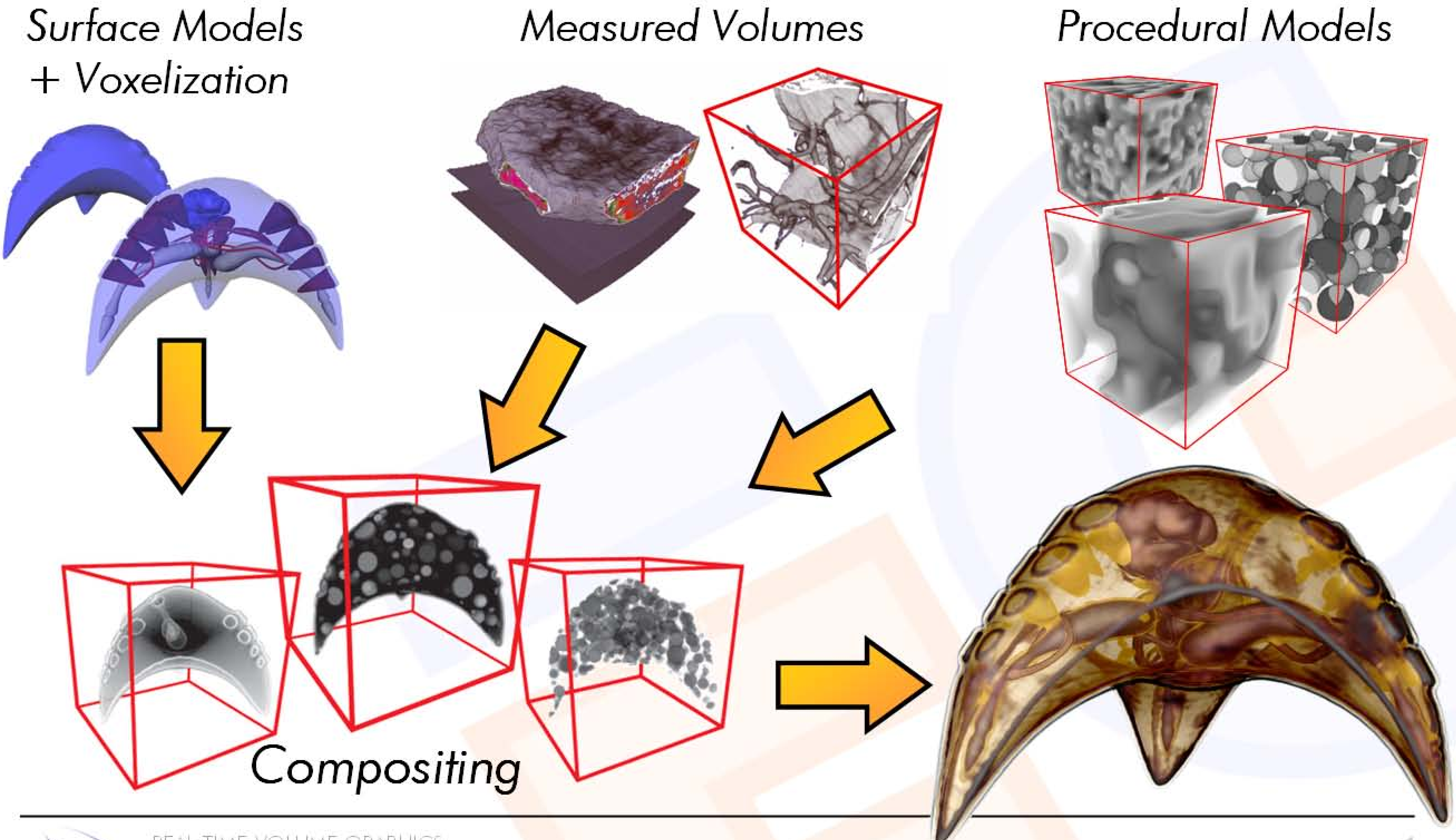
Real-Time Volume Graphics

[12] Volume Modeling, Deformation and Animation

Modeling Volume Data



Rendering into a 3D texture

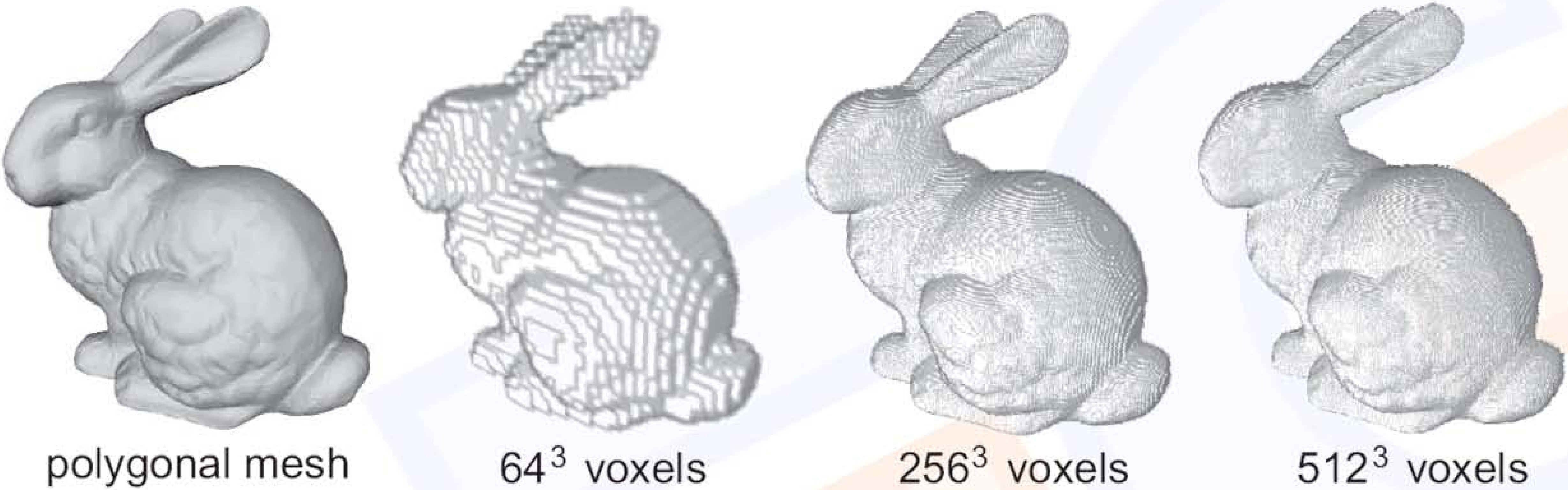
```
#ifdef GL_EXT_framebuffer_object
  GLuint framebufferObject;
  // create a frame buffer object
  glGenFramebuffersEXT(1, &framebufferObject);
  // create a 3D texture object
  GLuint textureName;
  glGenTextures(1, &textureName);
  glBindTexture(GL_TEXTURE_3D, textureName);
  glTexImage3D(GL_TEXTURE_3D, 0, GL_RGBA8,
    size_x, size_y, size_z,
    GL_RGBA, GL_UNSIGNED_BYTE, NULL);
  // bind the frame buffer object
  glBindFramebufferEXT(
    GL_FRAMEBUFFER_EXT, framebufferObject);

  for(int z = 0; z < size_z; ++z) {
    // attach a z-slice to color target
    glFramebufferTexture3DEXT(
```

Rendering into a 3D texture

```
for(int z = 0; z < size_z; ++z) {
  // attach a z-slice to color target
  glFramebufferTexture3DEXT(
      GL_FRAMEBUFFER_EXT,          // bind target
      GL_COLOR_ATTACHMENT0_EXT,  // attachment point
      GL_TEXTURE_3D,              // texture target
      textureName,                // texture object
      0,                          // render target id
      z);                         // 3D texture slice

  // now render into the z slice
  renderIntoSlice(z);
} // for(..

// unbind the frame buffer object
glBindFramebufferEXT(GL_FRAMEBUFFER_EXT, 0);
#endif // defined GL_EXT_framebuffer_object
```

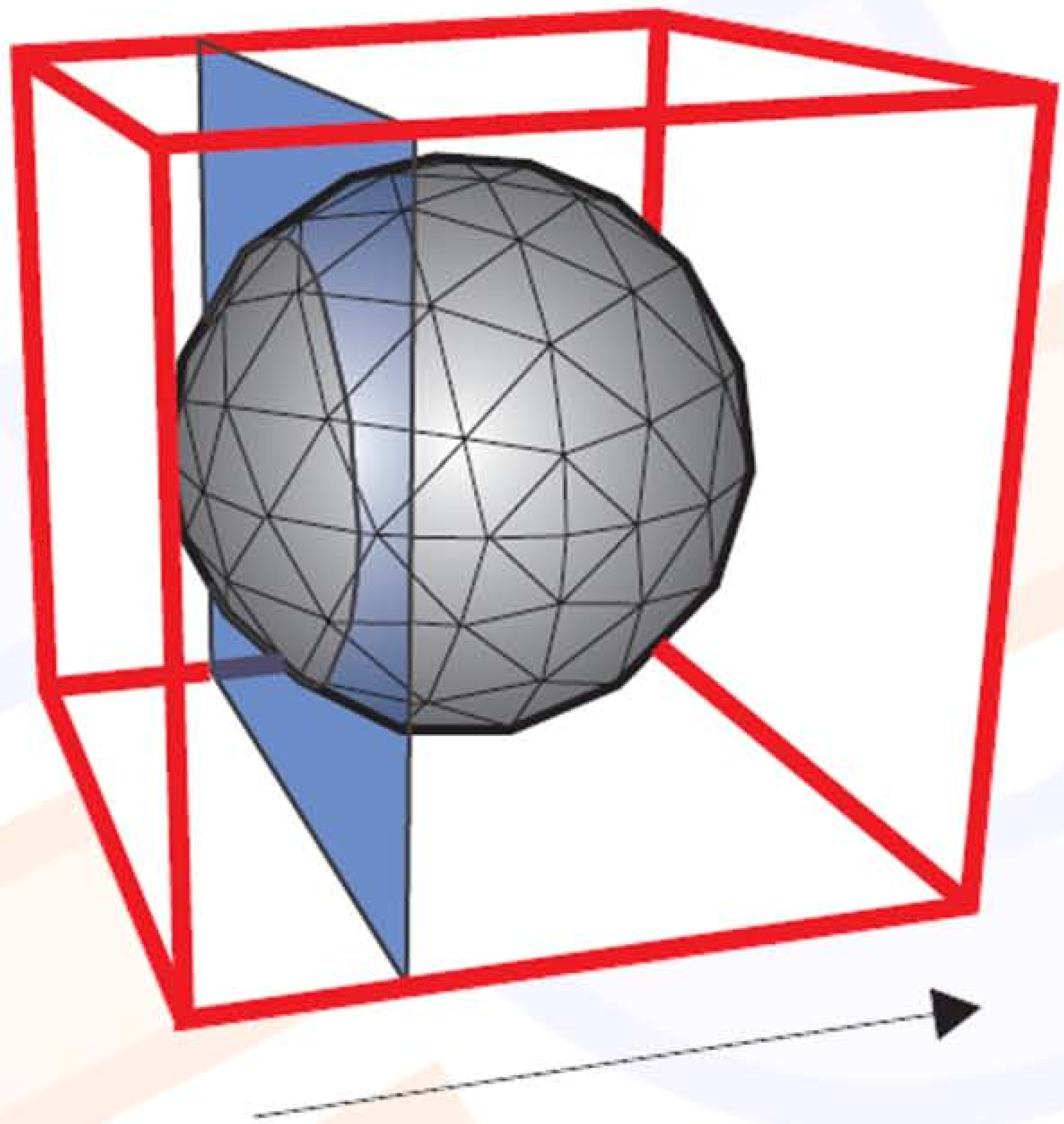
Voxelization

- Creating a binary volume out of a polygonal mesh-
  - Approaches similar to clipping against arbitrary objects



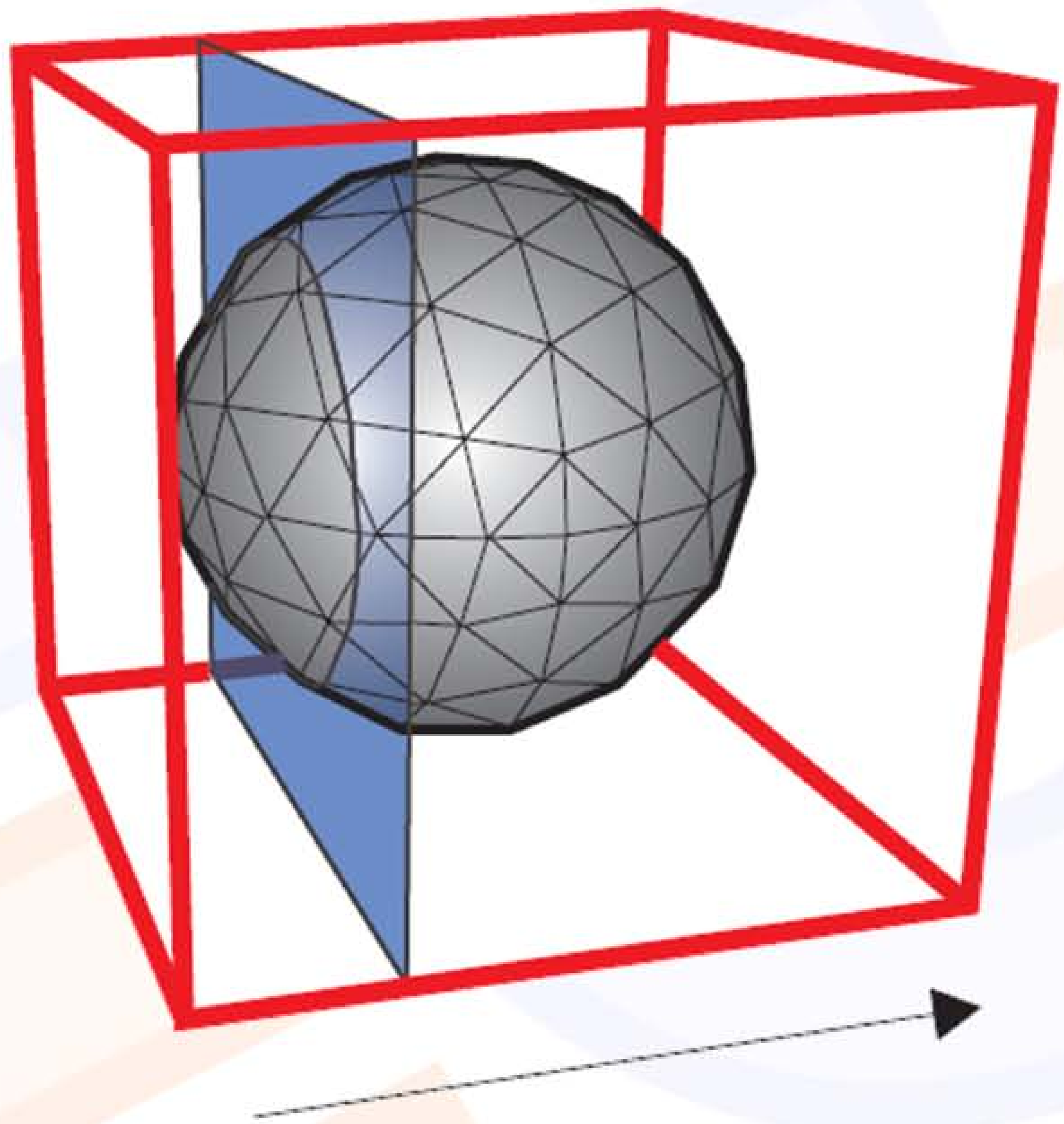
Arbitrary Closed Polygonal Meshes with consistent vertex ordering

Voxelization



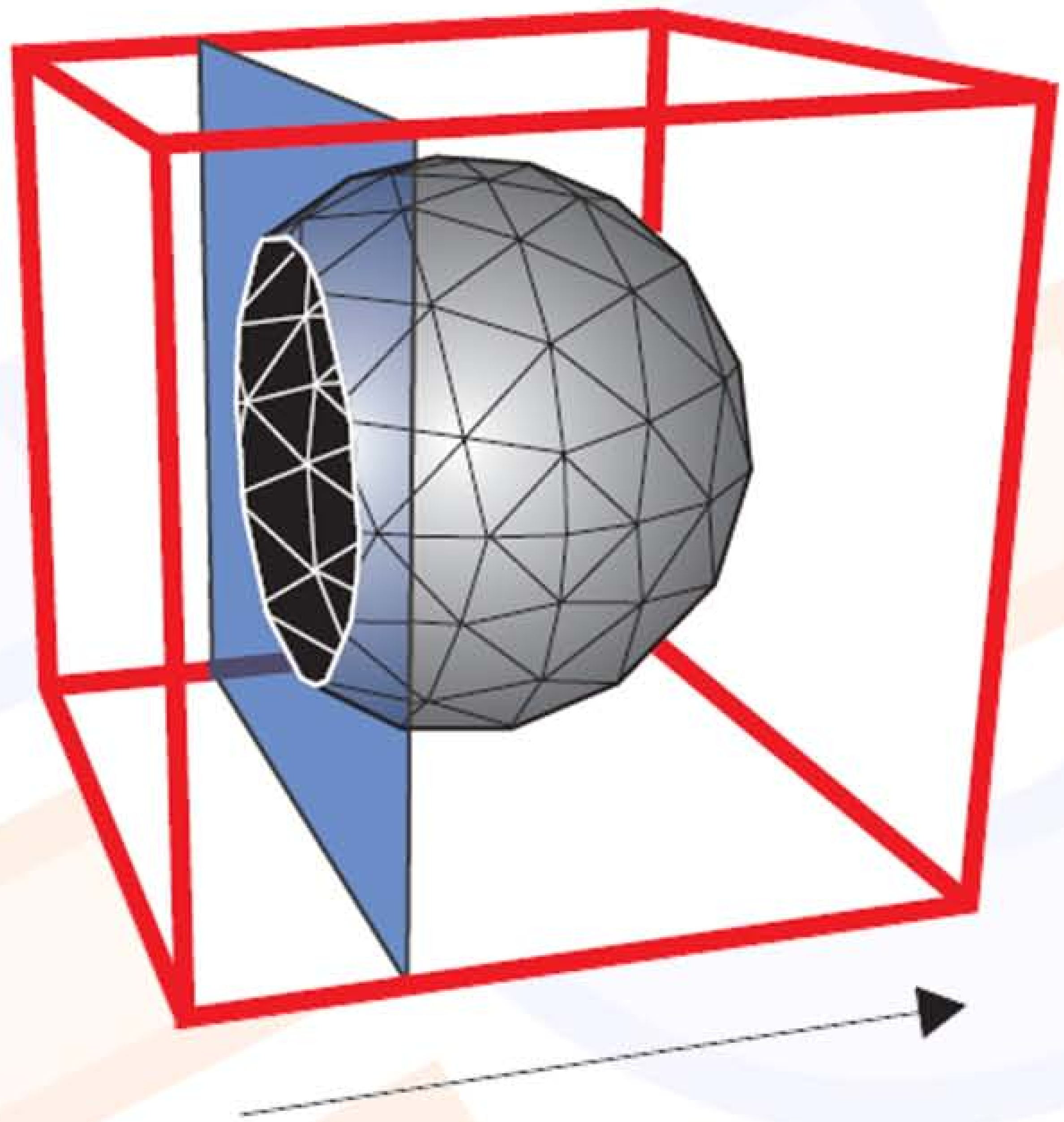
Voxelization

Step 1:
Setup a clipping plane with same position and orientation as slice.



Voxelization

Step 1:
Setup a clipping plane with same position and orientation as slice.

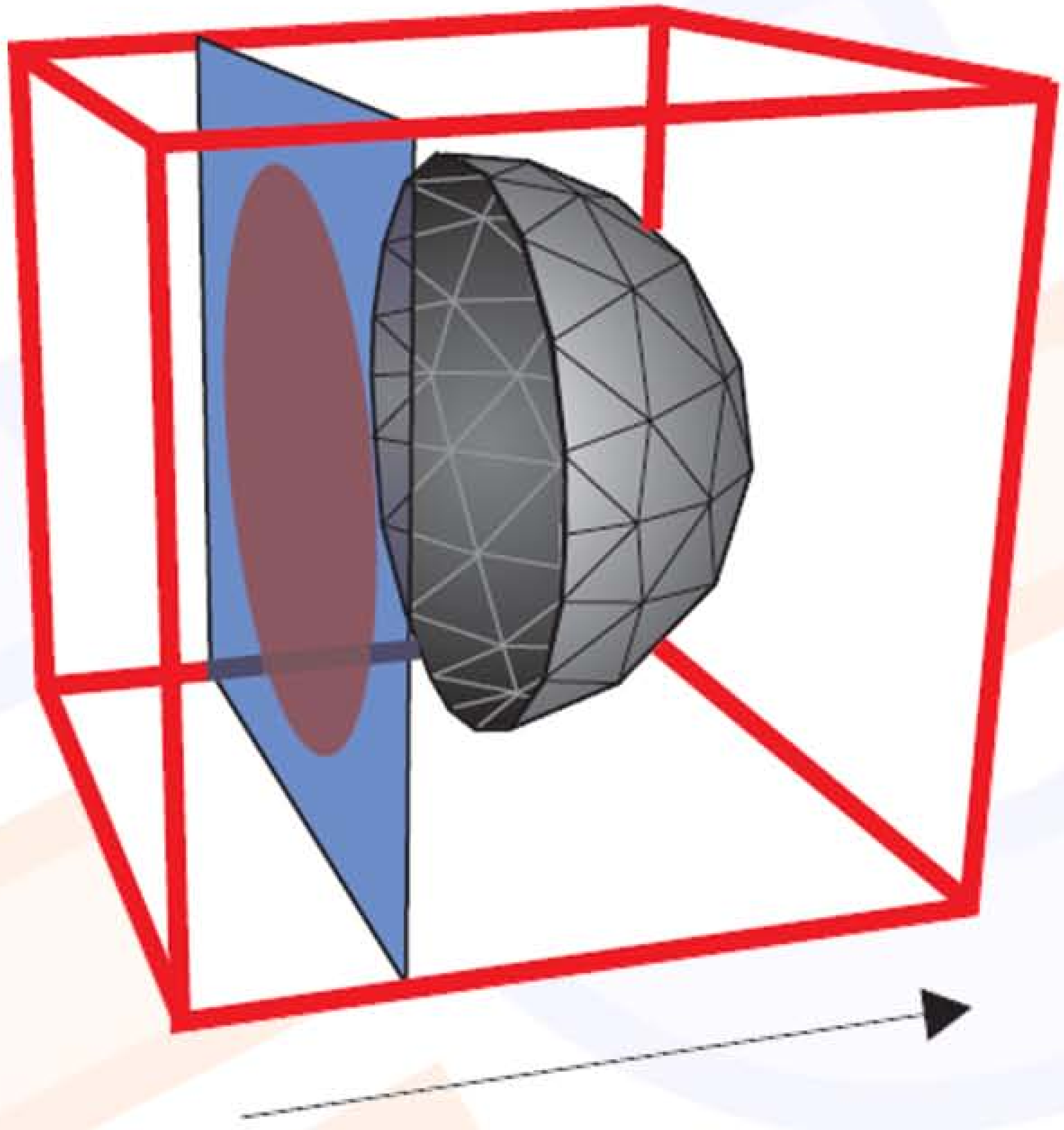


Voxelization

Step 1:
Setup a clipping plane with same position and orientation as slice.

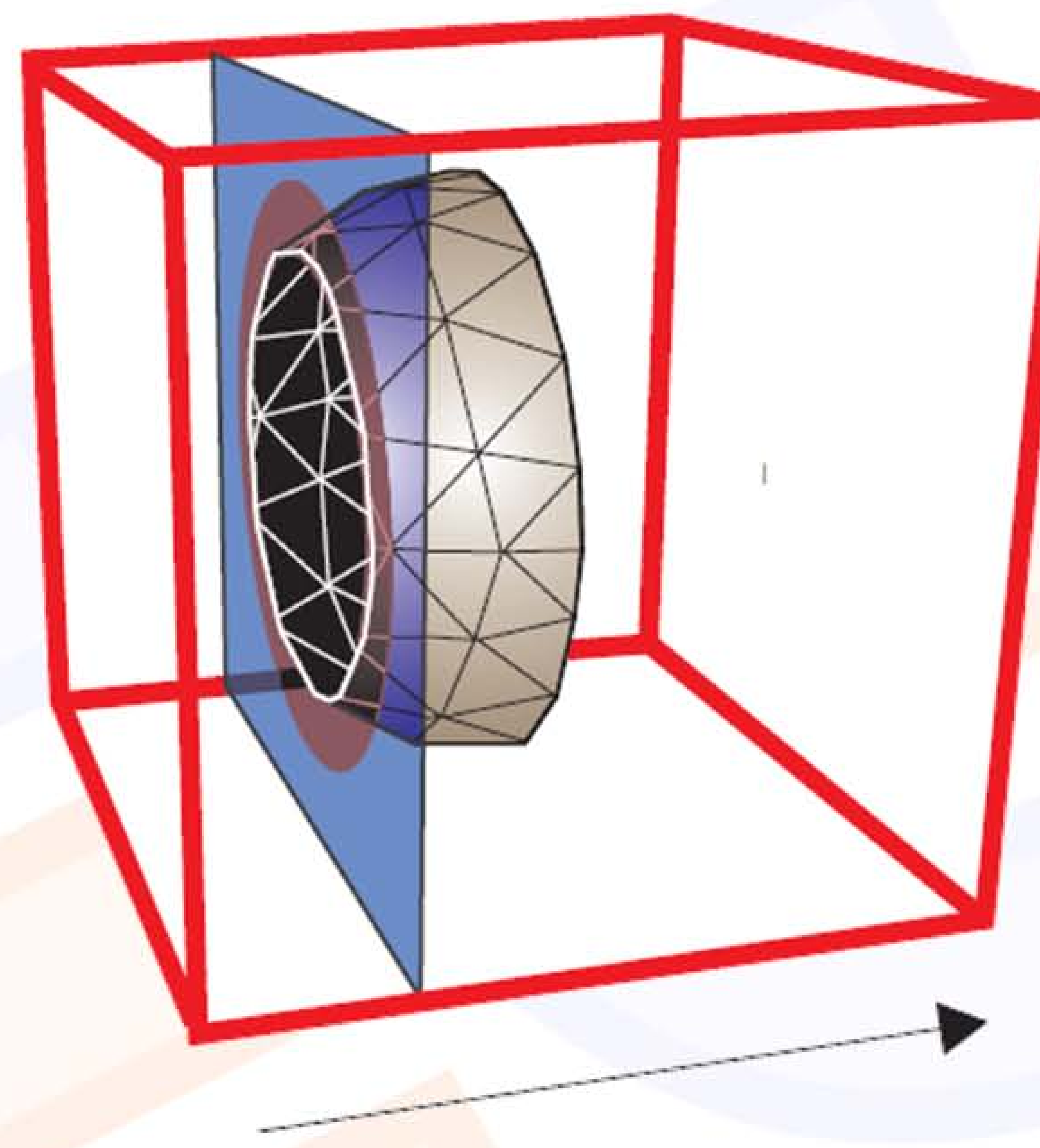
Step 2:
Clear the slice with the background color.

Render the back faces of the polygonal mesh in foreground color.



Voxelization

Step 3:
Render the front faces of the polygonal mesh in background color.

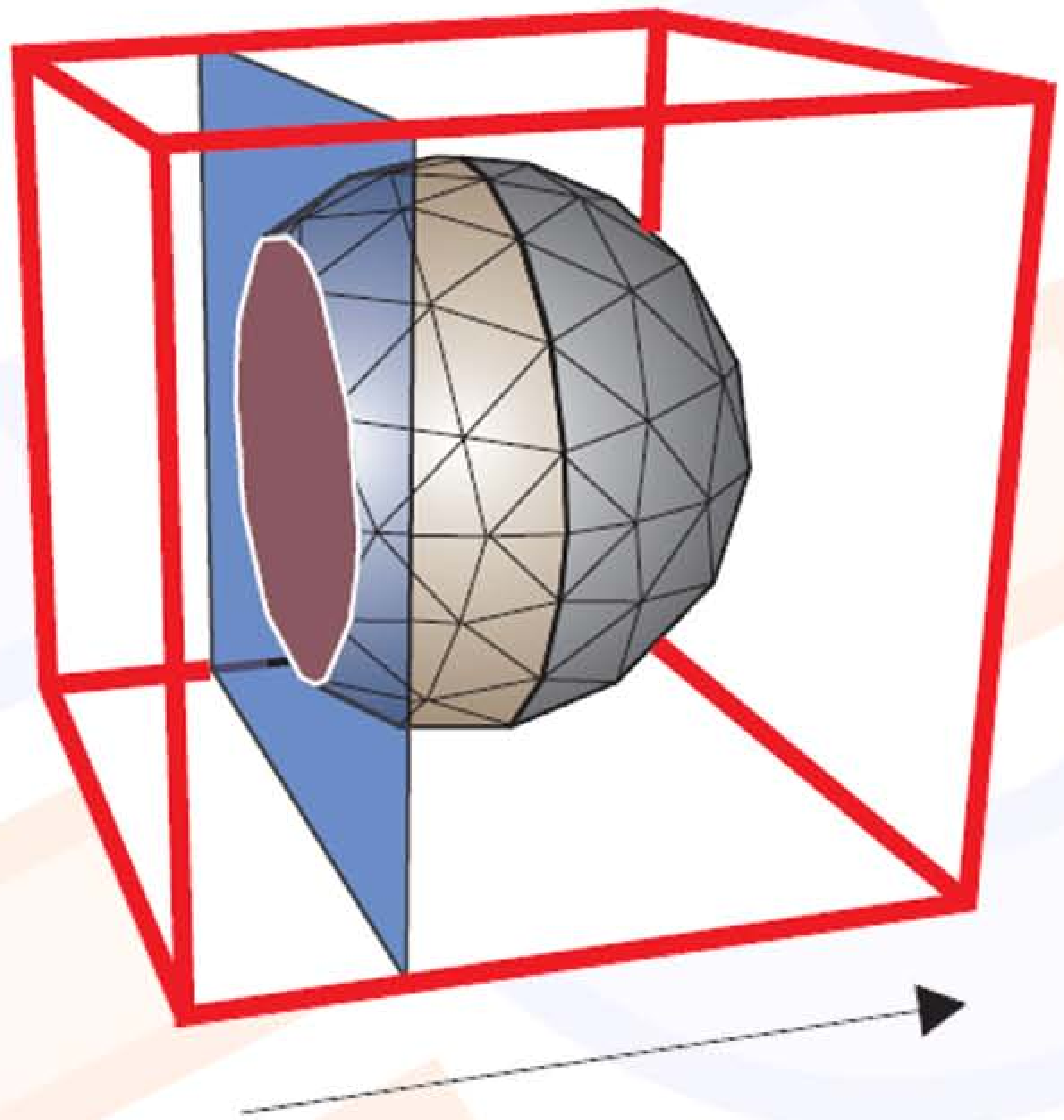


Voxelization

Step 3:
Render the front faces of the polygonal mesh in background color.

Result:
The slice buffer now contains the correct cross-section in foreground color.

Repeat the whole process for the next slice image.



Procedural Volumes

- Volume data which is defined by a procedure instead of a texture
- *Example:* Spectral Synthesis

$$v(x) = \sum_{i=0}^{N} A_i \sin(f_i\, x + \varphi_i)$$

Amplitude

Frequency

Phase Shift

Procedural Volumes

- Volume data which is defined by a procedure instead of a texture
- *Example*: Spectral Synthesis

$$v(x) = \sum_{i=0}^{N} A_i \sin(f_i\, x + \varphi_i)$$

- Fractal Power Spectrum:
  Amplitudes of the individual waves are inversely proportional their frequency.

Procedural Volumes

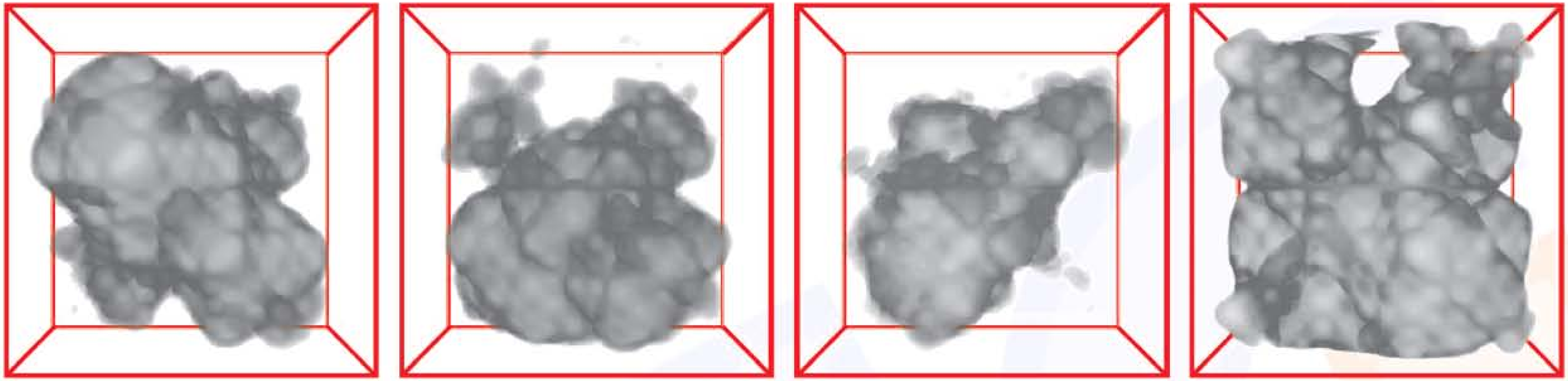
```
half4 main(half3  uvw  :  TEXCOORD0,
           uniform half3 phases[5],
           uniform half  startStep,
           uniform half  endStep) :  COLOR
{
    float value = 0.0;
    float frequency = 3.0;
    float amplitude = 0.5;

    for(int i = 0; i < 5; ++i) {
        half3 phase = phases[i];

        value += amplitude *
           sin(frequency*uvw.x + phase.x) *
           sin(frequency*uvw.y + phase.y) *
           sin(frequency*uvw.z + phase.z);

        amplitude /= 2.0;
        frequency *= 2.0;
    }
```

Procedural Volumes

```
    float frequency = 3.0;
    float amplitude = 0.5;

    for(int i = 0; i < 5; ++i) {
        half3 phase = phases[i];

        value += amplitude *
           sin(frequency*uvw.x + phase.x) *
           sin(frequency*uvw.y + phase.y) *
           sin(frequency*uvw.z + phase.z);

        amplitude /= 2.0;
        frequency *= 2.0;
    }

    value = abs(value);
    float alpha = smoothstep(startStep,endStep,value);

    return half4(value.rrr, alpha*alpha);
}
```

Procedural Volumes

Good for modeling clouds, fog and smoke



Phase shifts can be animated over time

Alternative: Use random noise instead of sine function

$$\text{turbulence}(\mathbf{x}) = \sum_{i=0}^{N} A_i \cdot \text{noise}(f_i \cdot \mathbf{x})$$

Volume Perturbation

Use procedural field to offset texture coordinates:

```
half4 main(half3  uvw  :  TEXCOORD0,
           uniform half       amplitude
           uniform sampler3D noiseTex,
           uniform sampler3D dataTex) :  COLOR
{
  // calculate the turbulence field
  half3 perturb = 0.0;
  perturb += 1.0   * tex3D(noiseTex, 2.0*uvw) - 0.5;
  perturb += 0.5   * tex3D(noiseTex, 4.0*uvw) - 0.25;
  perturb += 0.25  * tex3D(noiseTex, 8.0*uvw) - 0.125;
  perturb += 0.125 * tex3D(noiseTex,16.0*uvw) - 0.0625;

  uvw += amplitude * perturb;

  return tex3D(dataTexture,uvw);
}
```

Volume Perturbation

Original Volume

Procedural Fur

Deformation and Animation

Deformable Volumetric Objects

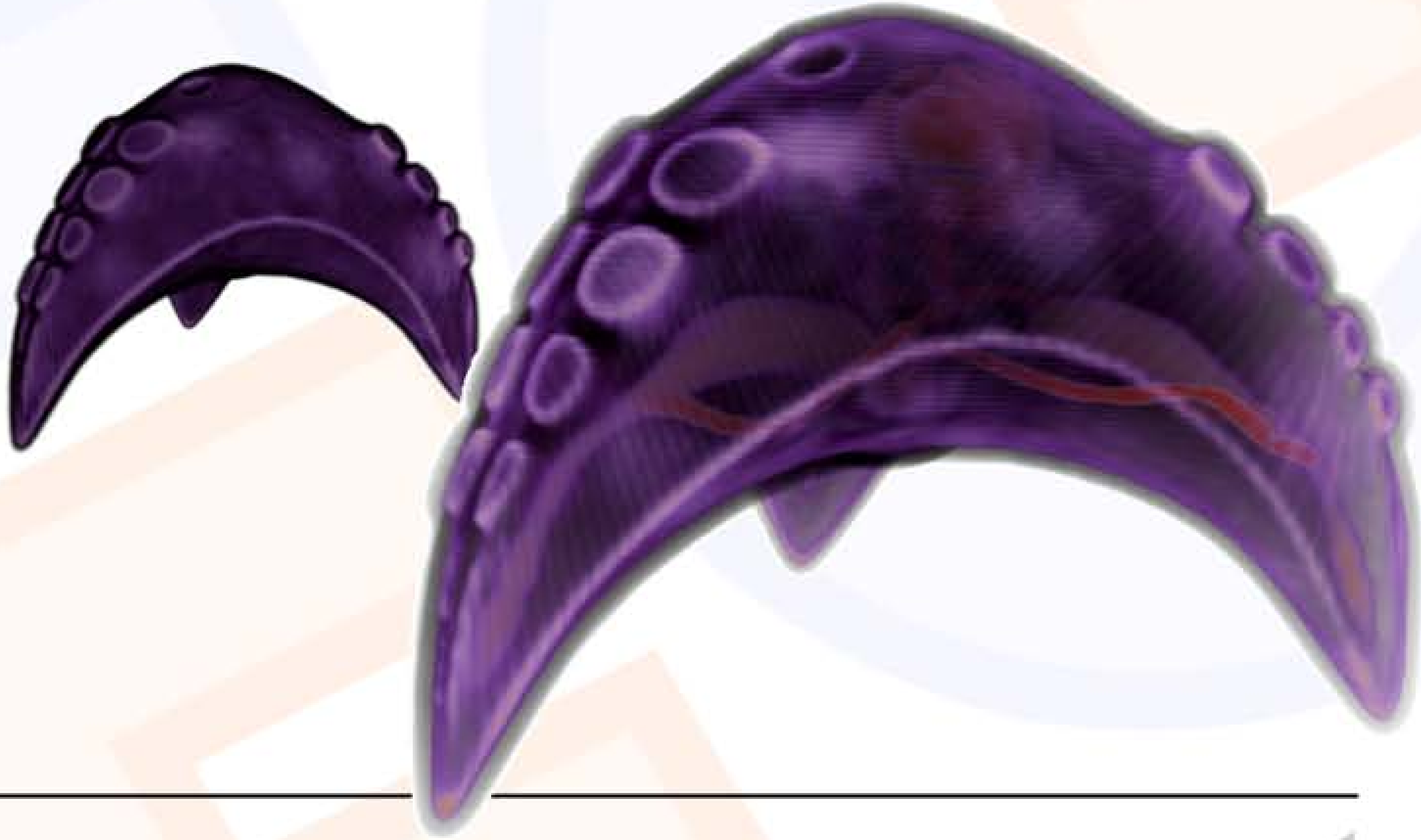
- *Applications in Science*
  - Medicine
  - Engineering
  - Natural Science

Deformation and Animation

Deformable Volumetric Objects

- *Applications in Science*
  - Medicine
  - Engineering
  - Natural Science

- *Applications in Arts*
  - Translucent Objects with true volumetric deformation
  - Keyframe Animation
  - Procedural Animation



Modelling

- Traditional Modelling:
  Separation of Shape from Appearance

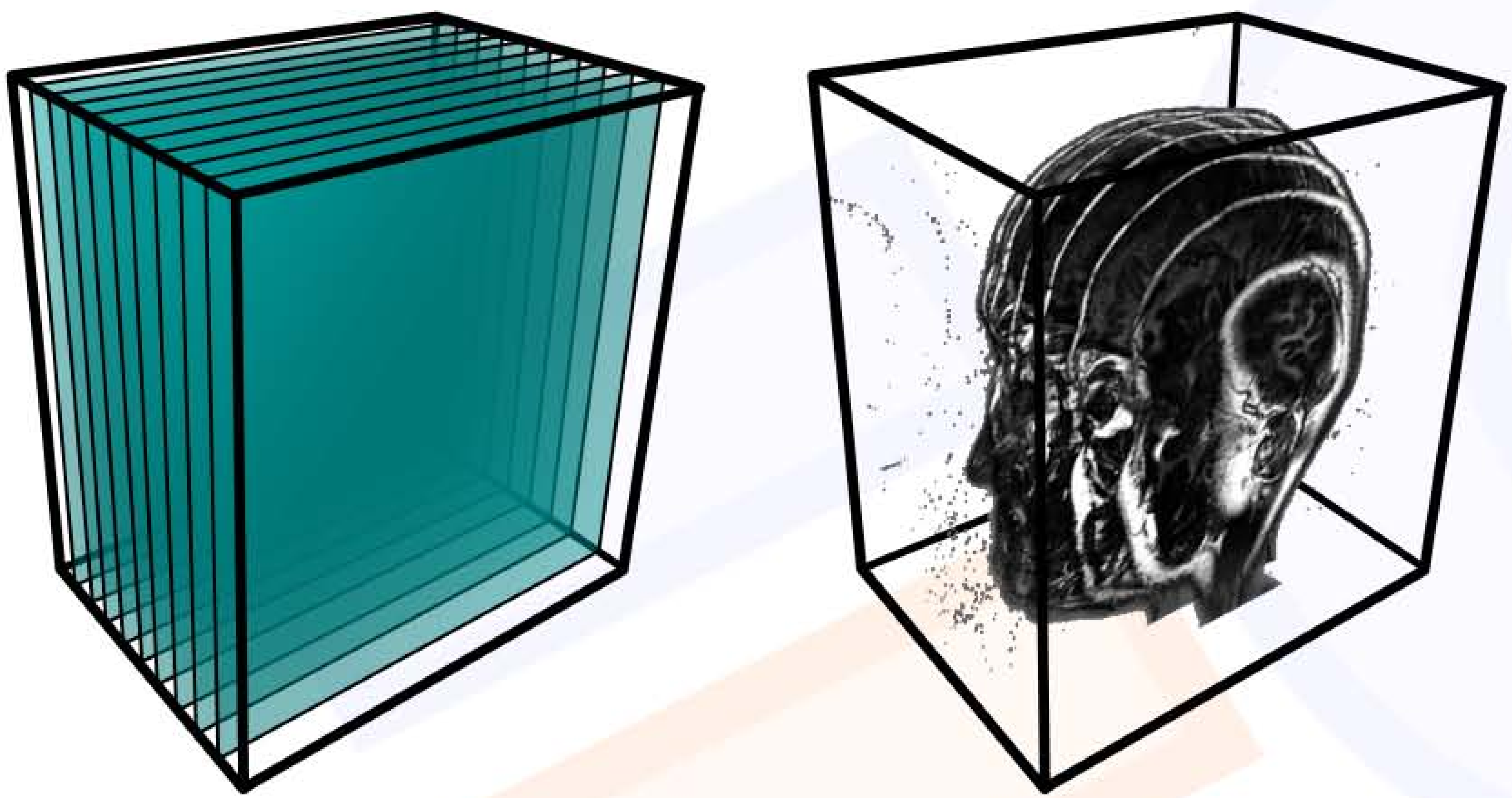
Images from Maya Animation Course, © Rezk-Salama, University of Siegen

- *Deformation of the Shape (Geometry) only*
- *Appearance (Materials, Textures etc.) remain unchanged*

Texture Based VR

Shape and Appearance

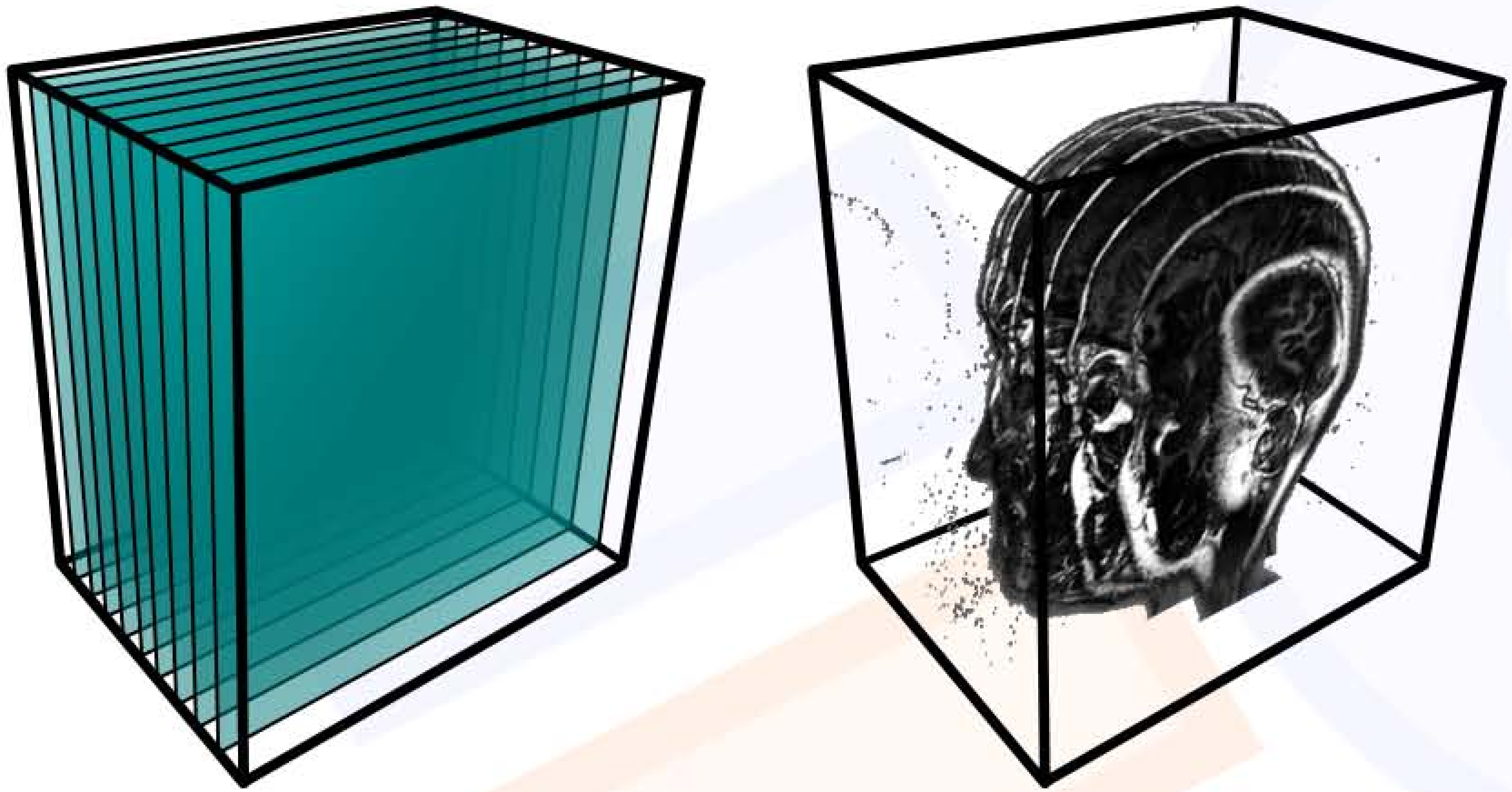
- Proxy geometry does not define the shape of object
- Both shape and appearance are defined by 3D textures



Texture Based VR

Shape and Appearance

- Proxy geometry does not define the shape of object
- Both shape and appearance are defined by 3D textures



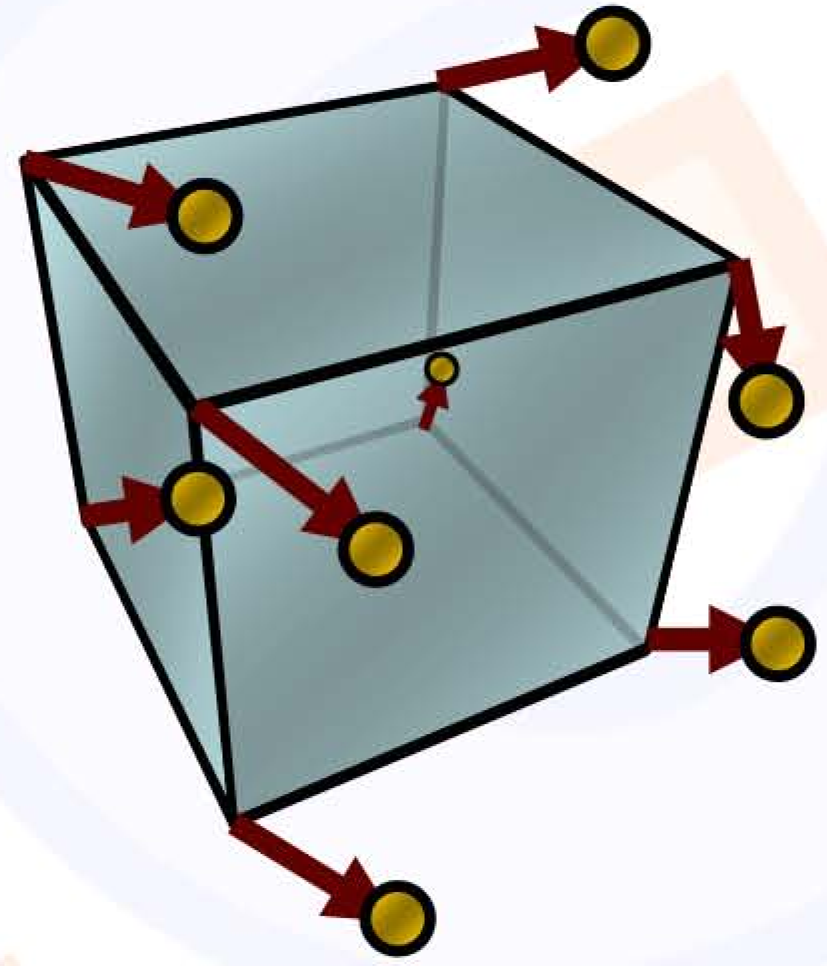
Should we deform the proxy geometry or the textures?

Mathematical Models

Deformation Models for Texture-Based VR

- Deforming the proxy geometry

First Idea:
Simply displace the 8 corner vertices of the bounding box (before slicing it)



Mathematical Models

Deformation Models for Texture-Based VR

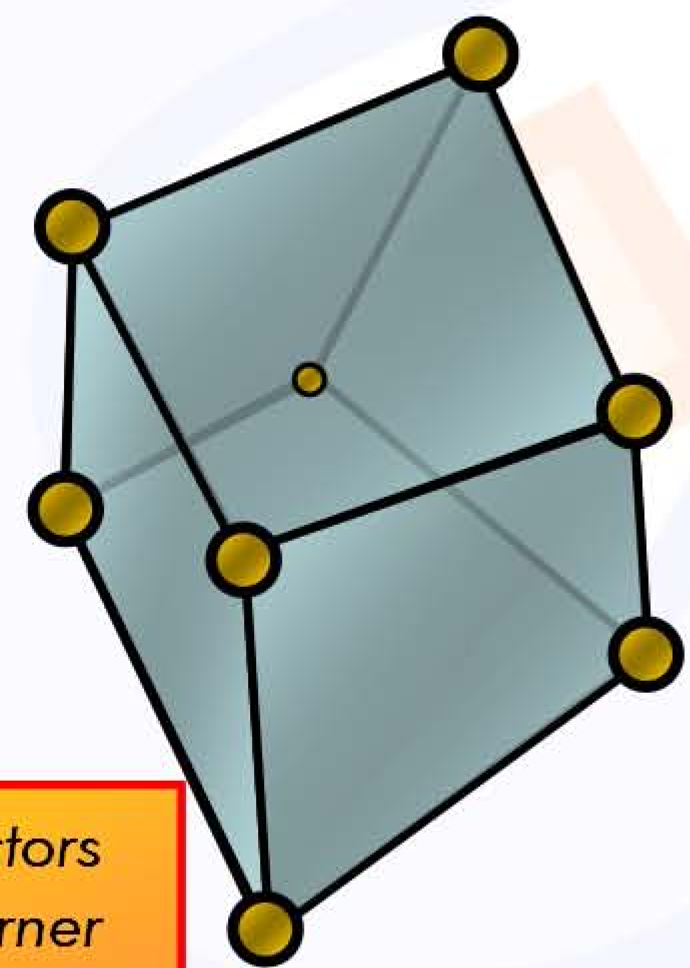
- Deforming the proxy geometry

First Idea:
Simply displace the 8 corner vertices of the bounding box (before slicing it)
Mathematical Description:

$$\Phi(\vec{x}) = \vec{x} + \sum_{i,j,k \in \{0,1\}} a_{ijk} \cdot \vec{t}_{ijk}$$

Trilinear interpolation weights of point x in the undeformed grid

Translation vectors given at the corner vertices



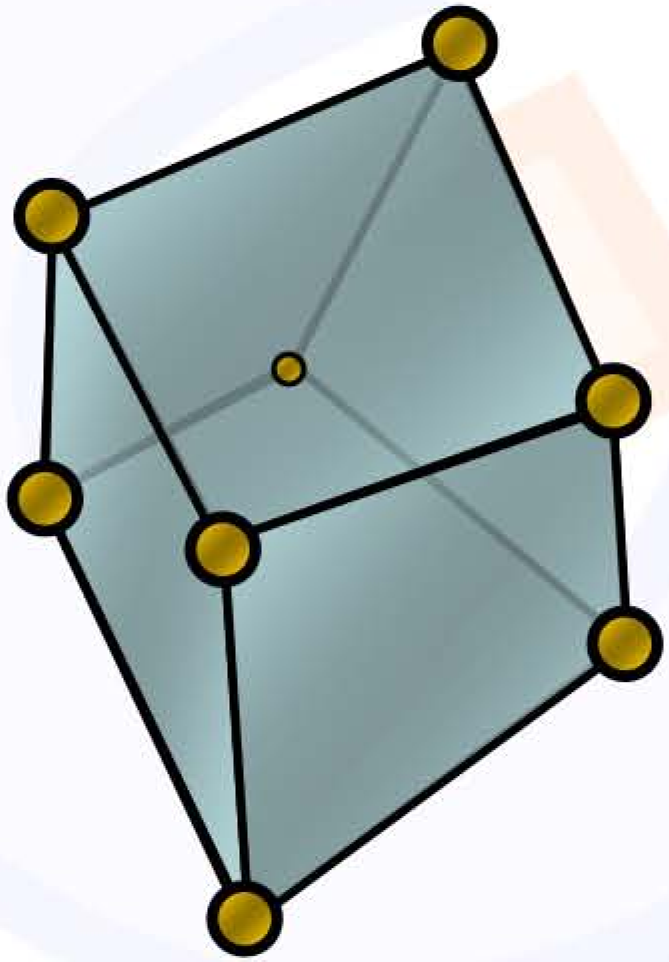
Mathematical Models

Deformation Models for Texture-Based VR

- Deforming the proxy geometry

First Idea:
Simply displace the 8 corner vertices of the bounding box (before slicing it)
Mathematical Description:

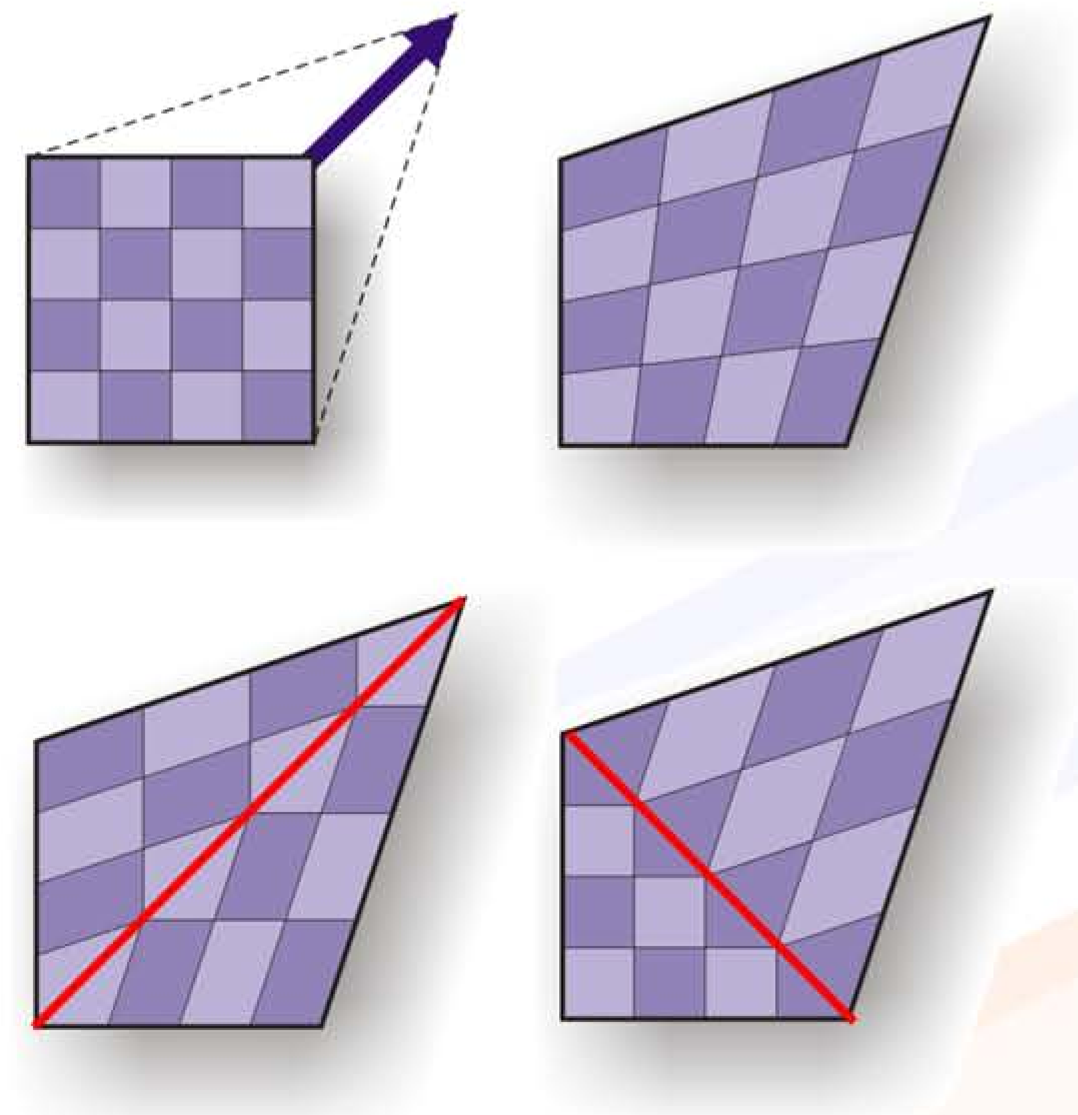
$$\Phi(\vec{x}) = \vec{x} + \sum_{i,j,k \in \{0,1\}} a_{ijk} \cdot \vec{t}_{ijk}$$



Difficulties: The inverse transformation is not again a trilinear function!

Mathematical Models

- *What do we need the inverse for?*



If we displace the vertices, but keep the texture coordinates constant,

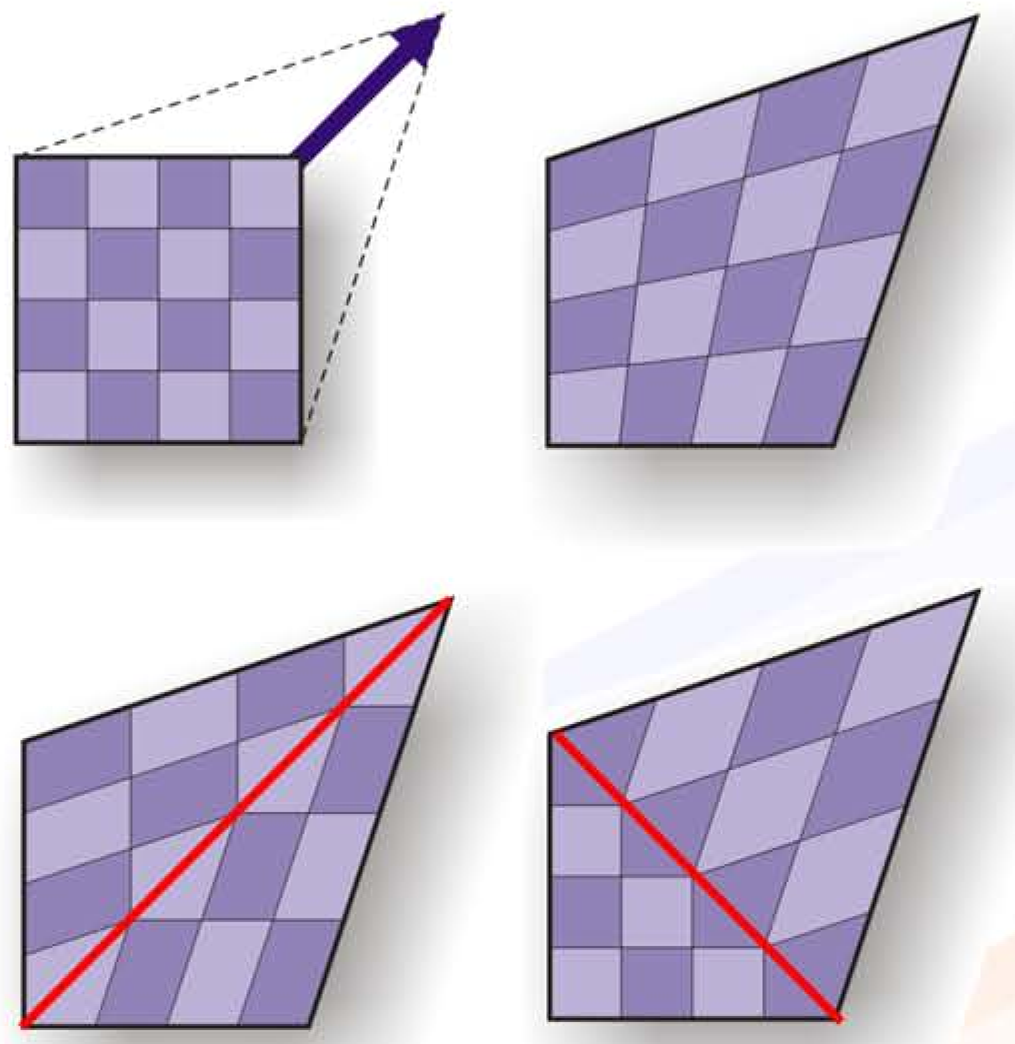
Tessellation into triangles produces undesired results.

Rasterization:
For the desired bilinear/trilinear mapping,

the inverse transformation is required to determine the correct texture coordinates.

Mathematical Models

- *What do we need the inverse for?*



If we displace the vertices, but keep the texture coordinates constant,

Tessellation into triangles produces undesired results.

Rasterization:
For the desired bilinear/trilinear mapping,

the inverse transformation is required to determine the correct texture coordinates.

In 3D: polygons also become non-planar in texture space!

Mathematical Models

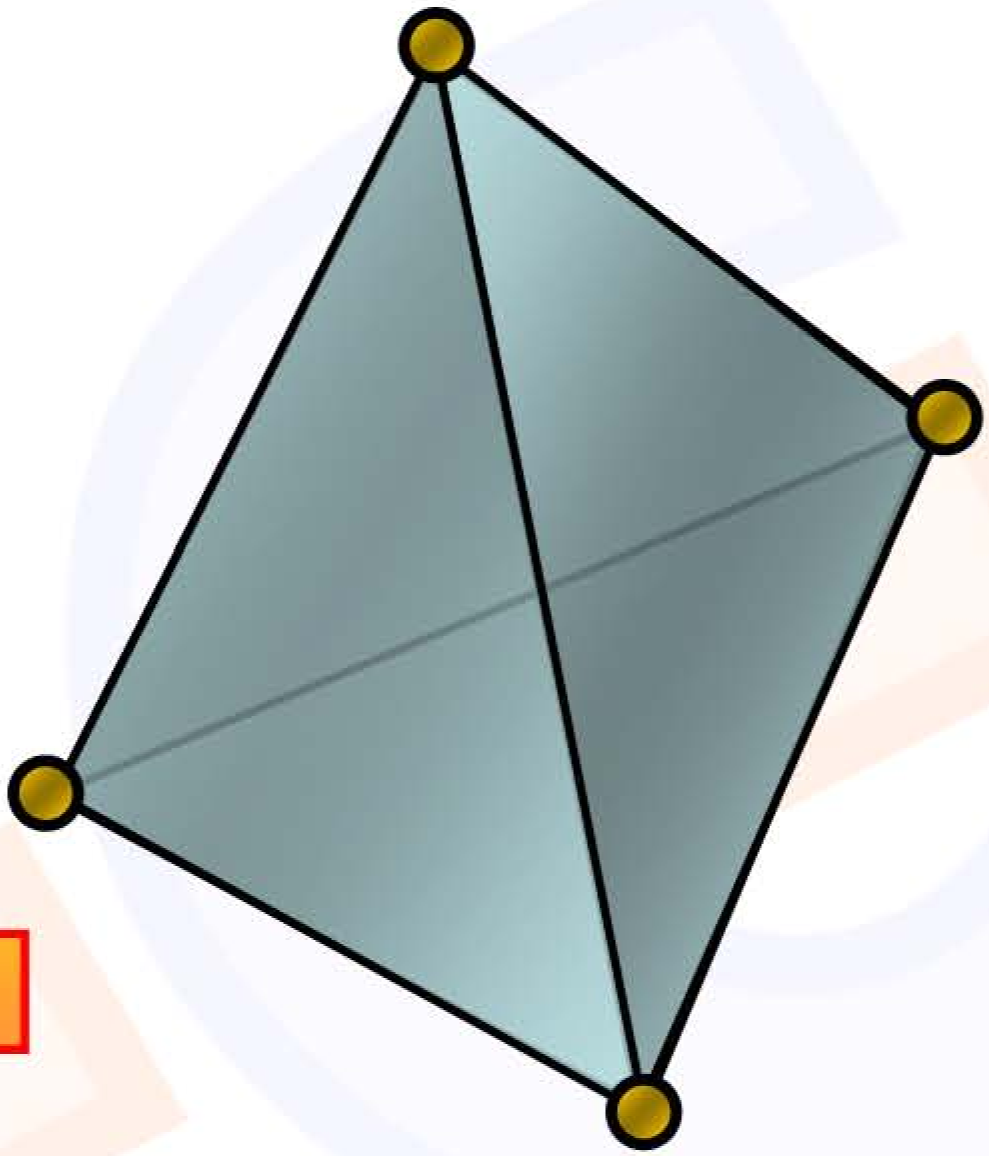
Deformation Models for Texture-Based VR

- Deforming the proxy geometry

Second Idea:
Use tetrahedra as proxy geometry
Displace the 4 corner vertices.
Mathematical Description:

$$\Phi(\vec{x}) = \mathbf{A}\vec{x} + \vec{b}$$

Rotation and Scaling — *Translation*



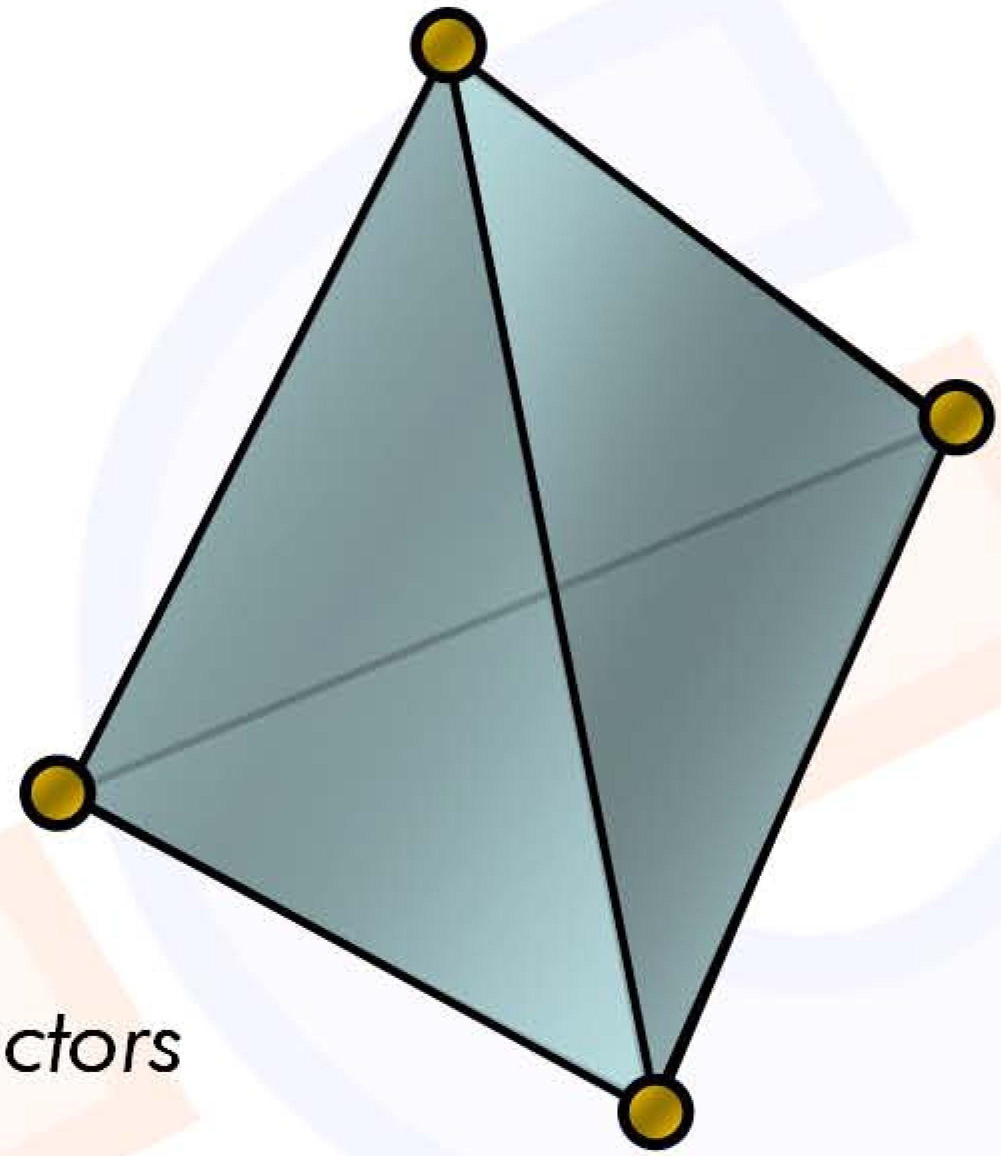
Mathematical Models

Deformation Models for Texture-Based VR

- Deforming the proxy geometry

Second Idea:
Use tetrahedra as proxy geometry
Displace the 4 corner vertices.
Mathematical Description:

$$\Phi(\vec{x}) = \mathbf{A}\vec{x} + \vec{b}$$



Fully determined by 4 displacement vectors

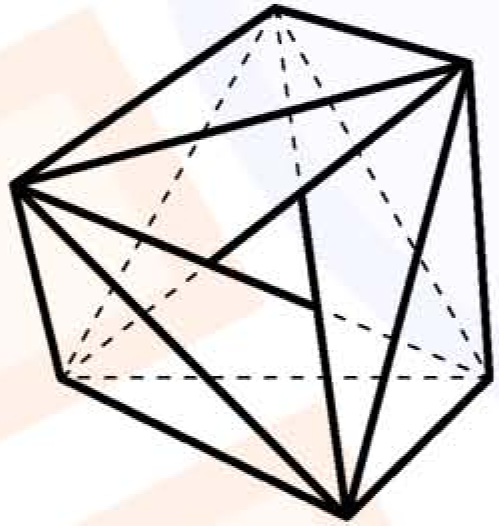
Difficulties: Tessellation, Depth Sorting

Tetrahedra Deformation

- Available in SGI's Volumizer API

Main Difficulties:

- Smooth Deformation requires high tessellation
- Depth sorting arbitrary tetrahedra meshes is a difficult problem
  - Especially true for non-convex tetrahedra meshes
  - Sorting not always possible (Visibility Cycles!)

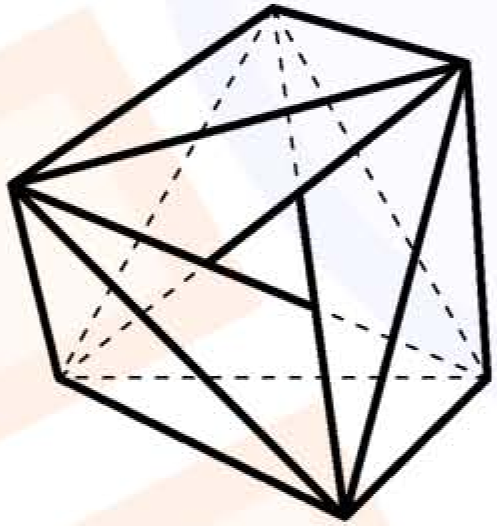


Tetrahedra Deformation

- Available in SGI's Volumizer API

Main Difficulties:

- Smooth Deformation requires high tessellation
- Depth sorting arbitrary tetrahedra meshes is a difficult problem
  - Especially true for non-convex tetrahedra meshes
  - Sorting not always possible (Visibility Cycles!)
- Slice Decomposition
  - Mainly performed on CPU



Mathematical Models

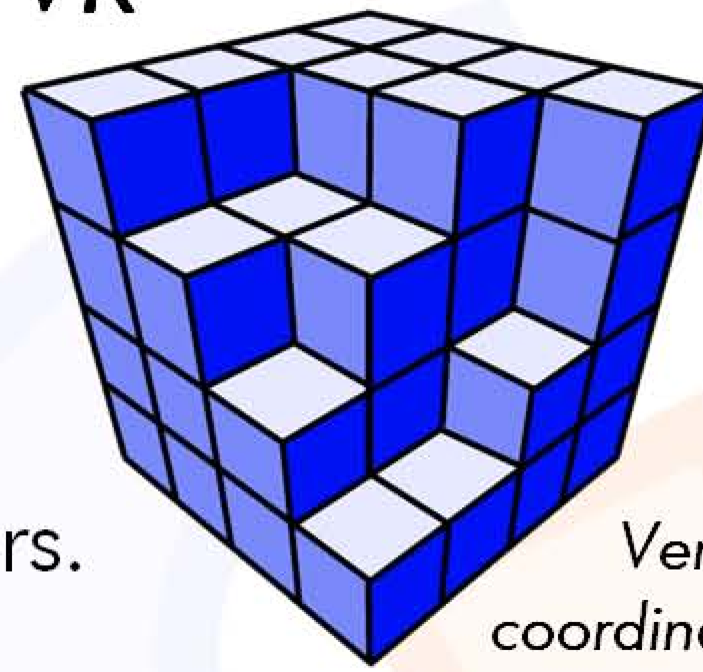
Deformation Models for Texture-Based VR

- Deforming the appearance (textures)

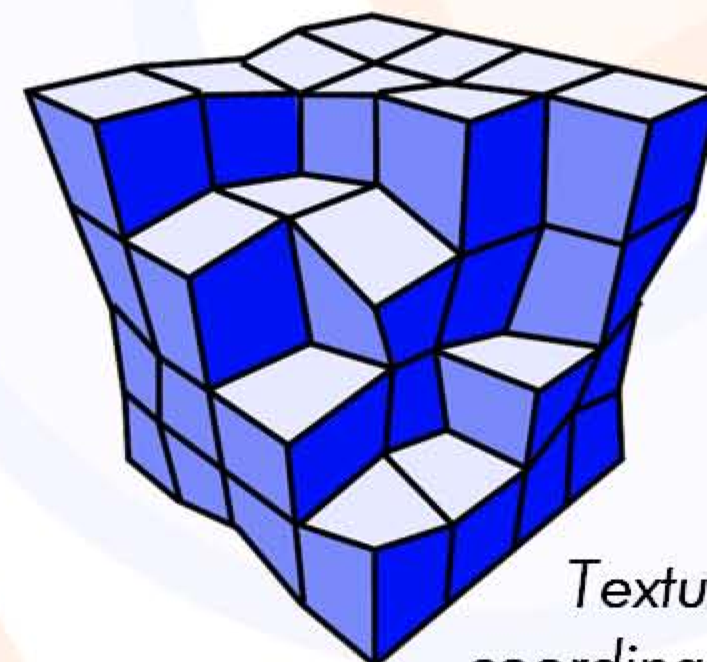
Piecewise Linear Transformation:
Subdivide into hexahedra cells (3D patches)
Displace the texture coordinates at the corners.
Mathematical Description:

$$\Phi(\vec{x}) = \vec{x} + \sum_{i,j,k \in \{0,1\}} a_{ijk} \cdot \vec{t}_{ijk}$$

($\boldsymbol{x}$ now refers to the texture coordinate)



Vertex coordinates



Texture coordinates

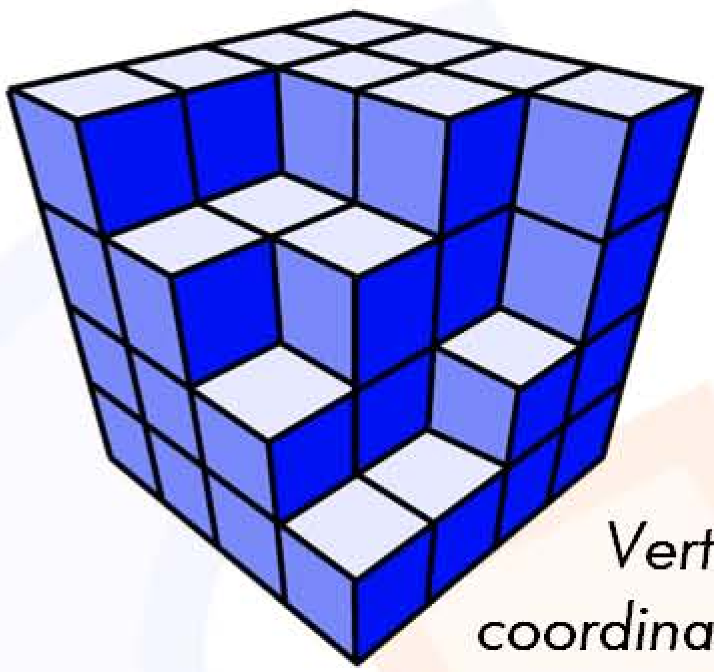
Piecewise Linear Patches

Advantages:

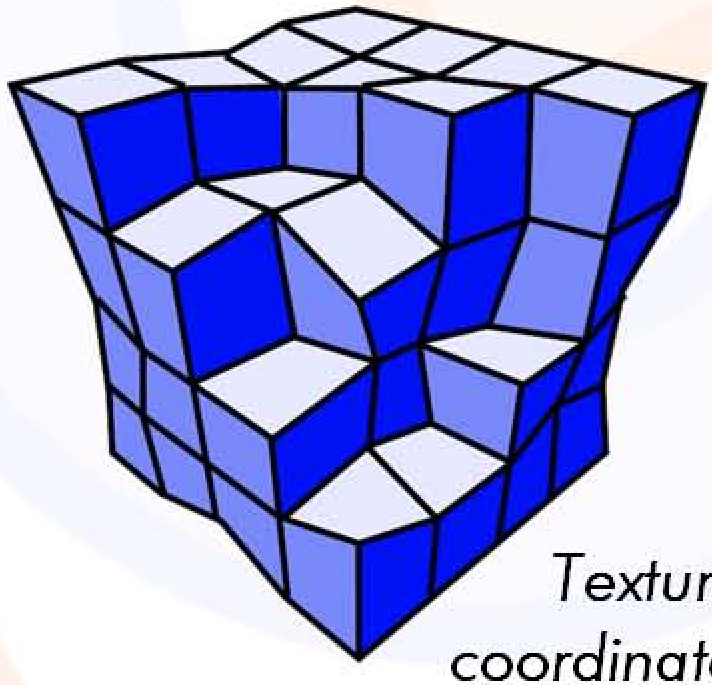
- *Geometry (vertices) is static, only texture coordinates change*
- *Slice decomposition is easy*
  - No expensive recomputation or real-time tessellation necessary
- *No depth sorting required!*
- *Adaptive subdivision possible*

Difficulties:

- How can we circumvent or approximate the *inverse deformation?*



Vertex coordinates

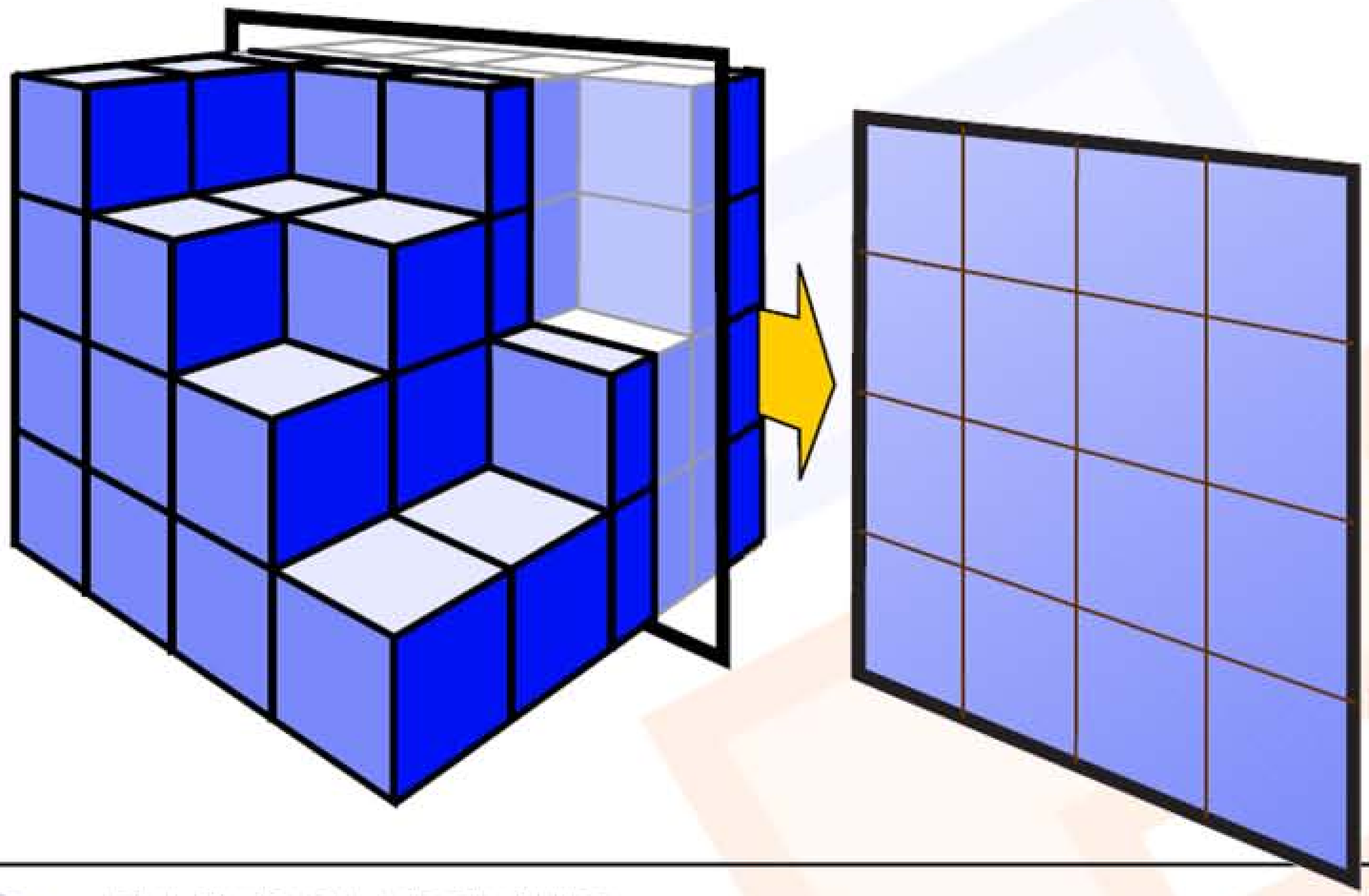


Texture coordinates

Piecewise Linear Patches

Rendering

- Store the volume as *a 3D texture*
- Static Geometry:
  use object aligned slices to preserve this benefit!



3 stacks of slices

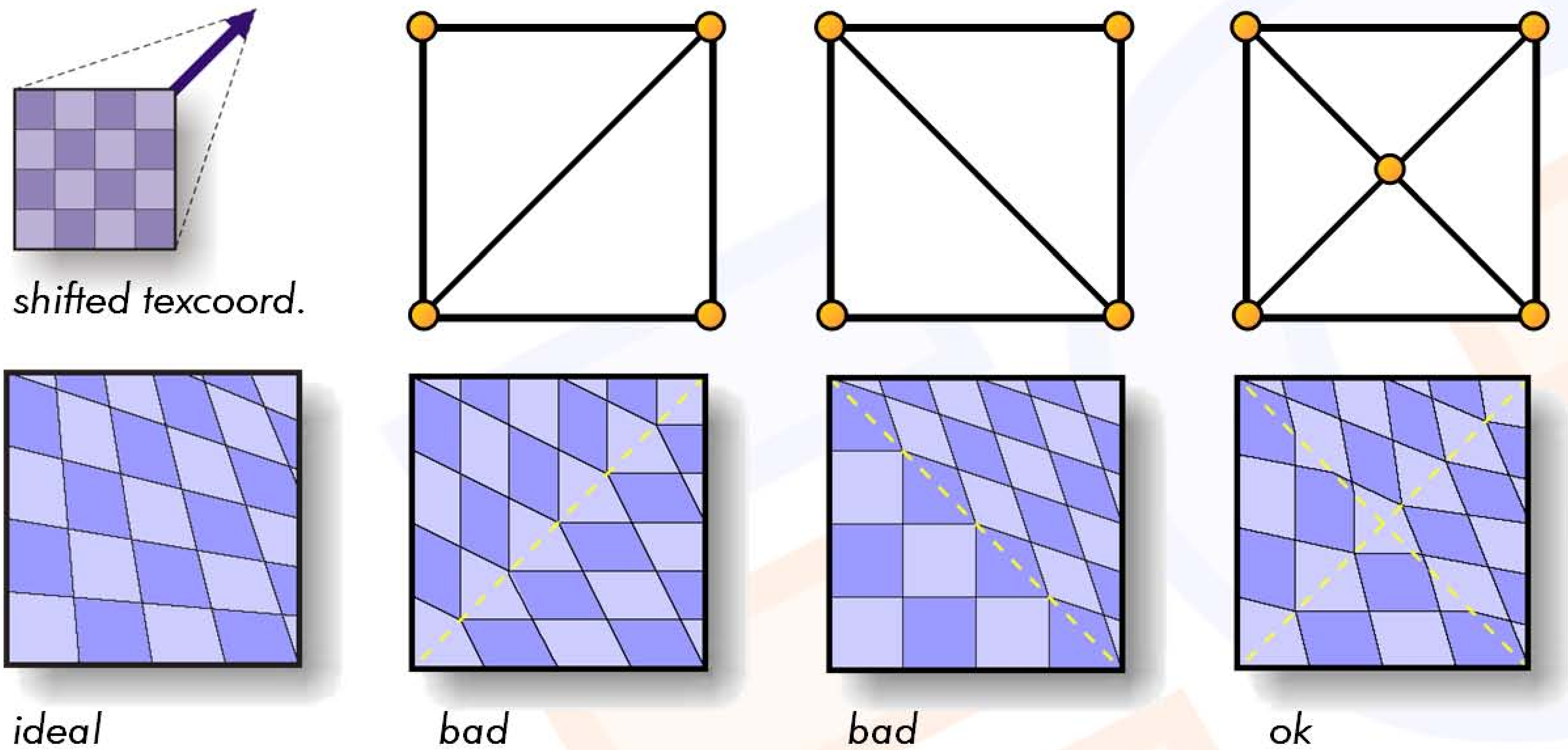
plus a 3D texture

How do we compute texture coordinates?

Piecewise Linear Patches

What do I need the inverse for?

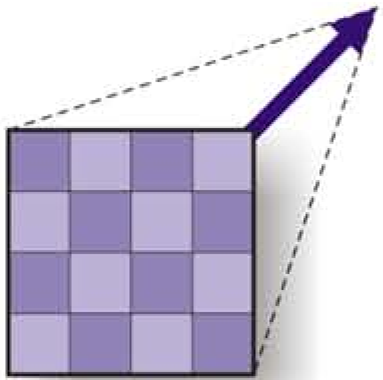
- *Texture Interpolation*



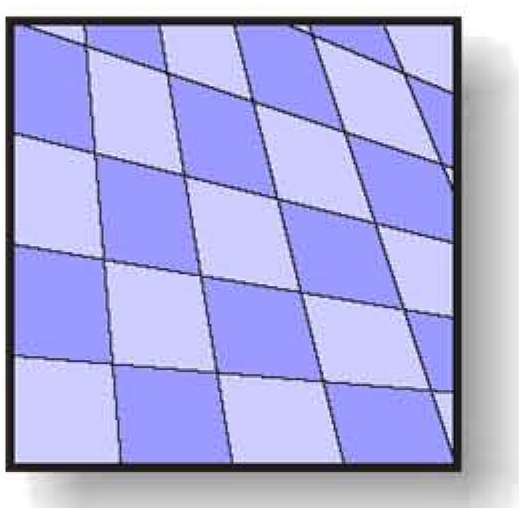
Piecewise Linear Patches

What do I need the inverse for?

- *Texture Interpolation*



shifted texcoord.



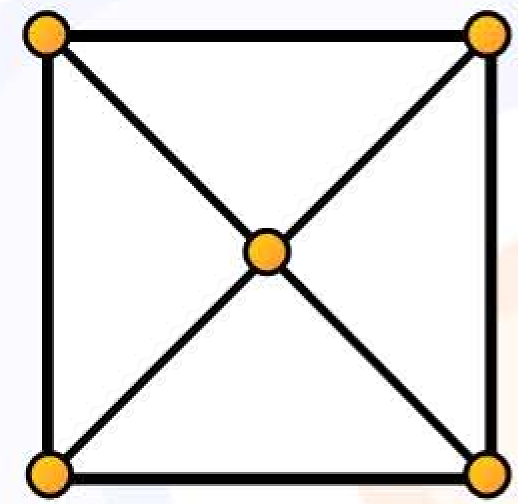
ideal

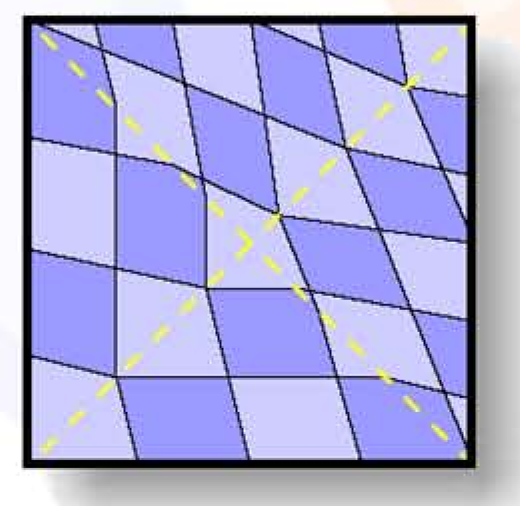
Approximate the correct bilinear interpolation by

4 interpolations in barycentric coordinates

Use higher tessellation if quality is not good enough

Geometry is static!
No depth sorting required!





ok

Piecewise Linear Patches

What do I need the inverse for?

- *Texture Interpolation*
- *Intuitive Modelling*
  - *The user does not want to manually specify texture coordinates*
  - *Instead: Picking and dragging of control points*
  - *Only coarse approximation to the correct inverse function is required:*

$$\widetilde{\Phi}^{-1}(\vec{x}) = \vec{x} + \sum_{i,j,k \in \{0,1\}} a_{ijk} \cdot -\vec{t}_{ijk}$$

simply negate the displacement vectors

Volumetric Deformation

Deformation Models for Texture-Based VR

- Deforming the appearance (textures)

Dependent Textures /Offset Textures
Specify a deformation field as an additional 3D texture.

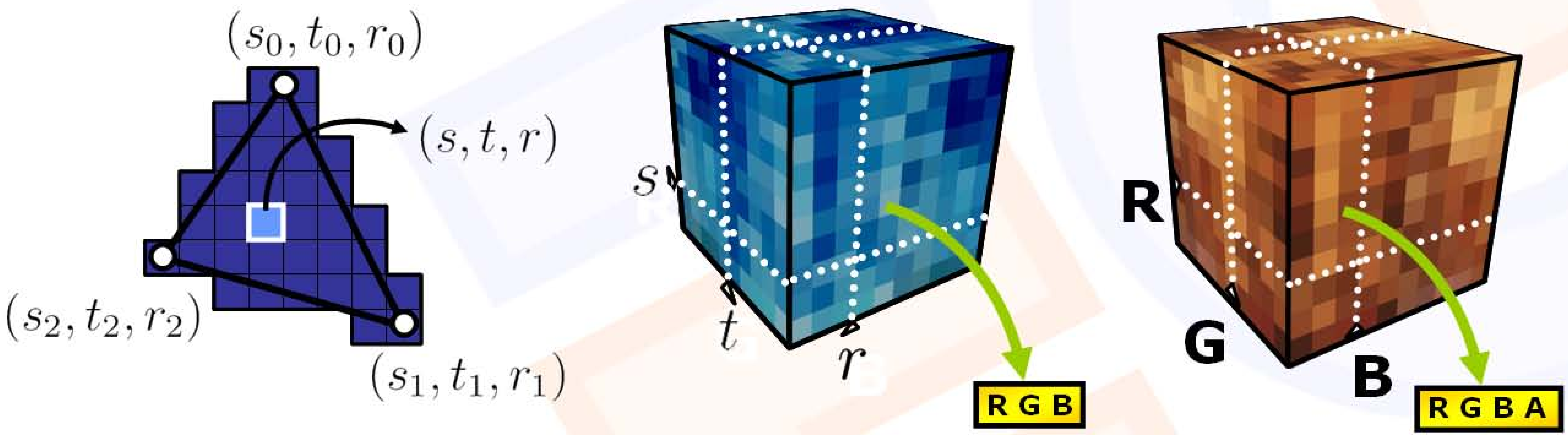
Volumetric Deformation

Deformation Models for Texture-Based VR

- Deforming the appearance (textures)

Dependent Textures /Offset Textures

Specify a deformation field as an additional 3D texture.



Dependent Textures

- Basically the same mathematical model as for piecewise linear patches
- Inverse mapping is avoided by 3D texture lookup
- Works both with object- and viewport-aligned slices
- Resolution of offset texture is independent of volume texture
- Runs completely within GPU (except slicing)
- Deformation field can be modified using render-to-3D-texture

Offset Textures

```
// Cg fragment shader for
// texture-space volume deformation

half4 main (float3 texcoords :  TEXCOORD0,
            uniform sampler3D offsetTexture,
            uniform sampler3D volumeTexture) : COLOR0
{
   float3 offset = tex3D(offsetTexture, uvw);

   uvw = uvw + offset;

   return tex3D(volumeTexture, uvw);
}
```

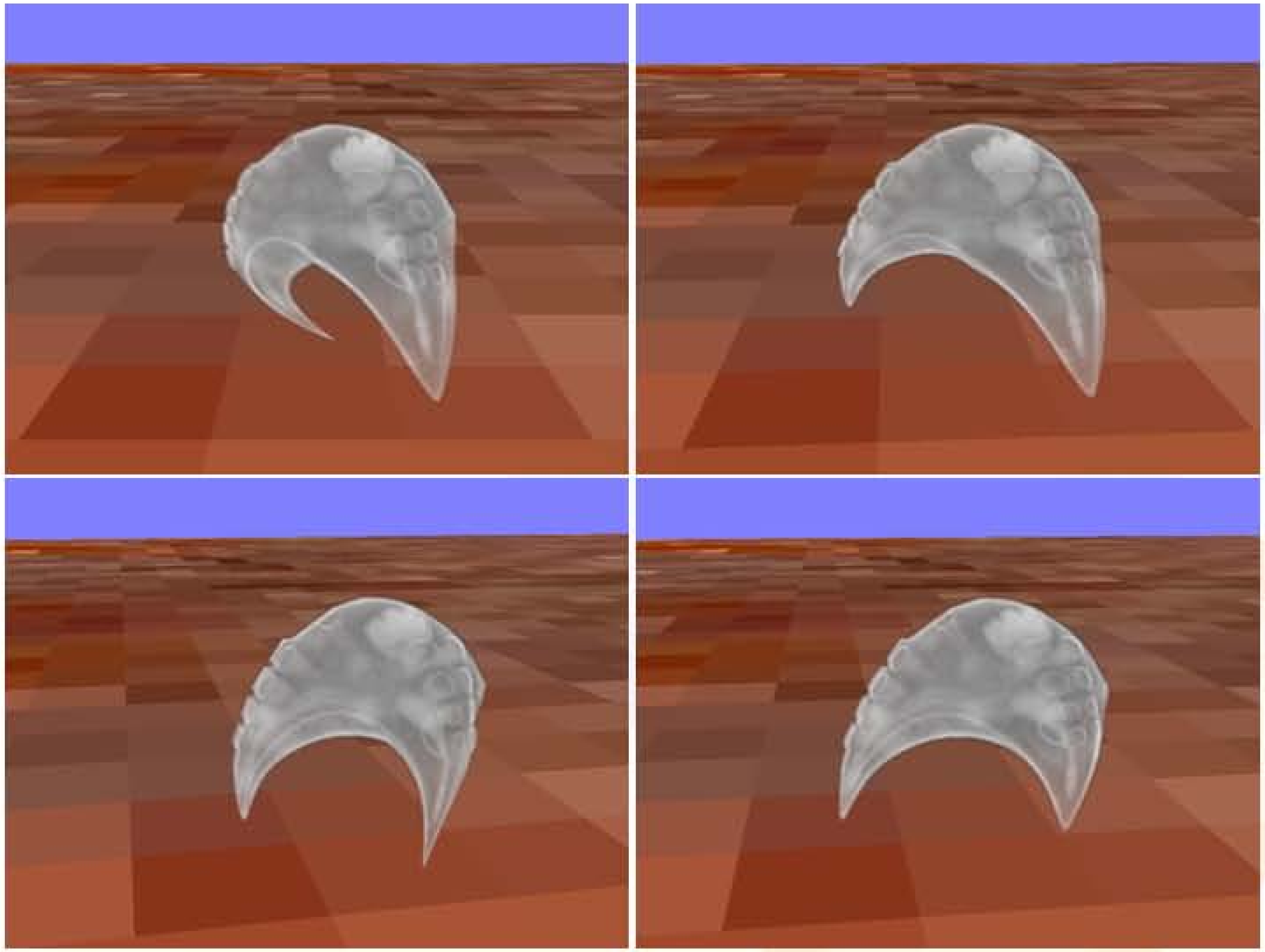
Volume Animation

- *Keyframe Animation/Blend Shapes:*
  - Easy with piecewise linear patches (simple vertex shader)
  - Offset textures: interpolate between different offset textures in fragment shader
- *Skeleton Animation:*
  - Use piecewise linear patches with matrix skinning in the vertex shader.
  - Dependent textures: Read the skin weights from 3D texture and caluclate offset in fragment shader.
- *Procedural Animation:*

  Calculate 3D offsets on-the-fly in the fragment shader

Texture Deformation

- Deformation field does not need to be stored in a texture
- Use procedural animation instead!



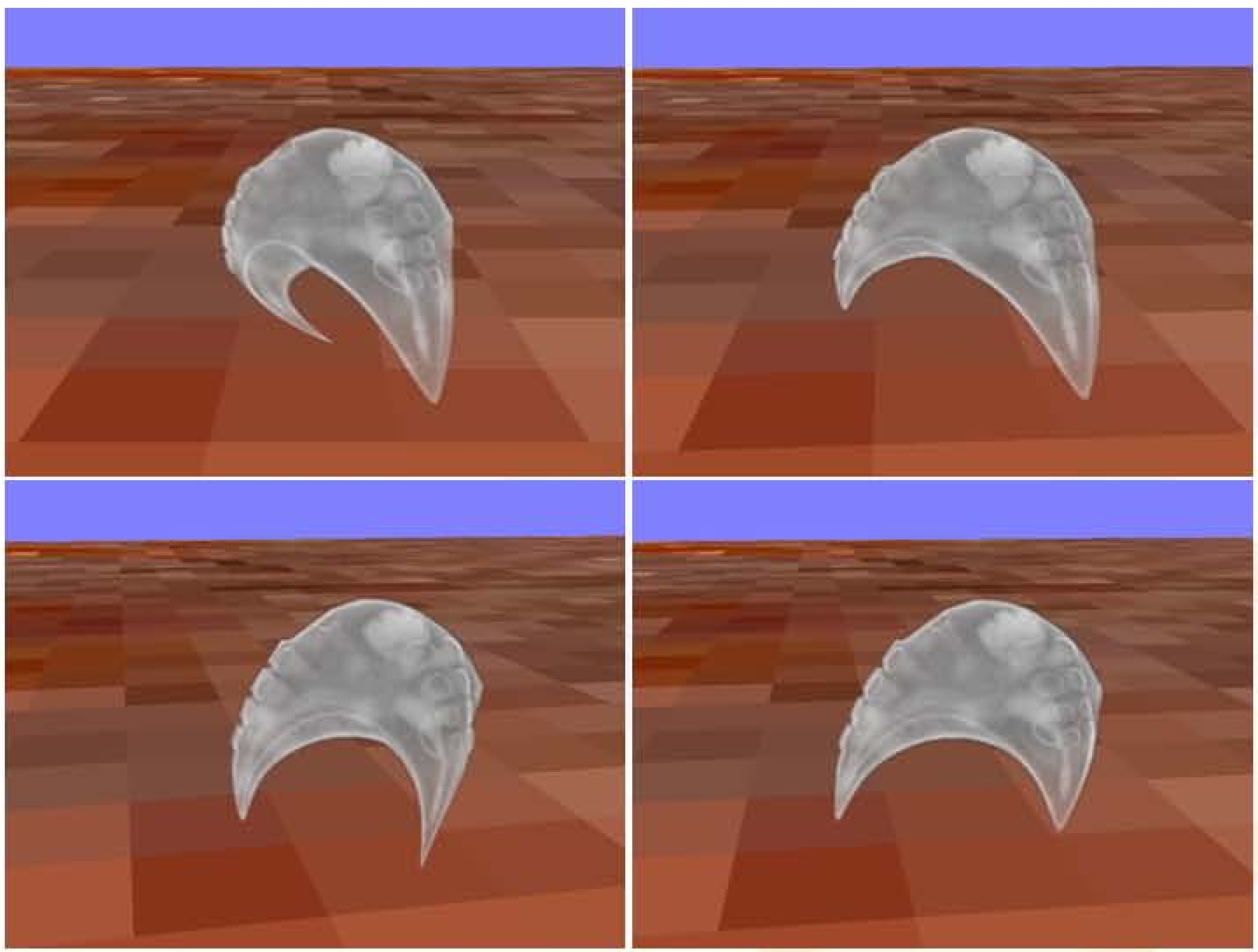
Example: Tripod Creature

Texture offsets parameterized in cylinder coordinates

Animation procedure moves 3 legs independently

Texture Deformation

- Deformation field does not need to be stored in a texture
- Use procedural animation instead!



```
#define PI (3.1415)

half modulo(half a, half b) {

    a -= floor(a/b)*b;
        if (a < 0) a+=b;
        return a;
}

half4 main( half3  uvw      : TEXCOORD0,
            uniform sampler3D volumeTexture,
            uniform half3 move1,
            uniform half3 move2,
            uniform half3 move3) : COLOR
{

        half3 P = uvw - half3(0.32,0.5,0.5);

        const half starangle = 2.0*PI/3.0;
        half angle = PI + atan2(P.z,P.x);
        half whichLeg = floor(angle/starangle);
        half A = modulo(angle, starangle)*3.0/2.0;
        half weight = sin(A);

        half moveY = 1.2-uvw.y;
        moveY *= moveY;
        moveY *= moveY;

        weight *= moveY;

        if (whichLeg  < 1) {
                uvw -= move1 * weight;
        } else if (whichLeg  < 2) {
                uvw -= move2 * weight;
        } else {
                uvw -= move3 * weight;
        }

        half4 color = tex3D(volumeTexture,uvw);

        return half4(color);
}
```