Volume Deformation and Animation

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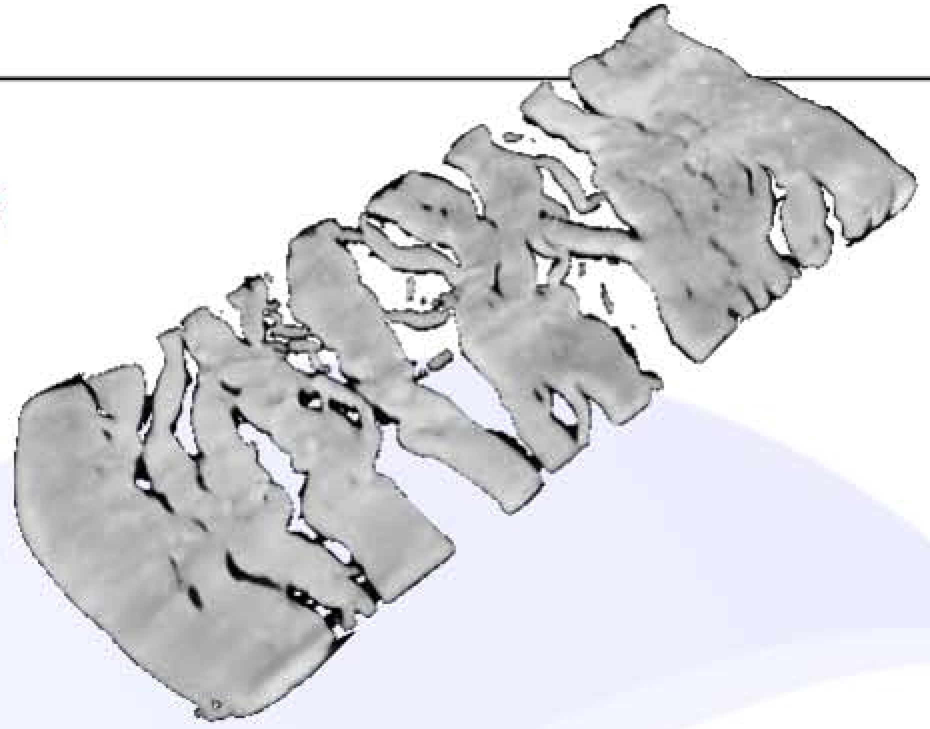
Motivation

Deformable Volumetric Objects

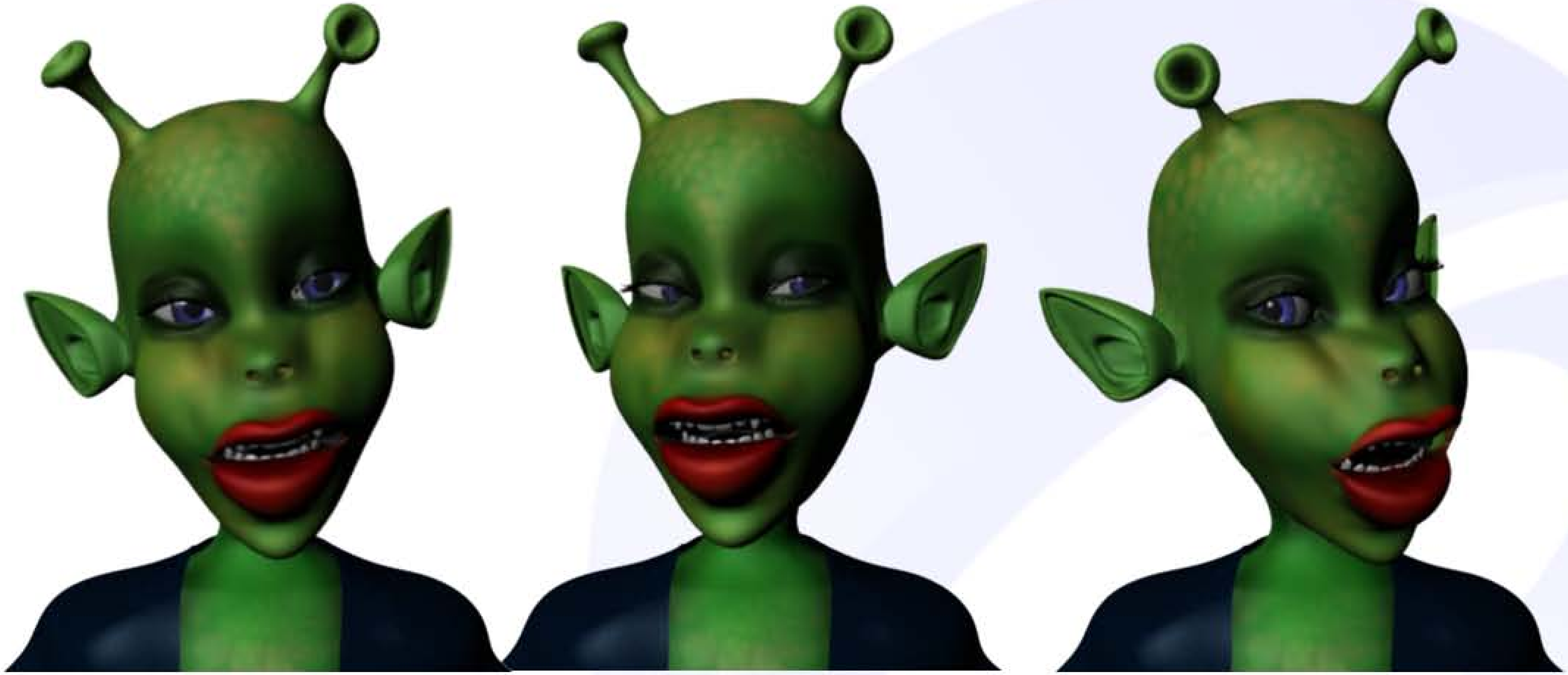
- ***Applications in Science***
  - Medicine
  - Engineering
  - Natural Science



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

Modelling

- Traditional Modelling:
  Separation of Shape from Appearance



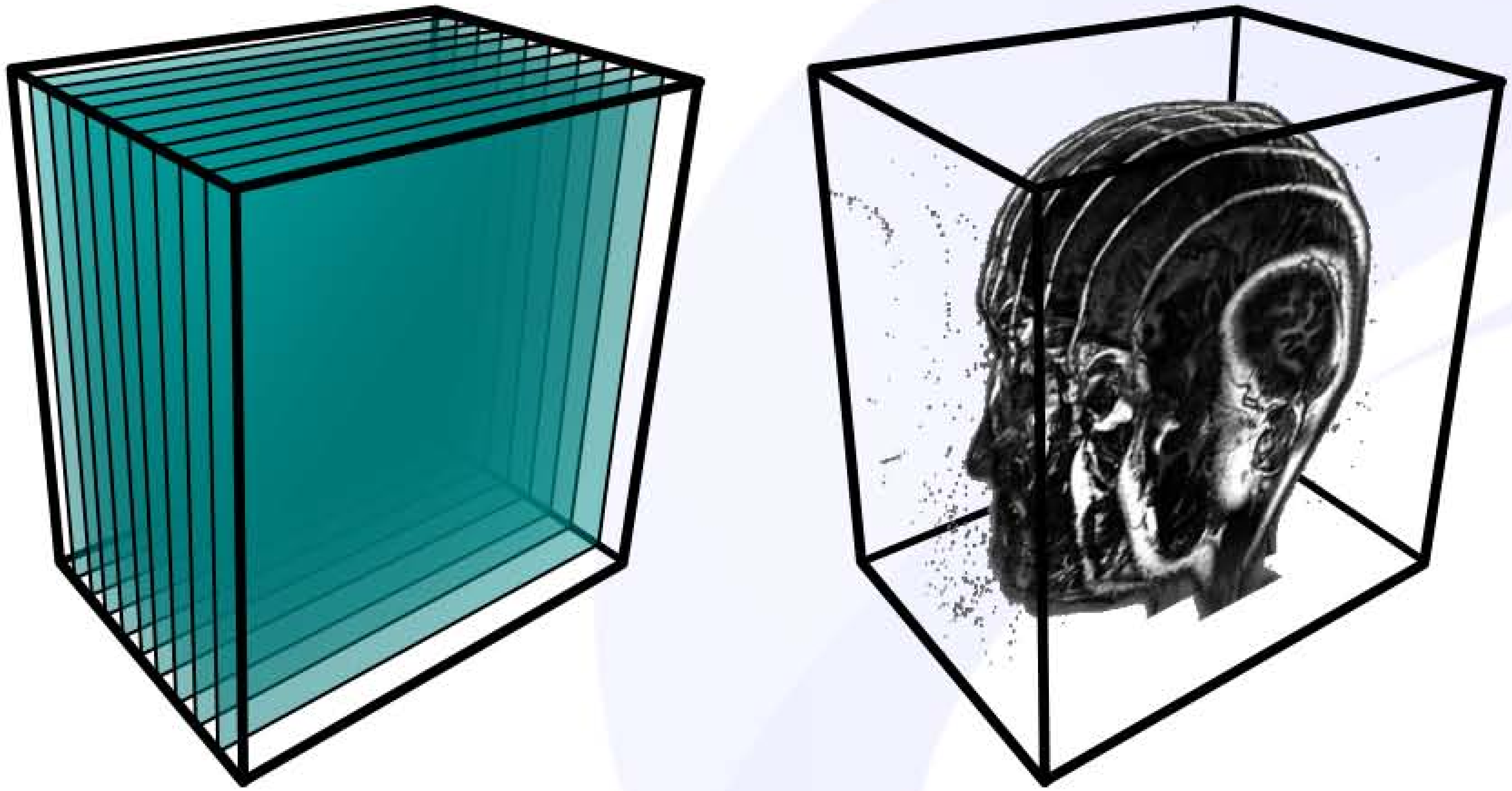
Images from Maya Animation Course, © Rezk-Salama, University of Siegen

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



Should we deform the proxy geometry or the textures?

Mathematical Models

Deformation Models for Texture-Based VR

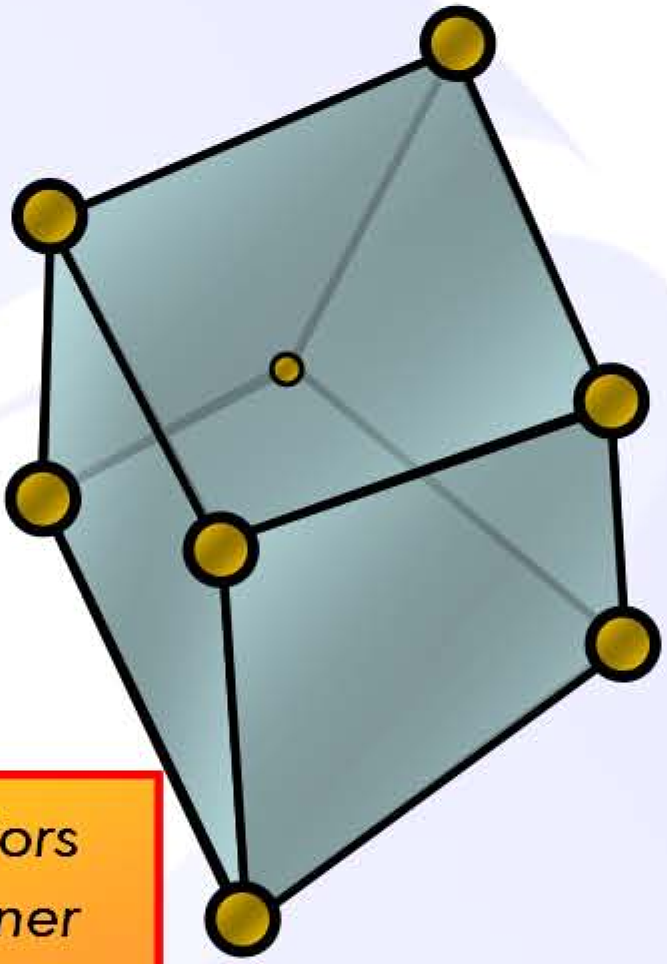
- Deforming the proxy geometry

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

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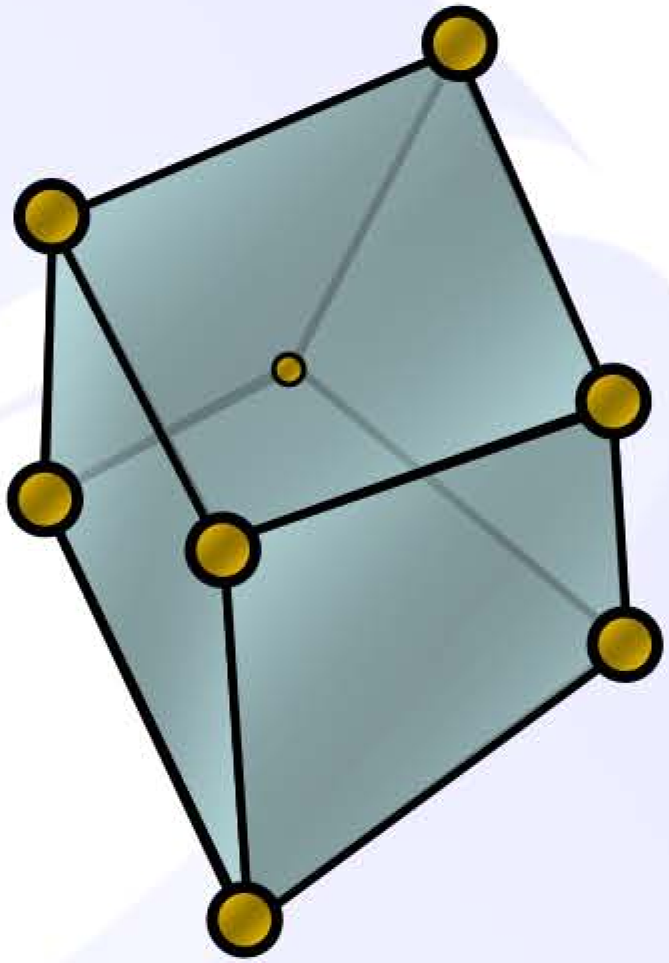
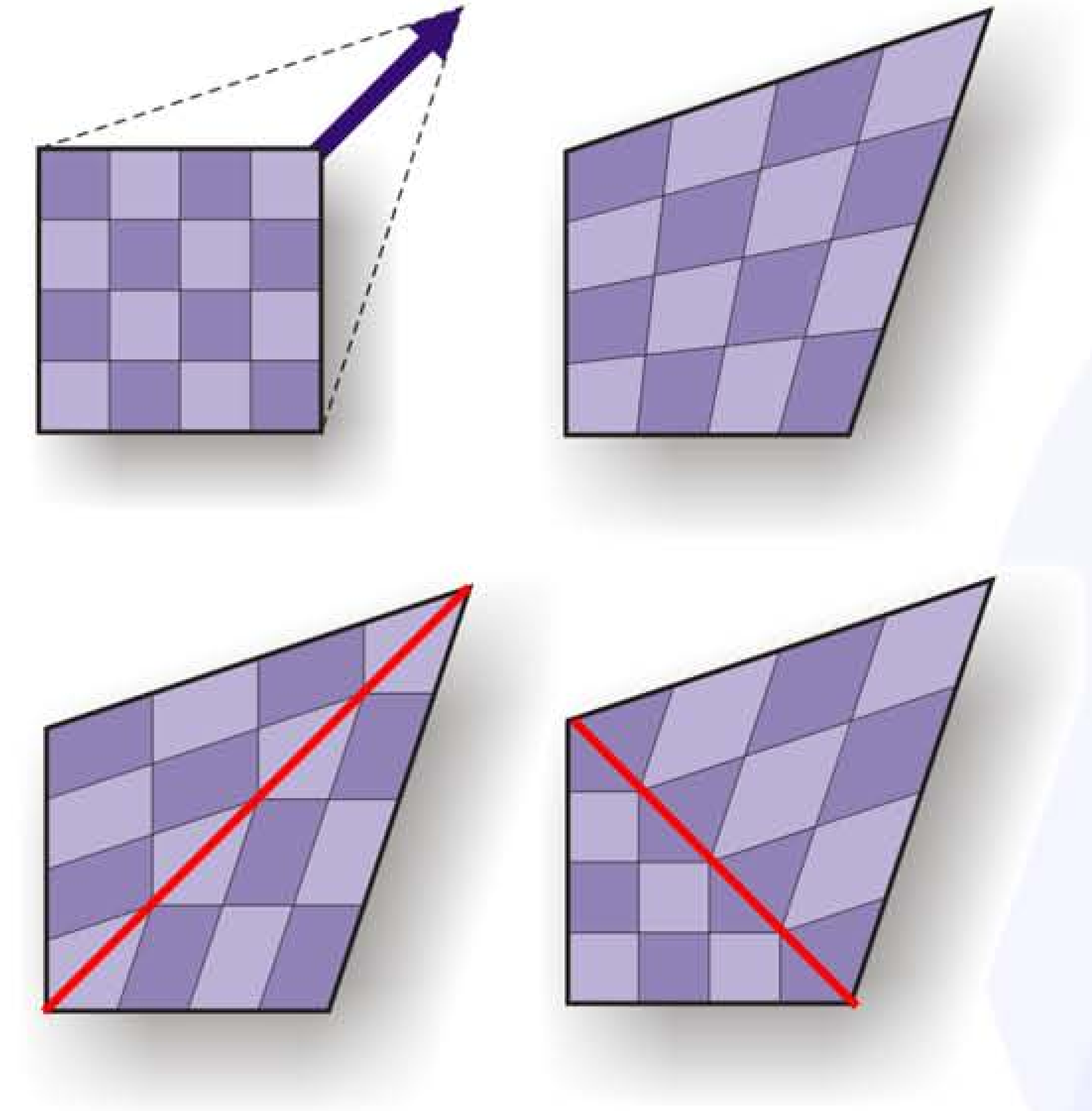


Difficulties: The inverse transformation is not again a trilinear function!

Mathematical Models

- *What do we need the inverse for?*



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

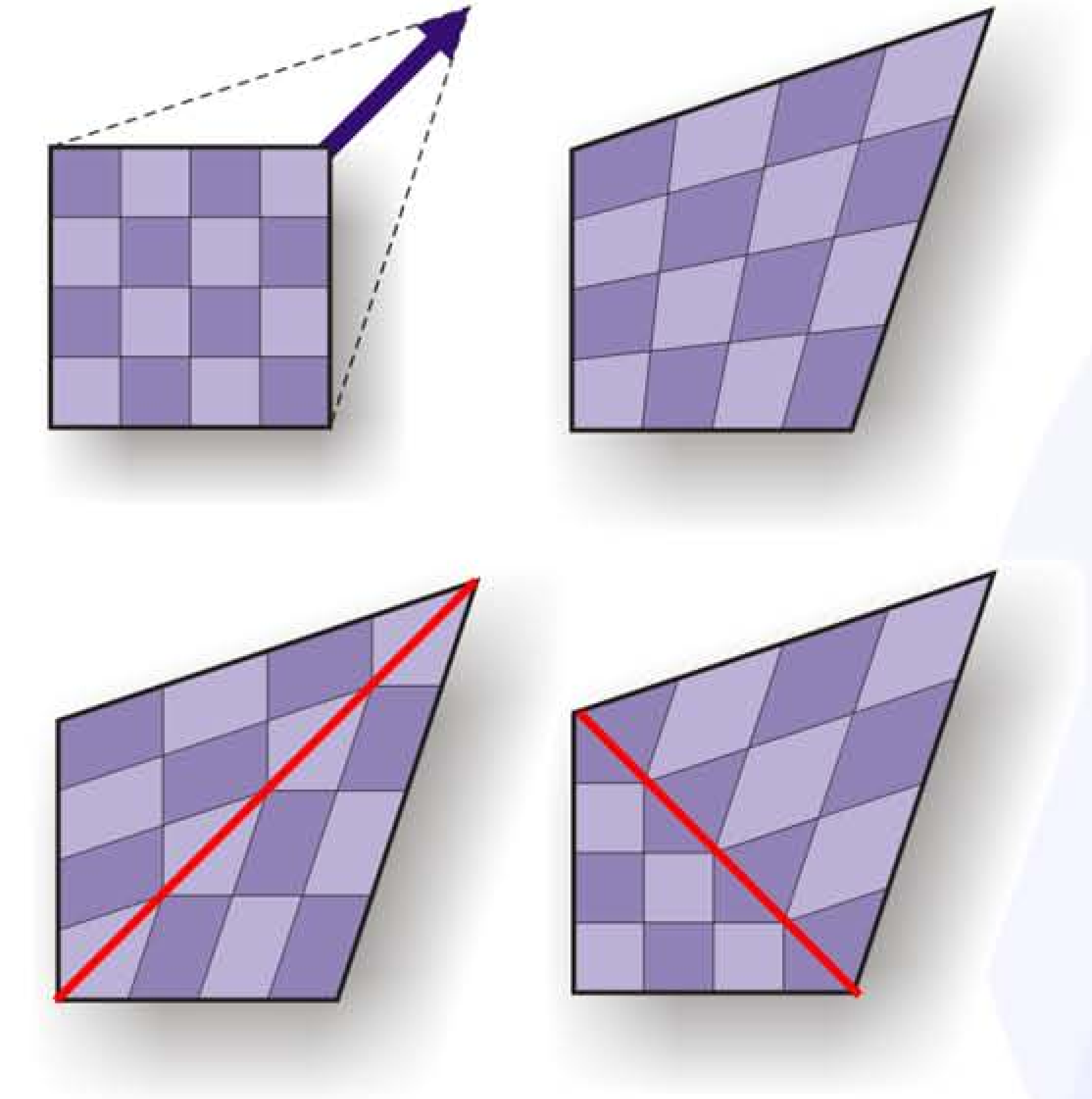
Tessellation into triangles produces undesired results.

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,

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Rasterization:
For the desired bilinear/trilinear mapping,

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

Mathematical Models

Deformation Models for Texture-Based VR

- Deforming the proxy geometry

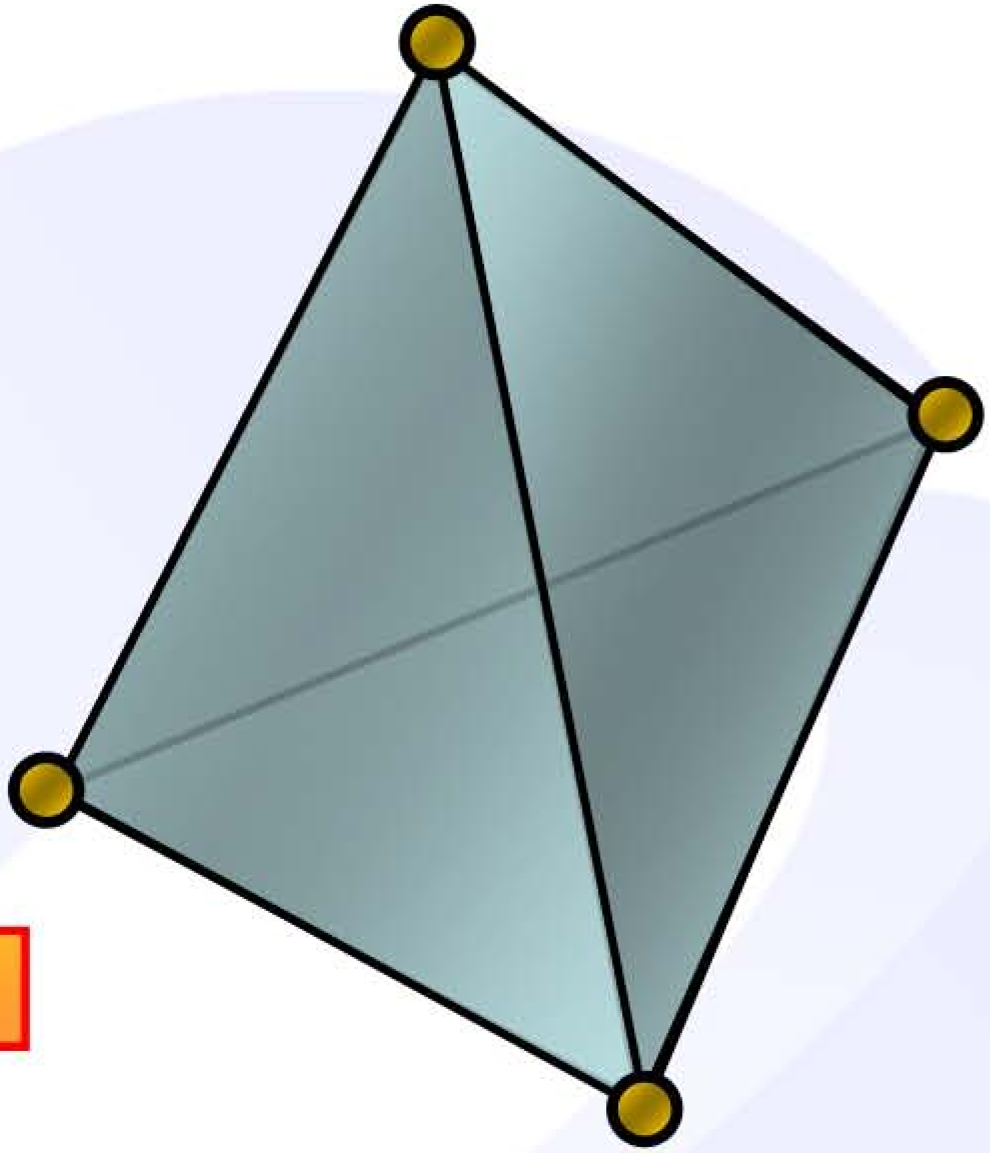
Second Idea:

Use tetrahedra as proxy geometry

Displace the 4 corner vertices.

Mathematical Description:

$$\Phi(\vec{x}) = \underbrace{\mathbf{A}}_{\text{Rotation and Scaling}}\vec{x} + \underbrace{\vec{b}}_{\text{Translation}}$$



Mathematical Models

Deformation Models for Texture-Based VR

- Deforming the proxy geometry

Second Idea:

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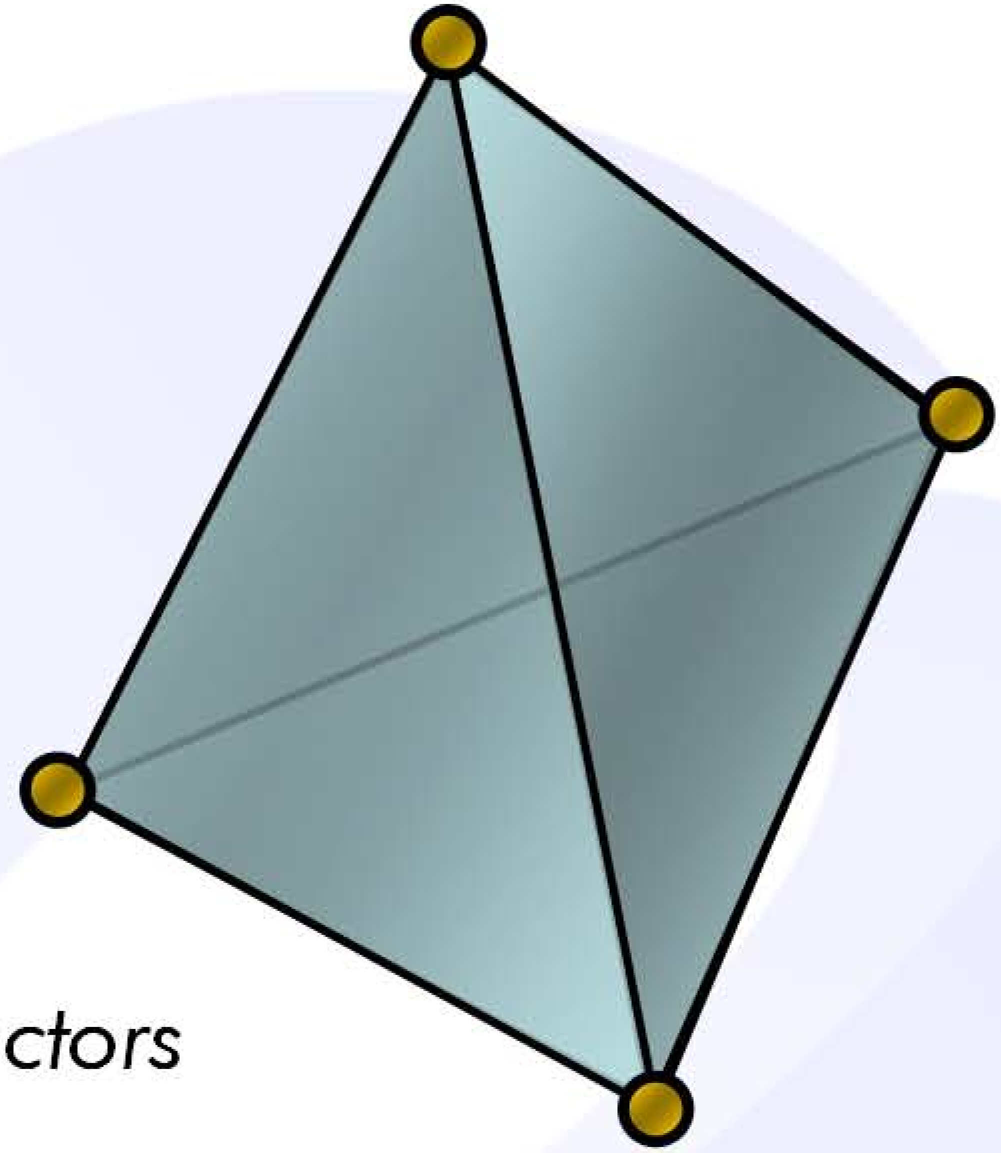


Fully determined by 4 displacement vectors

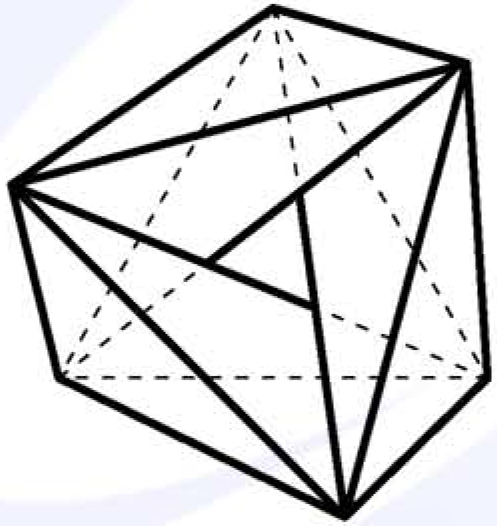
Difficulties: Tessellation, Depth Sorting

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!)
- Slice Decomposition
  - Mainly performed on CPU



Mathematical Models

Deformation Models for Texture-Based VR

- Deforming the appearance (textures)

Piecewise Linear Transformation:

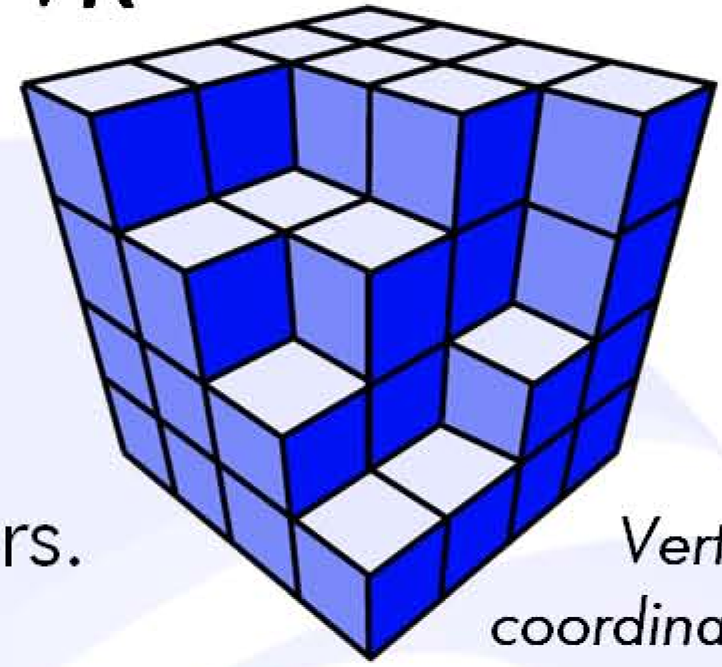
Subdivide into hexahedra cells (3D patches)

Displace the texture coordinates at the corners.

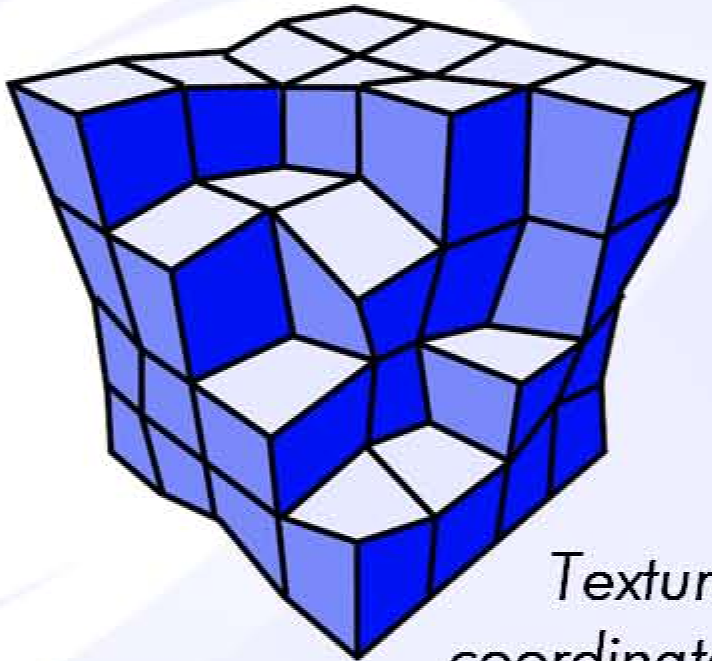
Mathematical Description:

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

*(**x** now refers to the texture coordinate)*



Vertex coordinates



Texture coordinates

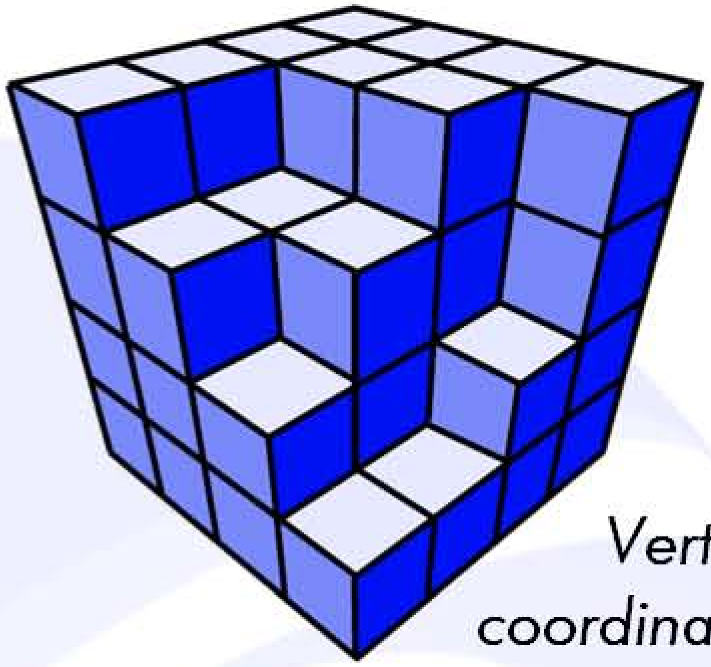
Piecewise Linear Patches

Advantages:

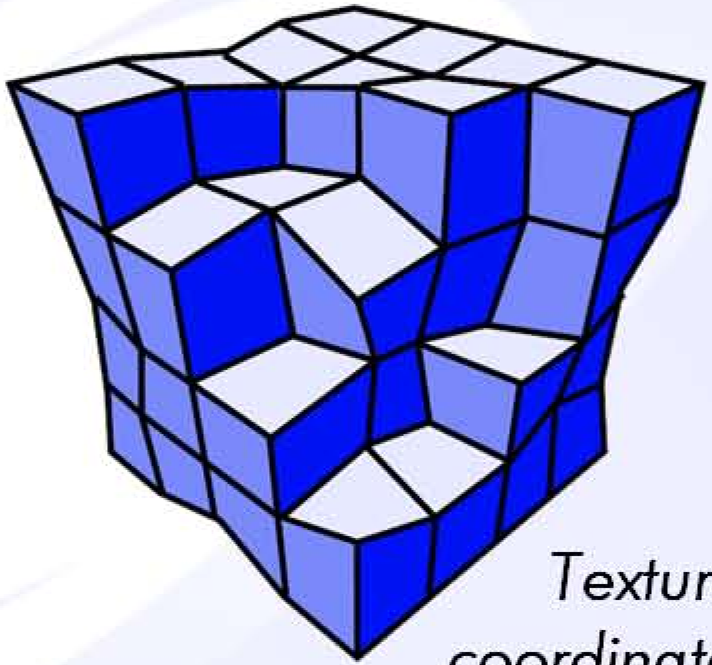
- *Geometry (vertices) is static, only texture coordinates change*
- *Slice decomposition is easy*
  - No expensive recomputation or real-time tessellation necessary
- *No depth sorting required!*
- *Adaptive subdivision possible*

Difficulties:

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



Vertex coordinates

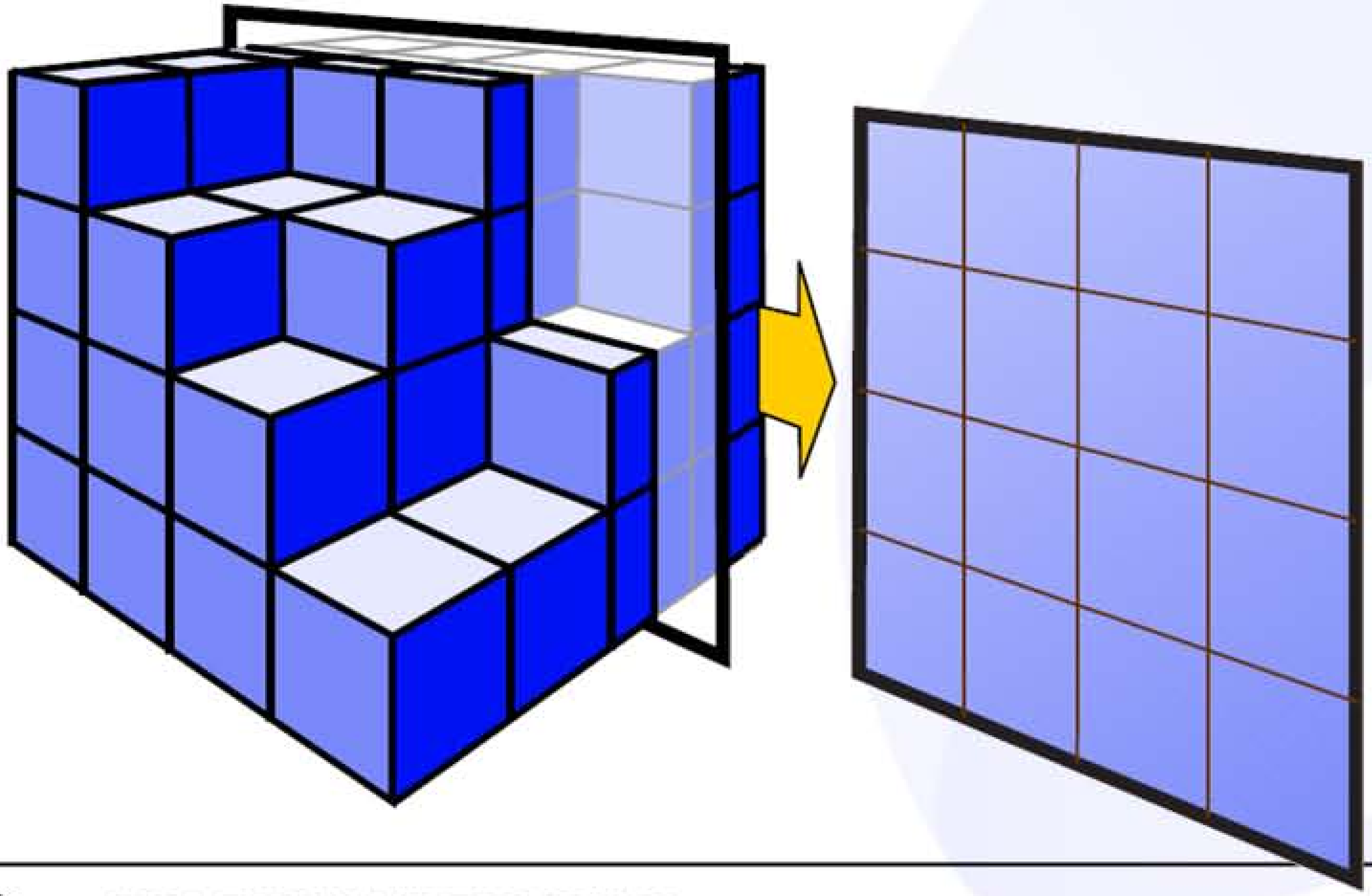


Texture coordinates

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

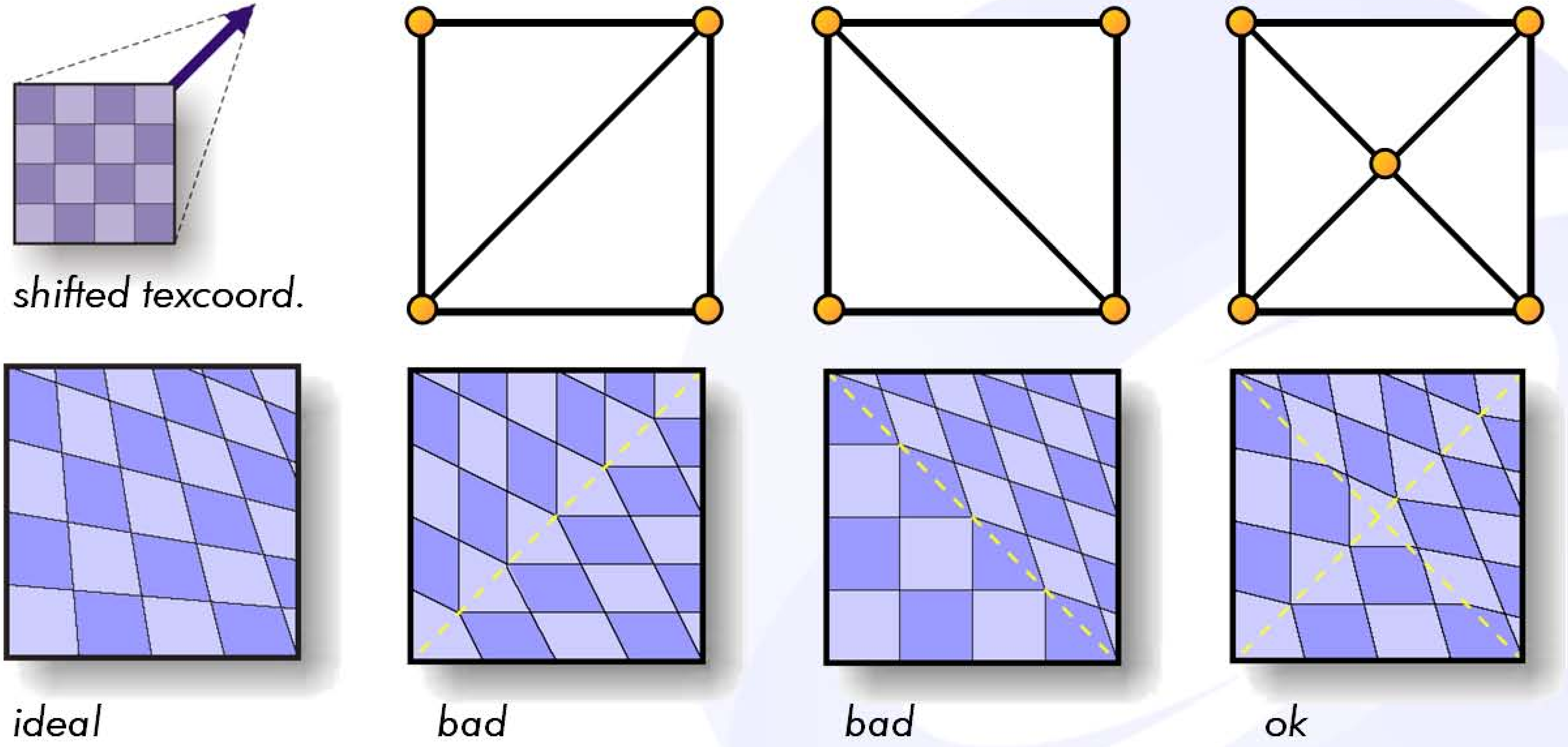
plus a 3D texture

How do we compute texture coordinates?

Piecewise Linear Patches

What do I need the inverse for?

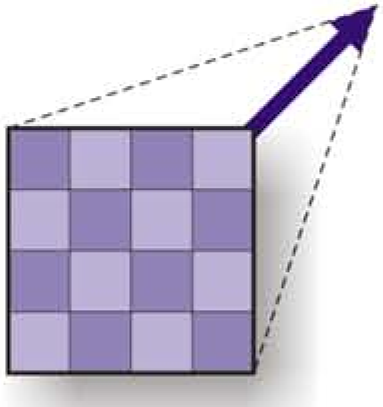
- *Texture Interpolation*



Piecewise Linear Patches

What do I need the inverse for?

- *Texture Interpolation*



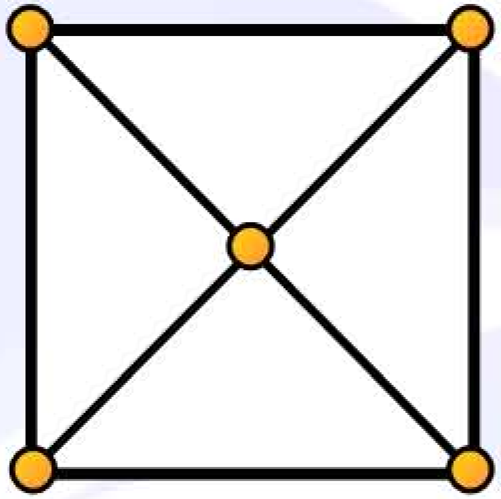
shifted texcoord.

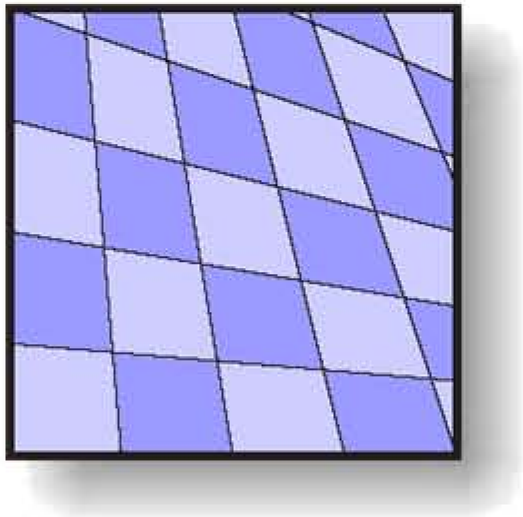
Approximate the correct bilinear interpolation by

4 interpolations in barycentric coordinates

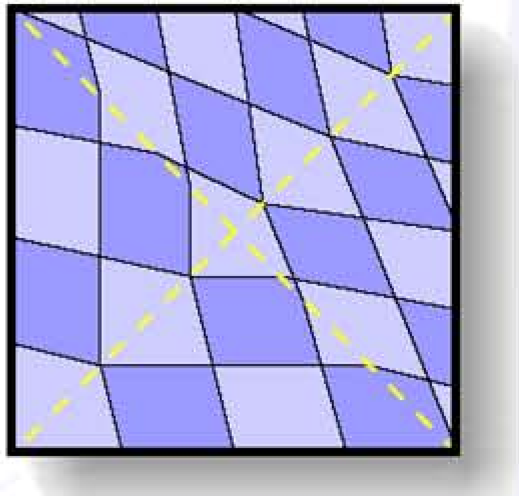
Use higher tessellation if quality is not good enough

Geometry is static!
No depth sorting required!





ideal



ok

Piecewise Linear Patches

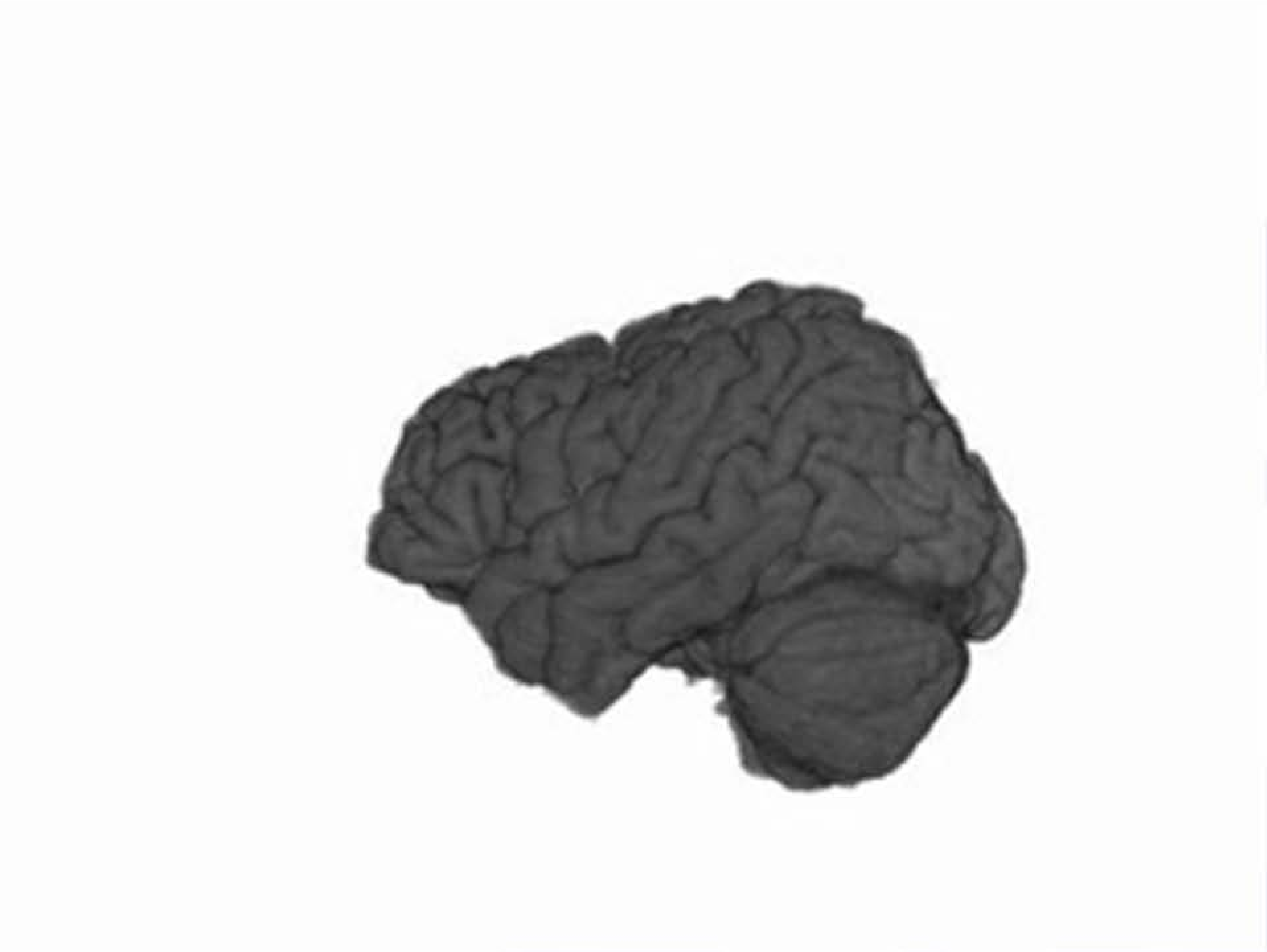
What do I need the inverse for?

- *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

Examples

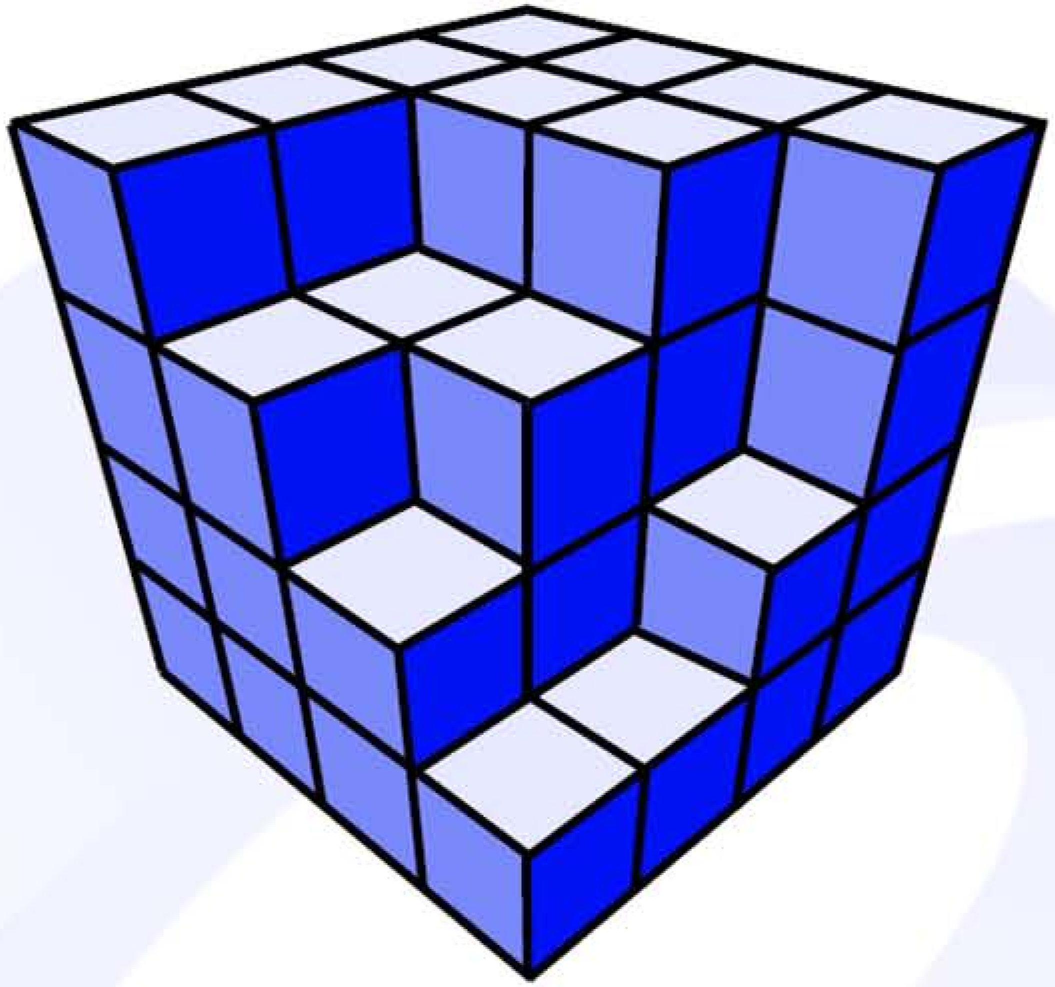


Piecewise Linear Patches

High Flexibility

- requires high subdivision level

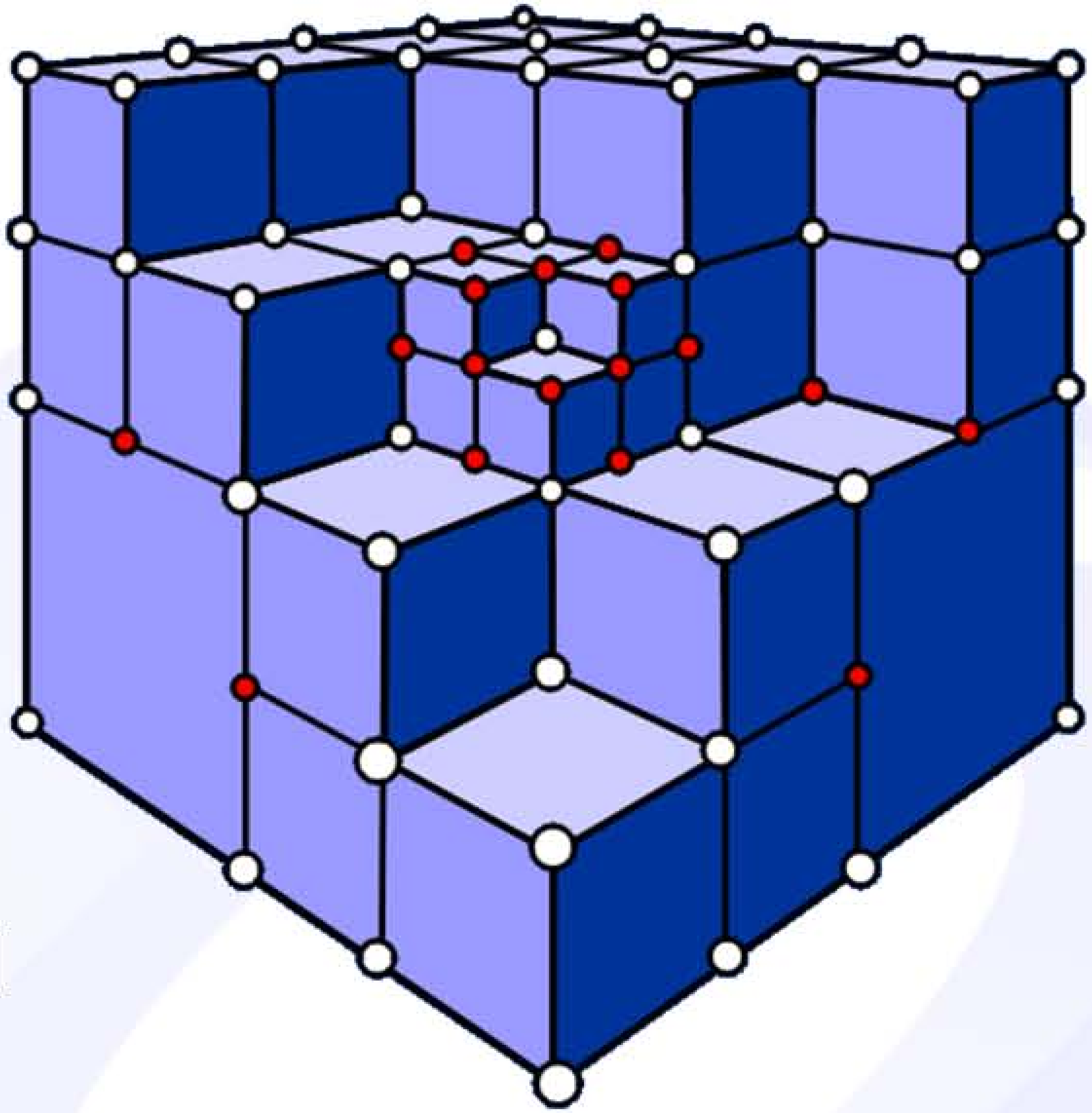
⇒ high number of free vertices



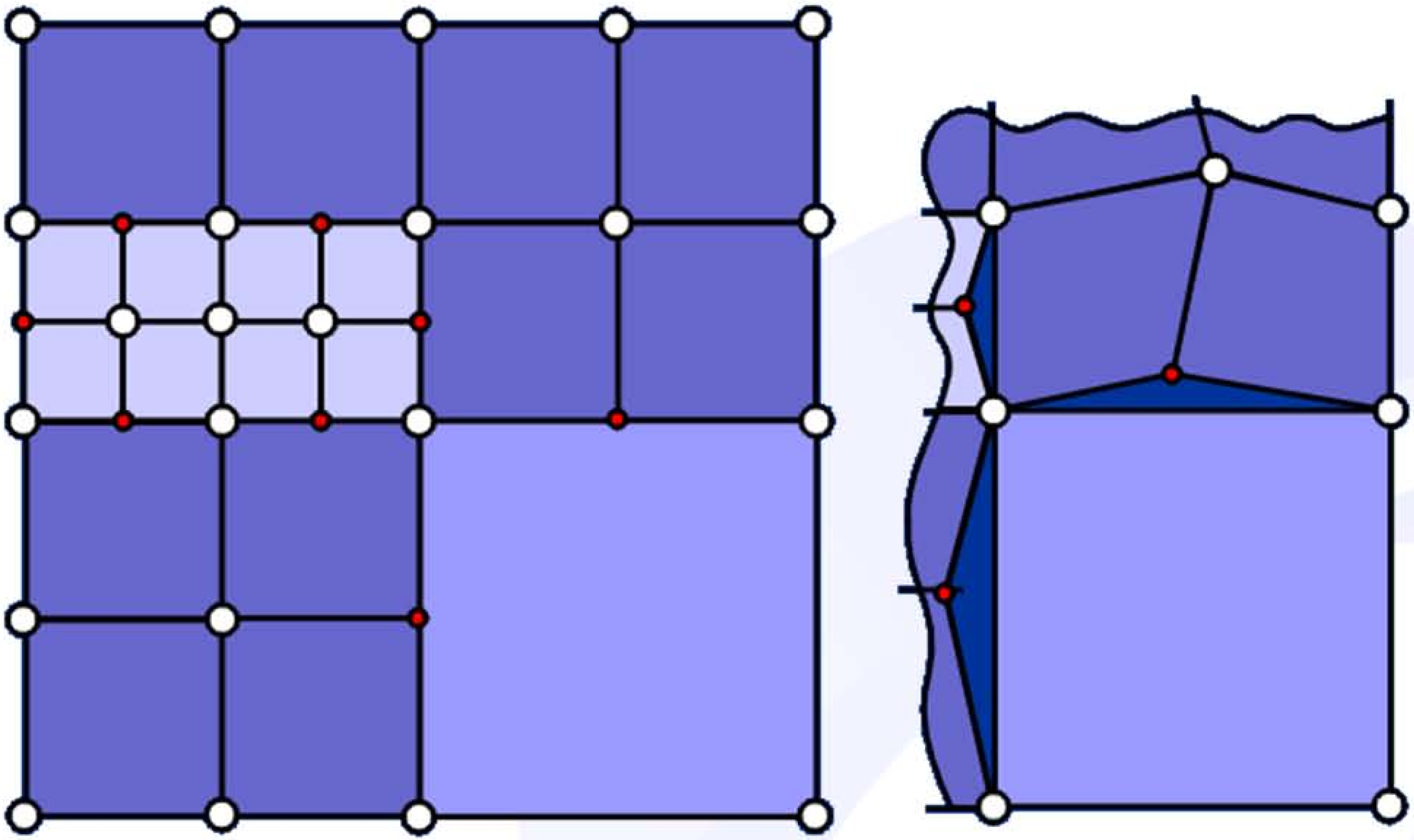
Piecewise Linear Patches

High Flexibility

- requires high subdivision level
- ⇨ high number of free vertices
- can be reduced by *Adaptive Subdivision*
  - Refine only where higher flexibility is required
  - *Octree structure*
- *Constraints required to prevent gaps in texture space!*

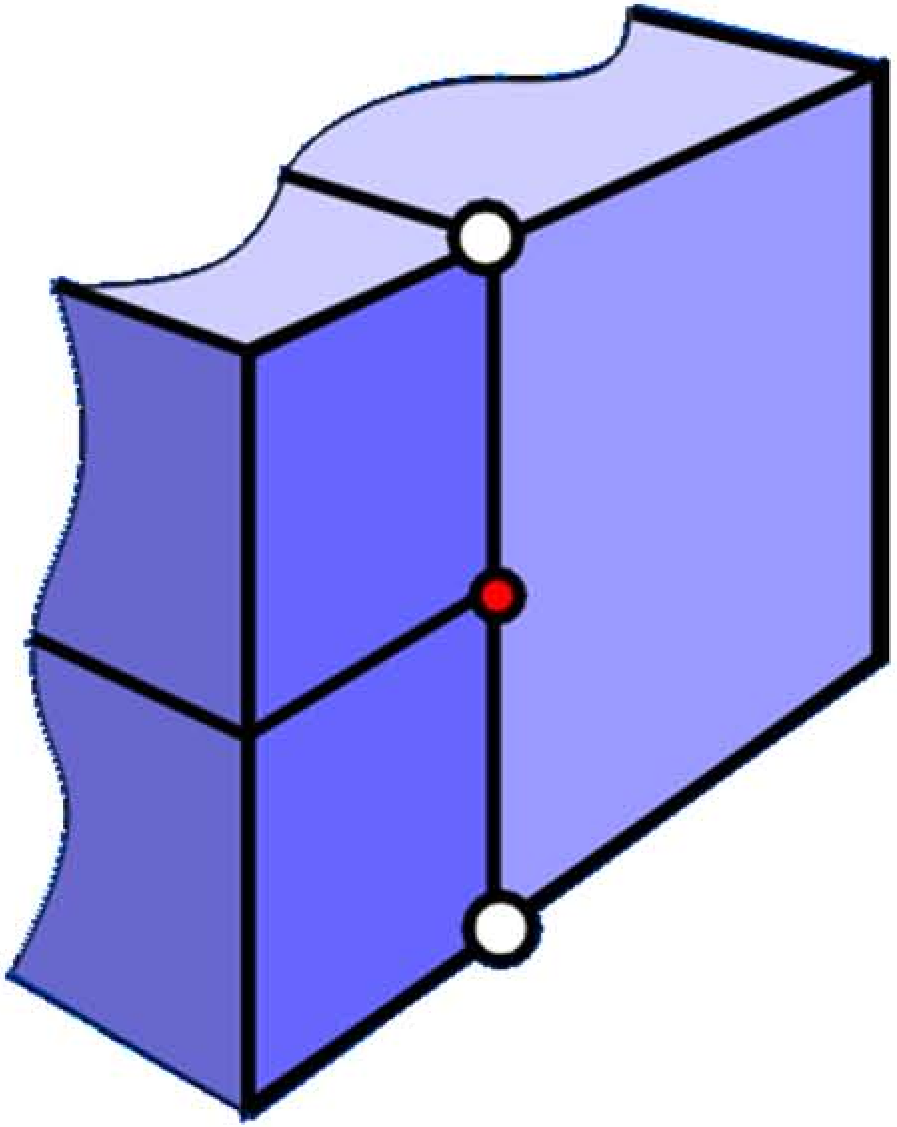


Adaptive Subdivision



- ○ Free Vertices
- ● Vertices with constraints

Edge Constraints



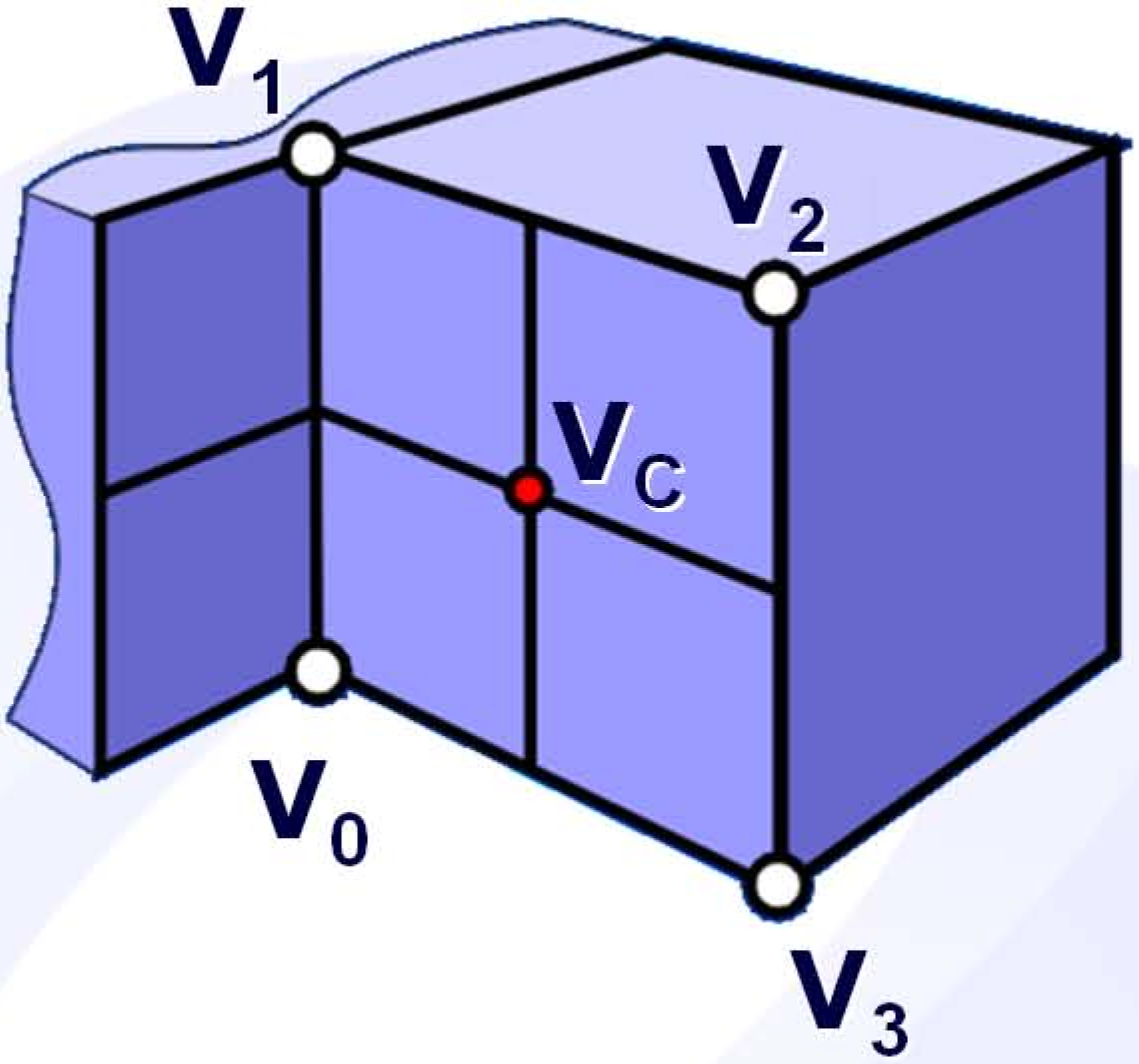
- Vertices on edges between different subdivision levels must stay ***collinear***

$$\vec{V}_C = \frac{1}{2}\vec{V}_0 + \frac{1}{2}\vec{V}_1$$

Face Constraints

- Vertices on faces with different subdivision levels must stay coplanar

$$\vec{V}_C = \frac{1}{4} \sum_{i=0...3} \vec{V}_i$$



Local Illumination

Local Illumination

- Pre-computed gradient vectors become invalid after the deformation
  - *Use on-the-fly gradient estimation techniques OR*
  - *Adapt pre-computed gradient vectors to the deformation*

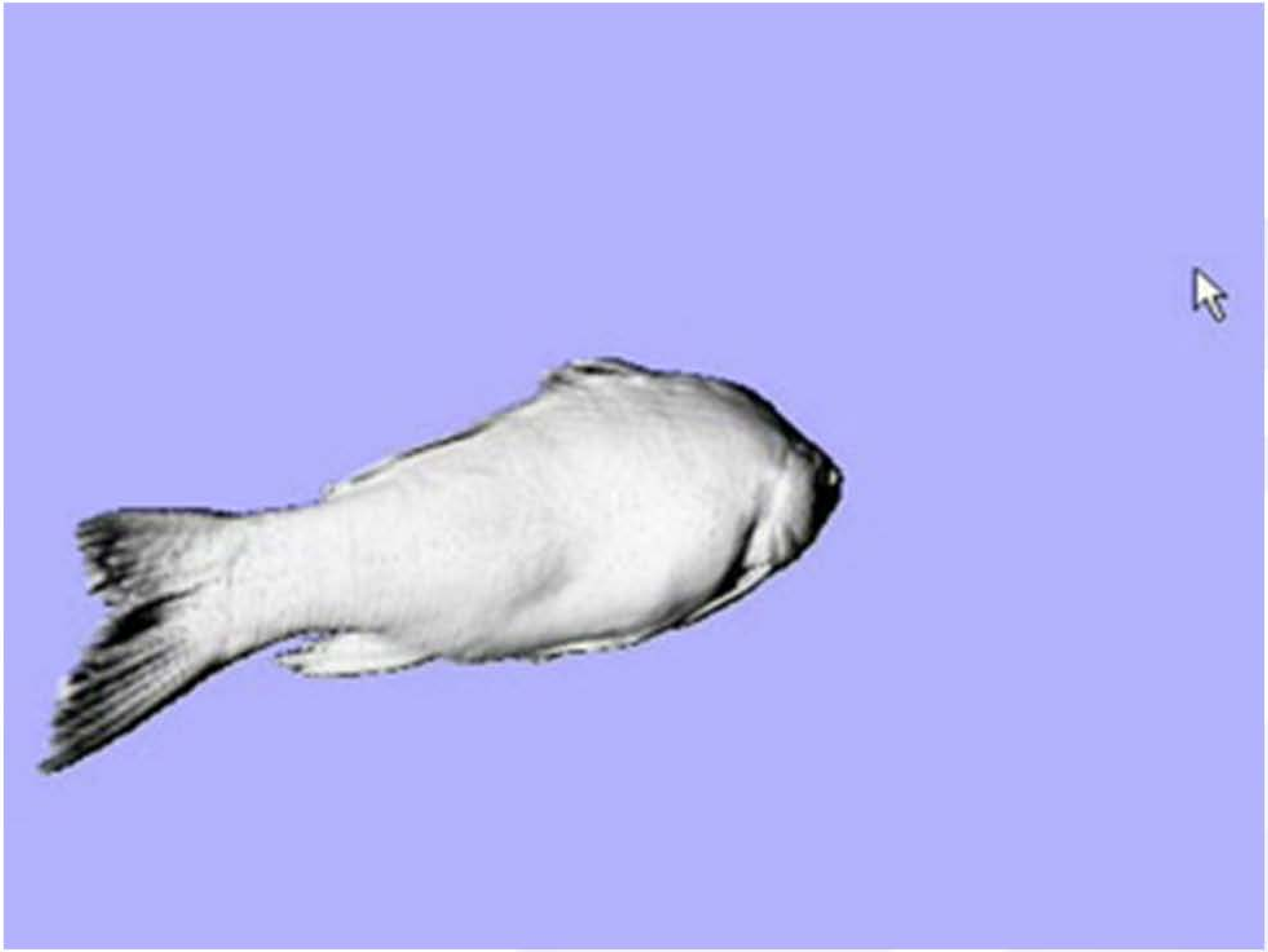
  Idea: Approximate trilinear mapping by affine matrix

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

(in homogenous coordinates)

Use this equation to approximate the inverse mapping and to adapt pre-computed gradient vectors

Examples

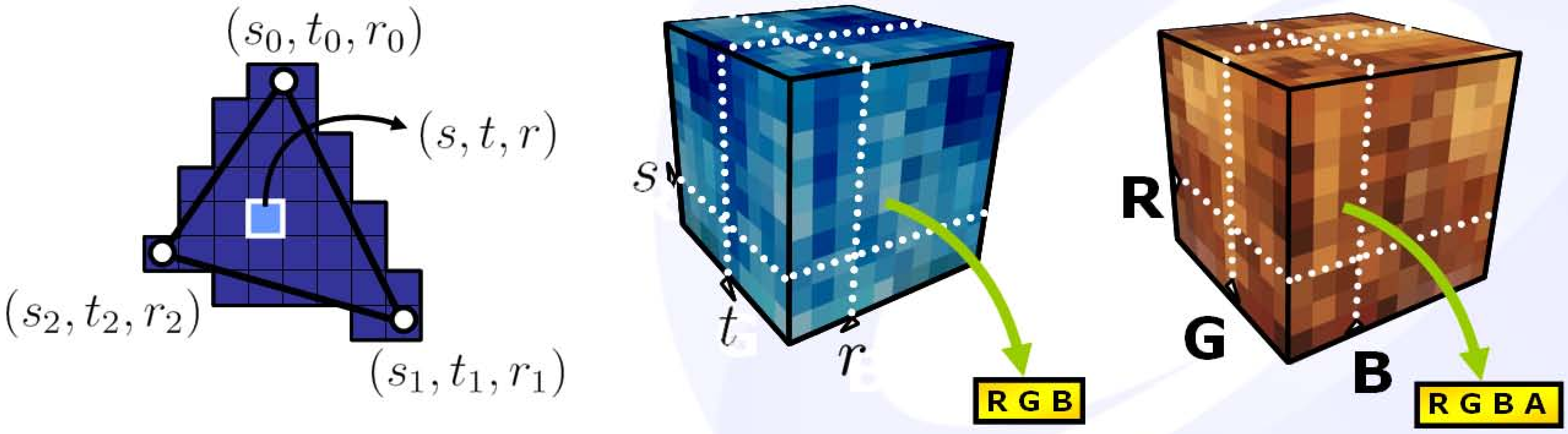


Volumetric Deformation

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
- No adaptive subdivision
- Gradient adaptation difficult
- Runs completely within GPU (except slicing)
- Deformation field can be modified using render-to-3D-texture ("über-buffers")

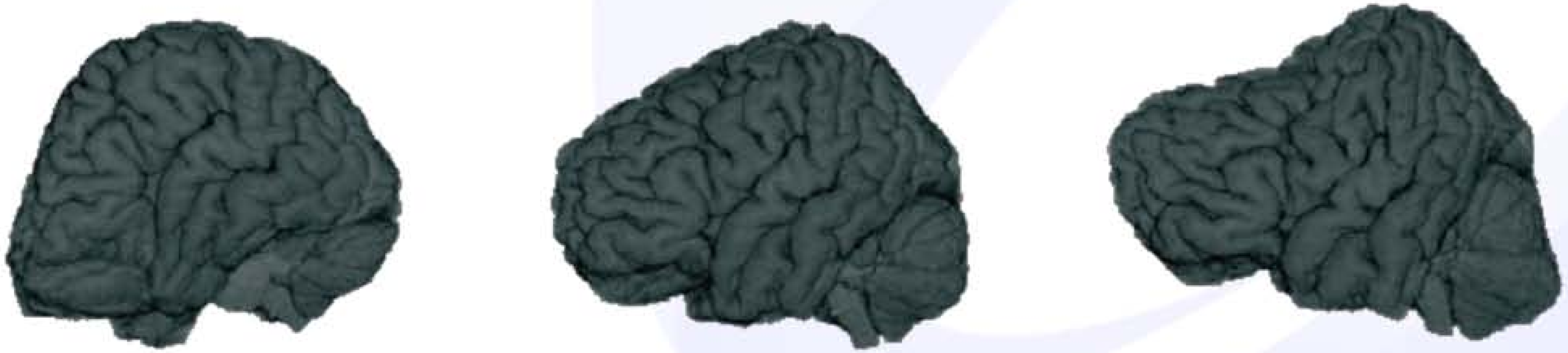
Offset Textures

```
// 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);
  }
```



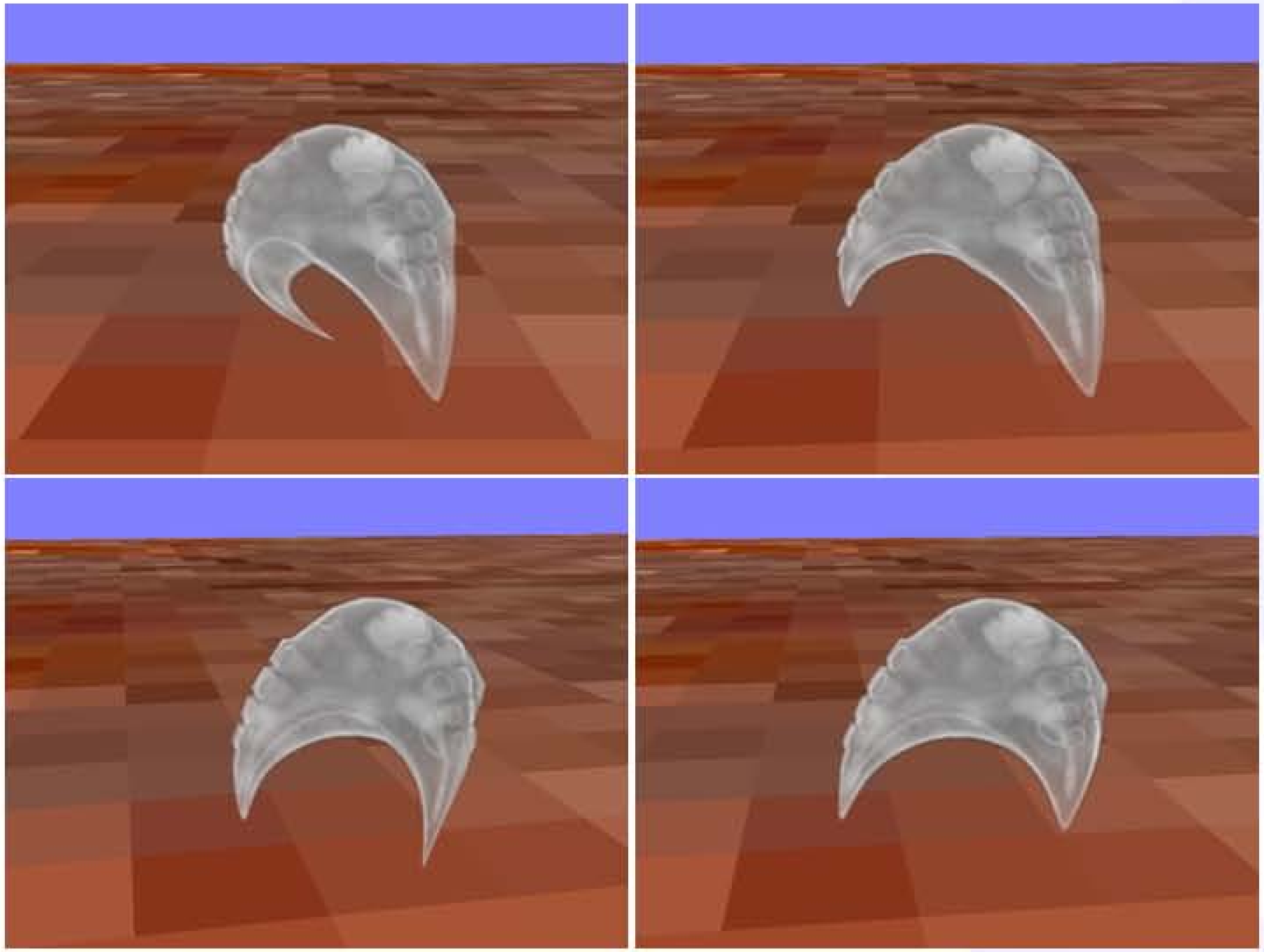
Volume Animation

- *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!



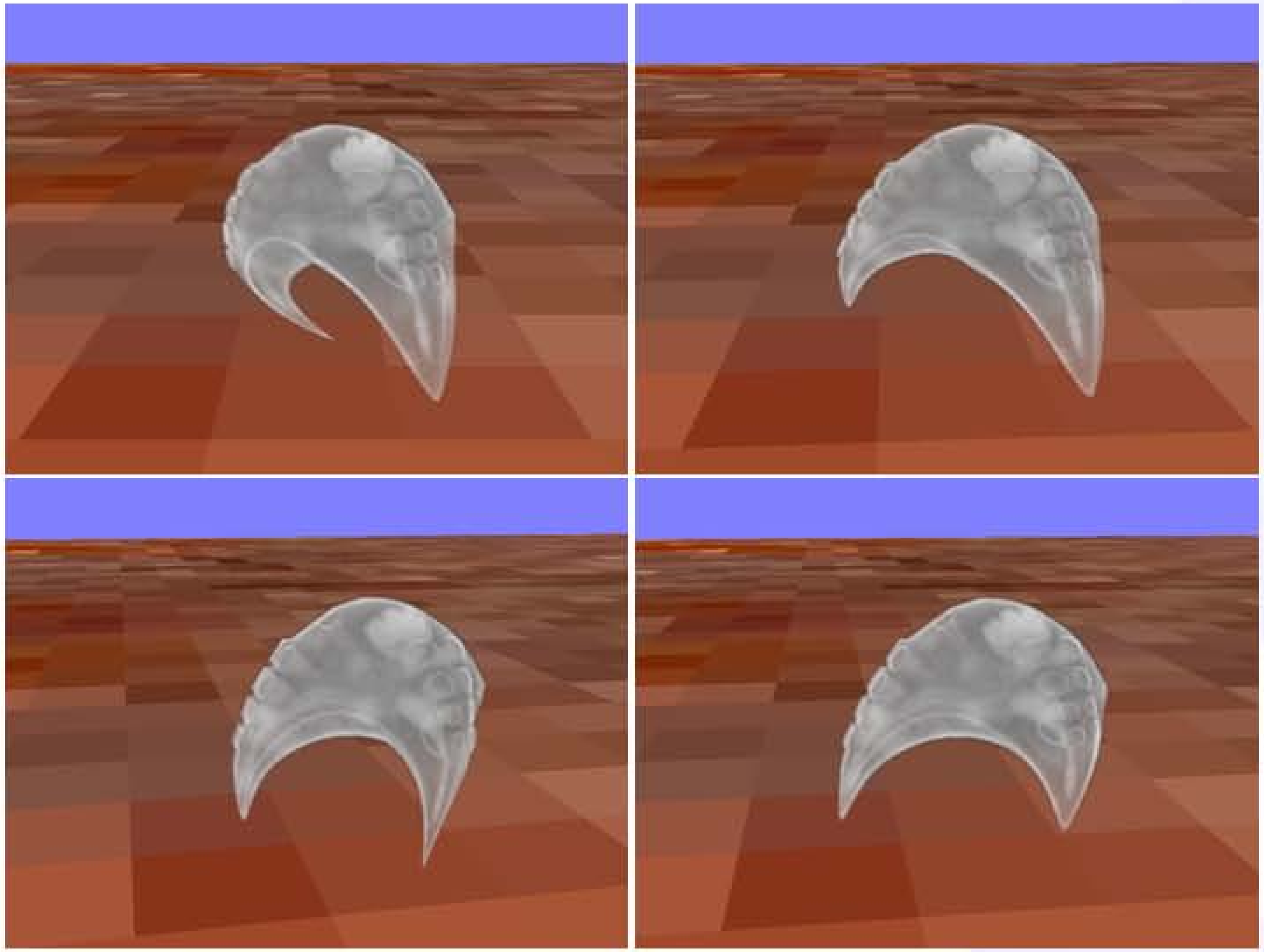
Example: Tripod Creature

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);
}
```

Thanks

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Thanks to my students:

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Timo Hambürger