensize.x ) + screencoord_x ) * 4;

    // get direction vector and ray start
    float4 dir_vec = d_direction_buffer[ screencoord_idx ];
    float4 startpos = d_startpos_buffer[ screencoord_idx ];

    // 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_idx ] = __saturatef( color );
    }
}
```

VoVis: Opacity Correction



Opacity Correction

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

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

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

$$\tilde{T}_i = T_i^{\left(\frac{\Delta \tilde{t}}{\Delta t}\right)}$$

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

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

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

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):

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

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

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

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

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



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):

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

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

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

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

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



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):

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

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

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

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

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



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):

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

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

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

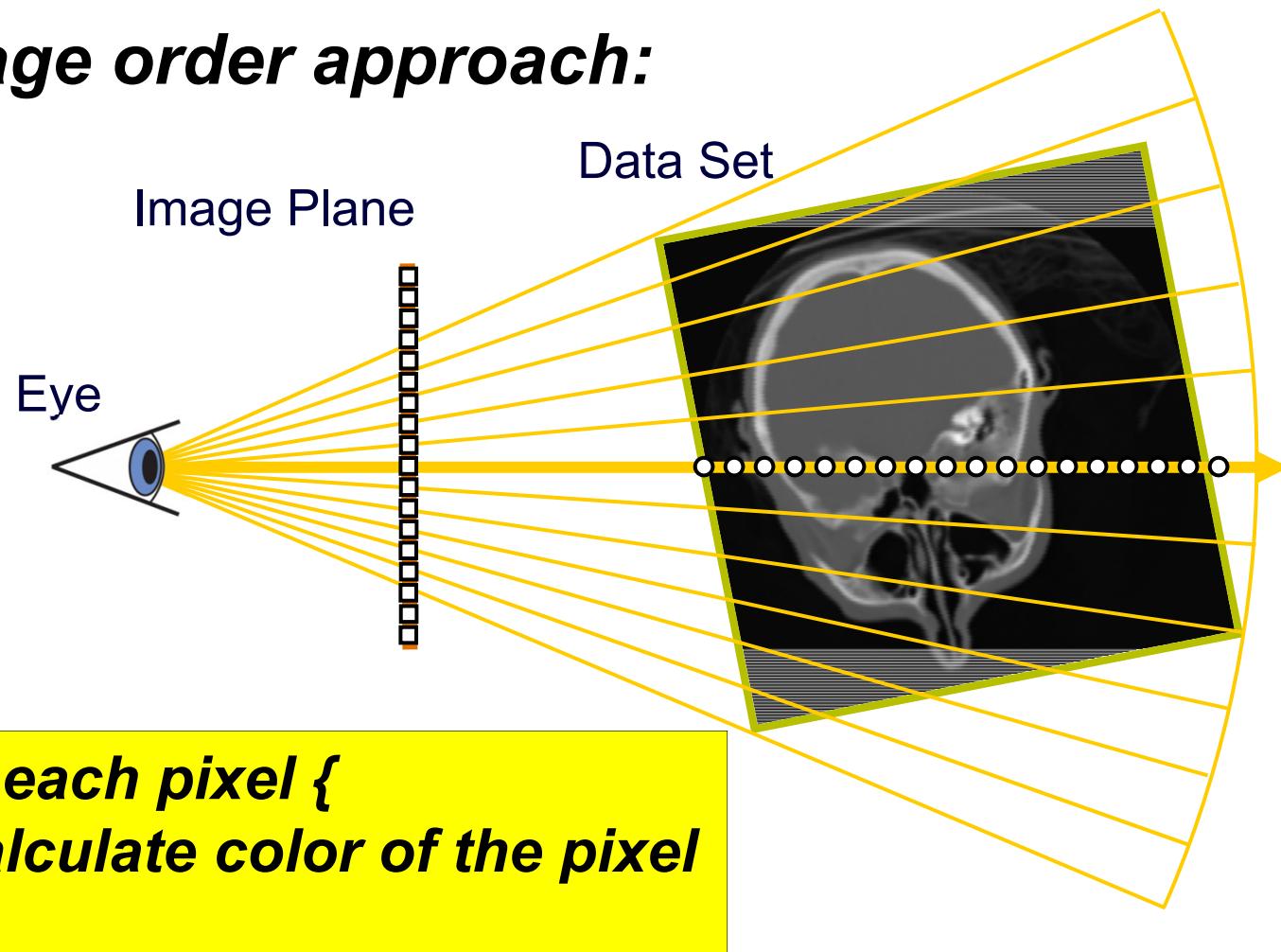
$$\lim_{\kappa_i \rightarrow 0} q_i \frac{(1 - e^{-\kappa_i \Delta t})}{\kappa_i} = \lim_{\kappa_i \rightarrow 0} \hat{C}_i \left(1 - e^{-\kappa_i \Delta t}\right) = 0$$
$$\lim_{\kappa_i \rightarrow \infty} q_i \frac{(1 - e^{-\kappa_i \Delta t})}{\kappa_i} = \lim_{\kappa_i \rightarrow \infty} \hat{C}_i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

VolVis: Image vs. Object Order

Direct Volume Rendering: Image Order



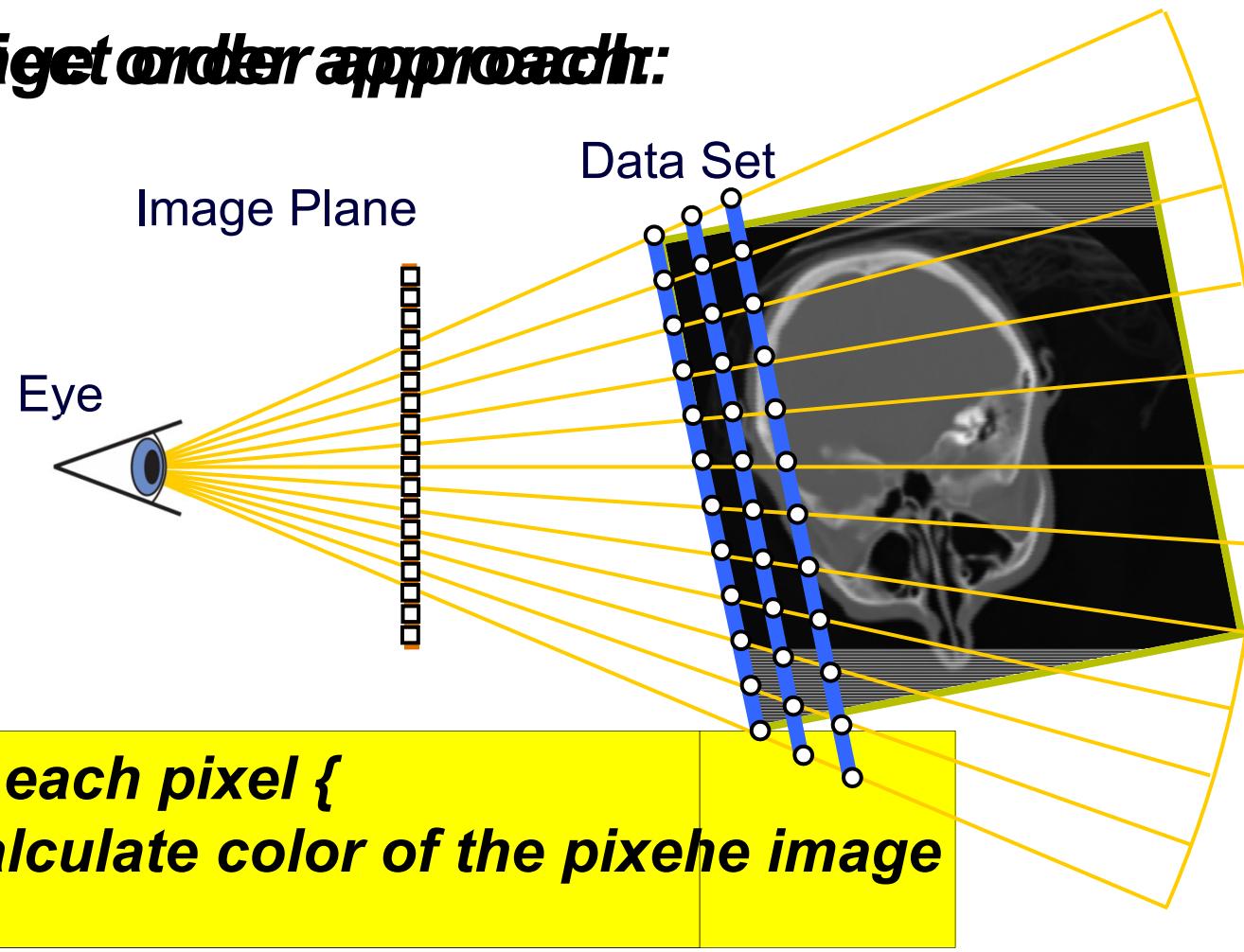
Image order approach:



Direct Volume Rendering: Object Order



Object order approach:



Basic Volume Rendering Summary



Volume rendering integral
for *Emission Absorption* model

The diagram illustrates the volume rendering integral. A black sphere representing a volume element is at position s_0 . Two arrows originate from it: one pointing back along the ray path, labeled $I(s)$, and another pointing forward, labeled $q(\tilde{s}) e^{-\tau(\tilde{s}, s)}$.

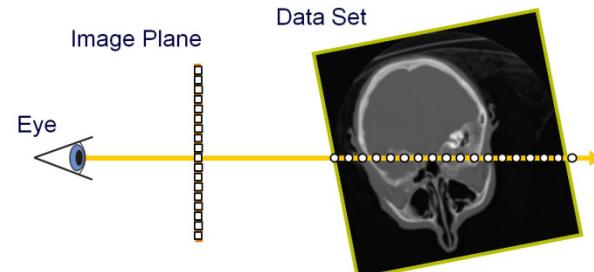
$$I(s) = I(s_0) e^{-\tau(s_0, s)} + \int_{s_0}^s q(\tilde{s}) e^{-\tau(\tilde{s}, s)} d\tilde{s}$$

Numerical solutions: ***back-to-front*** vs. ***front-to-back compositing***

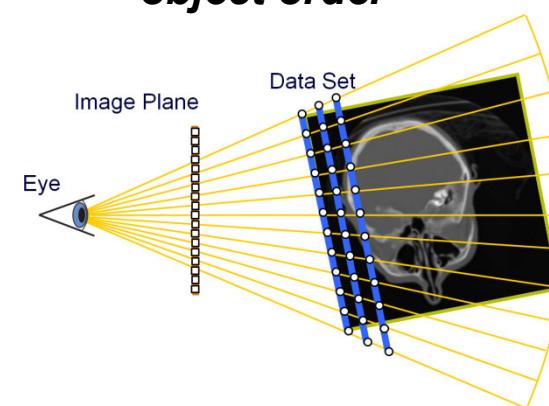
$$C'_i = C_i + (1 - A_i)C'_{i-1}$$

$$\begin{aligned} C'_i &= C'_{i+1} + (1 - A'_{i+1})C_i \\ A'_i &= A'_{i+1} + (1 - A'_{i+1})A_i \end{aligned}$$

Approaches: ***image order***



vs. ***object order***



Thank you.

Thanks for material

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