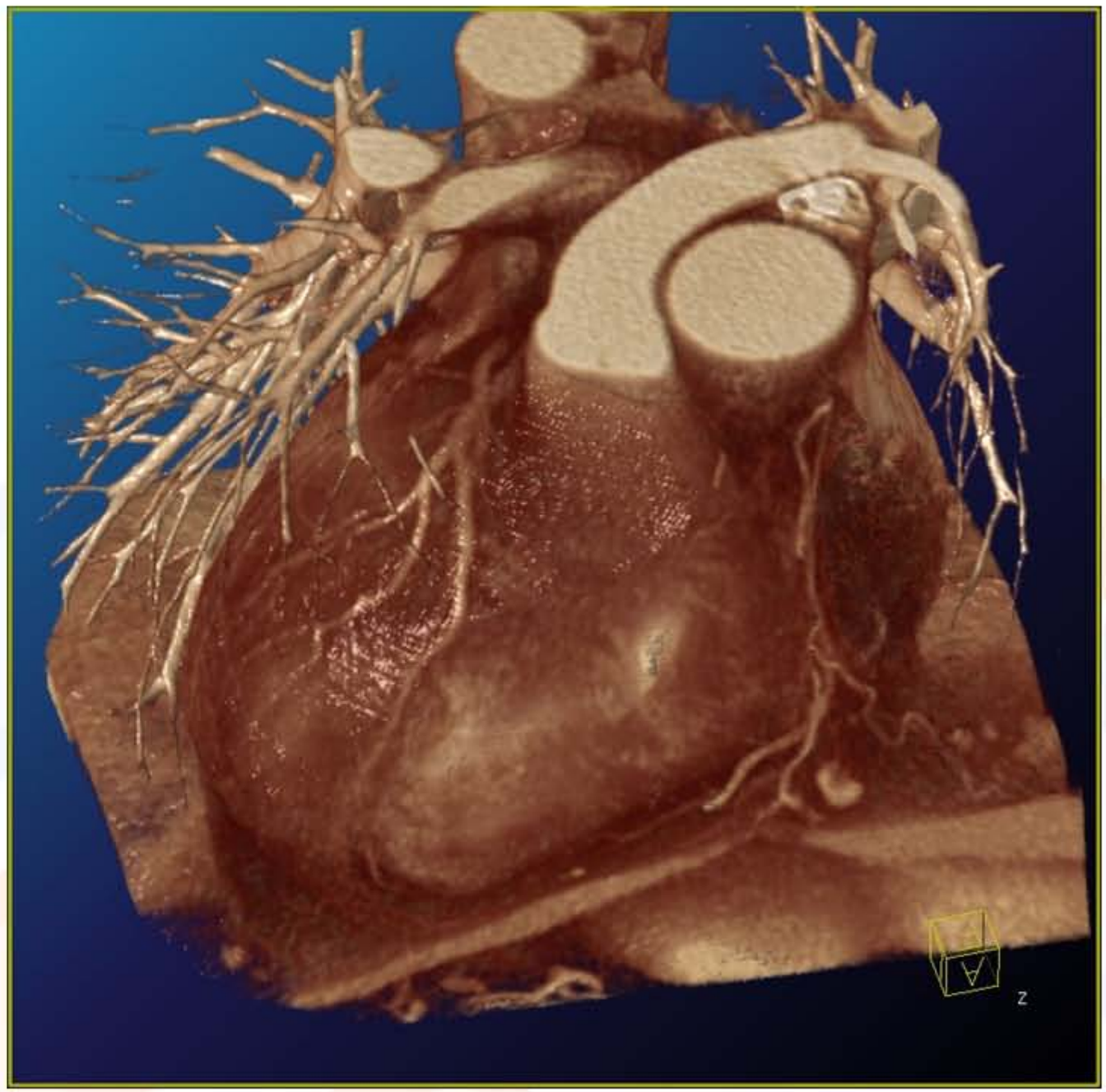
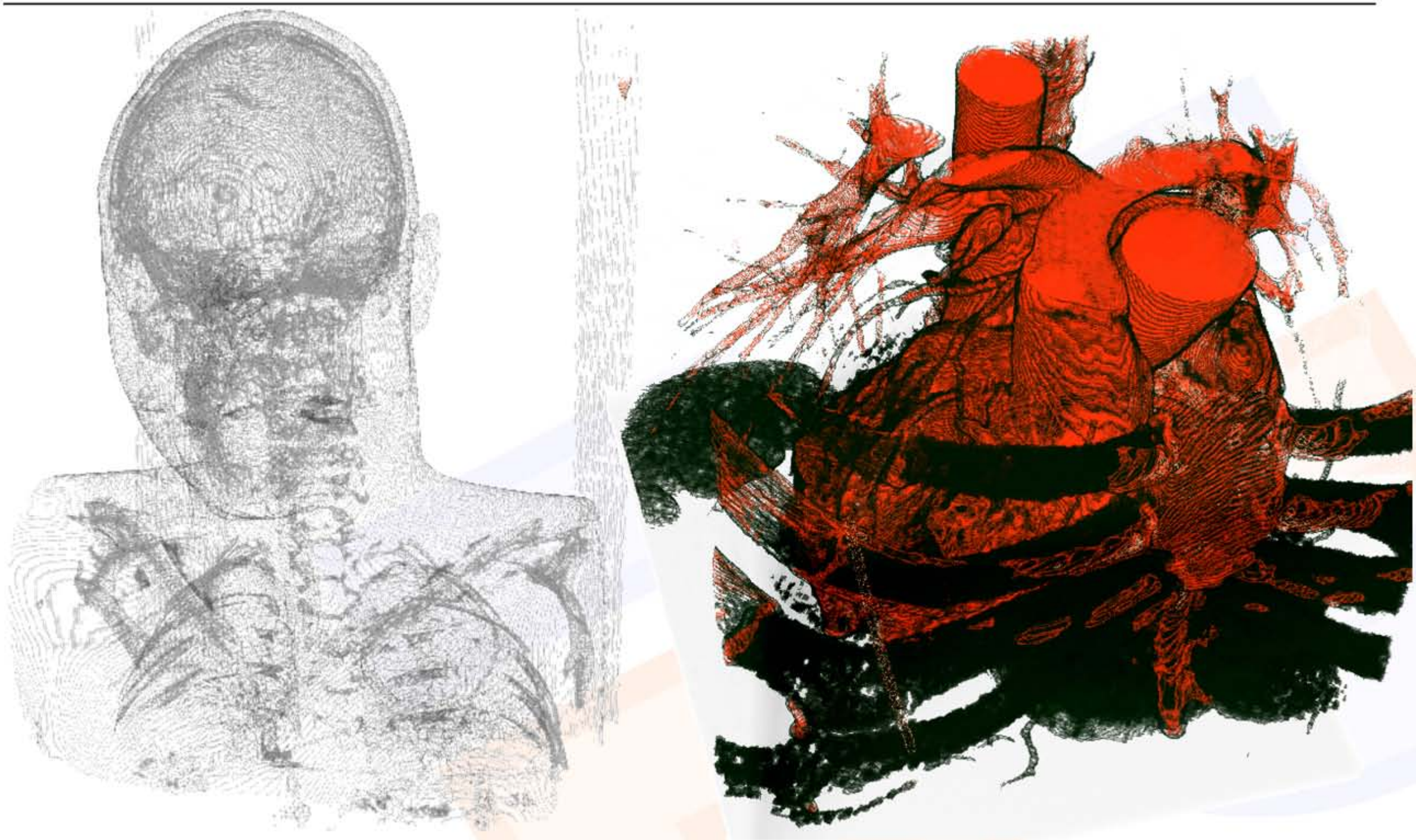
Real-Time Volume Graphics

[09] Improving Quality

This is what we want ...



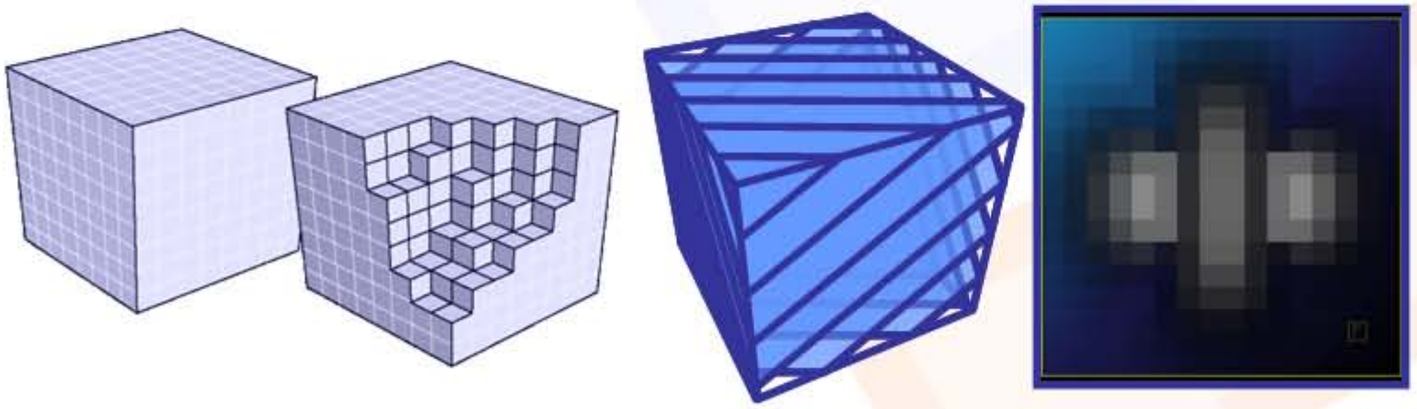
But sometimes this is what we get ...



Volume Rendering Artifacts

- Volume Rendering Pipeline
  - Where are errors introduced ?

Sampling



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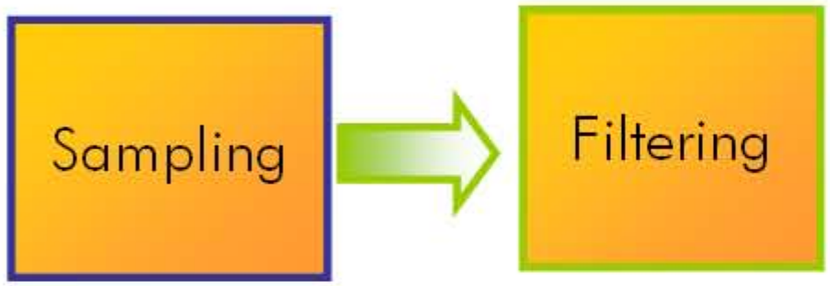

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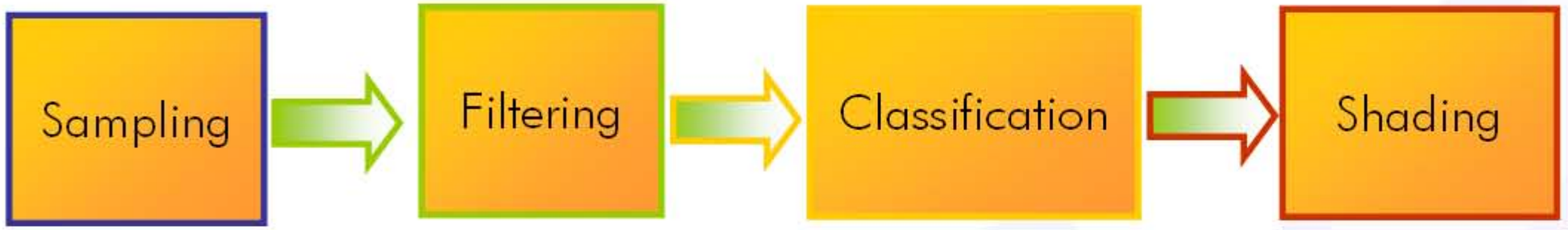

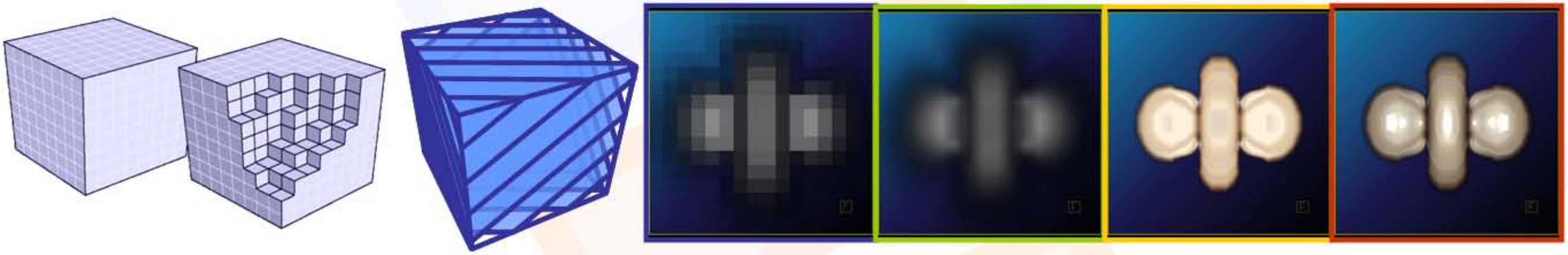

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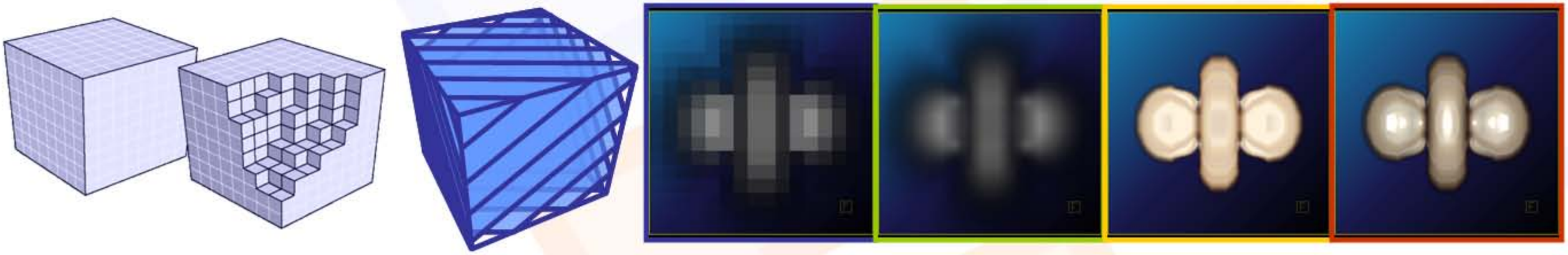

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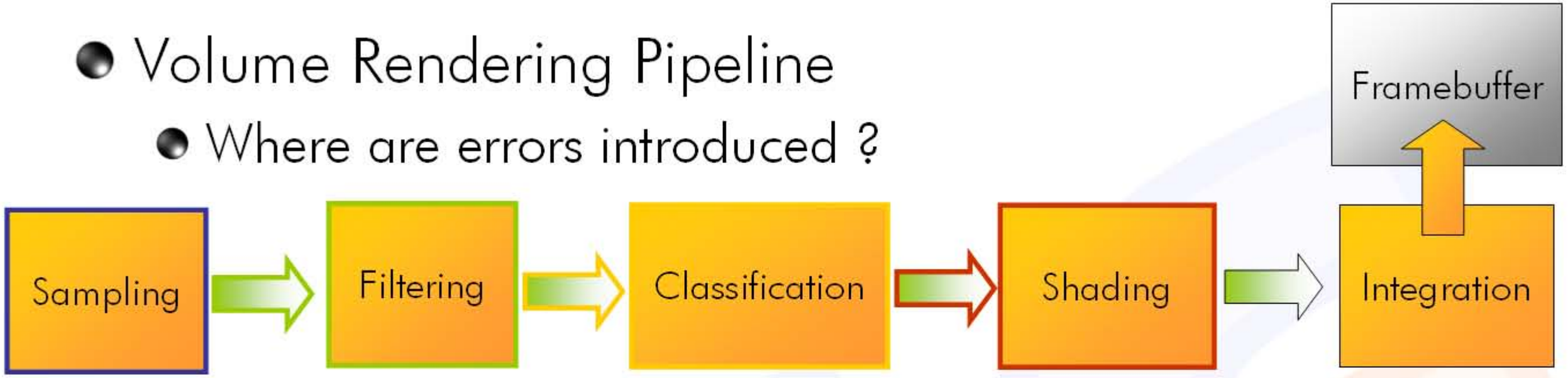
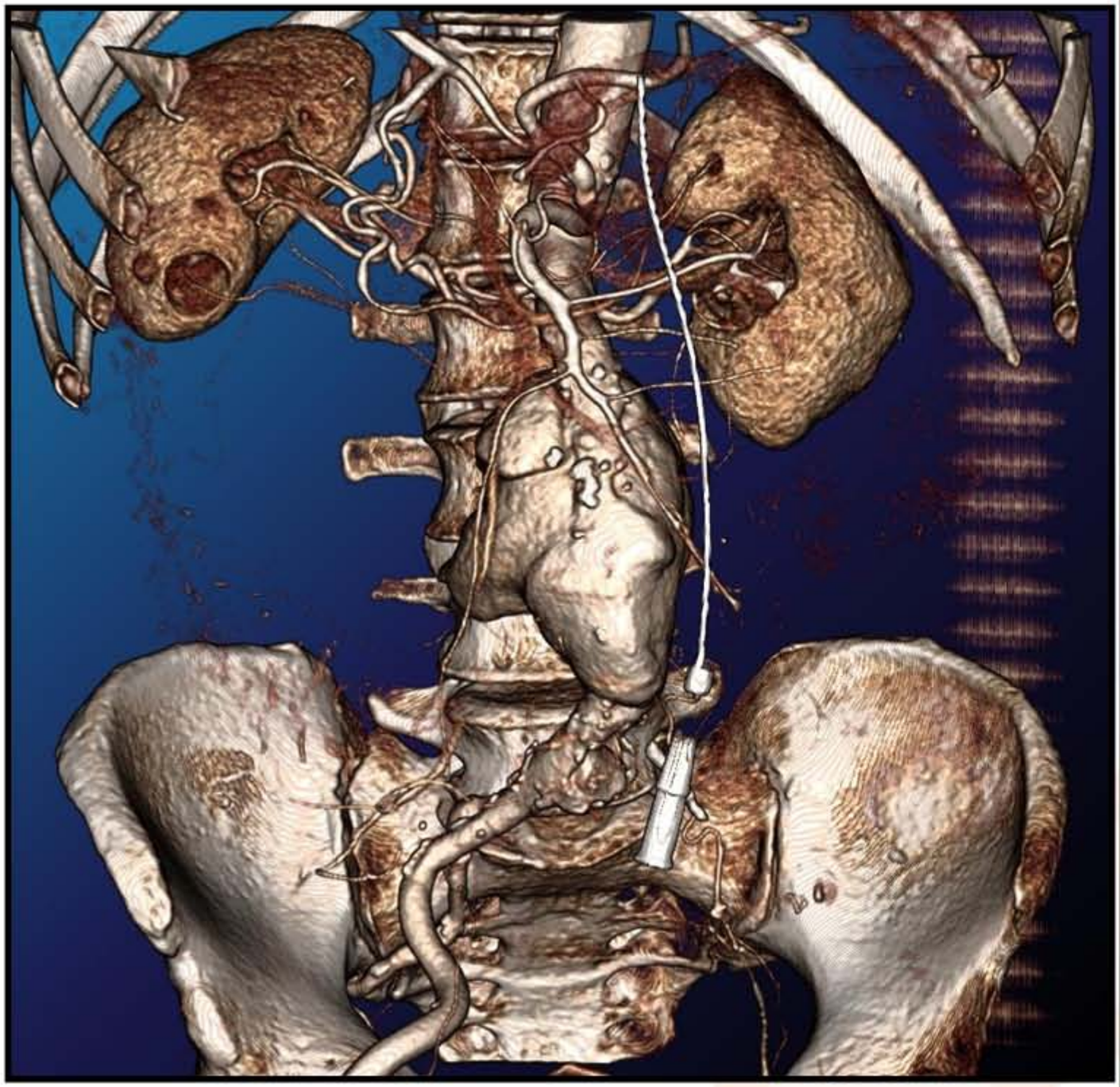
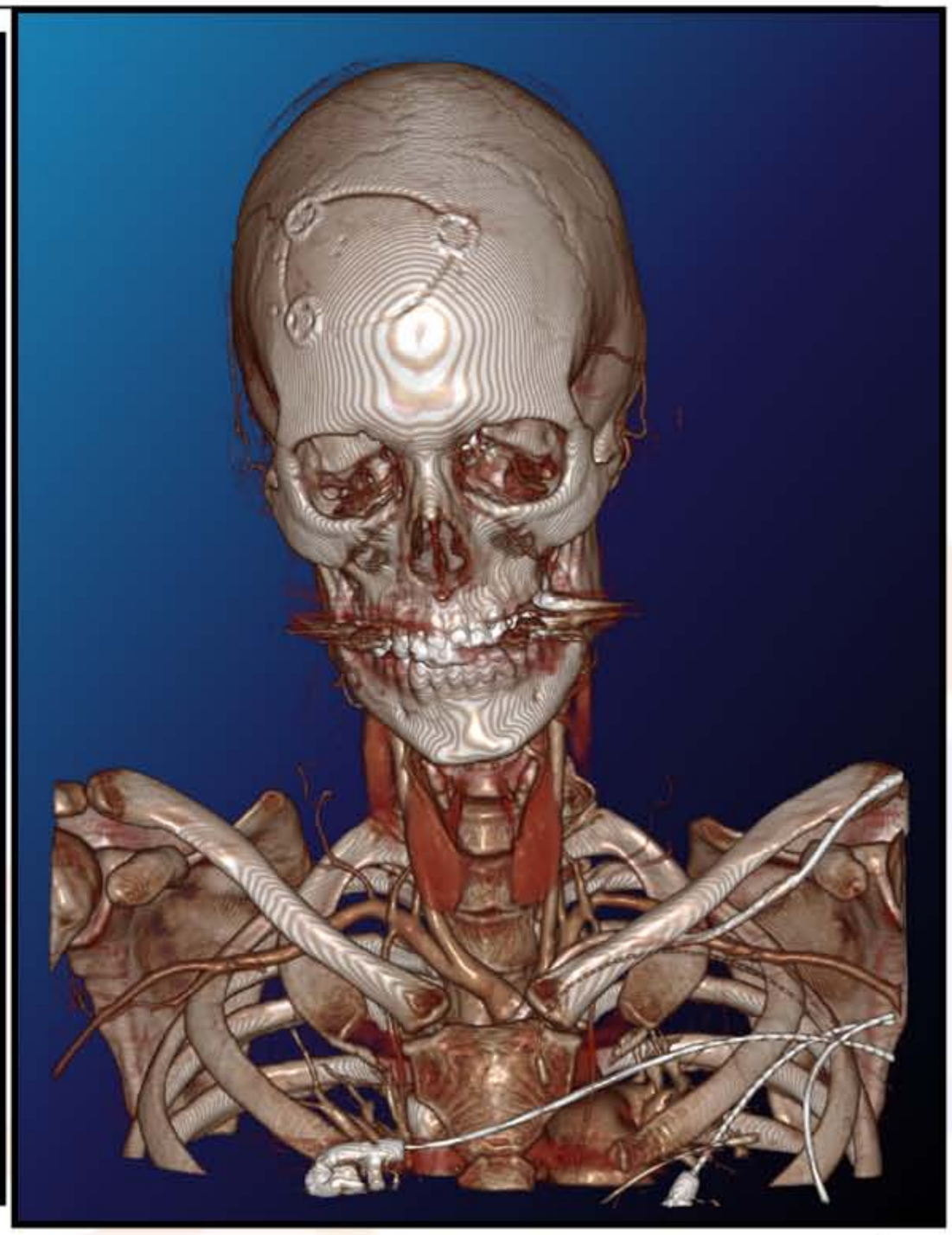


Sampling Artifacts





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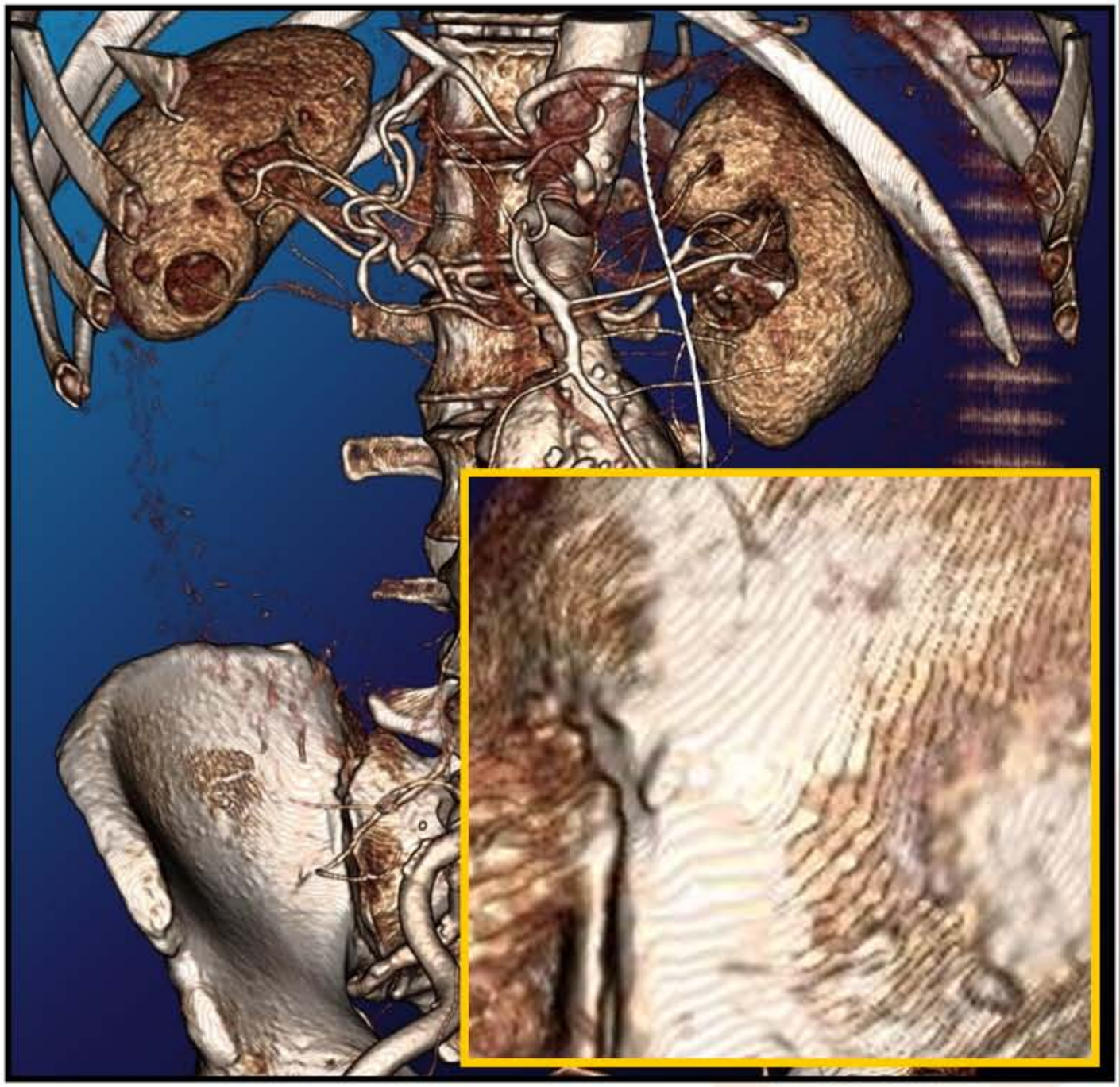
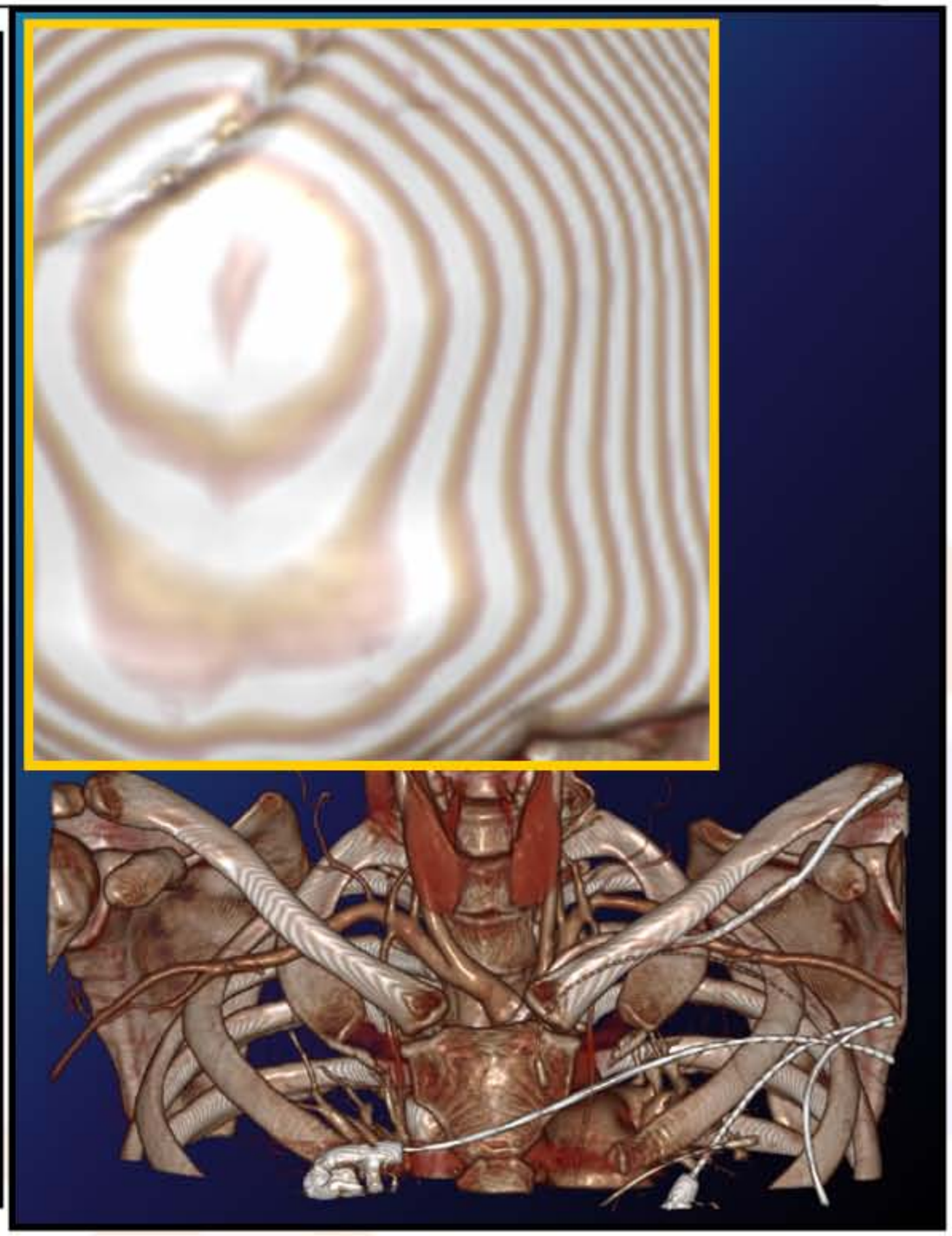
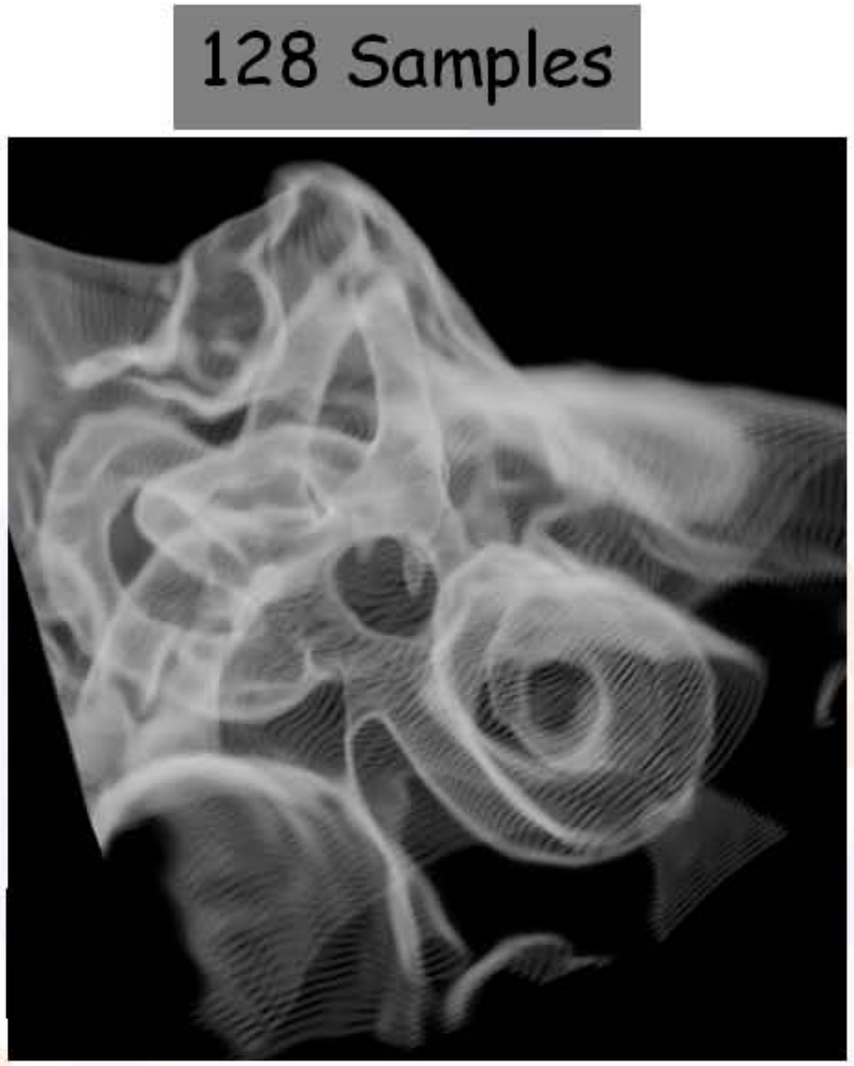




Sampling Artifacts

- Reason:
  - Low sampling rate

- Solutions:
  - Increase sampling rate to Nyquist frequency
    => at least 2 samples per voxel



- Adaptive Sampling
  - Higher sampling rate where data contains high frequencies

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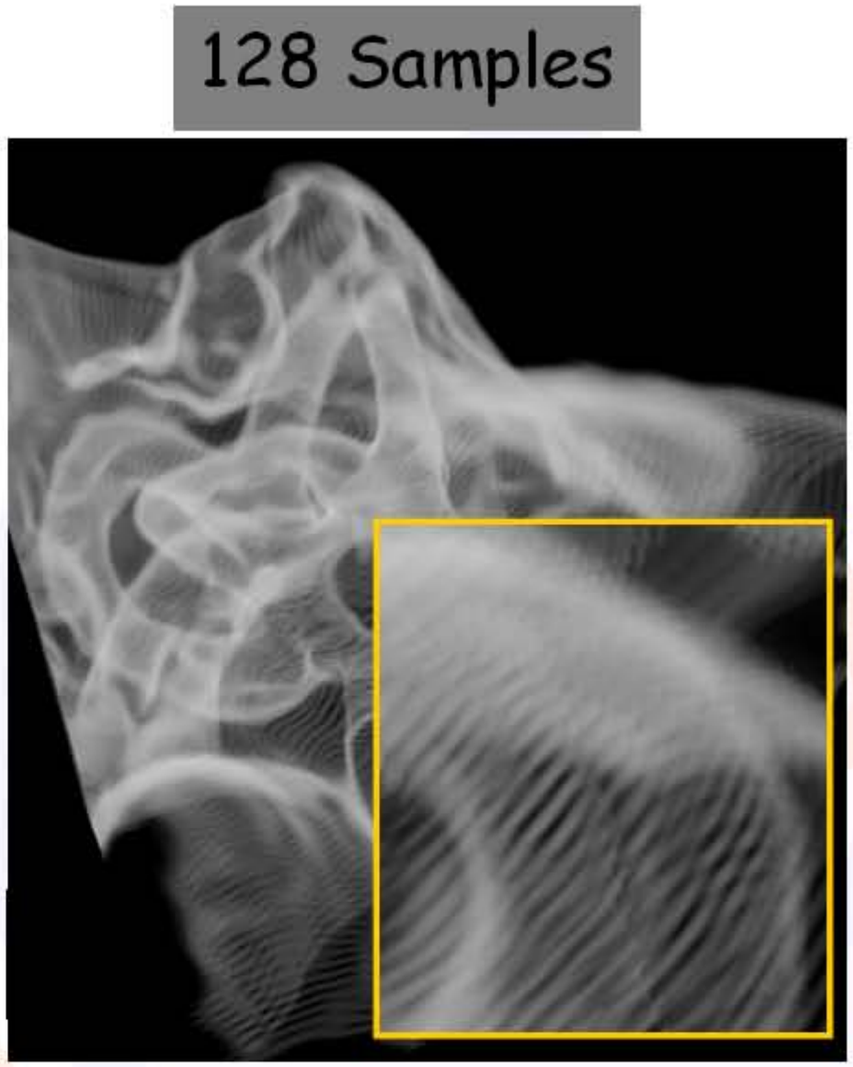

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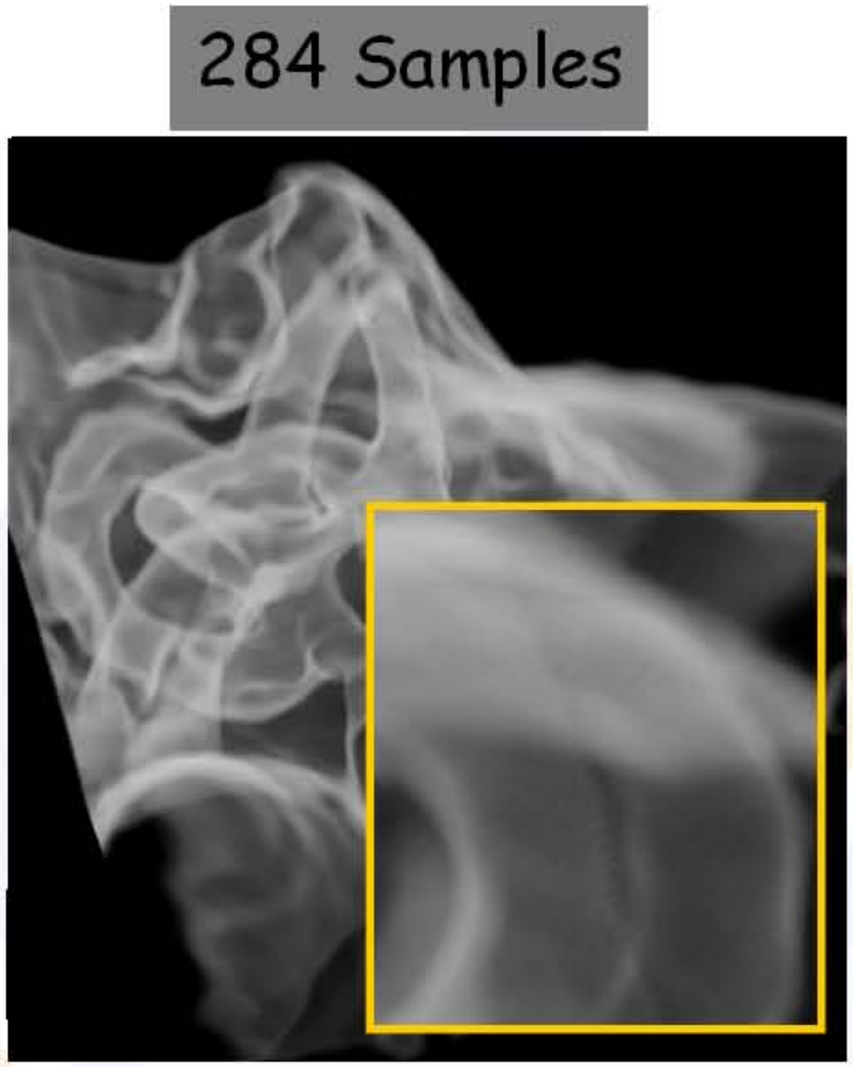
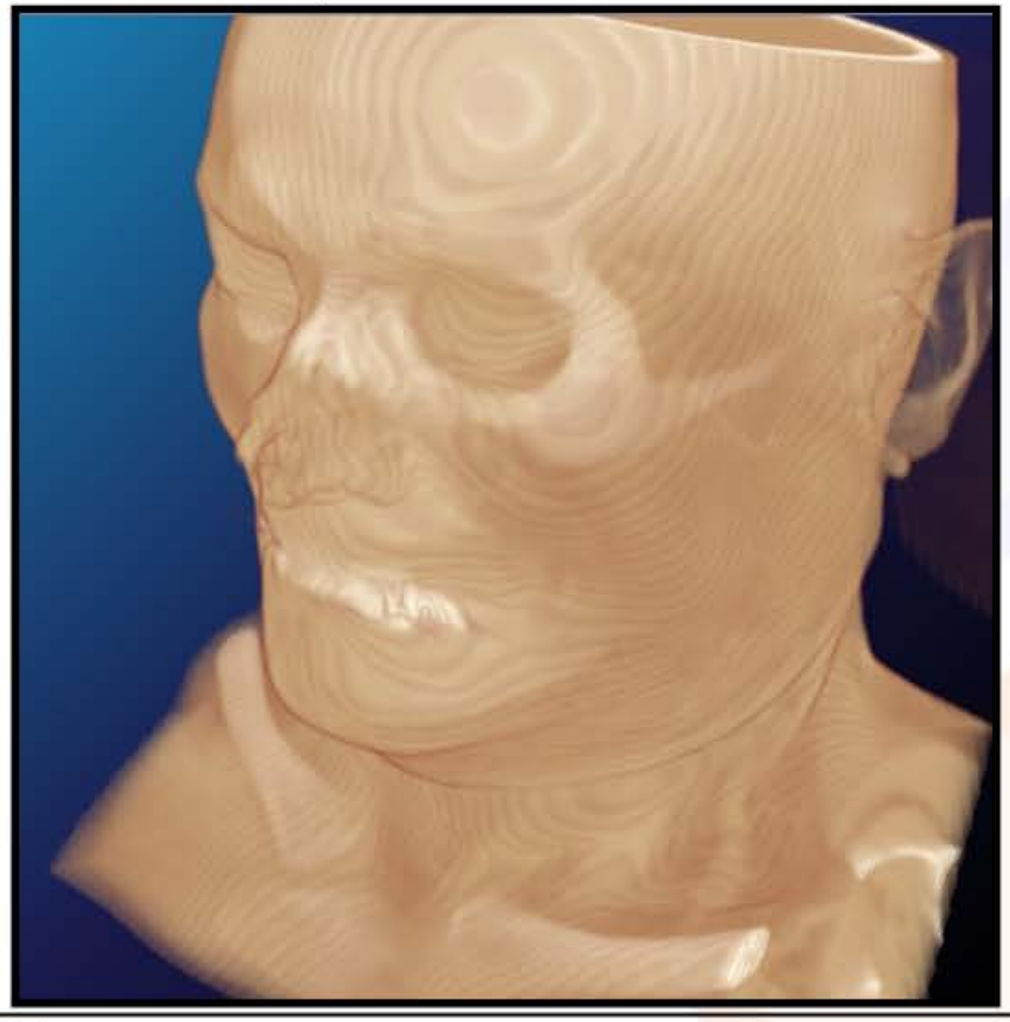


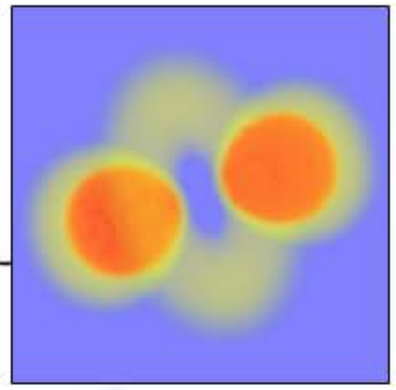
- Adaptive Sampling
  - Higher sampling rate where data contains high frequencies

Sampling Artifacts

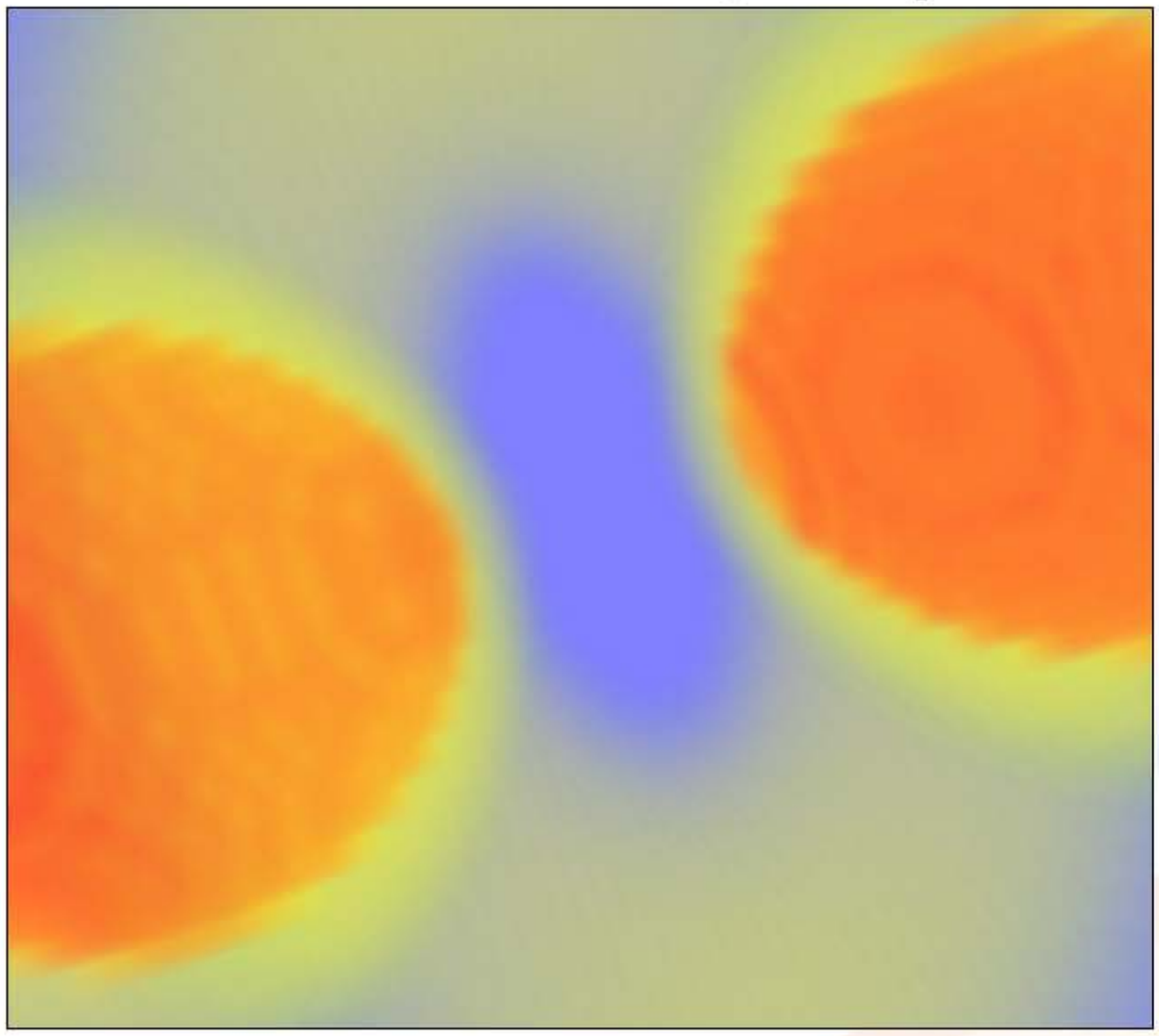
- Remove woodgrain artifact by stochastic jittering of ray-start position
  - Look-up noise texture to offset ray-position in view direction



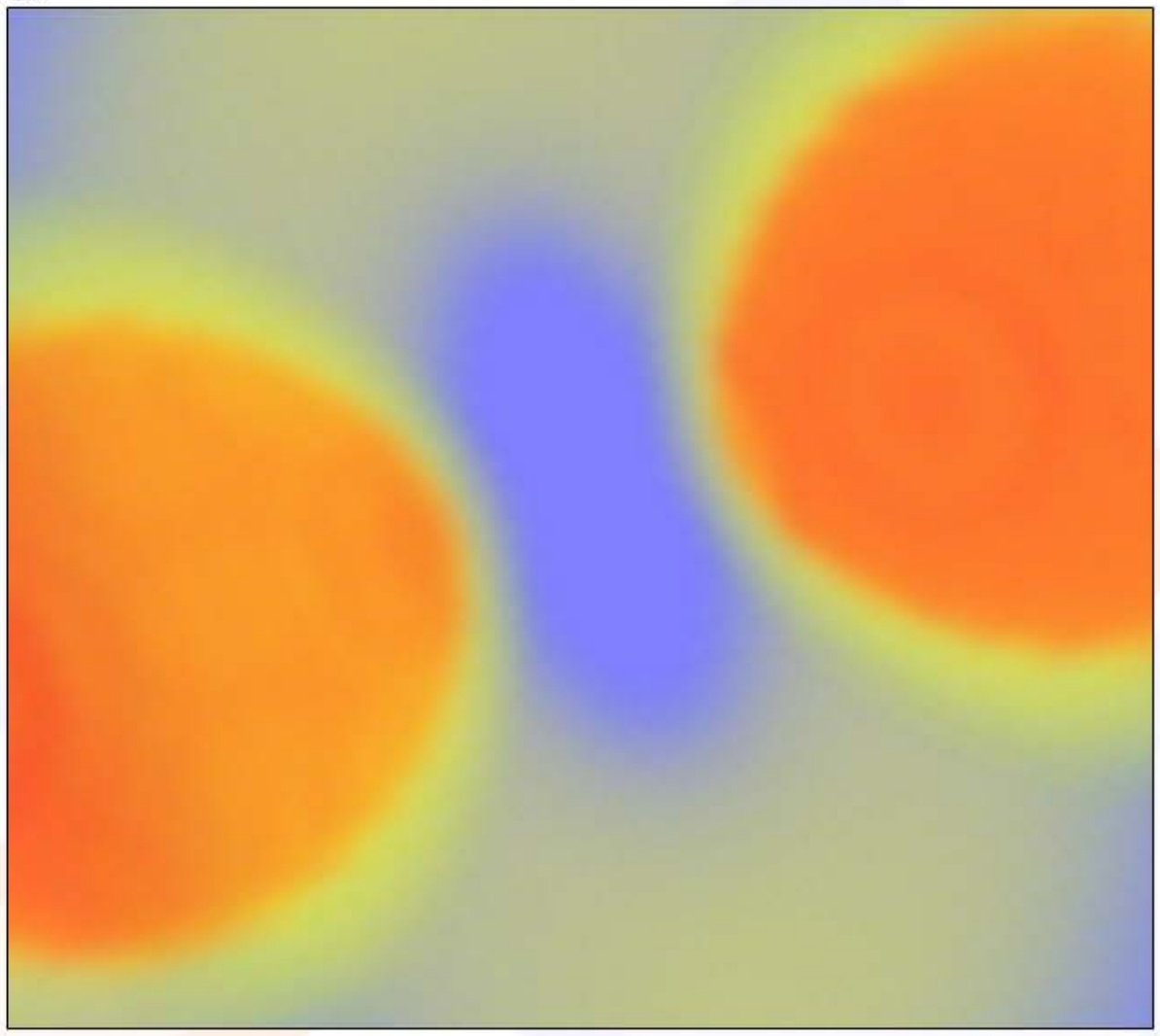
Filtering Artifacts



- 64^3 volume, object-aligned slices



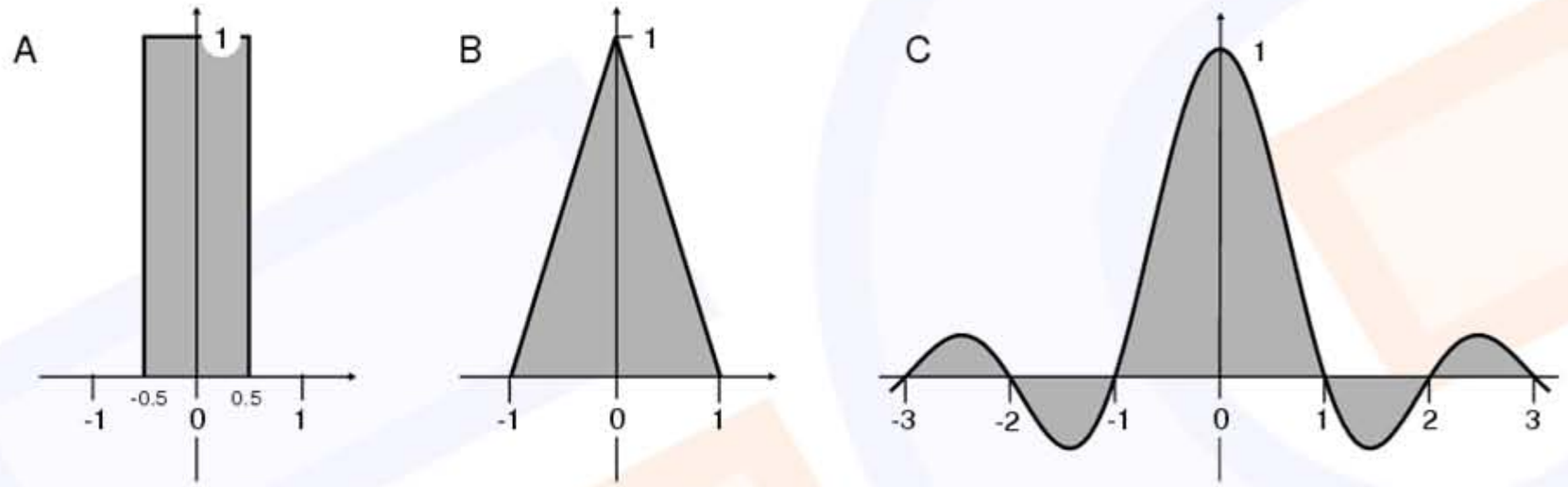
bi-linear filter



bi-cubic filter

Filtering Artifacts

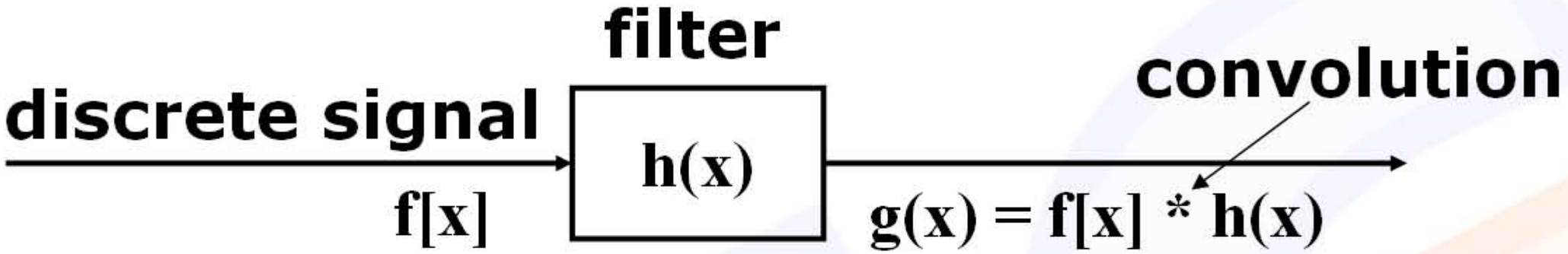
- Reason:
  - Internal filtering precision dependent on input texture format
  - Linear filters do not approximate the ideal reconstruction filter (sinc-Filter) very well



- Solutions:
  - Use internal format with higher precision
  - Implement a HQ filter in a fragment program

Filtering Artifacts / HQ-Filters

- Discretized version of convolution integral



$$g(x) = f[x] * h(x) = \sum_{i=\lfloor x \rfloor - m + 1}^{\lfloor x \rfloor + m} f[i]h(x - i)$$

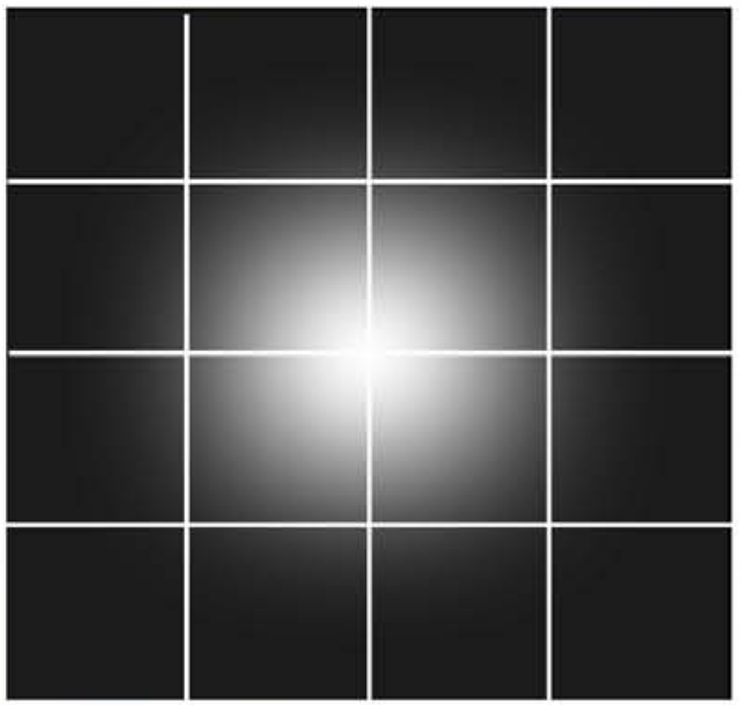
Filter width: $2m$

Filtering Artifacts / HQ-Filters

- Procedural evaluation of kernel and convolution
- Texture-based kernel and convolution

```
FetchInputSamples();
ComputeWeights_X();
for (i=0; i<3; i++)
  Convolution_X();
ComputeWeights_Y();
Convolution_Y();
```

see for example NVIDIA's
BicubicTexMagnification demo



pre-sampled B-spline kernel
from [Hadwiger et al. 2001]

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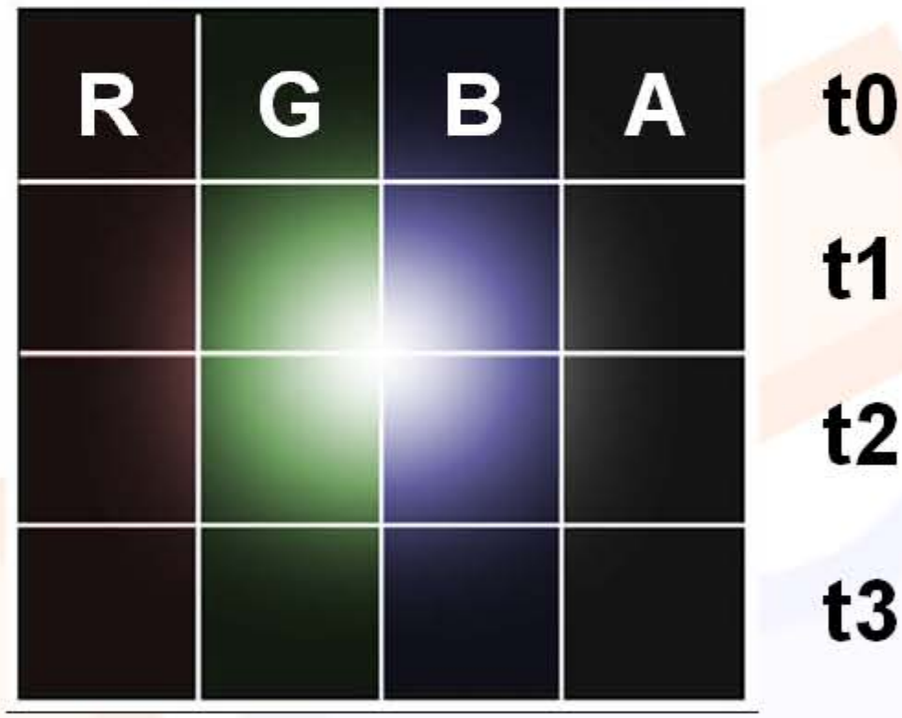

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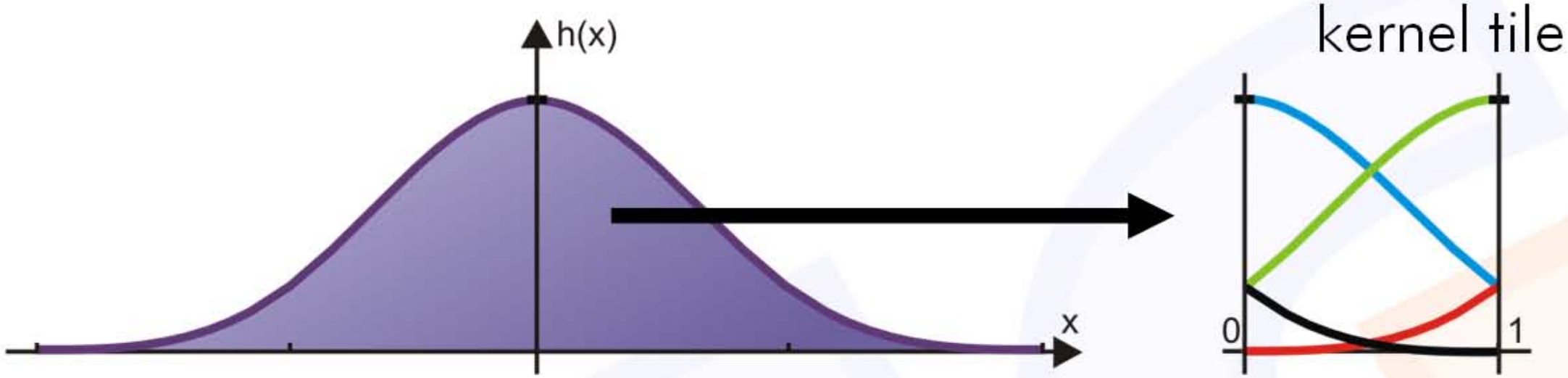
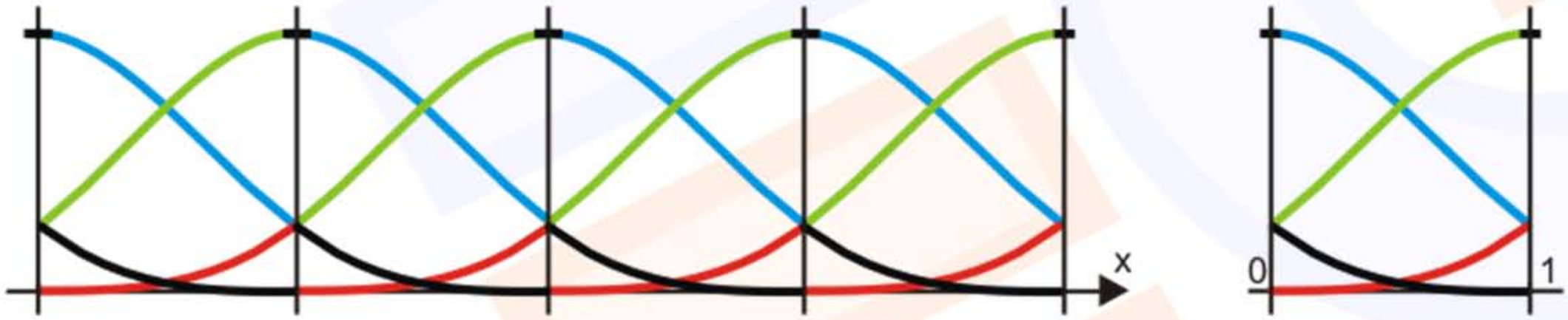
Filtering Artifacts / HQ-Filters

- Transform original kernel into look-up texture

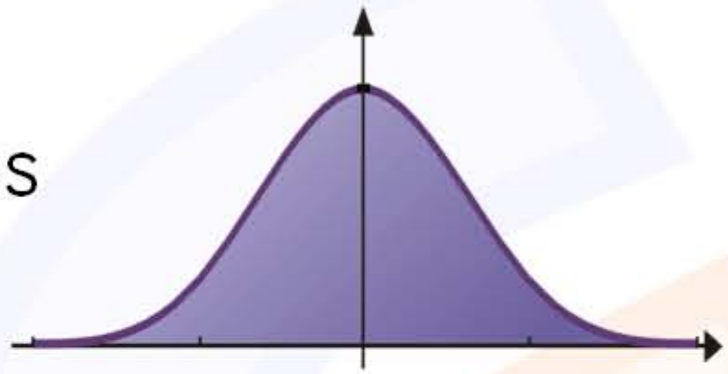


- Replicate kernel tile over output grid



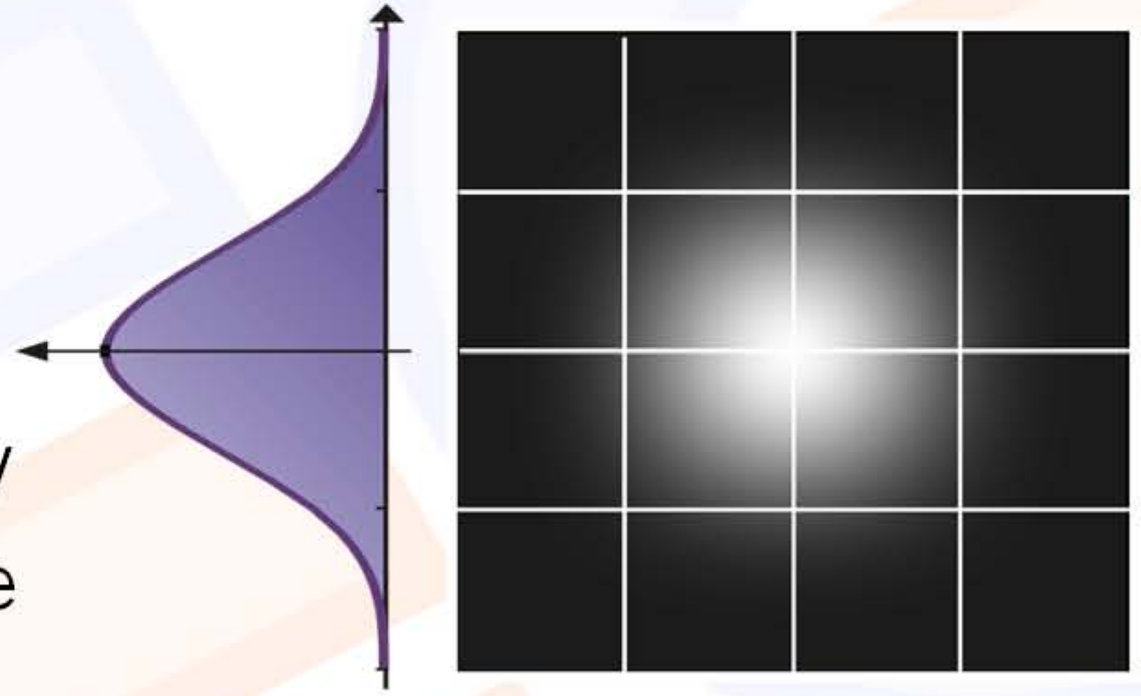
Filtering Artifacts / HQ-Filters

- Easy when kernel separable



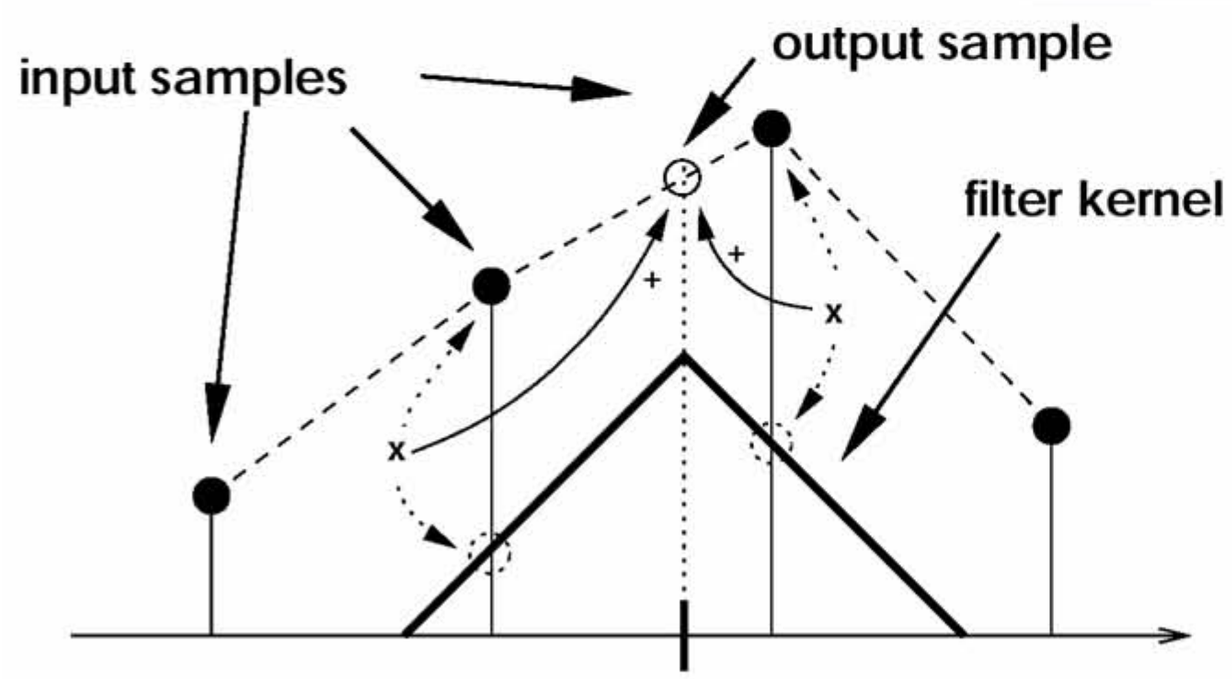
- Use same 1D kernel tile for all axes
- Sample two (or three) times and multiply weights

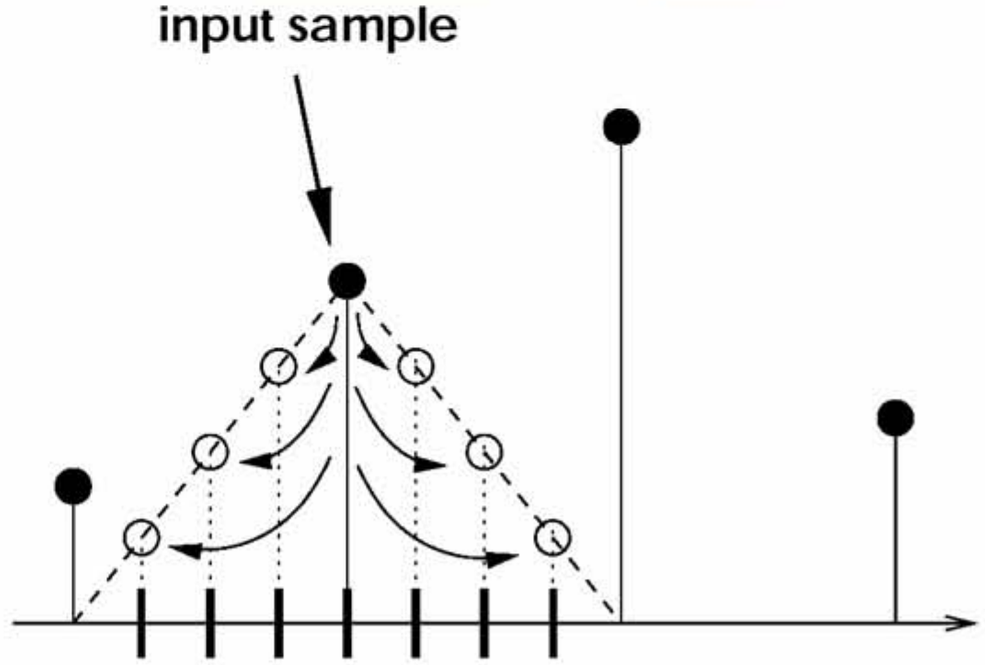
- Separable bi-cubic and tri-cubic filters need only one 1D RGBA kernel tile



Filtering Artifacts / HQ-Filters

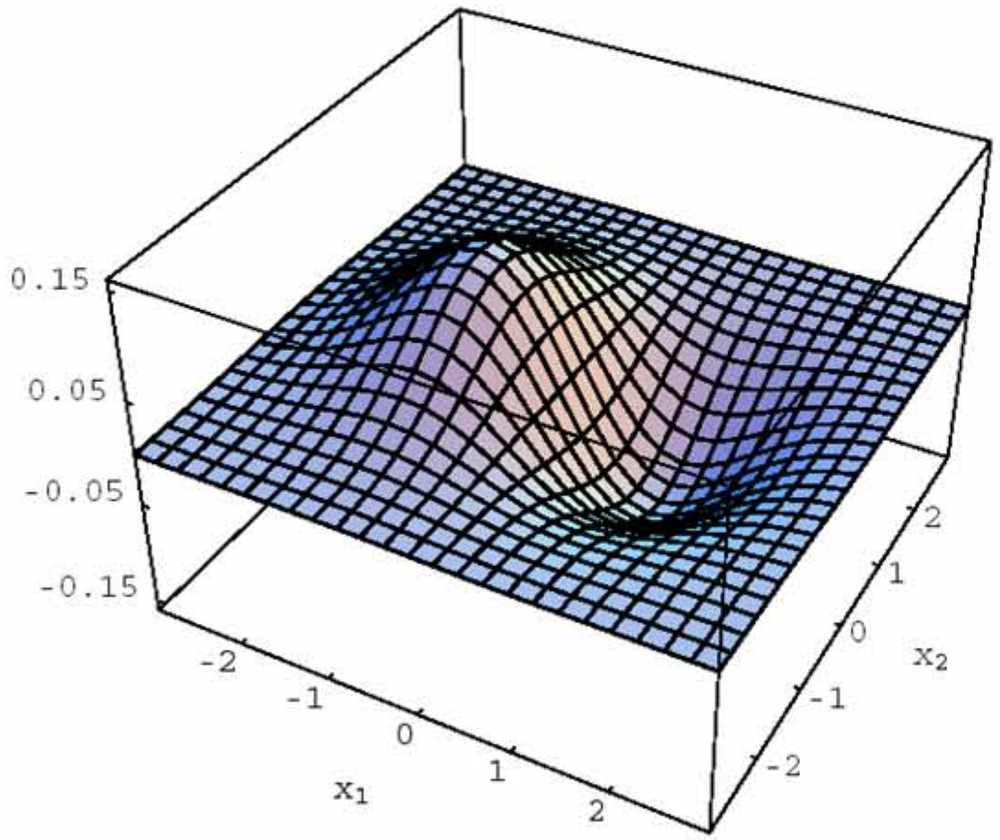
- Distribution instead of gathering
- Works for all filter shapes and sizes
- Works for separable and non-separable kernels
- Multi-pass evaluation of filter convolution sum



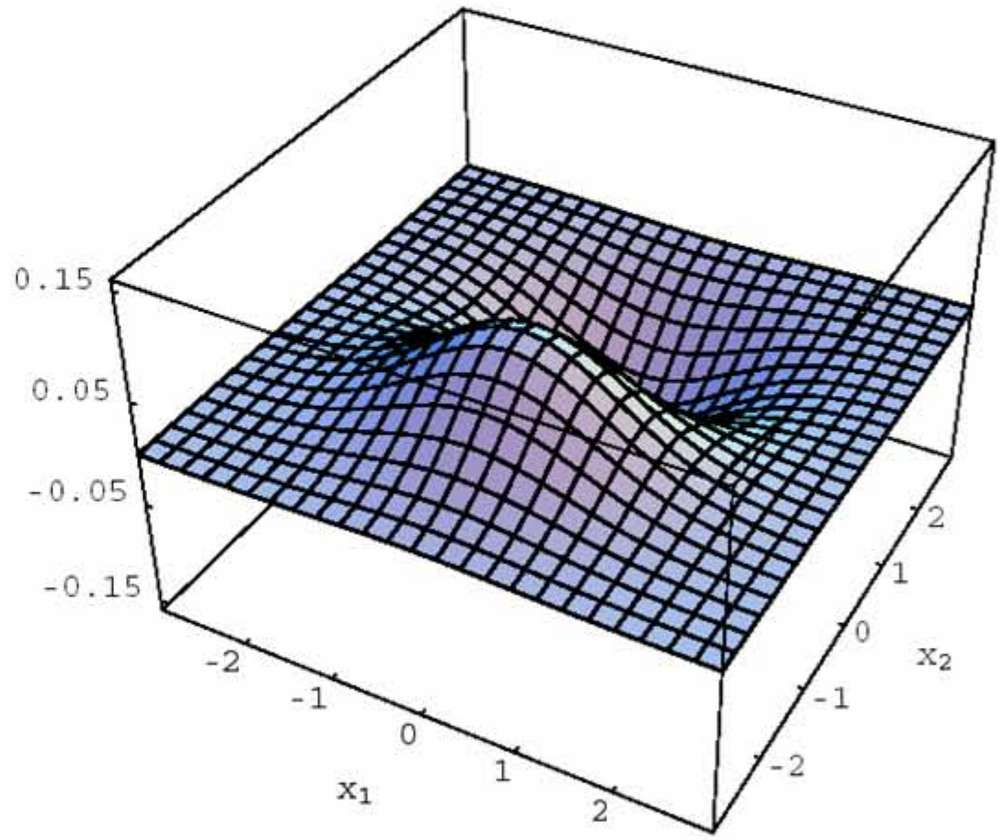


Filtering Artifacts / HQ-Filters

- Tri-cubic gradients and second derivatives for isosurfaces possible in real-time



$\partial G(x_1, x_2)/\partial x_1$

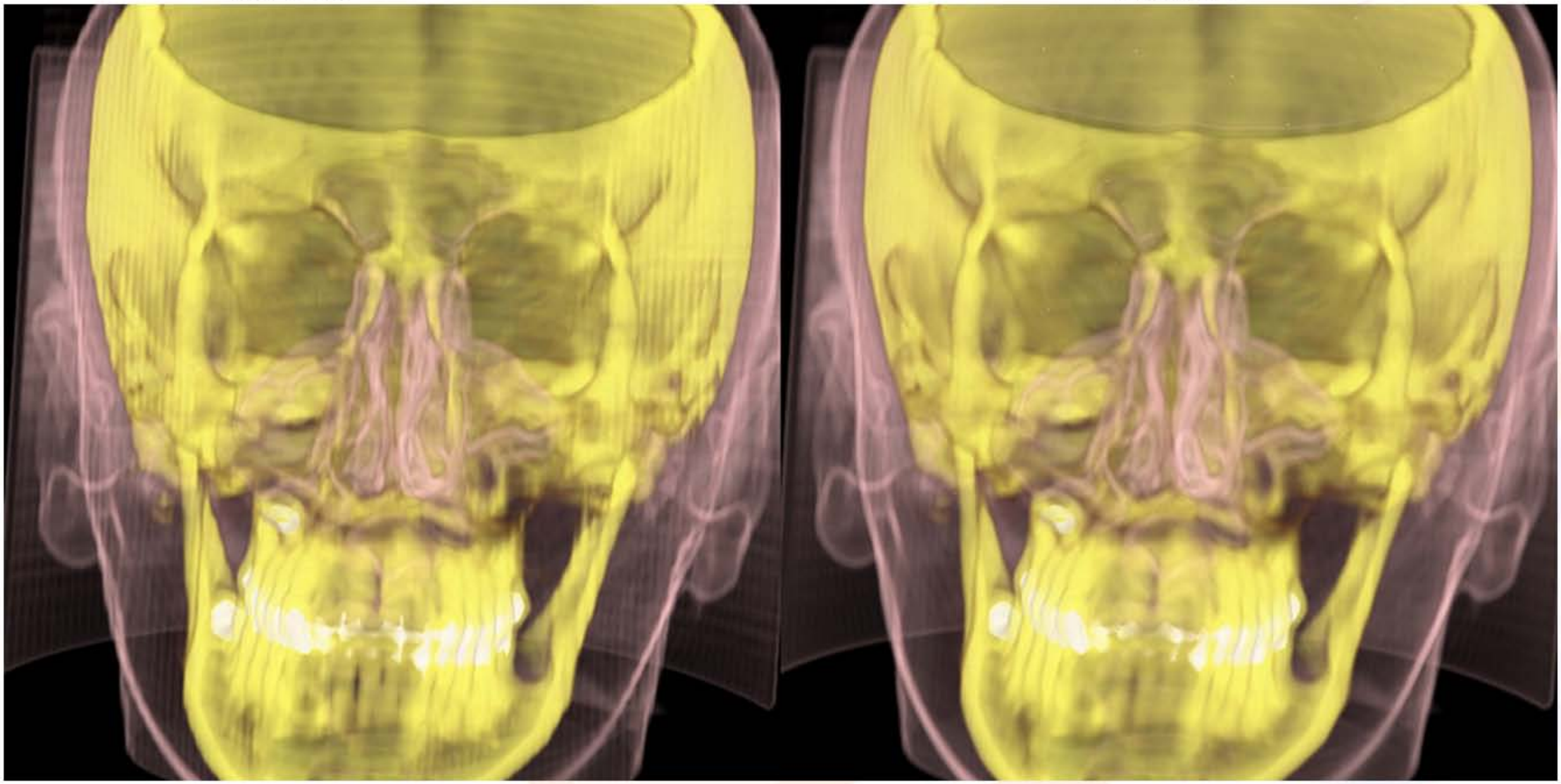


$\partial G(x_1, x_2)/\partial x_2$

Filtering Artifacts / HQ-Filters

linear

cubic



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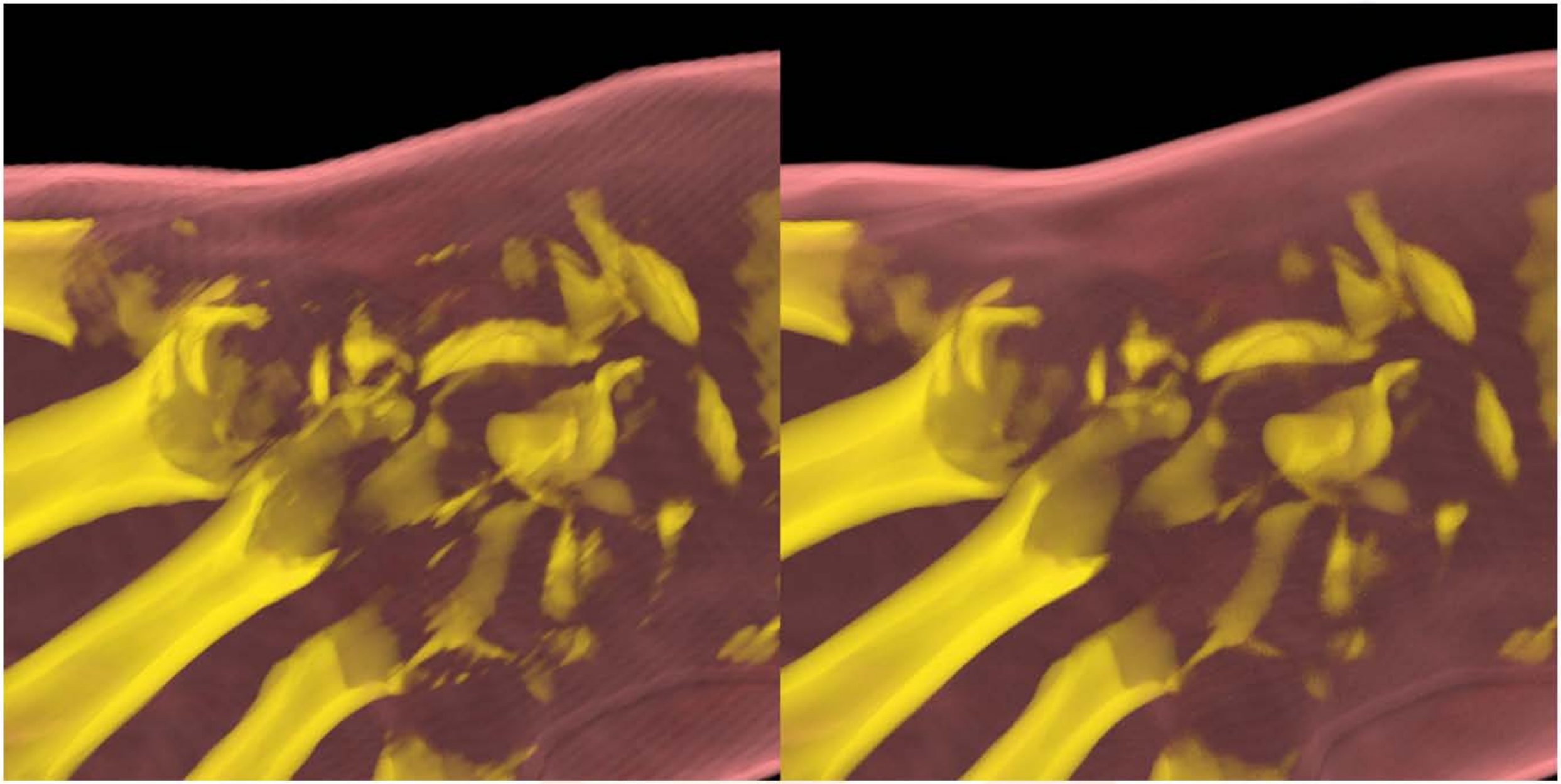
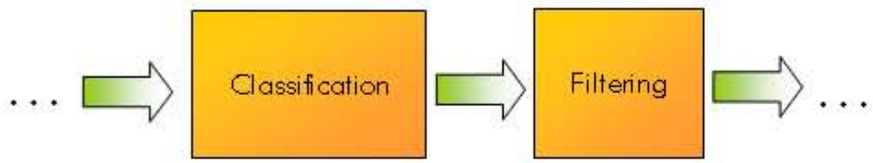
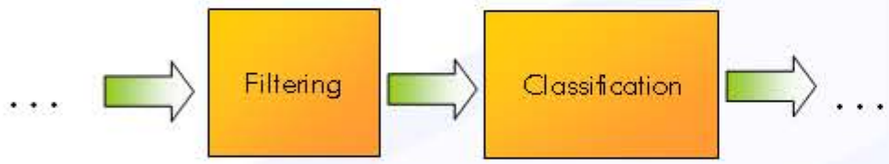


Classification Artifacts

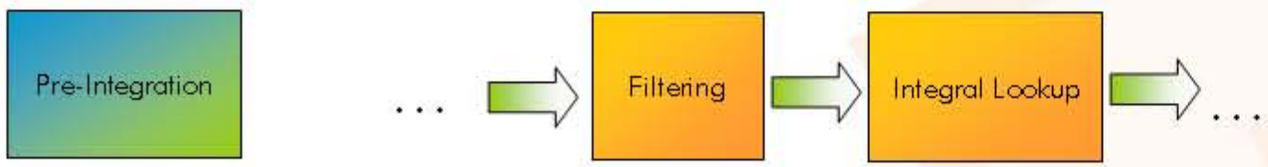
Pre-Classification

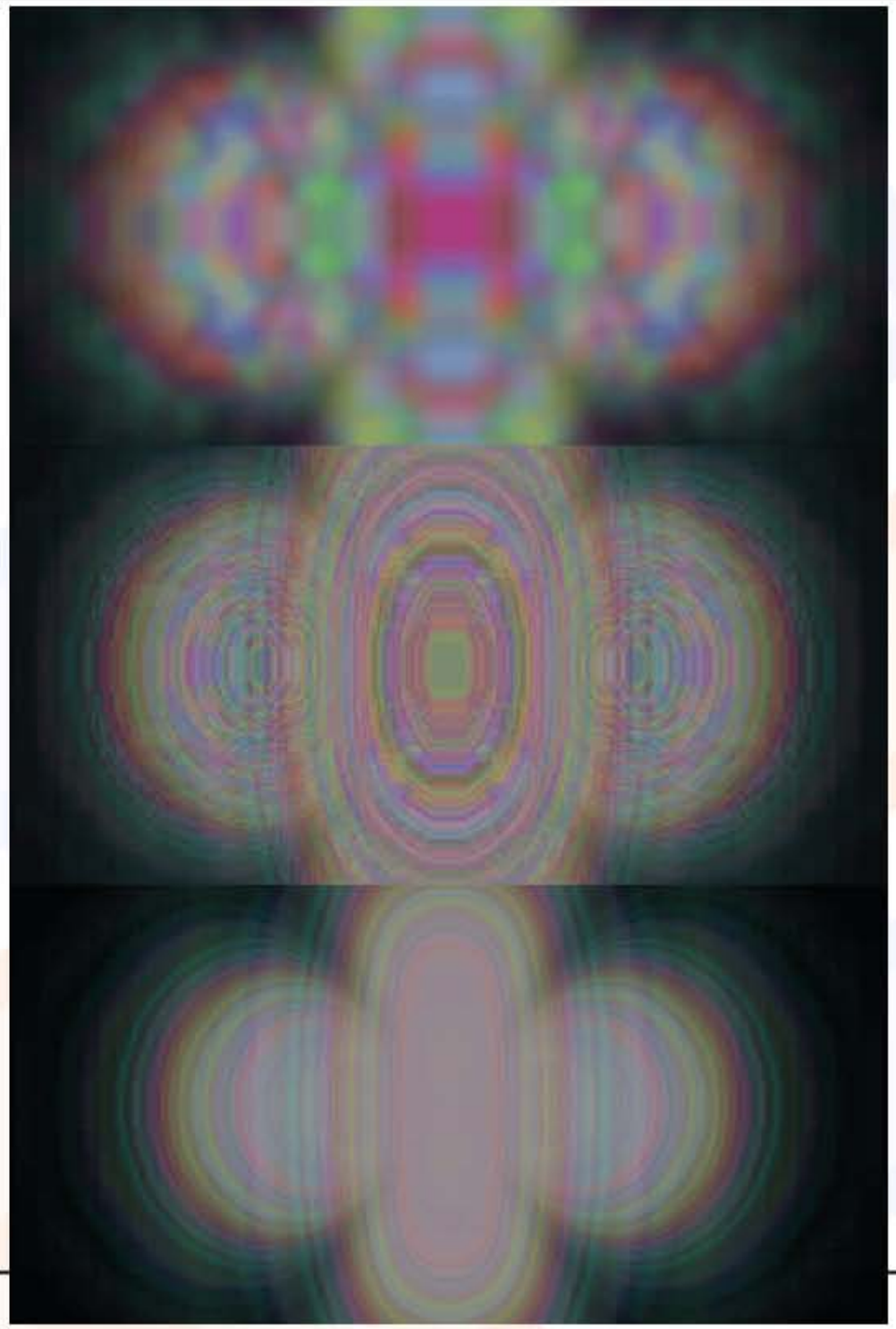


Post-Classification



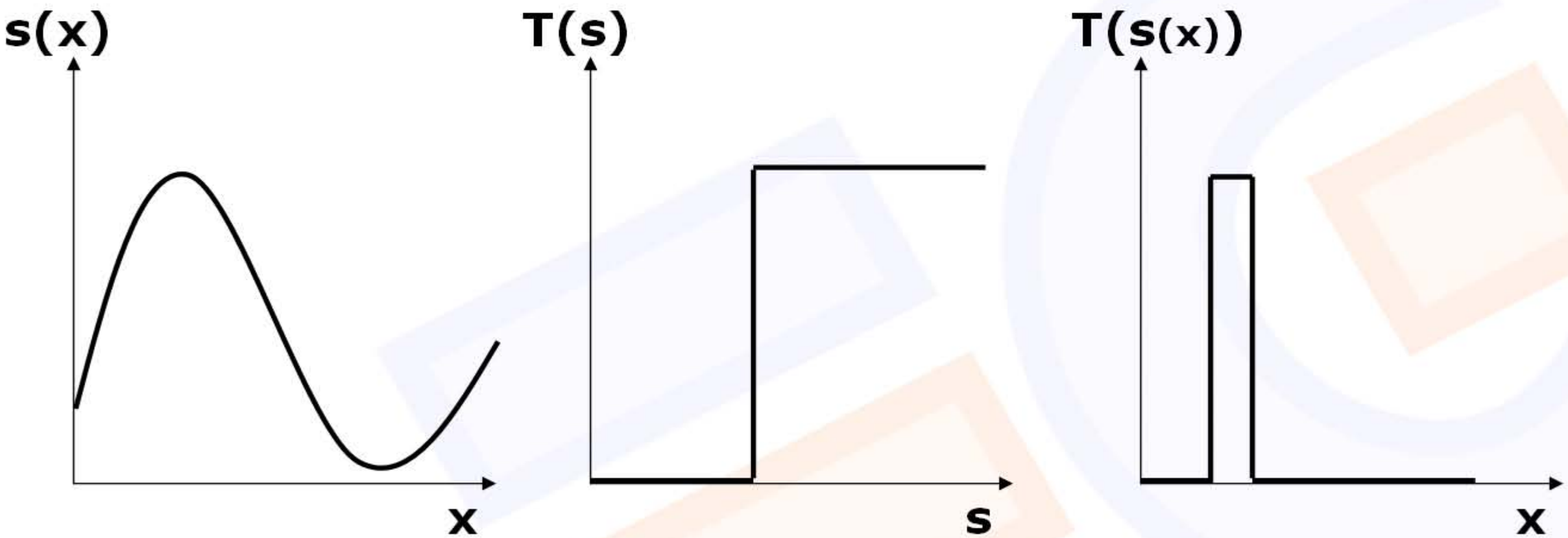
Pre-Integrated-Classification





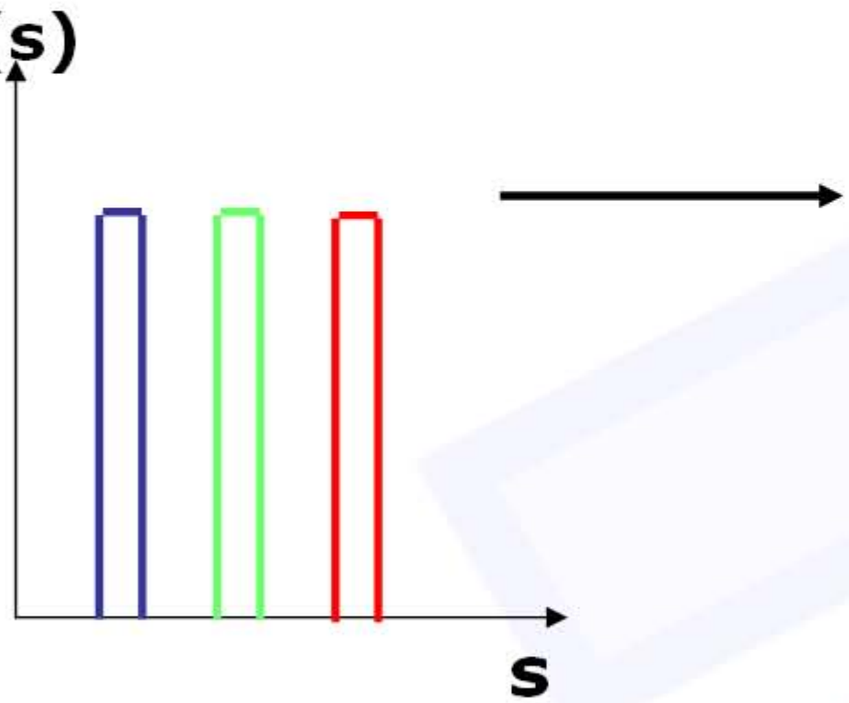
Classification Artifacts

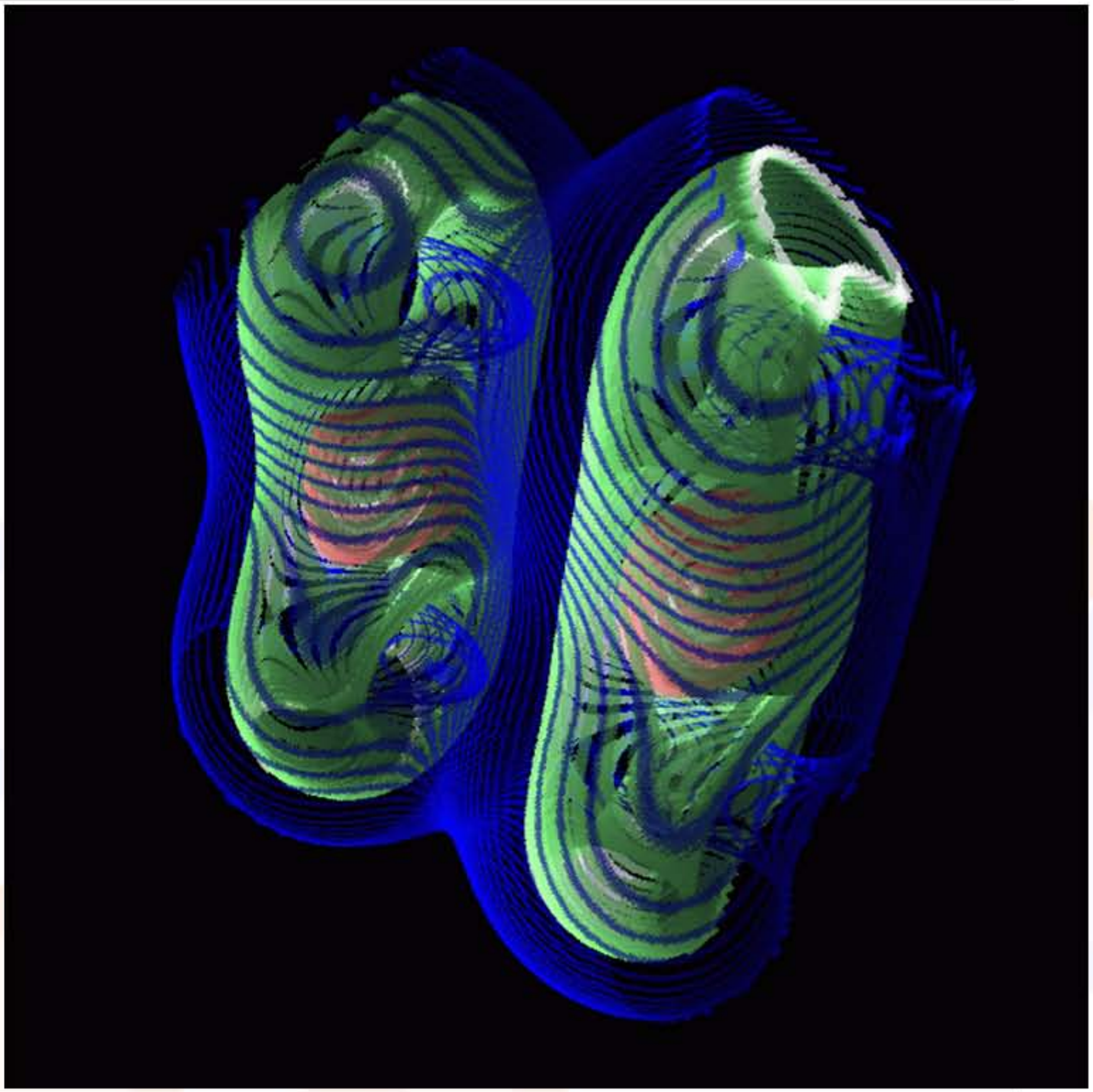
- High frequencies in the transfer function T increase required sampling rate



Classification Artifacts

multiple peaks





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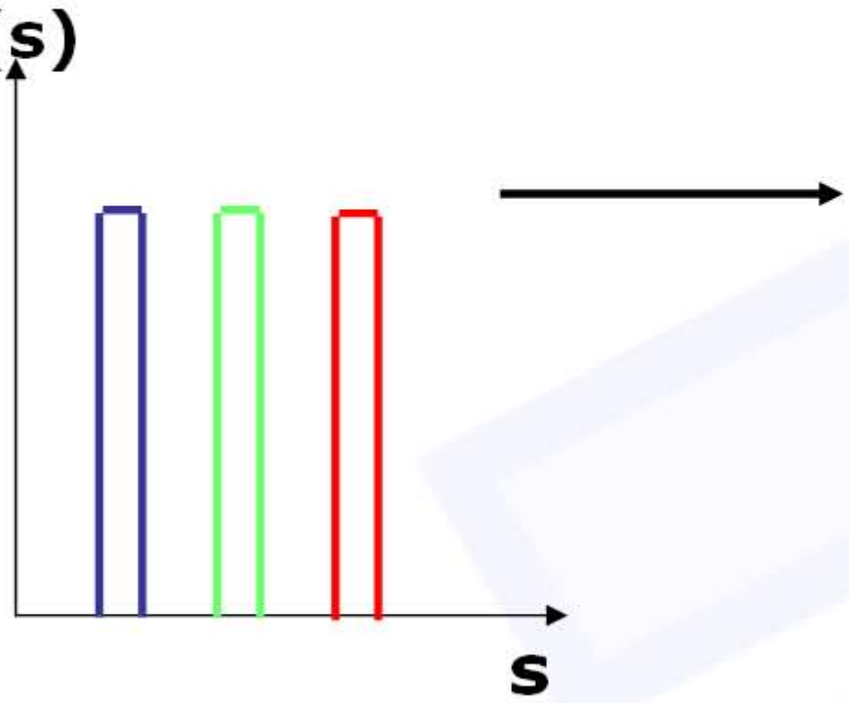

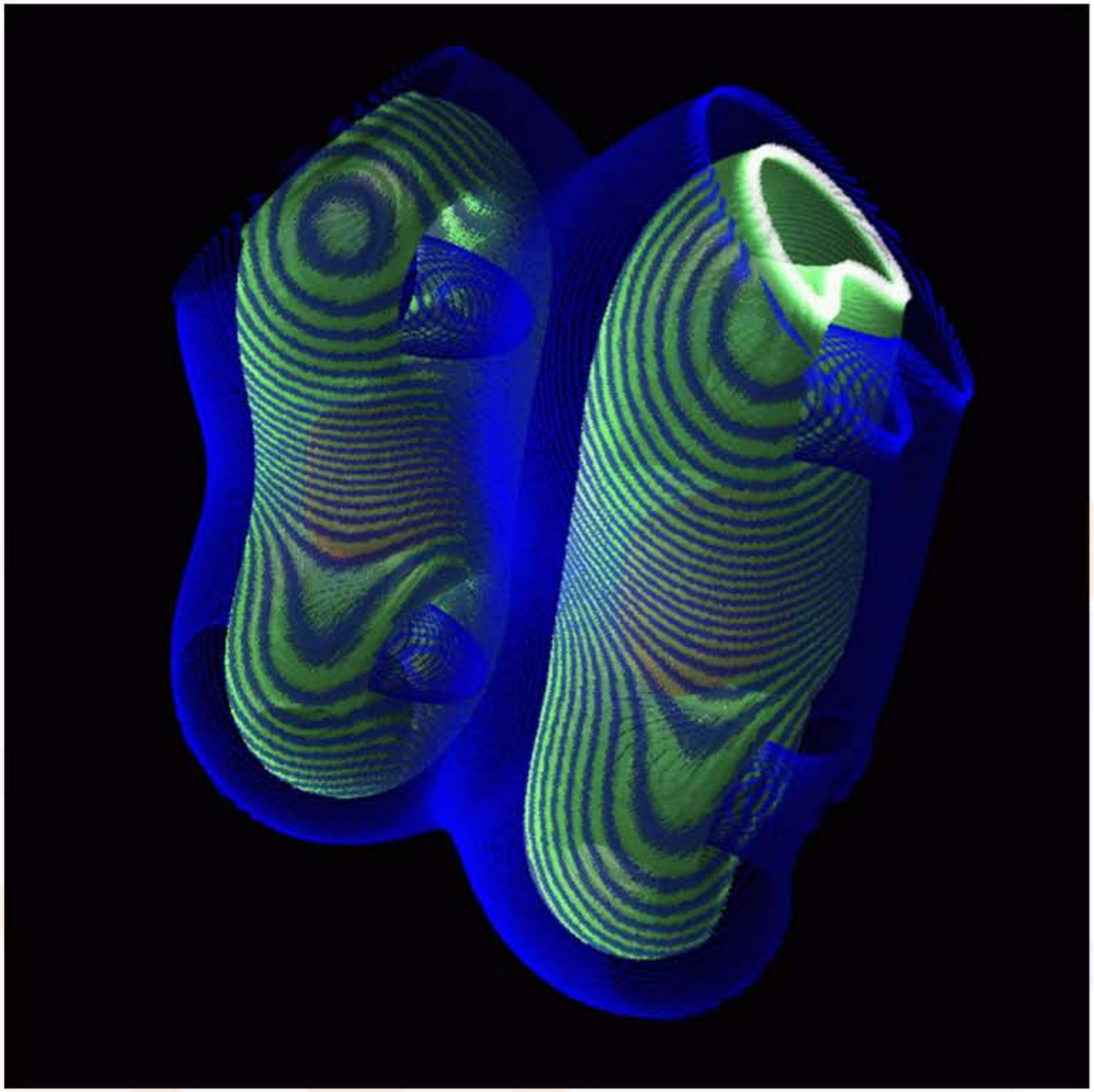

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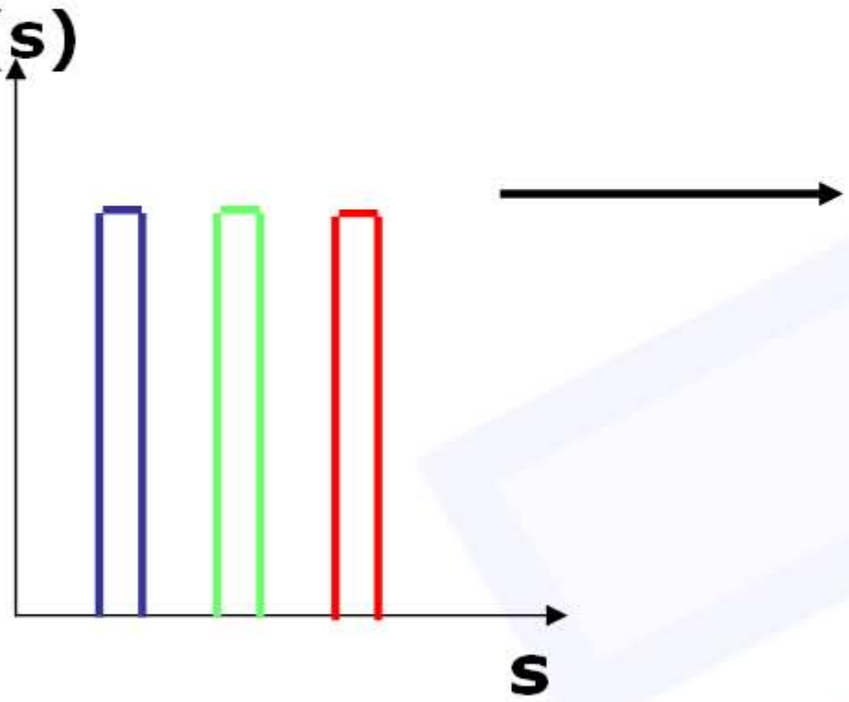

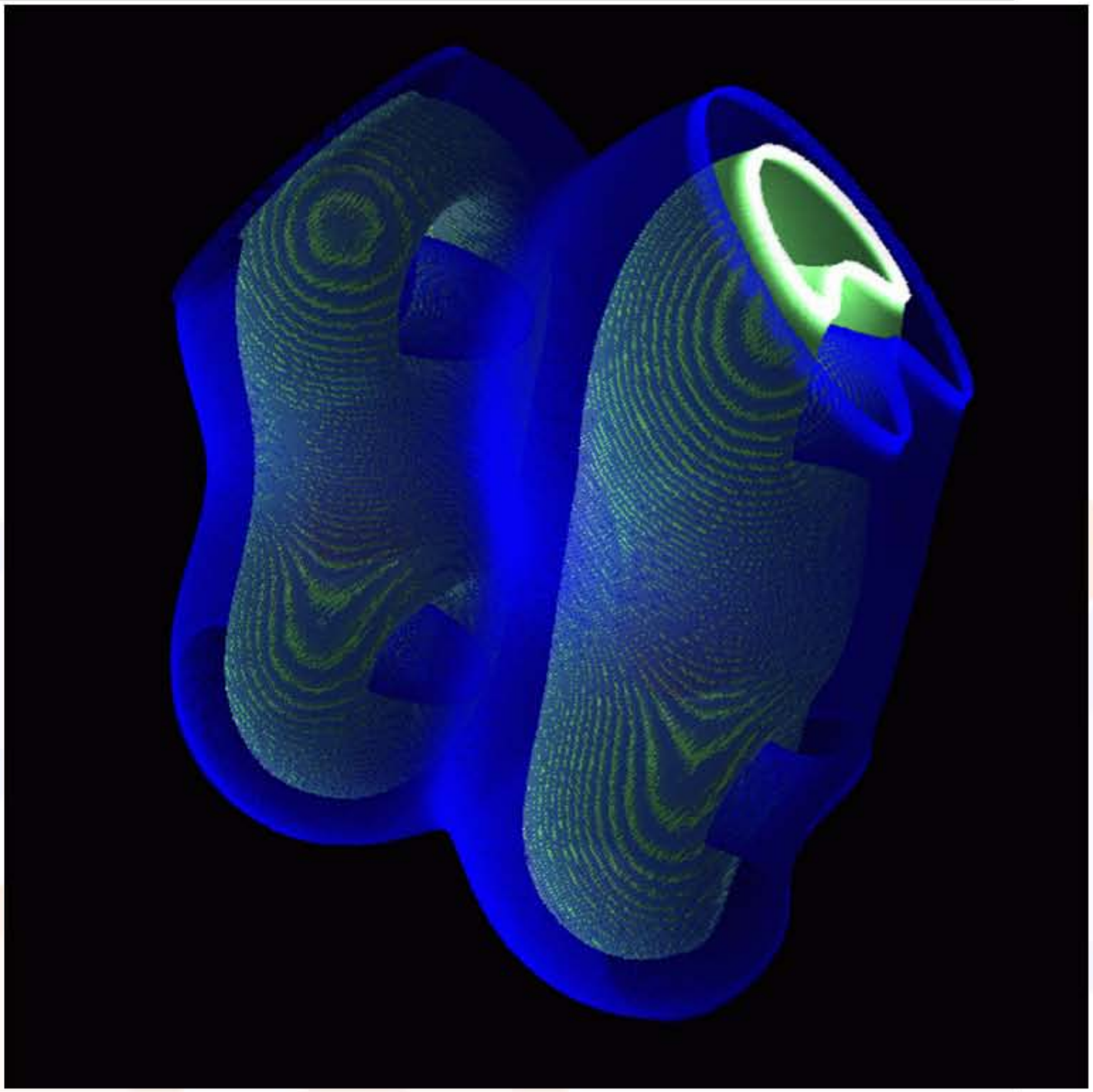

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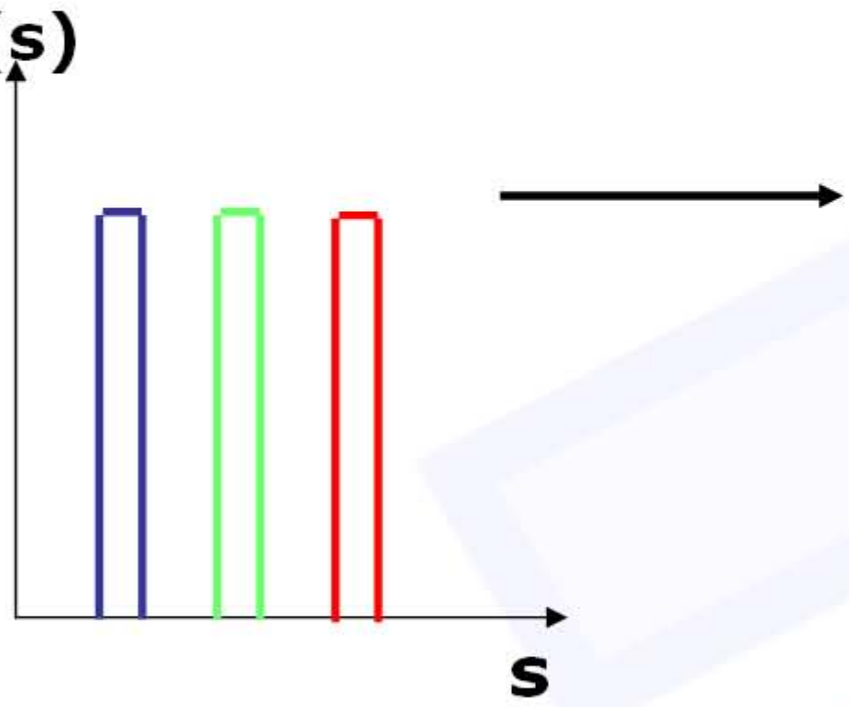
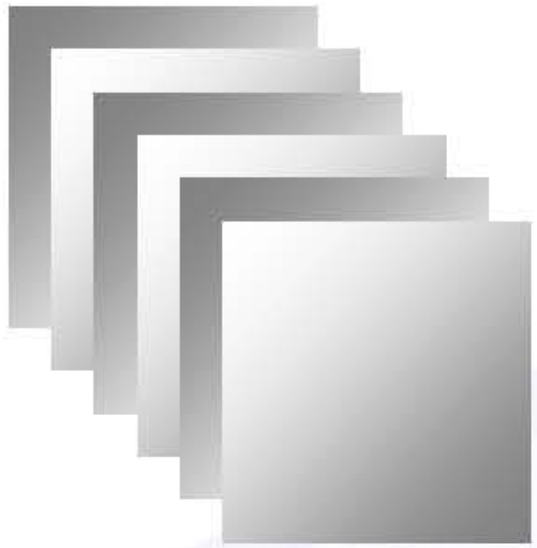
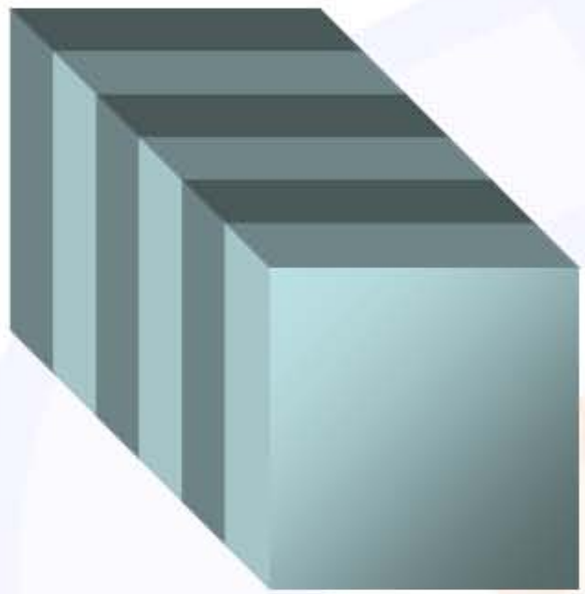
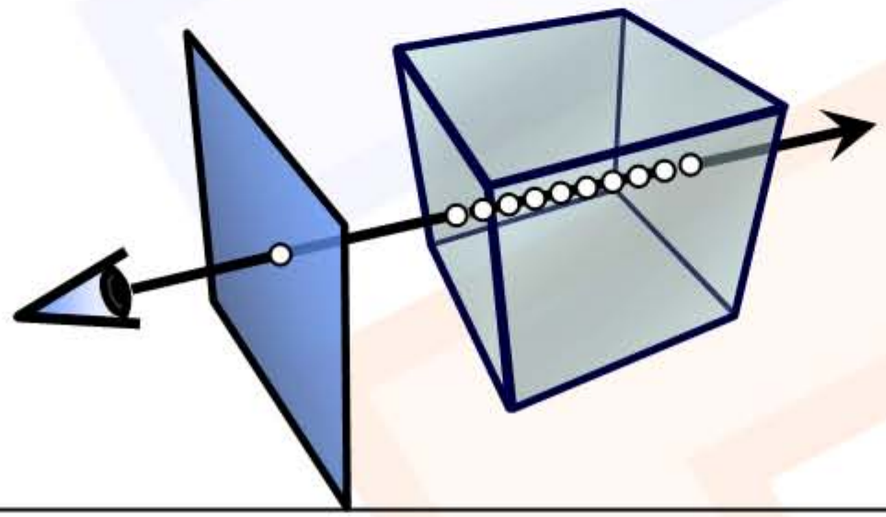
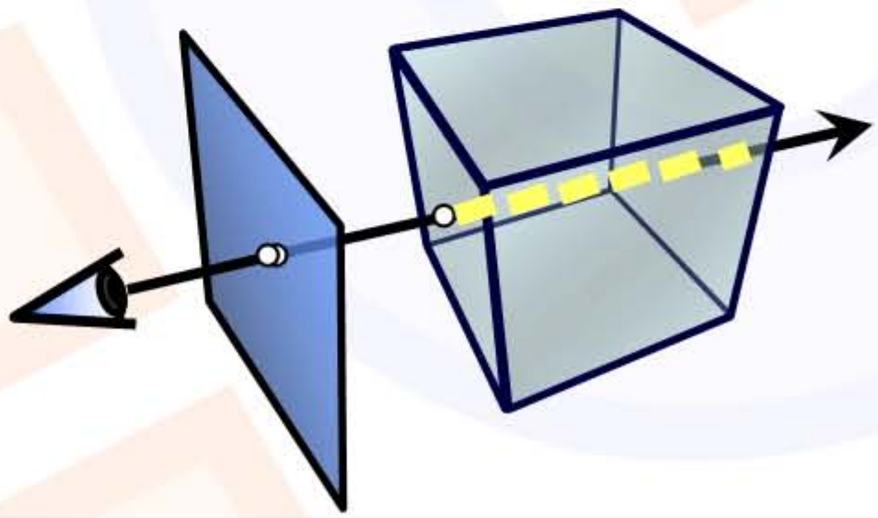


Classification Artifacts / Pre-integration

	slice-by-slice	slab-by-slab
image-order		
object-order	sample-by-sample 	raySegment-by-raySegment 

Classification Artifacts / Pre-integration

- Pre-integration table to large
  - 12bit x 12bit x RGBA8 = 4096x4096x32bit = 64MB

- Pre-integration table to slow to compute
  - even with integral functions

- Solution:
  - use Integral functions
  - Store integral functions in 1D floating point texture
  - two 1D table lookups

Classification Artifacts / Pre-integration

- Almost no performance penalty in sw raycasting
  - Cache last scalar value

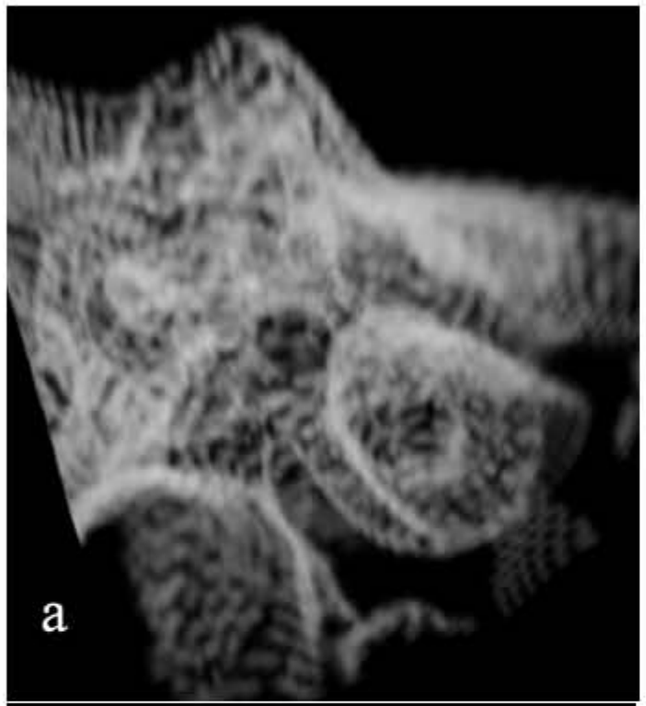
- Currently slower on graphics hardware
  - Temporary fragment registers are zeroed
  - Two lookups into the volume per fragment

  => multiple integration steps @ once (raycasting)

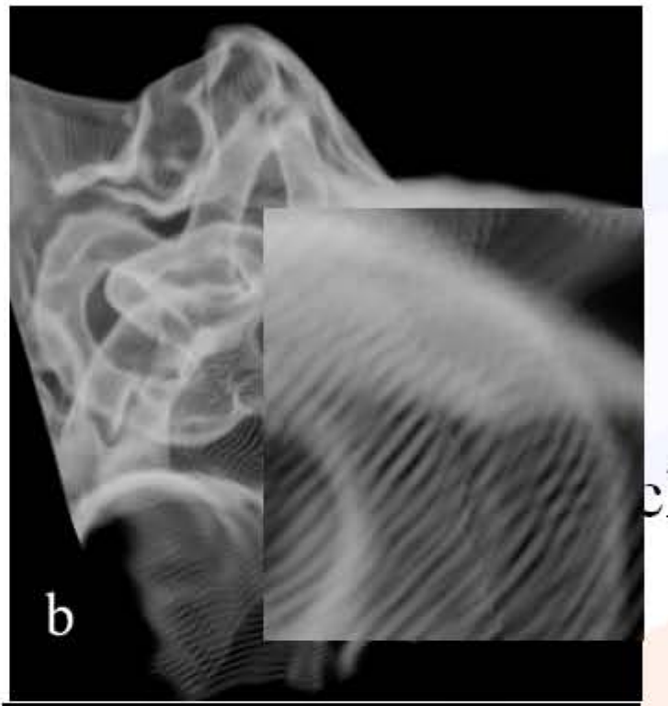
- Pre-integrated volume rendering still not "correct"
  - Assumes linear progression of scalar value along ray

    => Gaussian Transfer Functions (Kniss Vis'03)

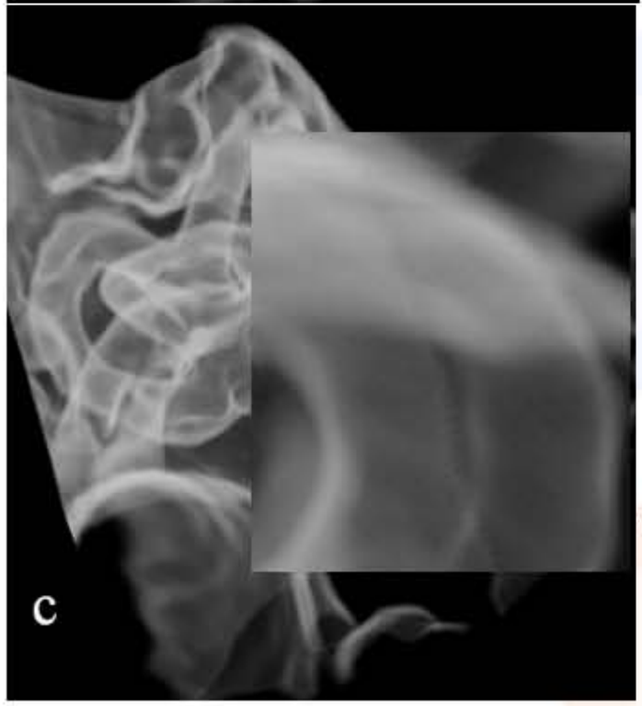
Classification Artifacts / Pre-integration



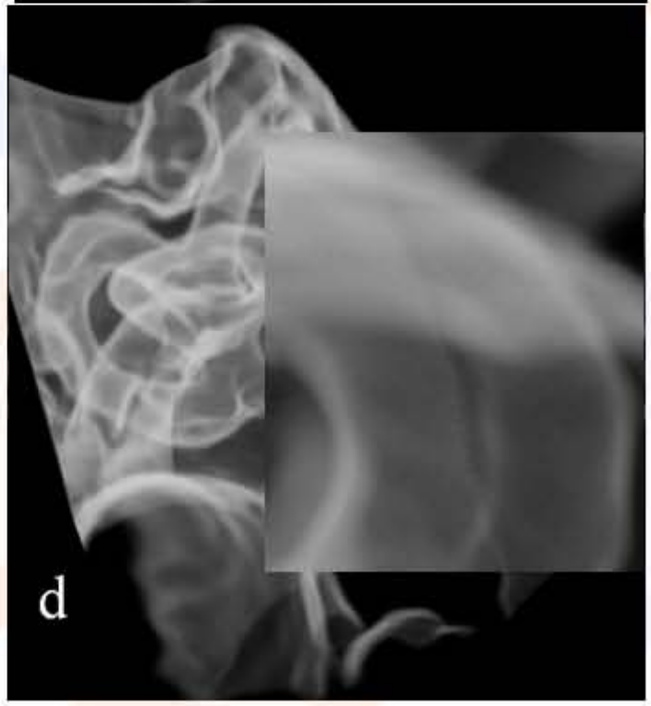
128 slices pre-classification



128 slices post-classification



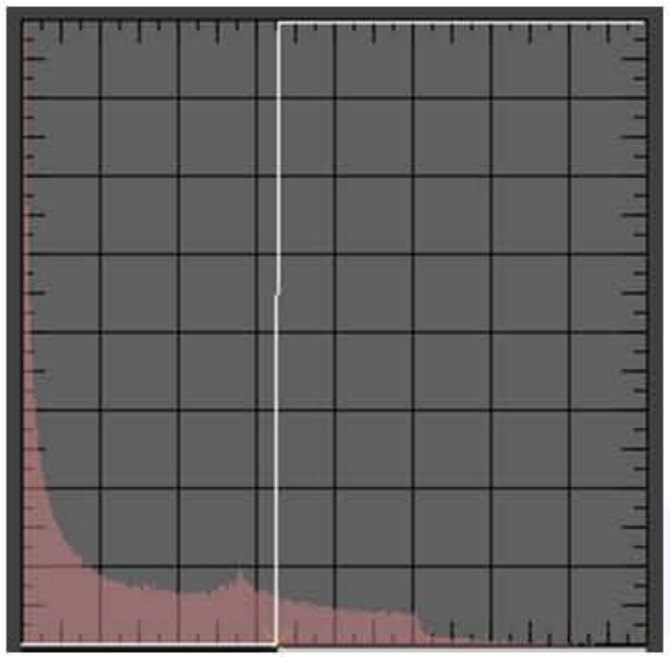
284 slices post-classification

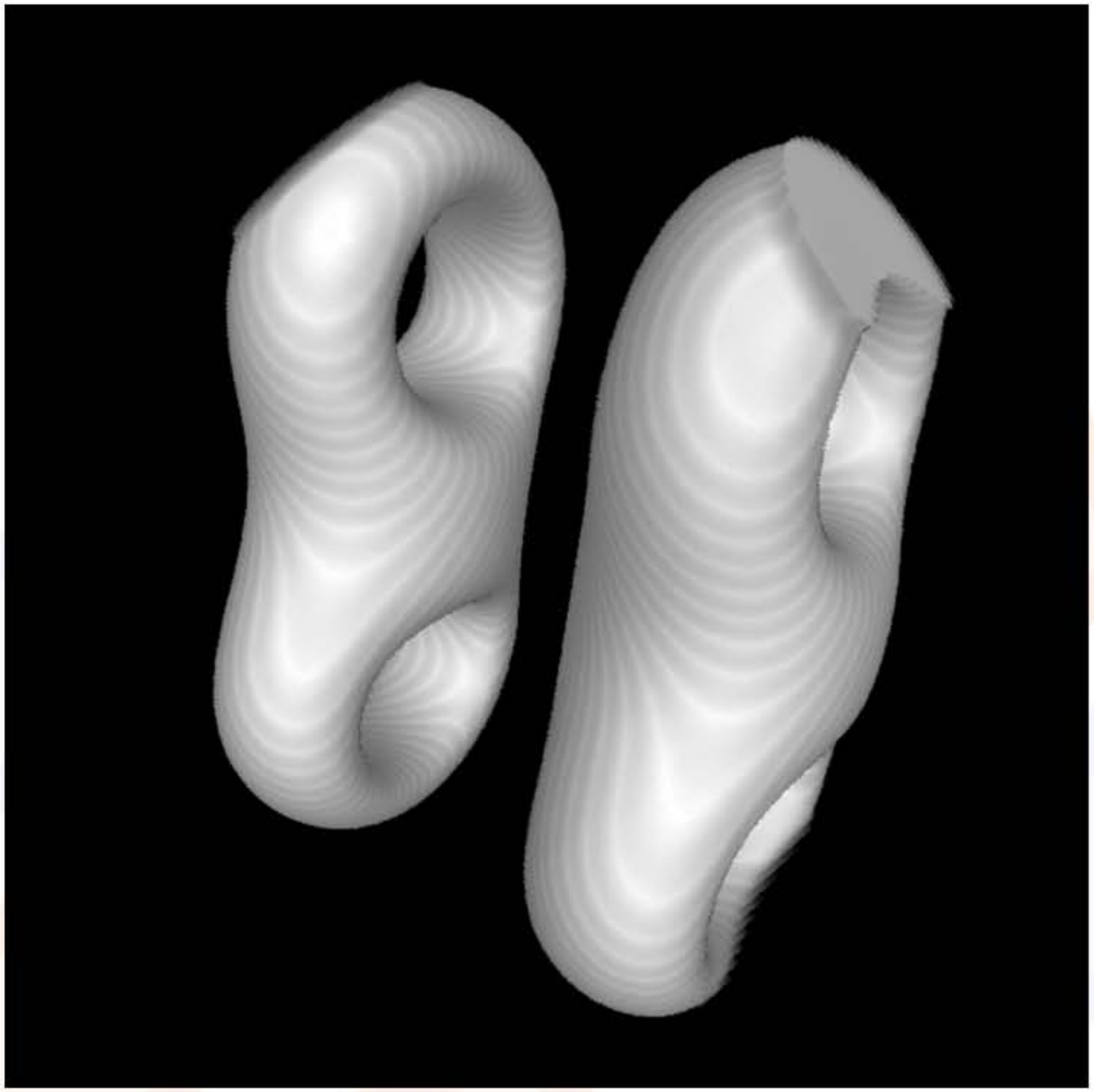


128 slices pre-integrated

Classification Artifacts / Pre-integration

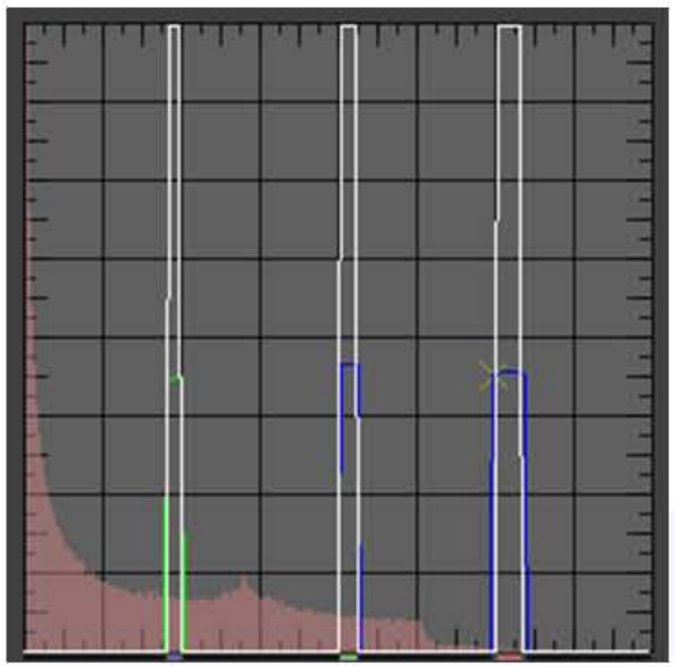
single step

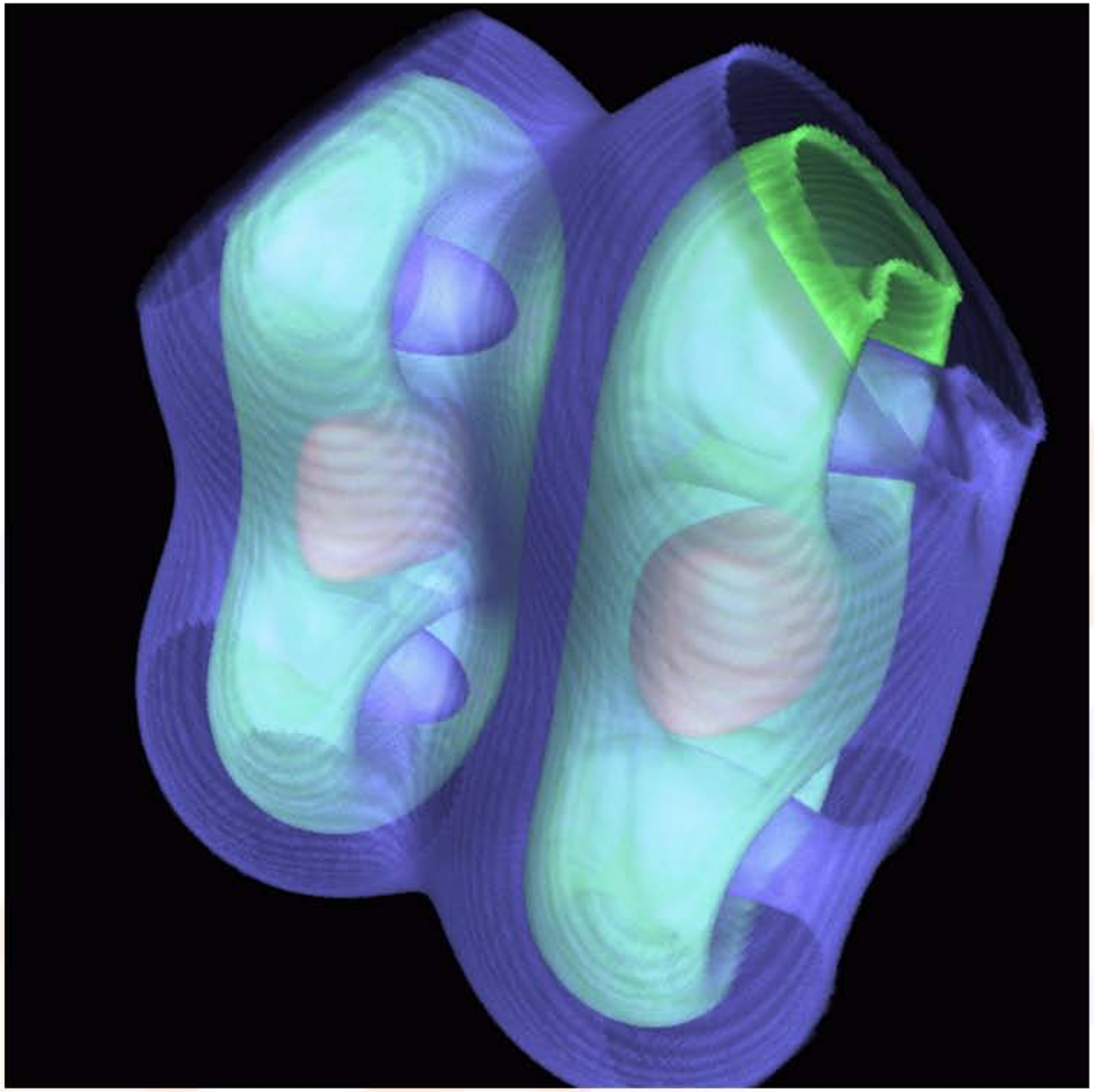




Classification Artifacts / Pre-integration

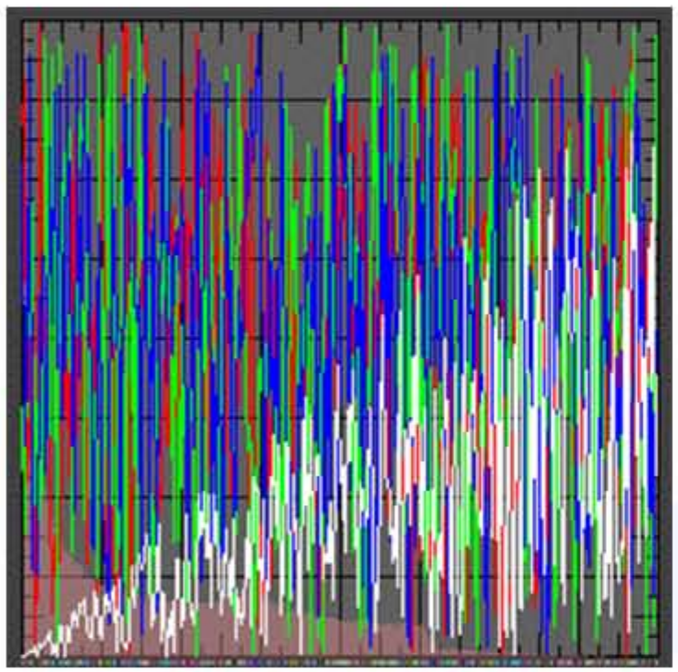
multiple peaks

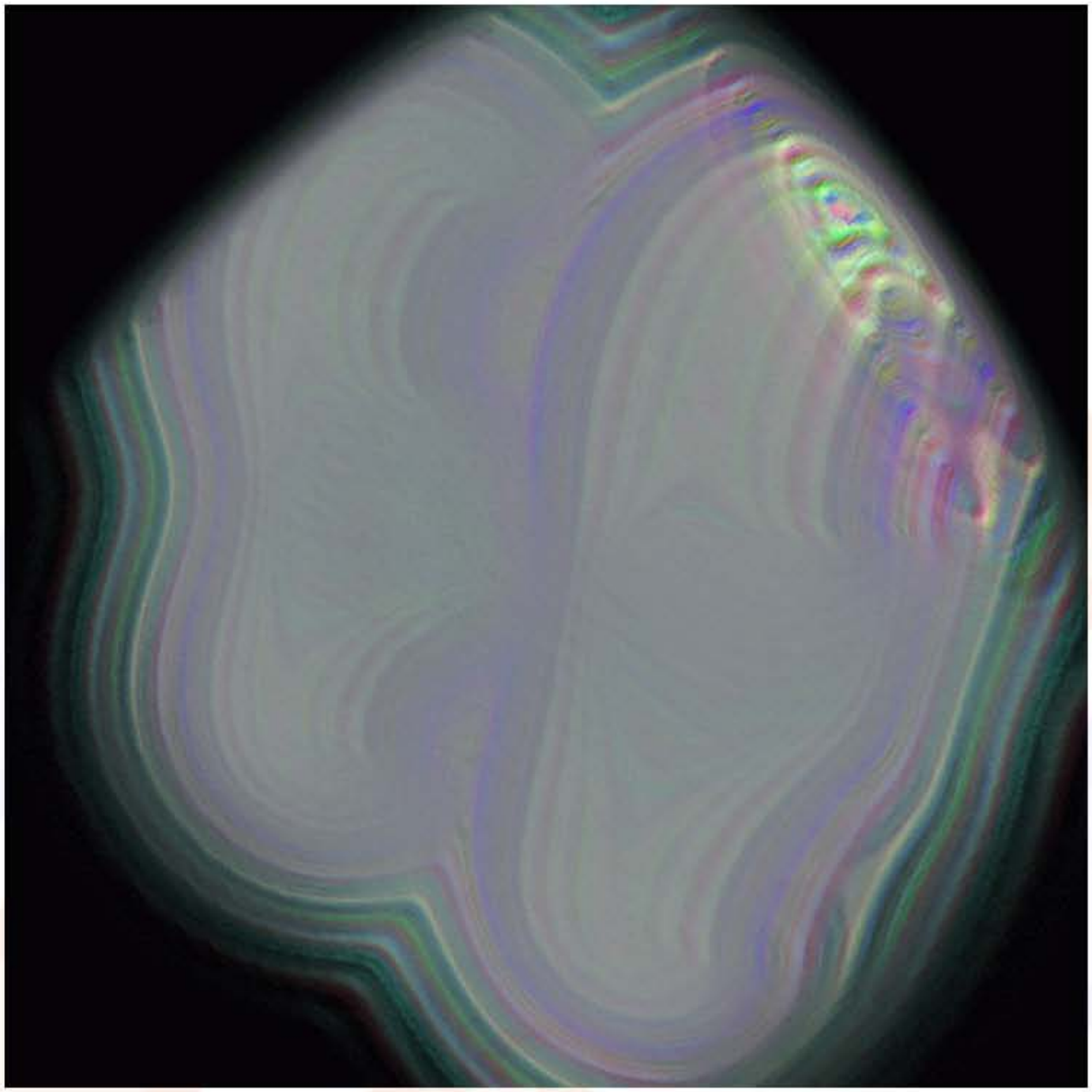




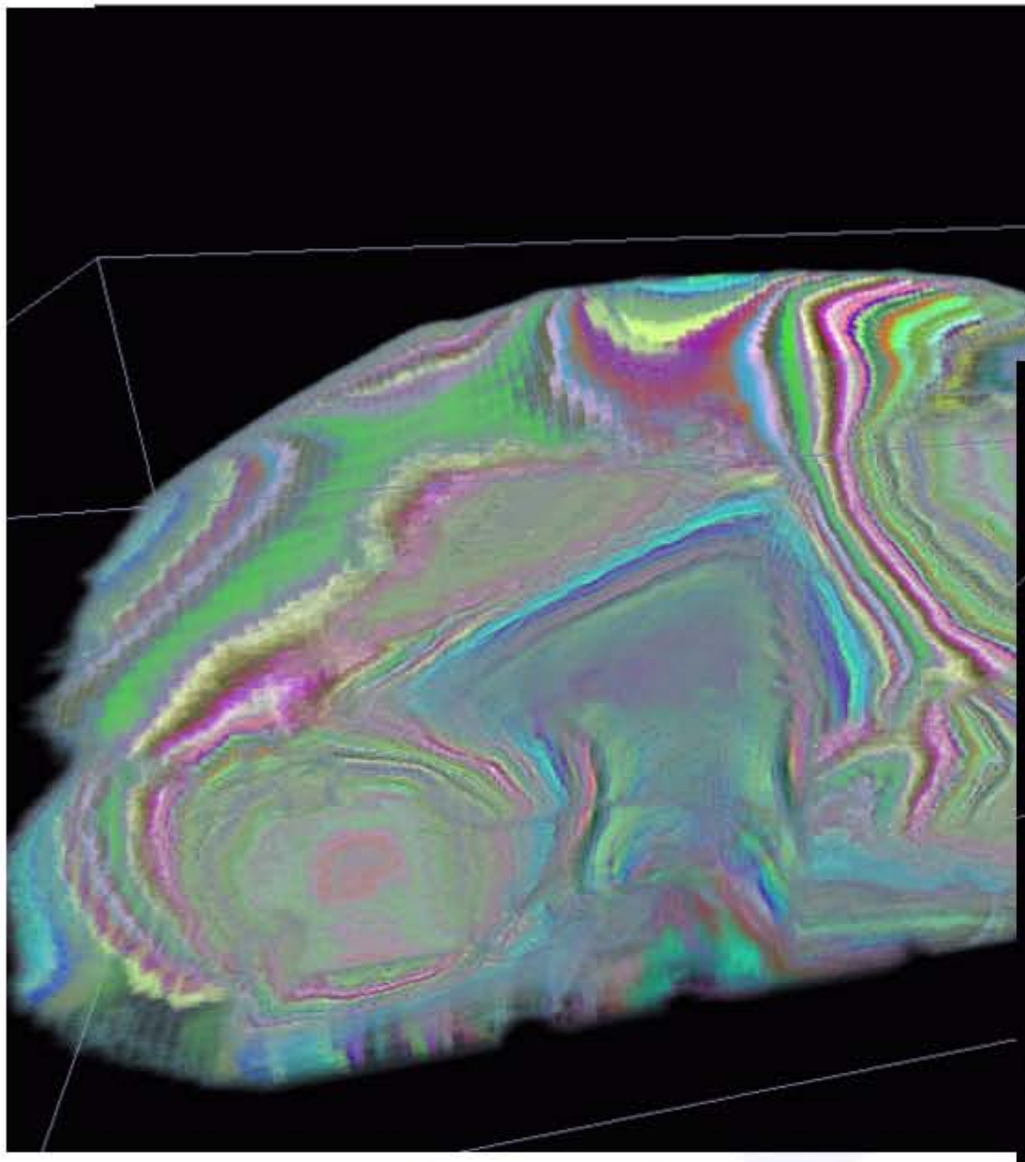
Classification Artifacts / Pre-integration

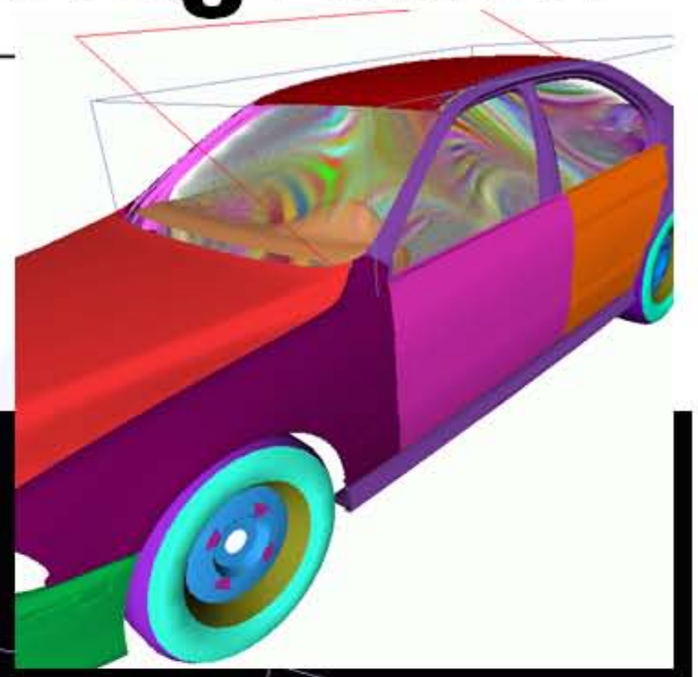
many peaks

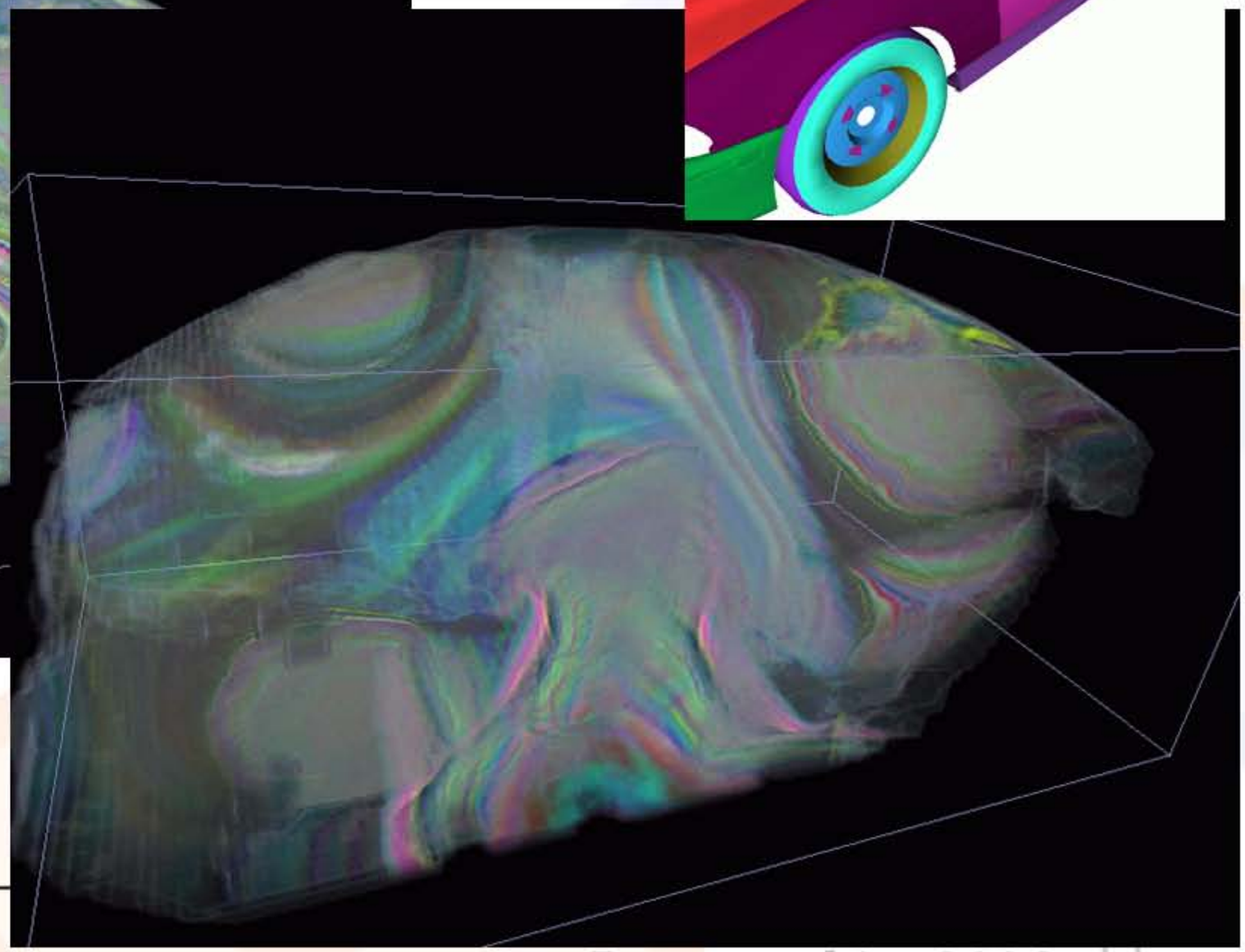




Classification Artifacts / Pre-integration





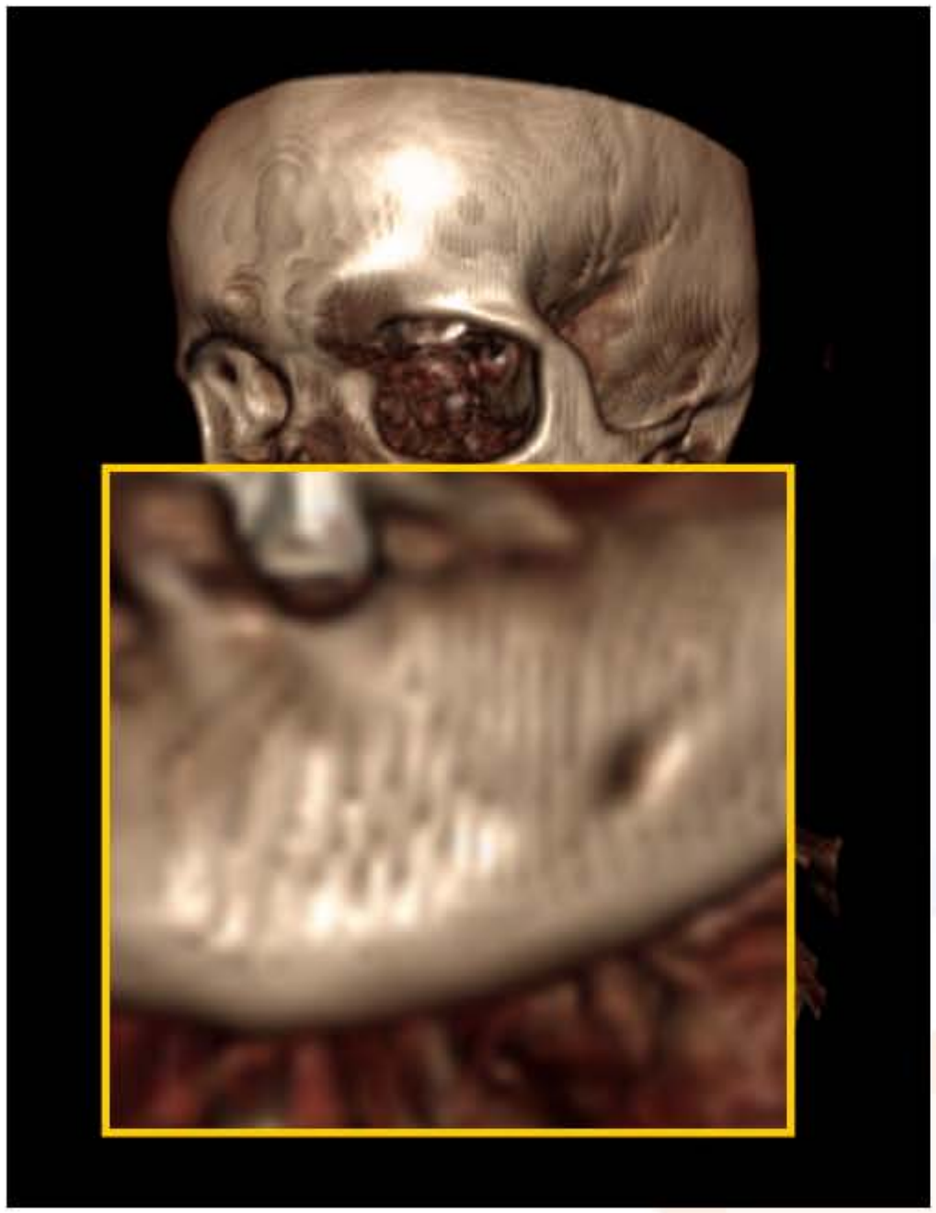


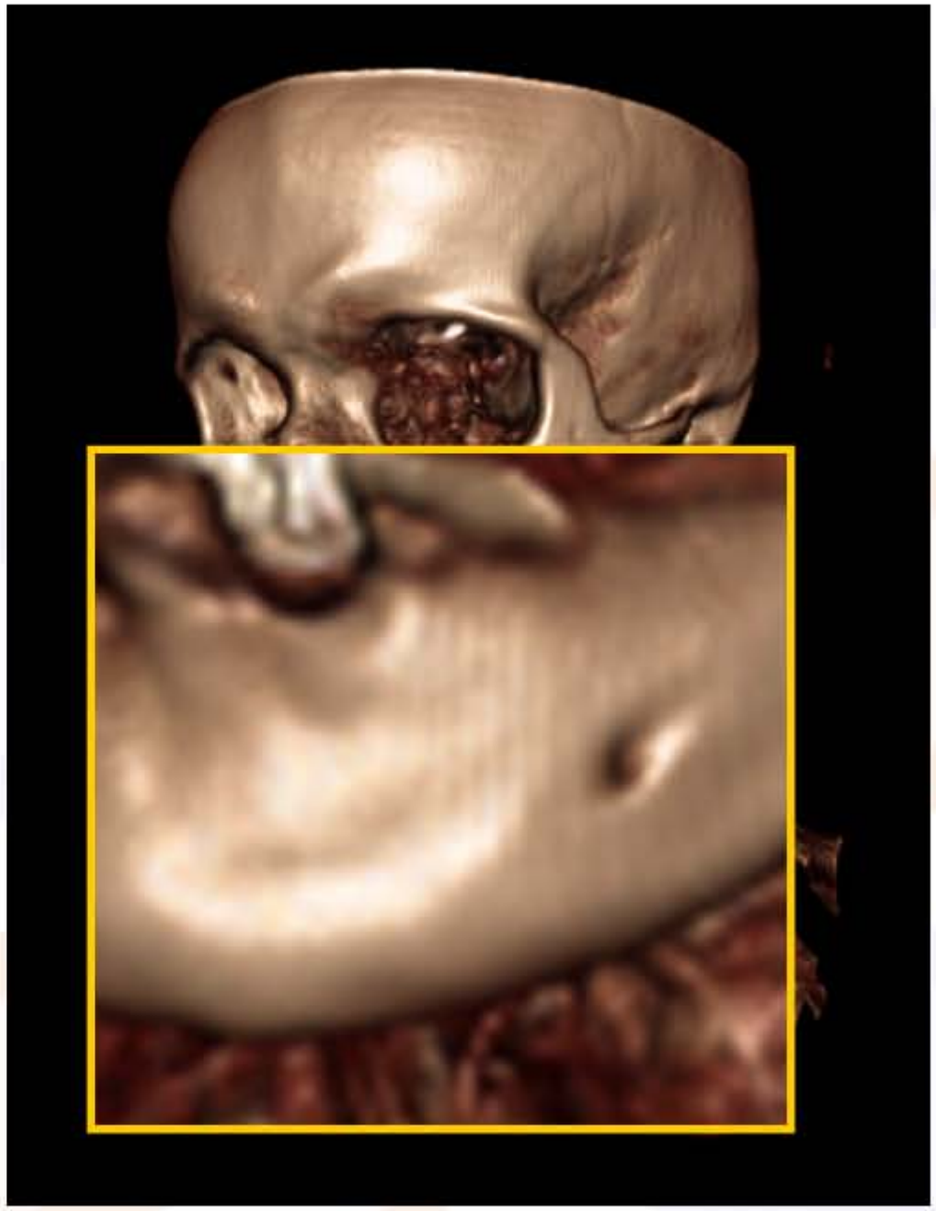
acoustic volume inside car cabine

REAL-TIME VOLUME GRAPHICS
Klaus Engel
Siemens AG, Erlangen, Germany

Shading Artifacts

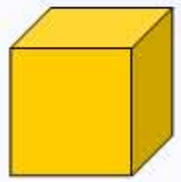
Shading Artifacts





Shading Artifacts

- Reasons:
  - Gradients are pre-computed and quantized
  - Interpolation of normals causes unnormalized normals
- Solutions:
  - Store gradients in high-precision texture, re-normalize in fragment program
    - ☹ too much memory
  - Compute gradients on-the-fly
    - ☺ high-quality gradient
    - 😐many texture fetches



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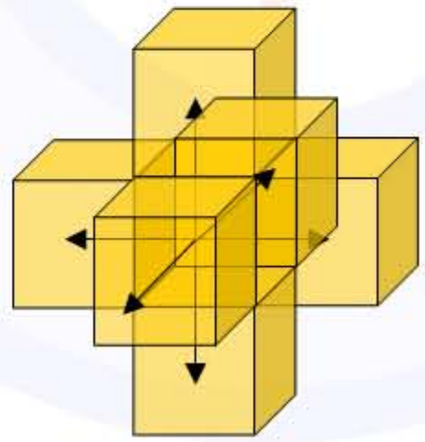


Shading Artifacts

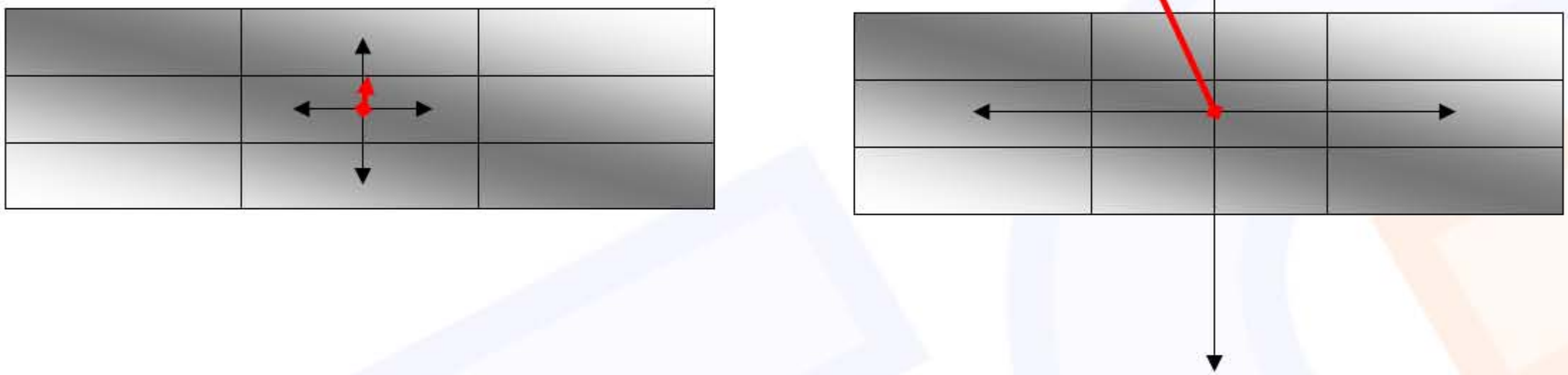
- Pass in shifted texture coordinates

Cg Fragment Program

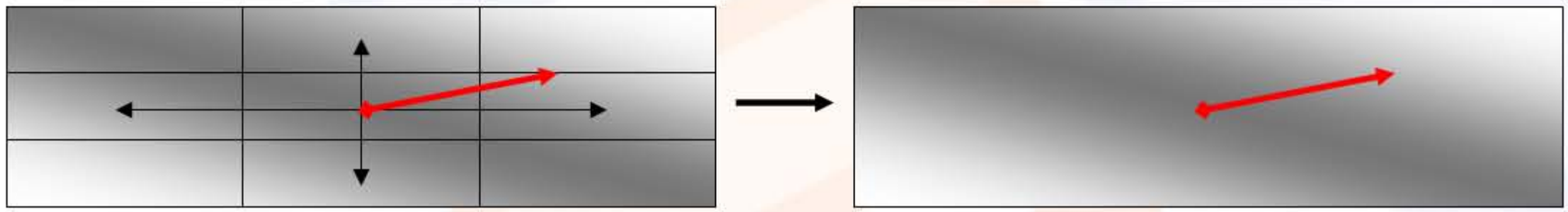
```
// samples for forward differences
half3 normal;
half3 sample1;
sample1.x = (half)tex3D(Volume, IN.TexCoord2).x;
sample1.y = (half)tex3D(Volume, IN.TexCoord4).x;
sample1.z = (half)tex3D(Volume, IN.TexCoord6).x;

// additional samples for central differences
half3 sample2;
sample2.x = (half)tex3D(Volume, IN.TexCoord3).x;
sample2.y = (half)tex3D(Volume, IN.TexCoord5).x;
sample2.z = (half)tex3D(Volume, IN.TexCoord7).x;

// compute central differences gradient
normal = normalize(sample2.xyz - sample1.xyz);
```

Shading Artifacts

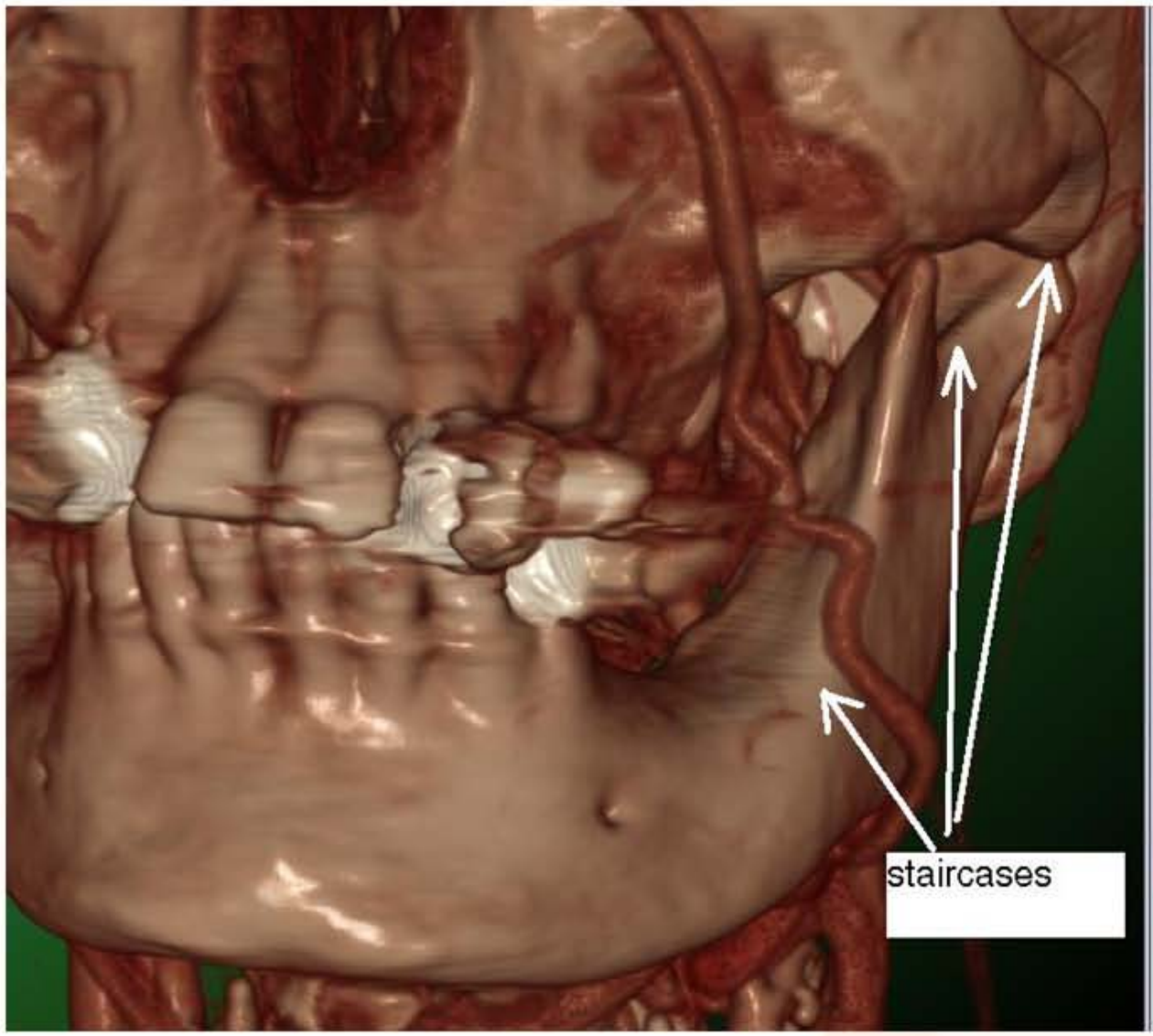
- Neighbor lookup for anisotropic voxel data
  - Constant offsets



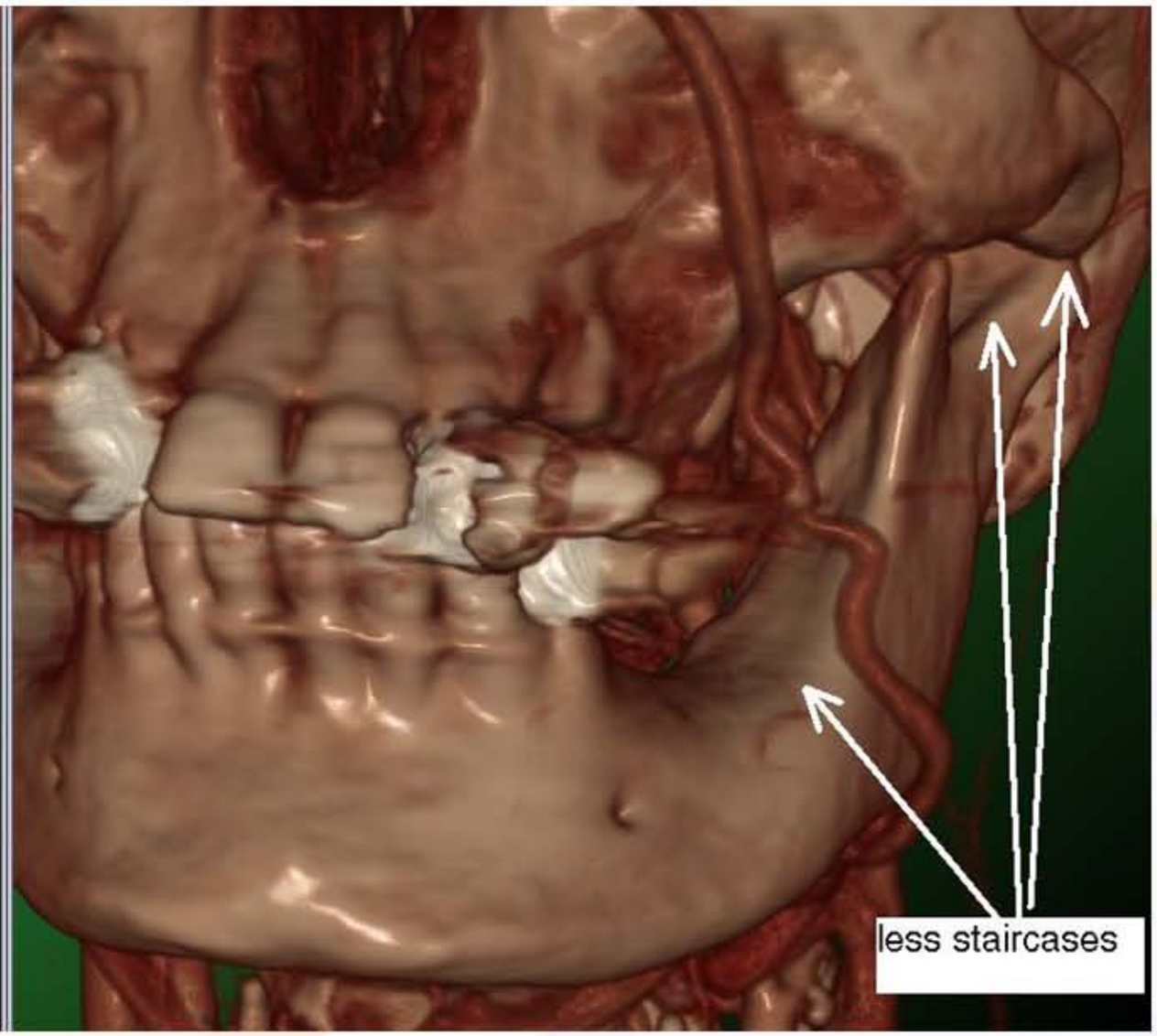
- Neighboring voxels + gradient correction



Shading Artifacts

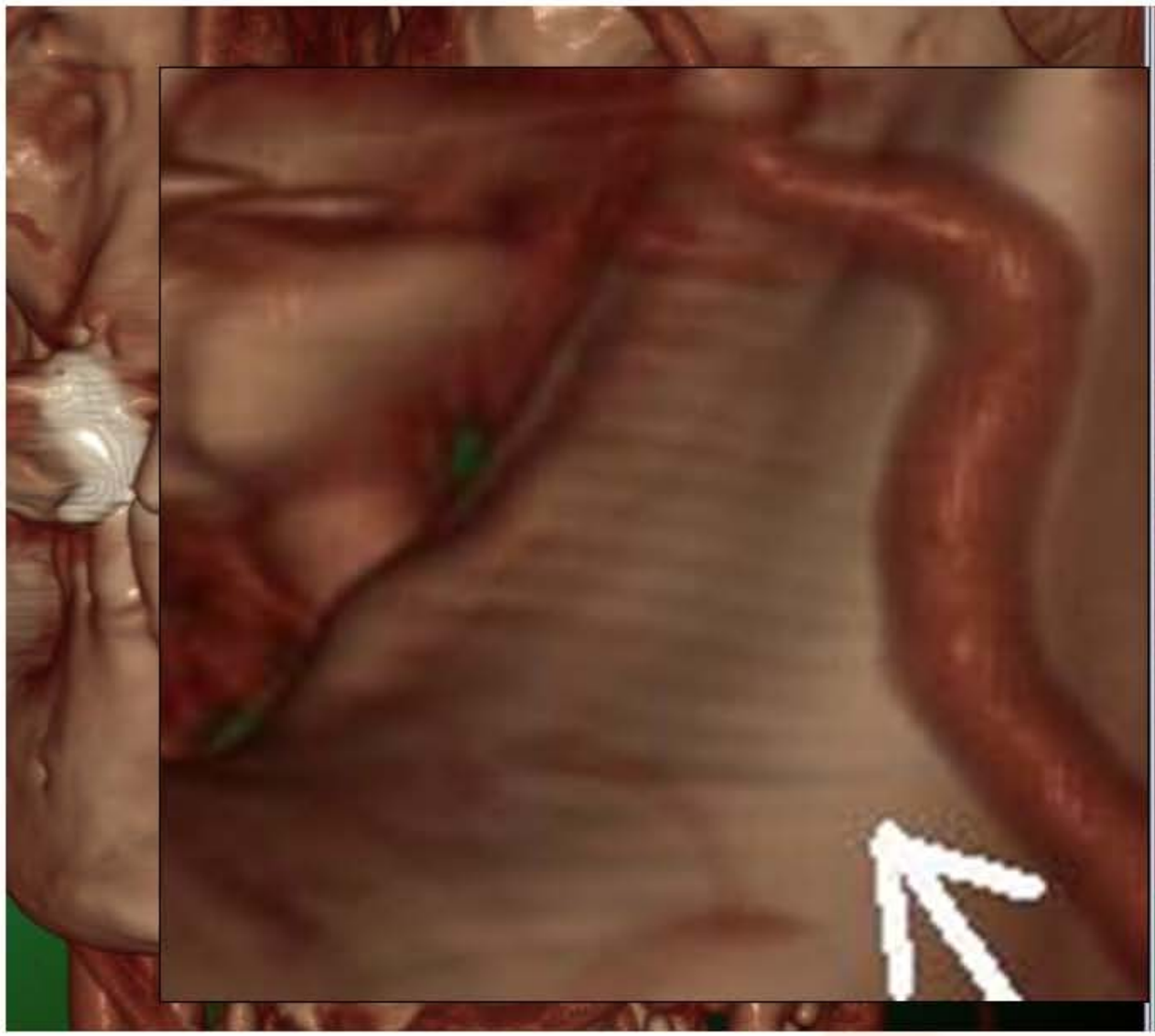


Constant offsets

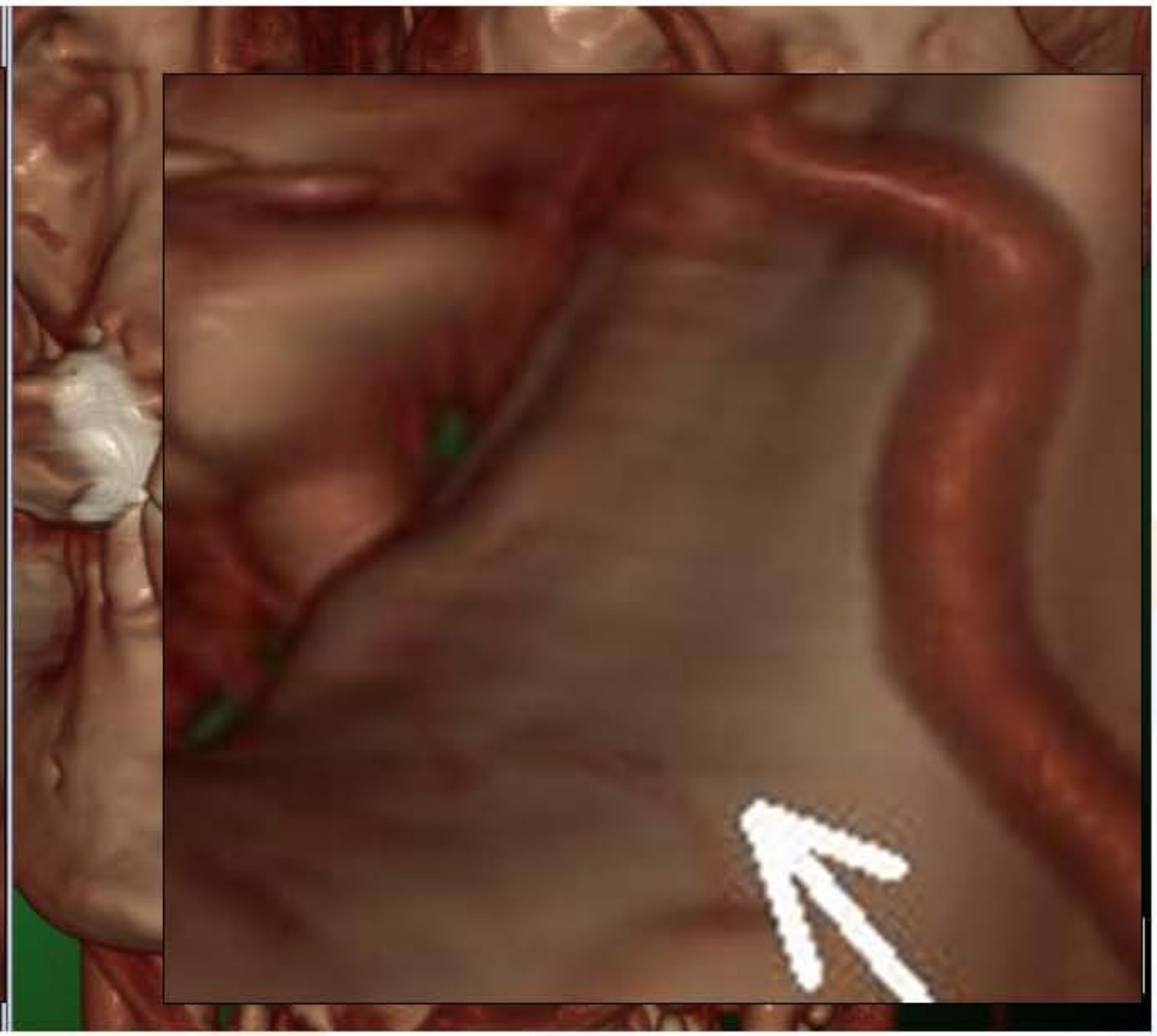


Neighboring voxels + gradient correction

Shading Artifacts

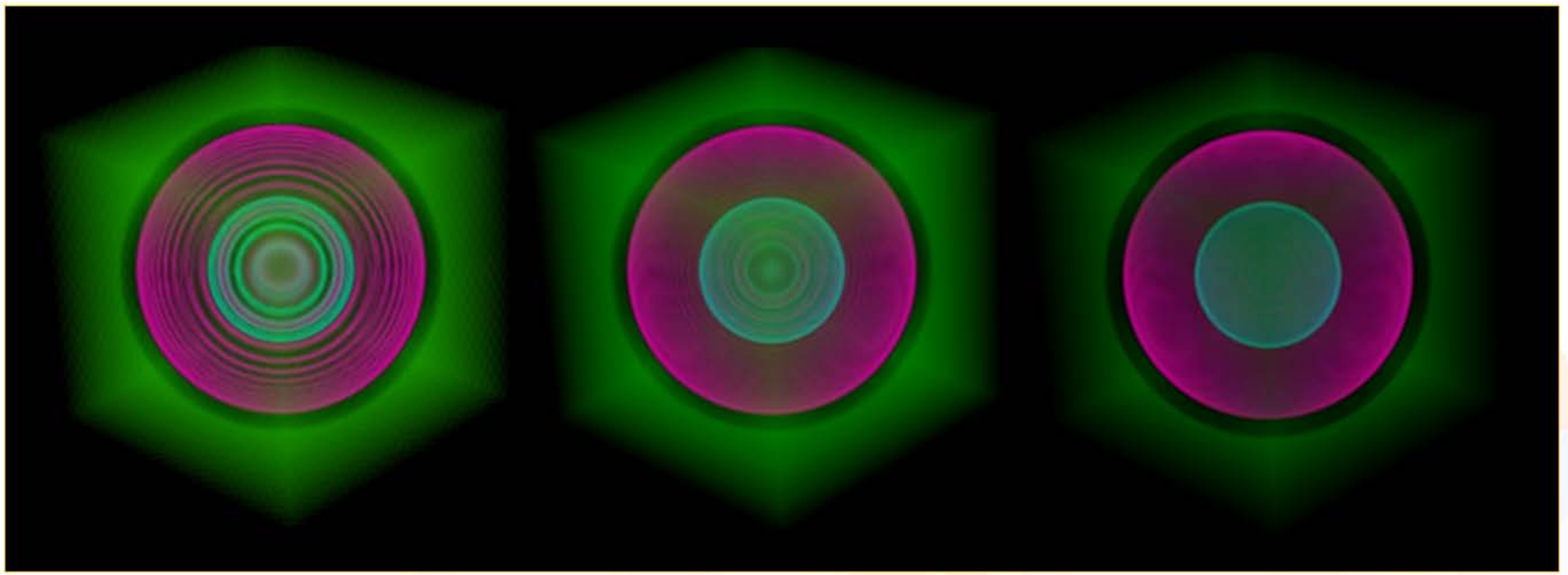


Constant offsets



Neighboring voxels + gradient correction

Blending Artifacts



8 bit
fixed point
blending

16 bit
floating point
blending

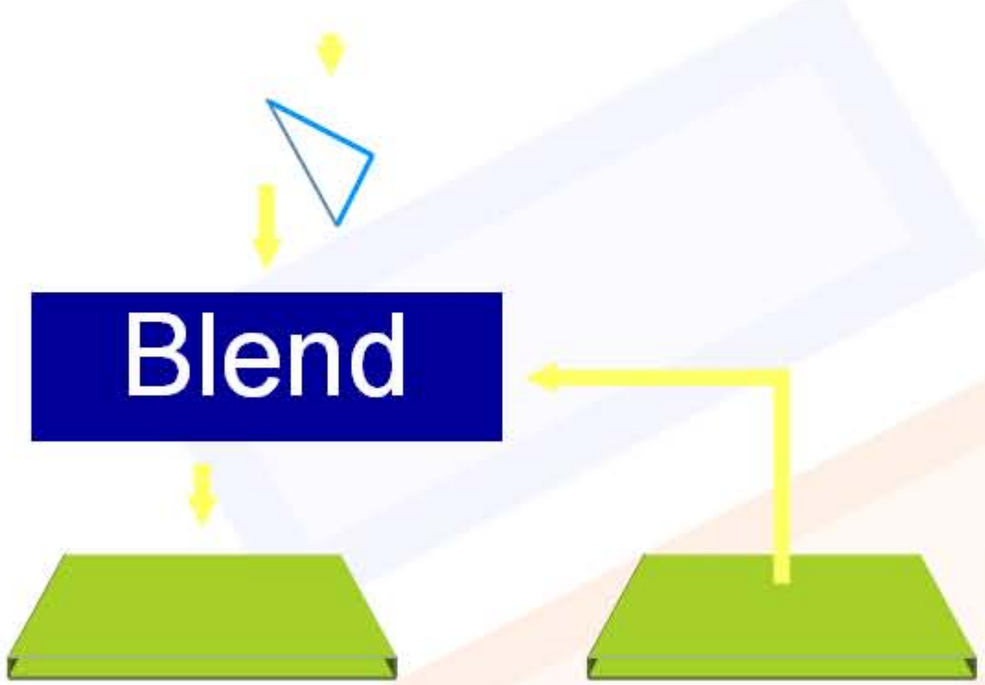
32 bit
floating point
blending

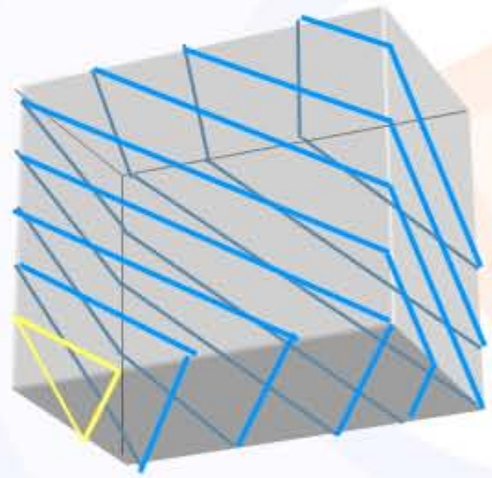
Blending Artifacts

- Reason:
  - 8 bit blending accumulates error in the framebuffer
  - Lower alpha values have higher error
- Solutions:
  - Blending into a floating point FBO
    - Nv4x support 16 bit floating point blending
    - Nv3x, R3xx and R4xx do not support floating point blending
      => implement blending in a fragment program
    - Ping-pong blending to prevent read/write race conditions

Blending Artifacts

- The graphics hardware does not support floating point blending (NV3x, R3xx, R4xx)
  => implement blending yourself
- Clean: ping-pong





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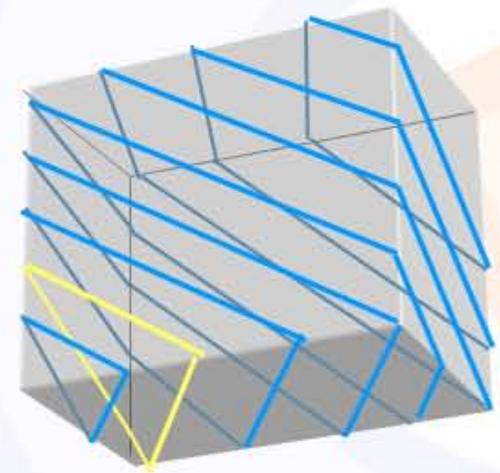

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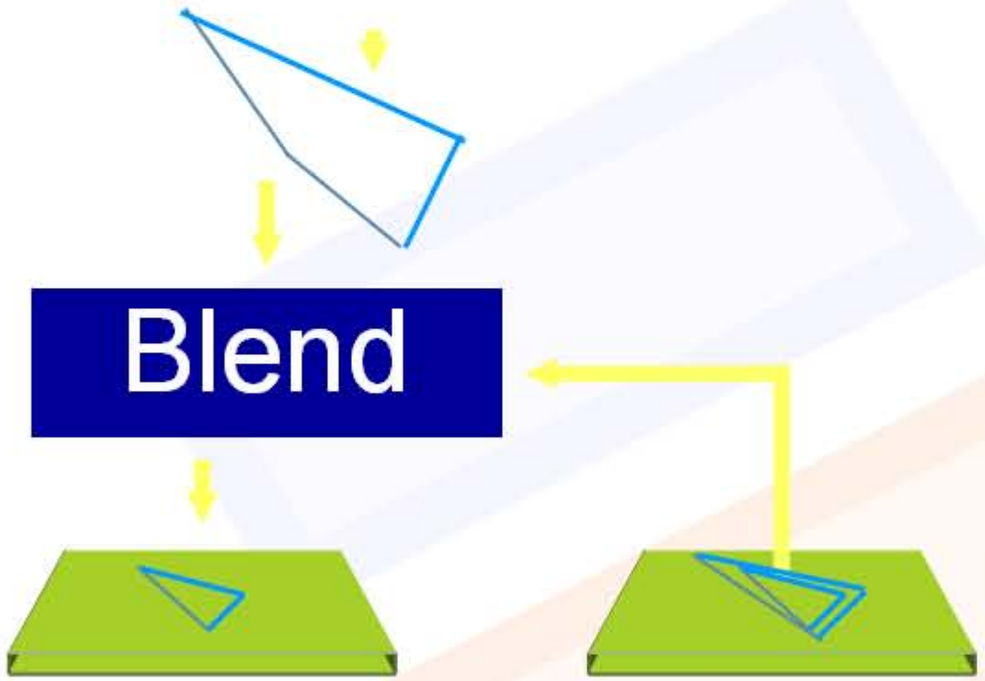

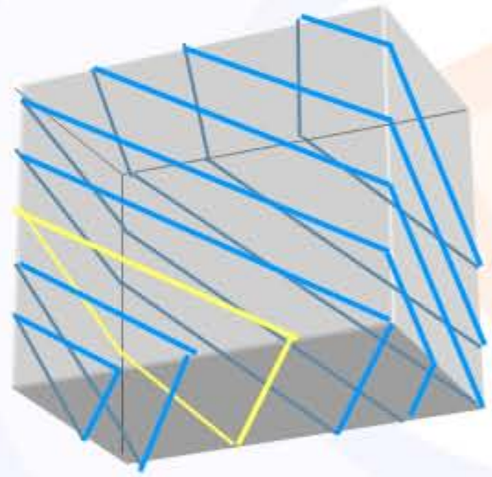

Blending Artifacts

- The graphics hardware does not support floating point blending (NV3x, R3xx, R4xx)
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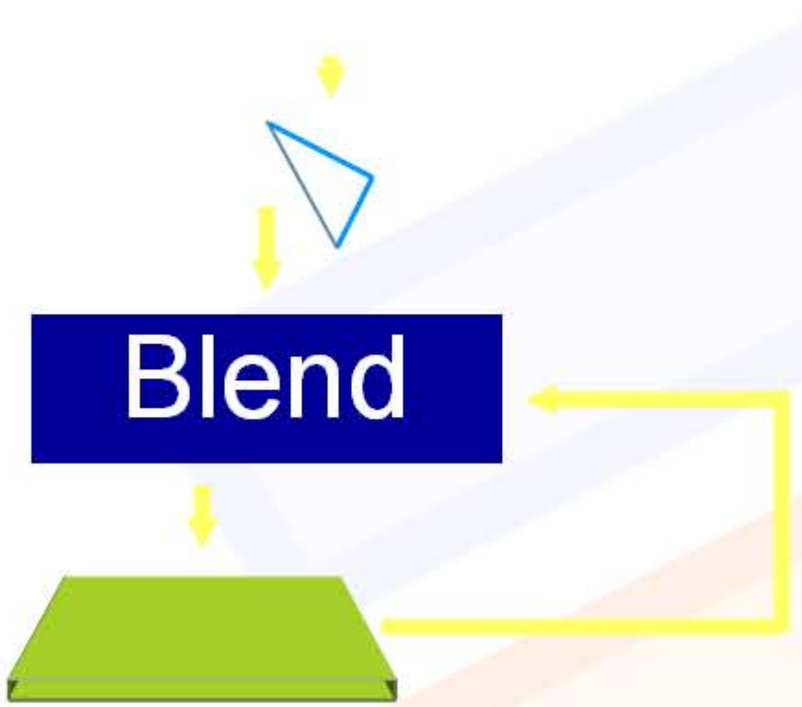
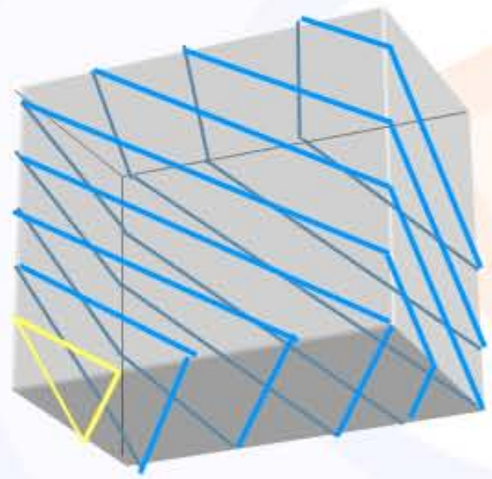
- Dirty: ping without the pong





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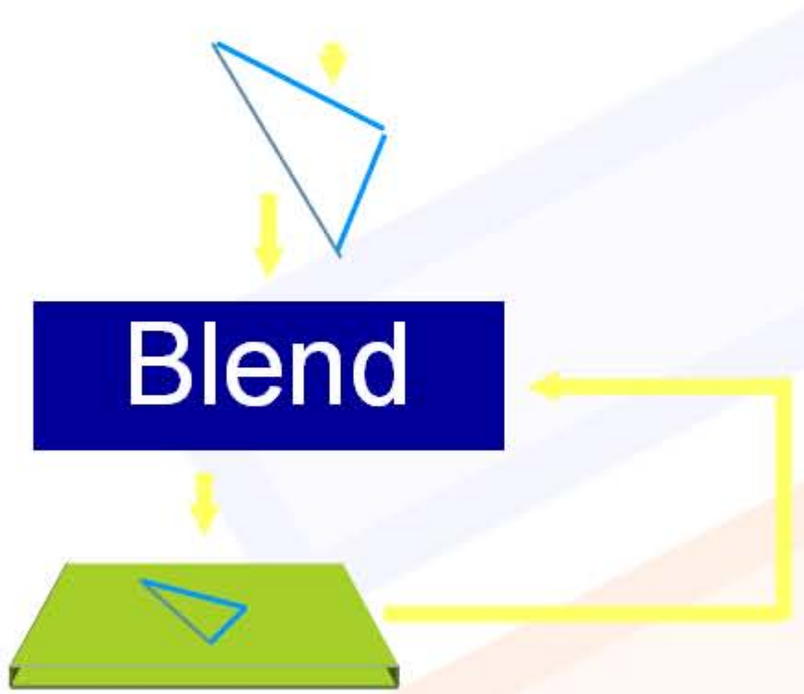

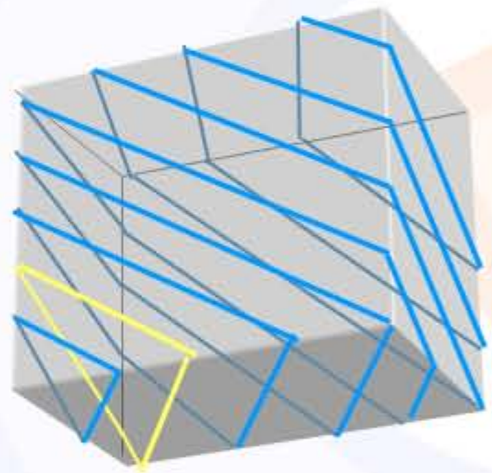

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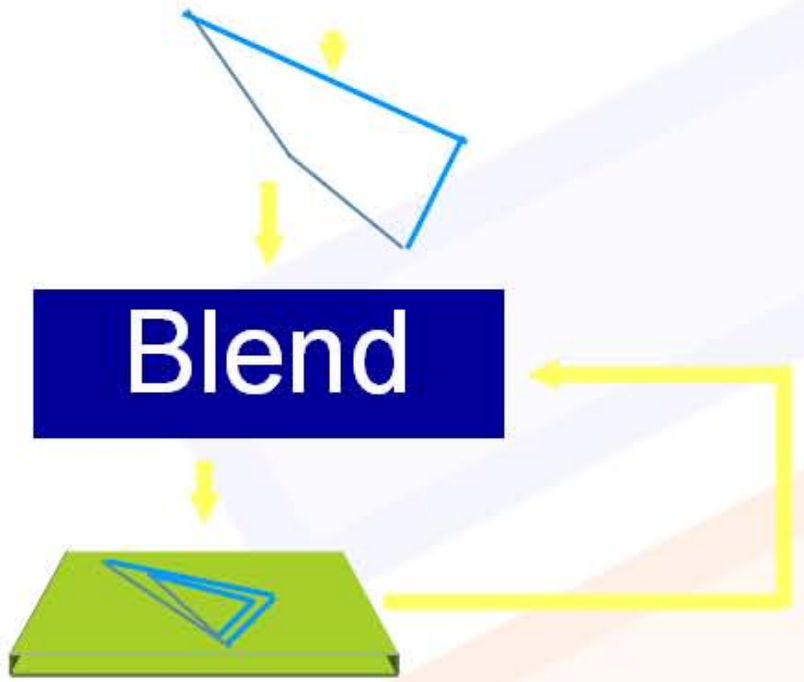

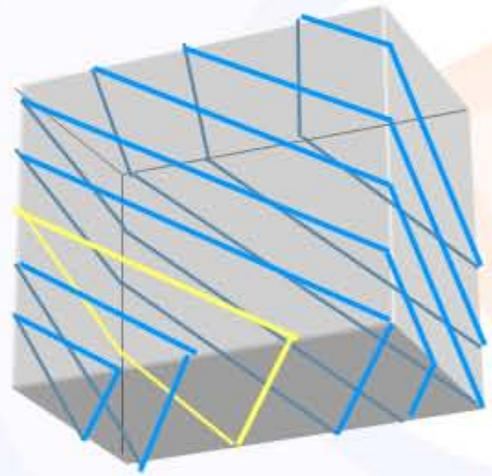

Conclusions

- Artifacts are introduced in various stages of the volume rendering process

- Current graphics hardware is flexible and precise enough to remove or suppress artifacts

- Real-Time performance can still be achieved in most cases