Bremen

CG VR

Advanced Computer Graphics
Advanced Shader Programming

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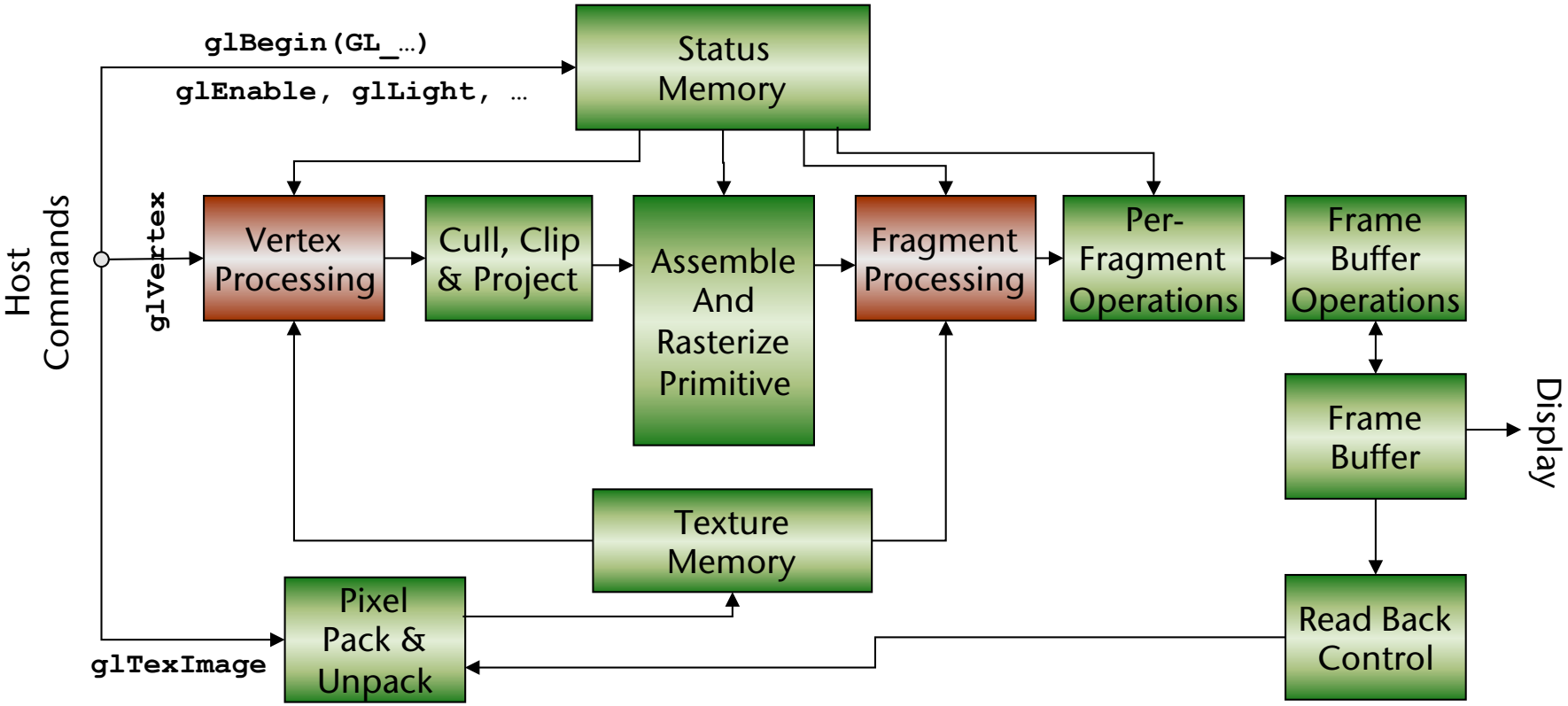
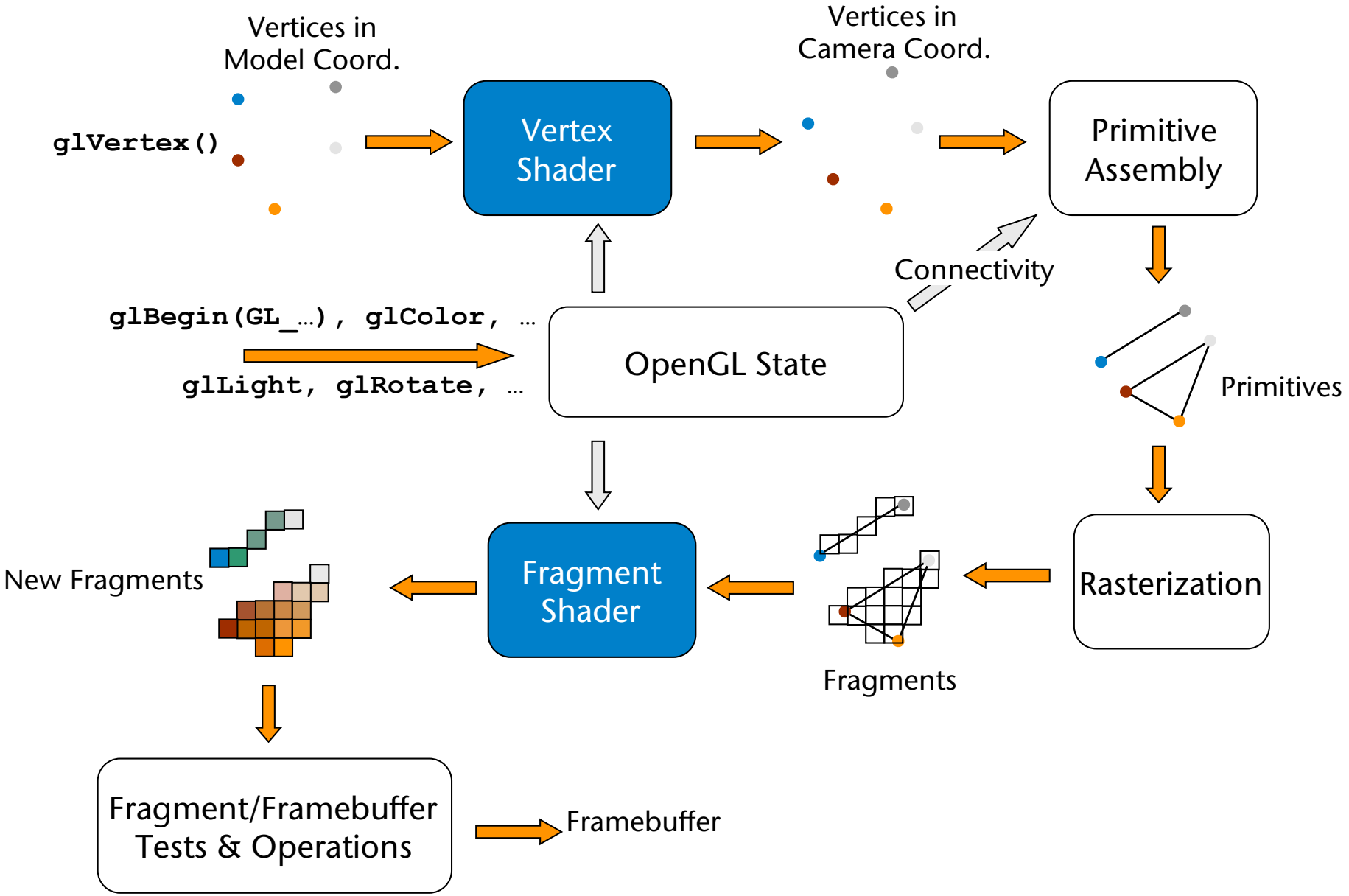
Recap

- Programmable *vertex und fragment processors*
  - Expose that which was already there anyway
- Texture memory = now general storage for any data



A More Abstract Overview of the Programmable Pipeline



More Versatile Texturing by Shader Programming

- Declare texture in the shader (vertex or fragment):

```
uniform sampler2D myTex;
```

- Load and bind texture in OpenGL program as usual:

```
glBindTexture( GL_TEXTURE_2D, myTexture );
glTexImage2D(...);
```

- Establish a connection between the two:

```
uint mytex = glGetUniformLocation( prog, "myTex" );
glUniform1i( mytex, 0 );  // 0 = texture unit, not ID
```

- Access in fragment shader:

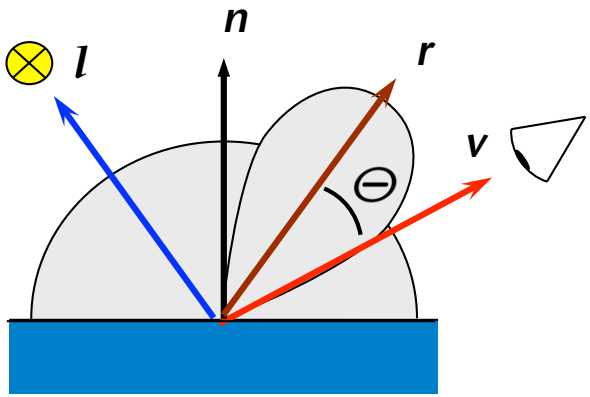
```
vec4 c = texture2D( myTex, gl_TexCoord[0].xy );
```

Example: A Simple "Gloss" Texture

- Idea: expand the conventional Phong lighting by introducing a *specular reflection coefficient* that is mapped from a texture on the surface

$$I_{\text{out}} = \left(r_d \cos \Phi + r_s \cos^p \Theta\right) \cdot I_{\text{in}}$$

$$r_s = r_s(u, v)$$

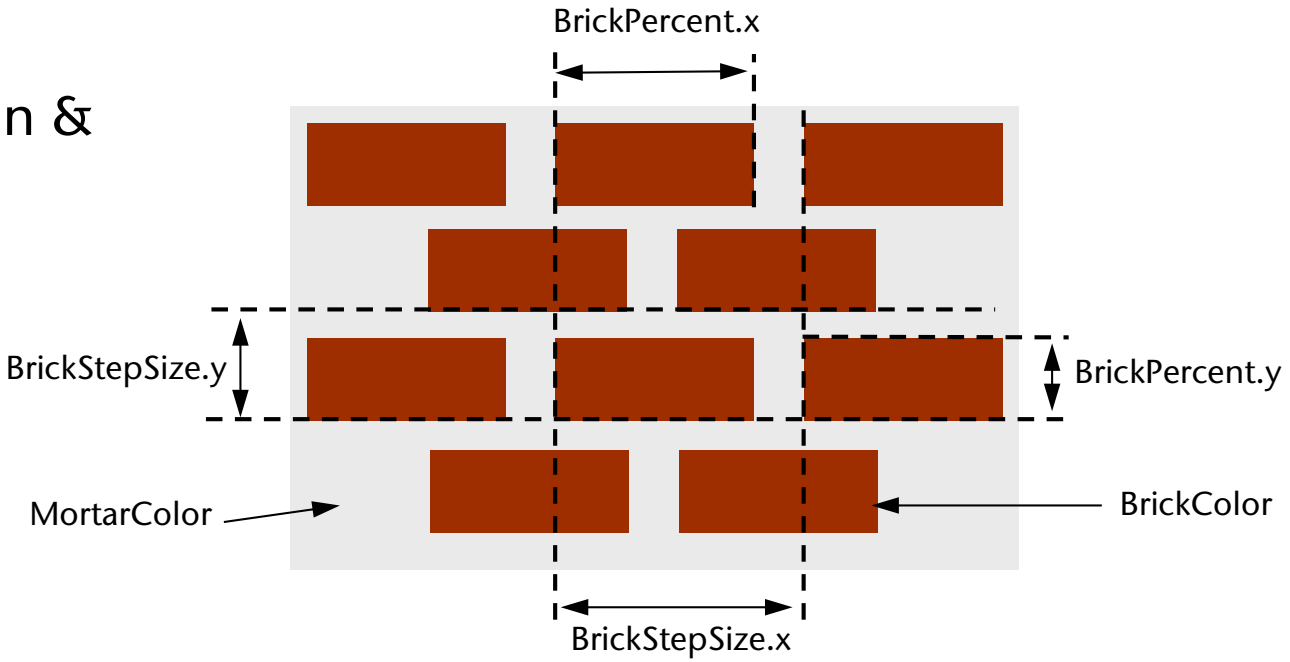


`demos/shader/vorlesung_demos/gloss.{frag,vert}`

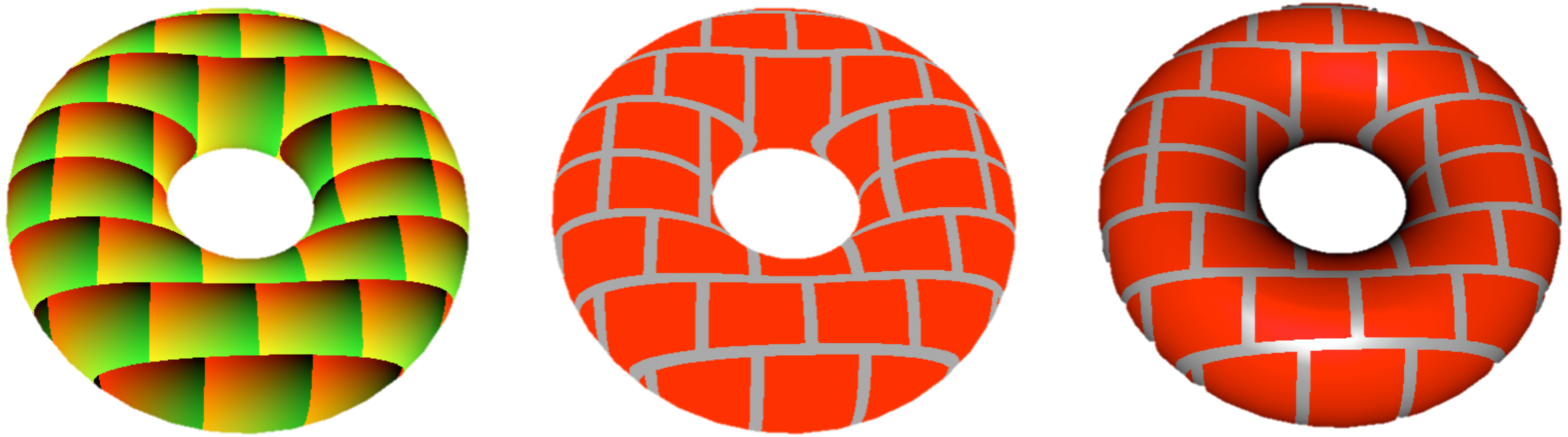
Procedural Textures Using Shader Programming

- Goal:
  Brick texture

- Simplification & parameters:



- General mechanics:
  - Vertex shader: normal lighting calculation
  - Fragment shader:
    - For each fragment, determine if the point lies in the brick or in the mortar on the basis of the x/y coordinates of the corresponding point in the *object's space*
    - After that, multiply the corresponding color with intensity from lighting model
- First three steps towards a complete shader program:

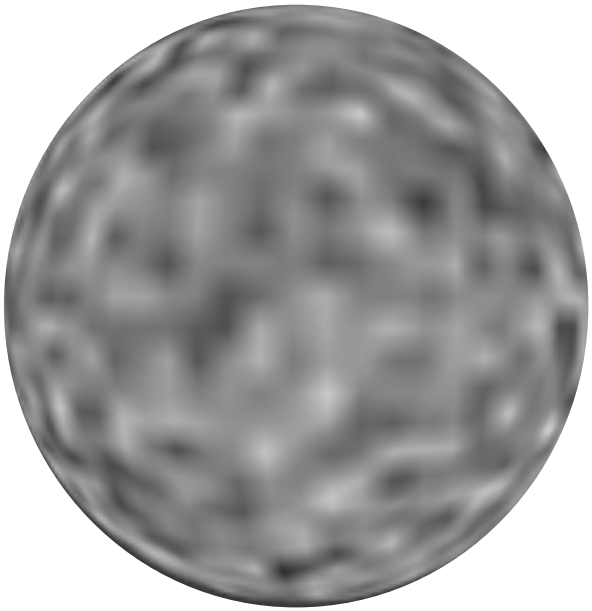


demos/shader/vorlesung_demos/brick.vert and brick[1-3].frag

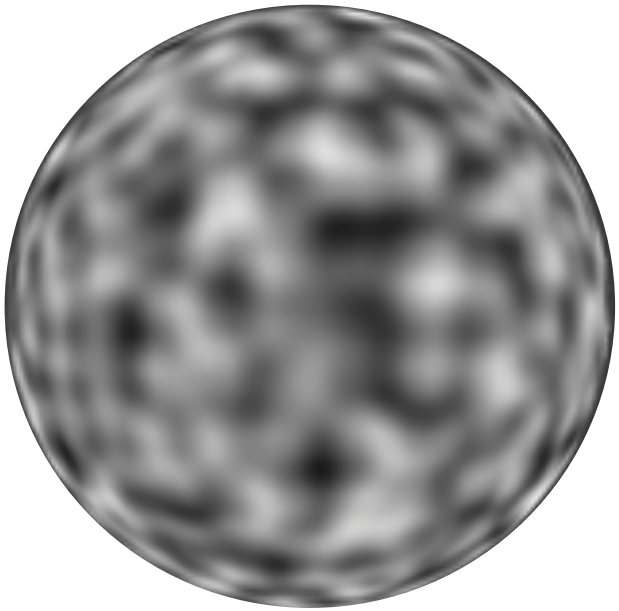
Noise

- Most procedural textures look too "clean"
- Idea: add all sorts of noise
  - Dirt, grime, random irregularities, etc., for a more realistic appearance
- Ideal qualities of a noise function:
  - At least C^2-continuous
  - It's sufficient if it looks random
  - No obvious patterns or repetitions
  - Repeatable (same output with the same input)
  - Convenient domain, e.g. [-1,1]
  - Can be defined for 1-4 dimensions
  - Isotropic (invariant under rotation)

- Why we don't just use a noise texture:

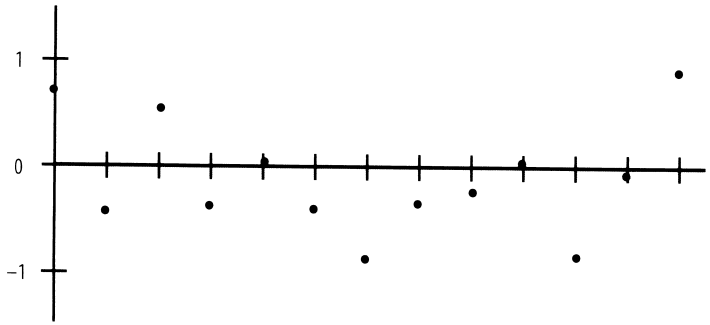


Sphere rendered with a 3D texture to provide the noise. Notice the artifacts from linear interpolation.

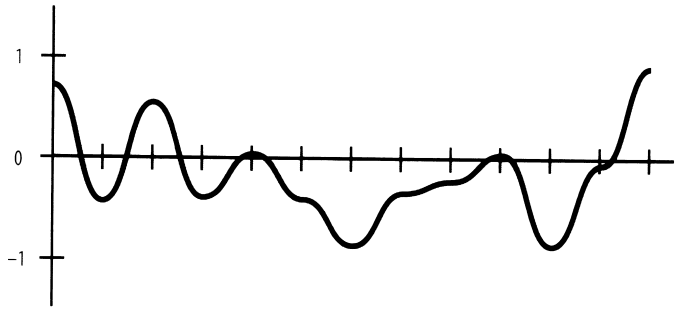


Sphere rendered with procedural noise.

- Simple idea, demonstrated by a 1-dimensional example:
  1. Choose random y-values from [-1,1] at the integer positions:

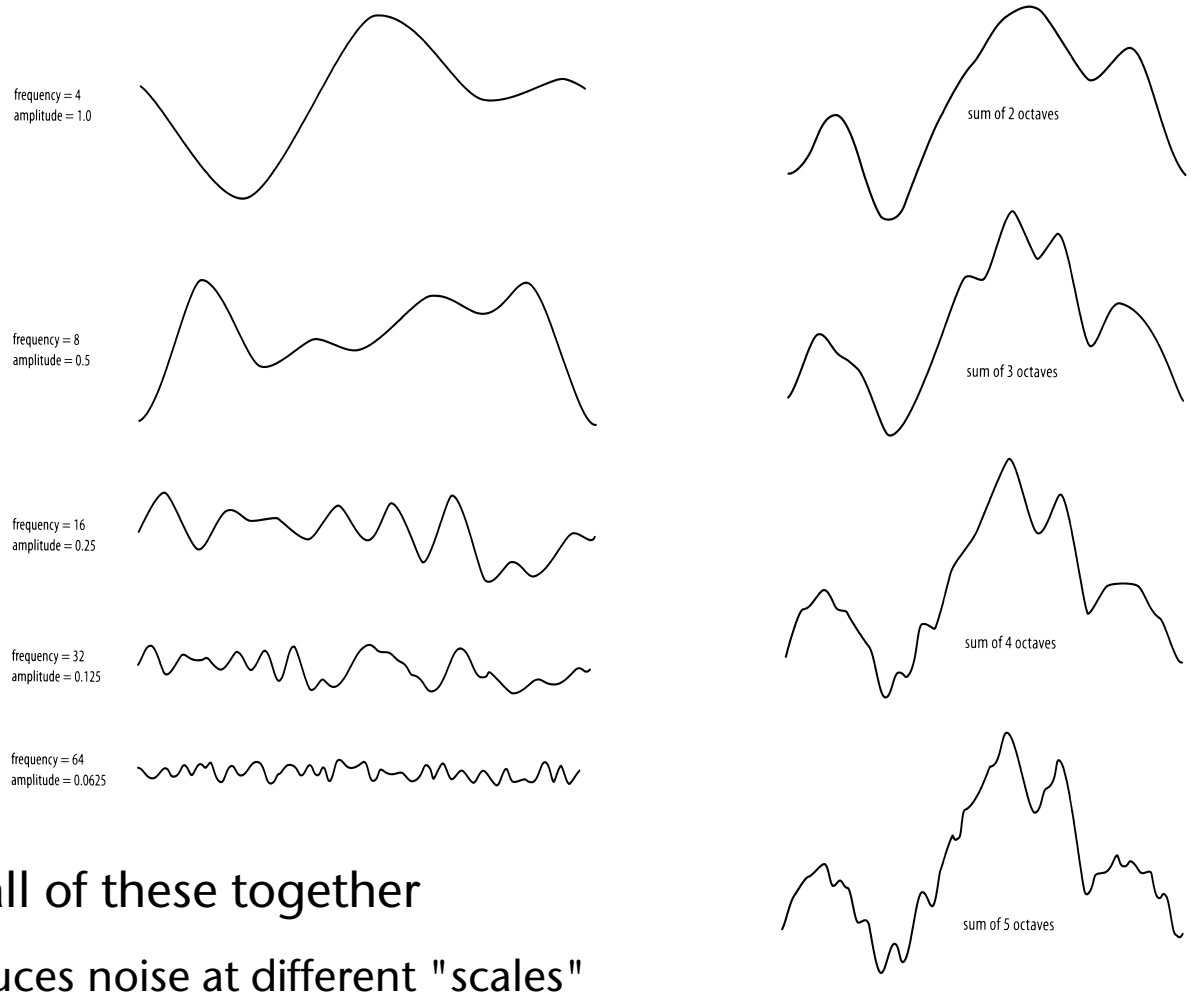


  2. Interpolate in between, e.g. cubically (linearly isn't sufficient):



- This kind of noise function is called *value* noise

3. Generate multiple noise functions with different frequencies:



4. Add all of these together
   - Produces noise at different "scales"

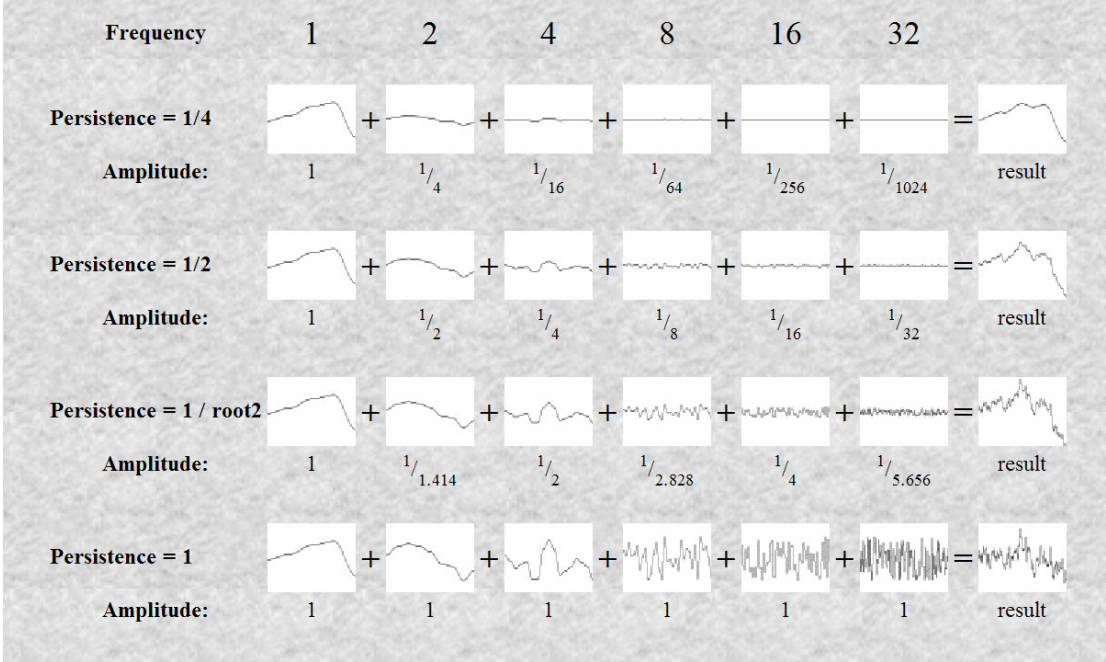
- Persistence = "how much amplitude is scaled for successive octaves scaled for successive octaves"

$$\text{perlin}(x) = \sum_{i=0}^{\infty} p^i n_i(2^i x) \quad , x \in [0,1], p \in [0,1]$$

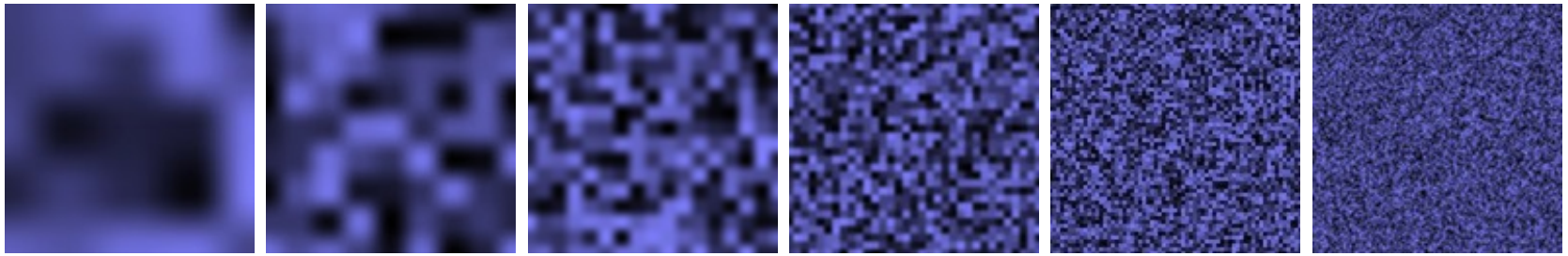
Scaling along x for octaves

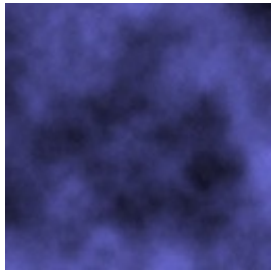
Persistence

- Example:

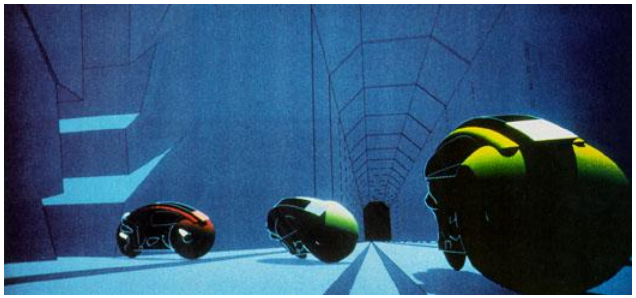


- The same thing in 2D:





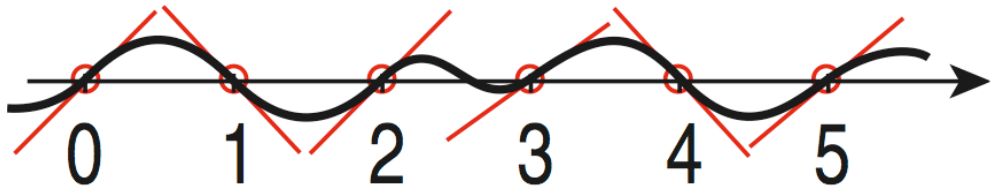
Result



- Easily allows itself to be generalized into higher dimensions
- Also called *pink noise,* or *fractal noise*
- Ken Perlin first dealt with this during his work on TRON

Gradient Noise

- Specify the gradients (instead of values) at integer points:

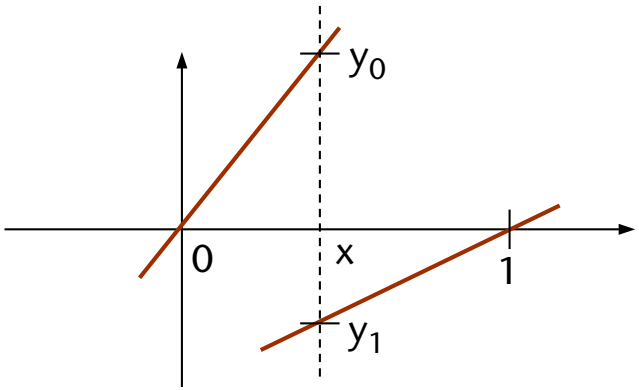


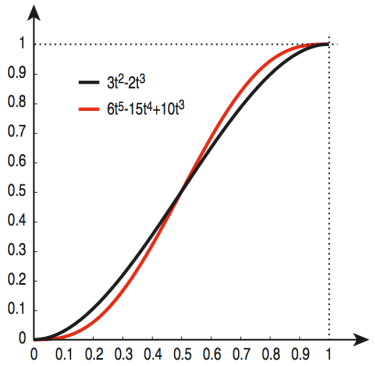
- Interpolation to obtain values:
  - At position x, calculate y_0 and y_1 as values of the lines through x=0 and x=1 with the previously specified (random) gradients
  - Interpolate y_0 and y_1 with a sinusoidal blending function, e.g.

or

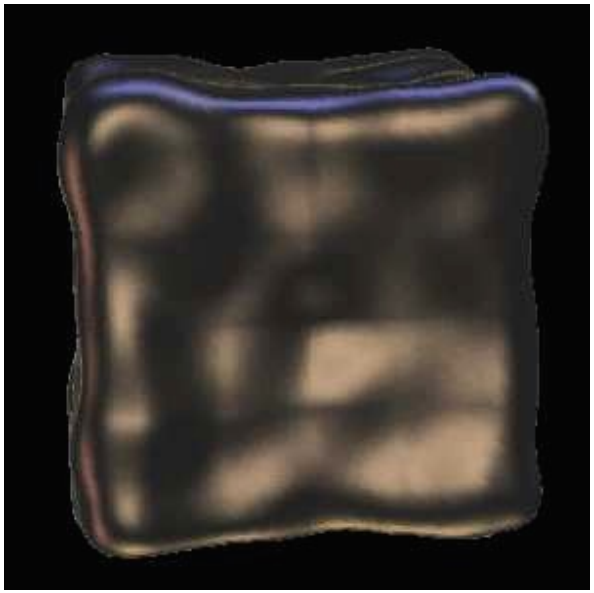
$$h(x) = 3x^2 - 2x^3$$

$$q(x) = 6x^5 - 15x^4 + 10x^3$$

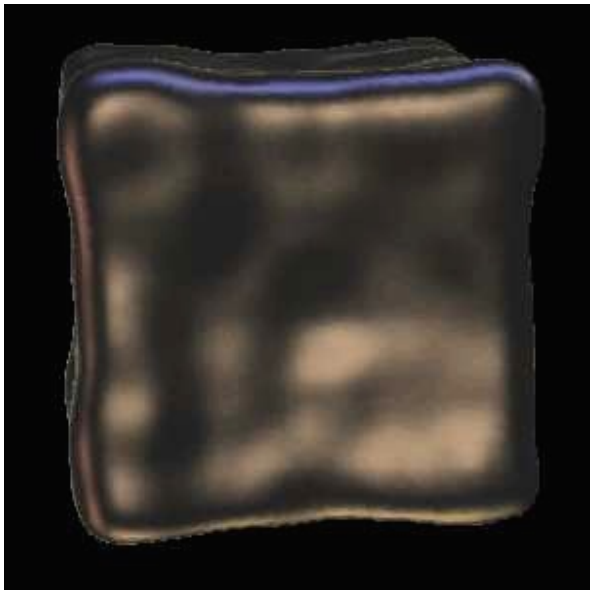




- Advantage of the quintic blending function: $q''(0) = q''(1)$
  → the entire noise function is C^2-continuous
- Example where one can easily see this:



Ken Perlin



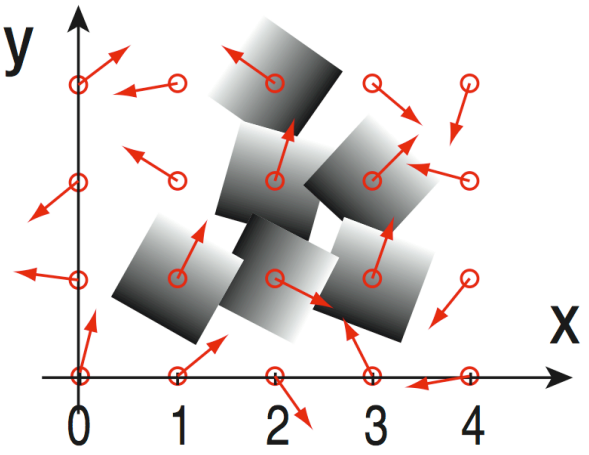
Cubic interpolation

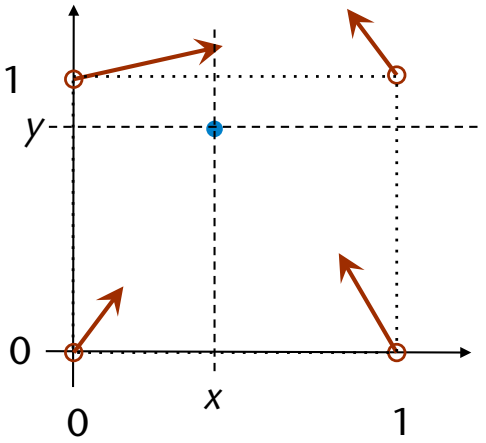
Quintic interpolation

- Gradient noise in 2D:
  - Set gradients at *integer grid points*
    - *Gradient* = 2D vector, not necessarily with length 1
  - Interpolation (as in 1D):
    - W.l.o.g., P = $(x,y) \in [0,1]x[0,1]$
    - Let the following be the gradients:
      g_{00} = gradient at (0,0), g_{01} = gradient at (0,1),
      g_{10} = gradient at (1,0), g_{11} = gradient at (1,1)
    - Calculate the values z_{ij} of the "gradient ramps" g_{ij} at point P :

$$z_{00} = g_{00} \cdot \begin{pmatrix} x \\ y \end{pmatrix} \qquad z_{10} = g_{10} \cdot \begin{pmatrix} x-1 \\ y \end{pmatrix}$$

$$z_{01} = g_{01} \cdot \begin{pmatrix} x \\ y-1 \end{pmatrix} \qquad z_{11} = g_{11} \cdot \begin{pmatrix} x-1 \\ y-1 \end{pmatrix}$$



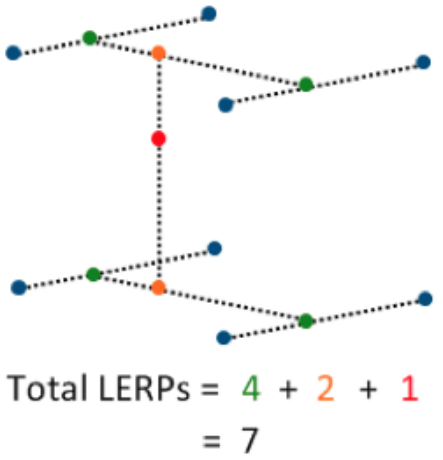


- Blending of 4 z-values through bilinear interpolation:

$$z_{x0} = (1 - q(x))z_{00} + q(x)z_{10}\ , \qquad z_{x1} = (1 - q(x))z_{01} + q(x)z_{11}$$

$$z_{xy} = (1 - q(y))z_{x0} + q(y)z_{x1}$$

- Analogous in 3D:
  - Specify gradients on a 3D grid
  - Evaluate $2^3 = 8$ gradient ramps
  - Interpolate these with tri-linear interpolation and the blending function



- And in *d*-dim. space? → complexity is $O(2^d)$!

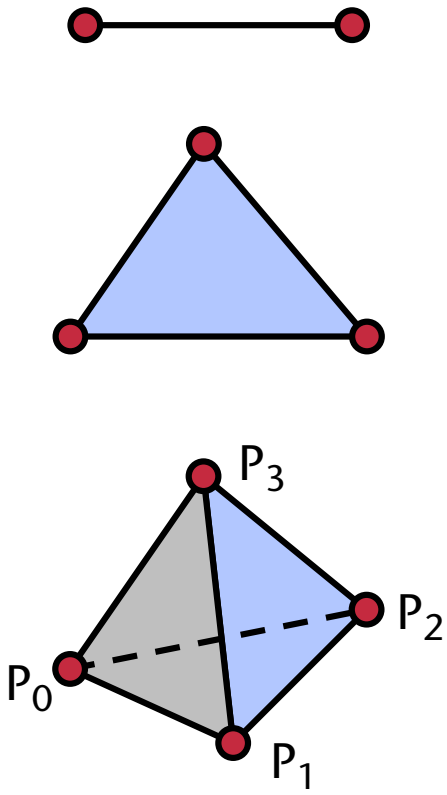
Simplex Noise

- d-dimensionaler simplex :=
  combination of $d+1$ affinely independent points
- Examples:
  - 1D simplex = line, 2D simplex = triangle, 3D simplex = tetrahedron
- In general:
  - Points $P_0, \ldots, P_d$ are given
  - d-dim. simplex = all points X with

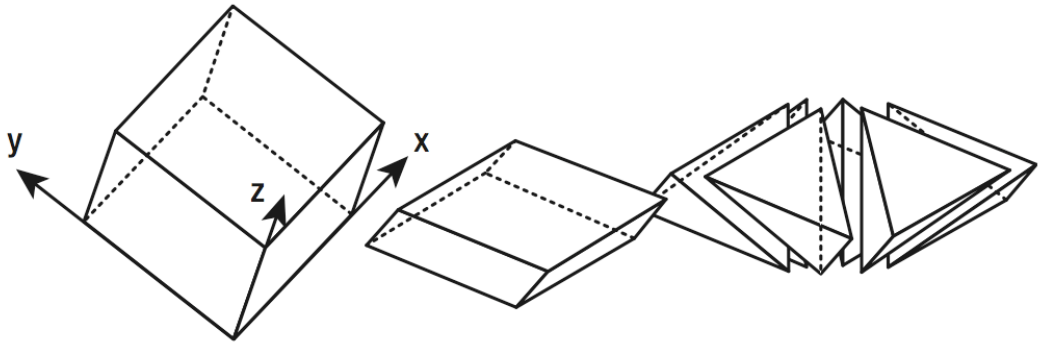
$$X = P_0 + \sum_{i=1}^{d} s_i \mathbf{u}_i$$

with

$$\mathbf{u}_i = P_i - P_0 \ , \ s_i \geq 0 \ , \ \sum_{i=0}^{d} s_i \leq 1$$

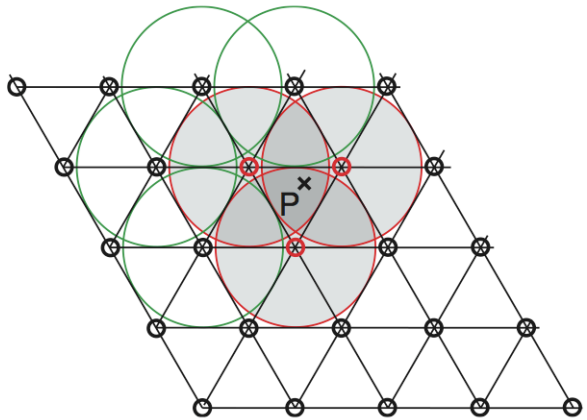


- In general, the following is true:
  - A *d*-dimensional simplex has *d*+1 vertices
  - With equilateral *d*-dimensional simplices, one can partition a cube that was suitably "compressed" along its diagonals

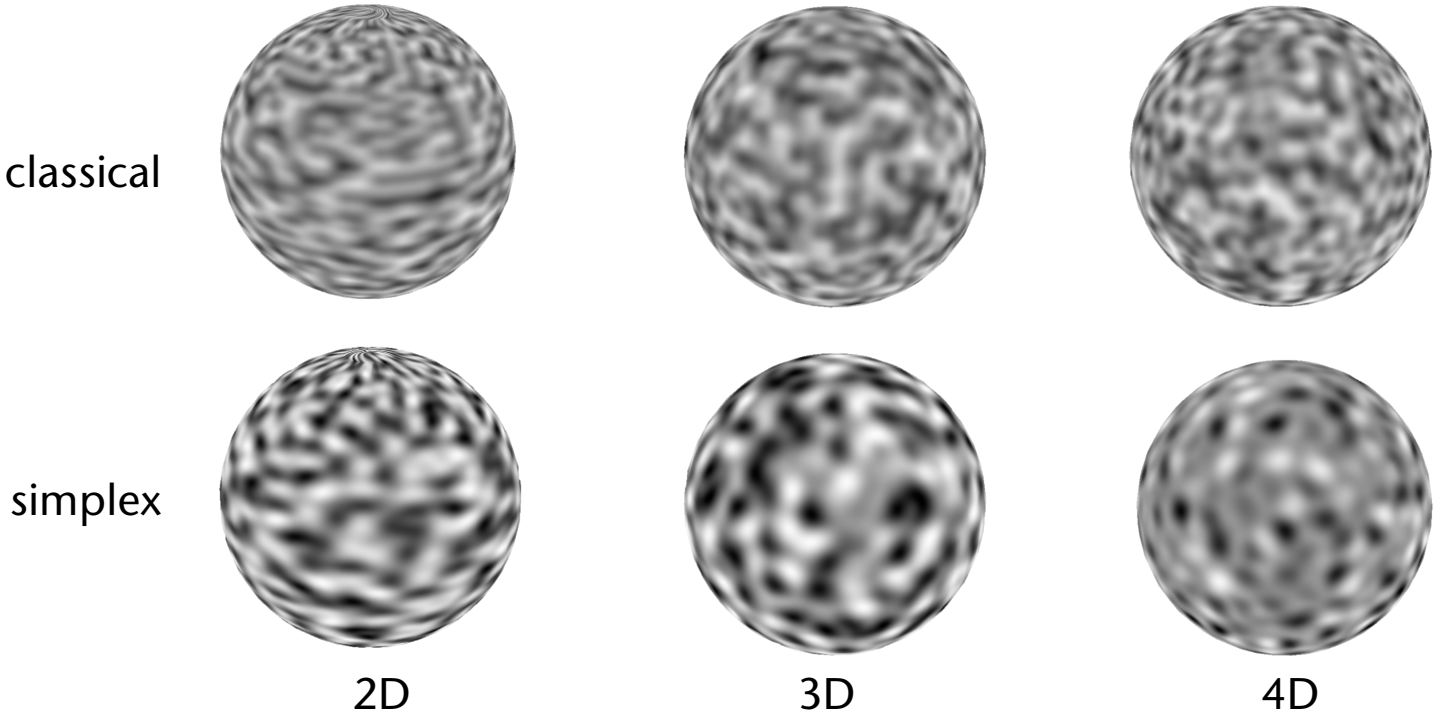


    - Such a "compressed" *d*-dimensional cube contains *d*! many simplices
  - Consequence: with equilateral *d*-dimensional simplexes, one can partition *d*-dimensional space (*tessellation*)

- Construction of the noise function over a simplex tessellation (hence *"simplex noise"*):
  1. Determine the simplex in which a point *P* lies
  2. Determine all of its corners and the gradients in the corners
  3. Determine (as before) the value of these "gradient ramps" in *P*
  4. Generate a weighted sum of these values
  - Choose weighting functions so that the “influence” of a simplex grid point only extends to its incident simplexes



- A huge advantage: has only complexity $O(d)$
- For details see "Simplex noise demystified" (on the course's homepage)
- Comparison between classical value noise and simplex noise:



- Four noise functions are defined in the GLSL standard:

  `float noise1(gentype), vec2 noise2(gentype),`
  `vec3  noise3(gentype), vec4 noise4(gentype).`

- Calling such a noise function:

  v = noise2($f*x + t$, $f*y + t$)

  - With *f,* one can control the spatial frequency,
    With *t,* one can generate an animation (*t*="time").
  - Analogous for 1D and 3D noise

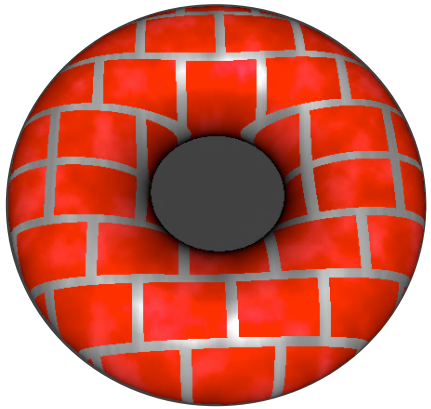
- Caution: range is [-1,+1]!

- Cons:

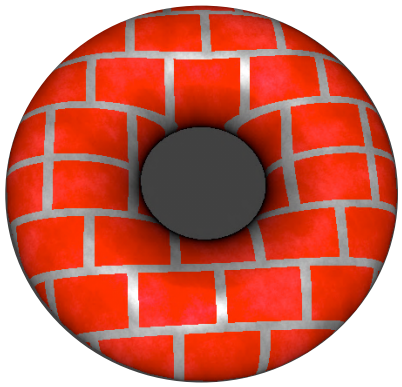
  - Are not implemented everywhere
  - Are slooooooooow...

Example: Application of Noise to our Procedural Texture

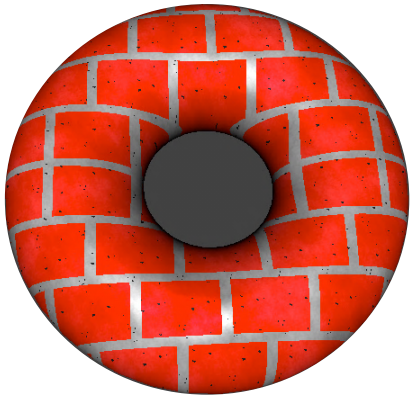
- Our procedural brick texture (please ignore the uneven outer torus contour, that's an artifact from Powerpoint):



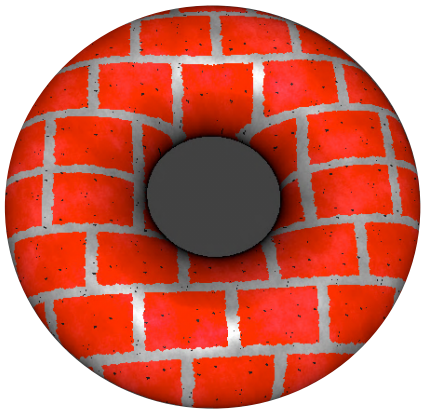
With variation in color



With fine-grain variations



With black spots



With curvy brick edges

The code for this example is on the course's homepage (after unpacking the archive, it is in directory *vorlesung_demos* files *brick.vert* and *brick[4-7].frag*)

Other Examples for the Applications of Noise

Ken Perlin's famous solid texture marble vase, 1985

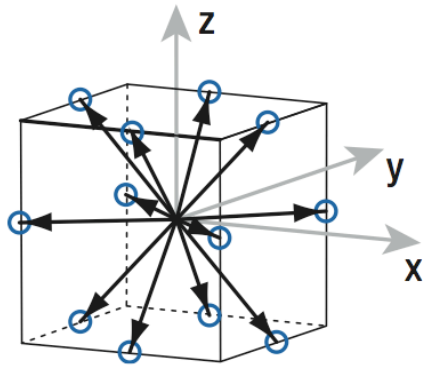
Procedural bump mapping, done by computing noise in the pixel shader and using that for perturbing the surface normal

g = a * perlin(x,y,z)

grain = g - int(g)

Remark on Implementation

- Goal: repeatable noise function
  - That is, f(x) always returns the same value for the same x
- Choose fixed gradients at the grid points
- Observation: a few different ones are sufficient
  - E.g. for 3D, gradients from this set are sufficient:

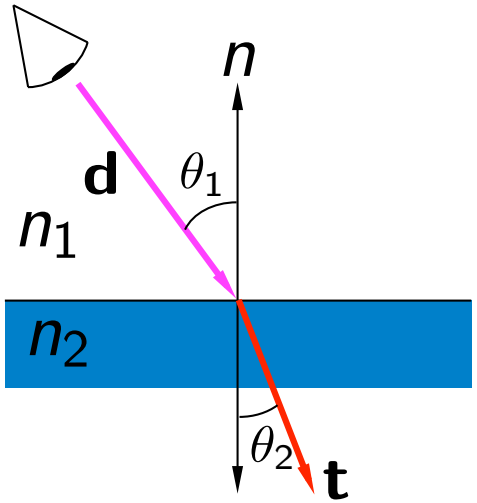


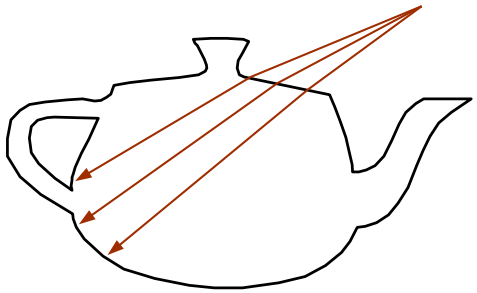
$$
\begin{aligned}
&g_0 = (0,1,1), g_1 = (0,1,-1),\\
&g_2 = (0,-1,1), g_3 = (0,-1,-1),\\
&g_4 = (1,0,1), g_5 = (1,0,-1),\\
&g_6 = (-1,0,1), g_7 = (-1,0,-1),\\
&g_8 = (1,1,0), g_9 = (1,-1,0),\\
&g_{10} = (-1,1,0), g_{11} = (-1,-1,0)
\end{aligned}
$$

- Integer coordinates of the grid points can be simply hashed→ index into a table of pre-defined gradients

Light Refraction

- With shaders, one can implement approximations of simple global effects
- Example: light refraction
- What does one need to calculate the refracted ray?
  - Snell's Law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$
  - Needed: **n**, **d**, n_1, n_2
  - Everything is available in the fragment shader
  - So, one can calculate **t** *per pixel*
- So why is rendering transparent objs difficult?
  - In order to calculate the correct intersection point of the refracted ray, one needs the entire geometry!

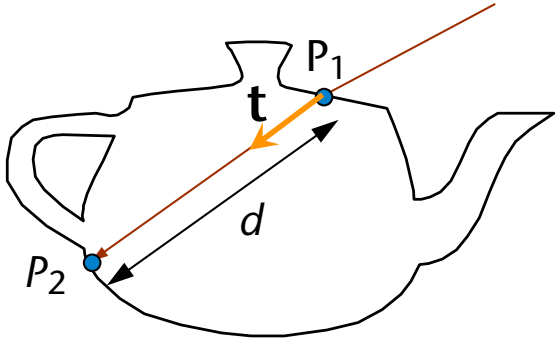


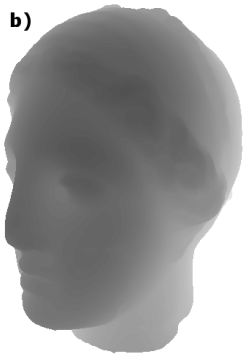


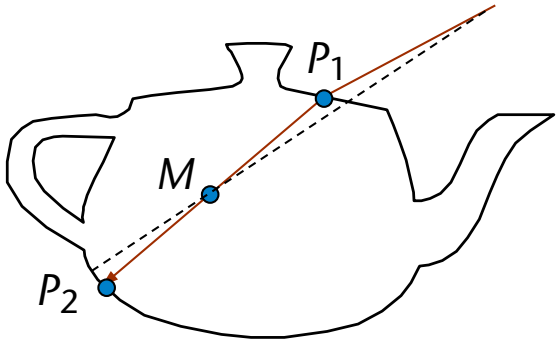
- Goal: approximate transparent object with two planes, which the incoming & refracted rays intersect
- Step 1: determine the next intersection point

$$P_2 = P_1 + d\mathbf{t}$$

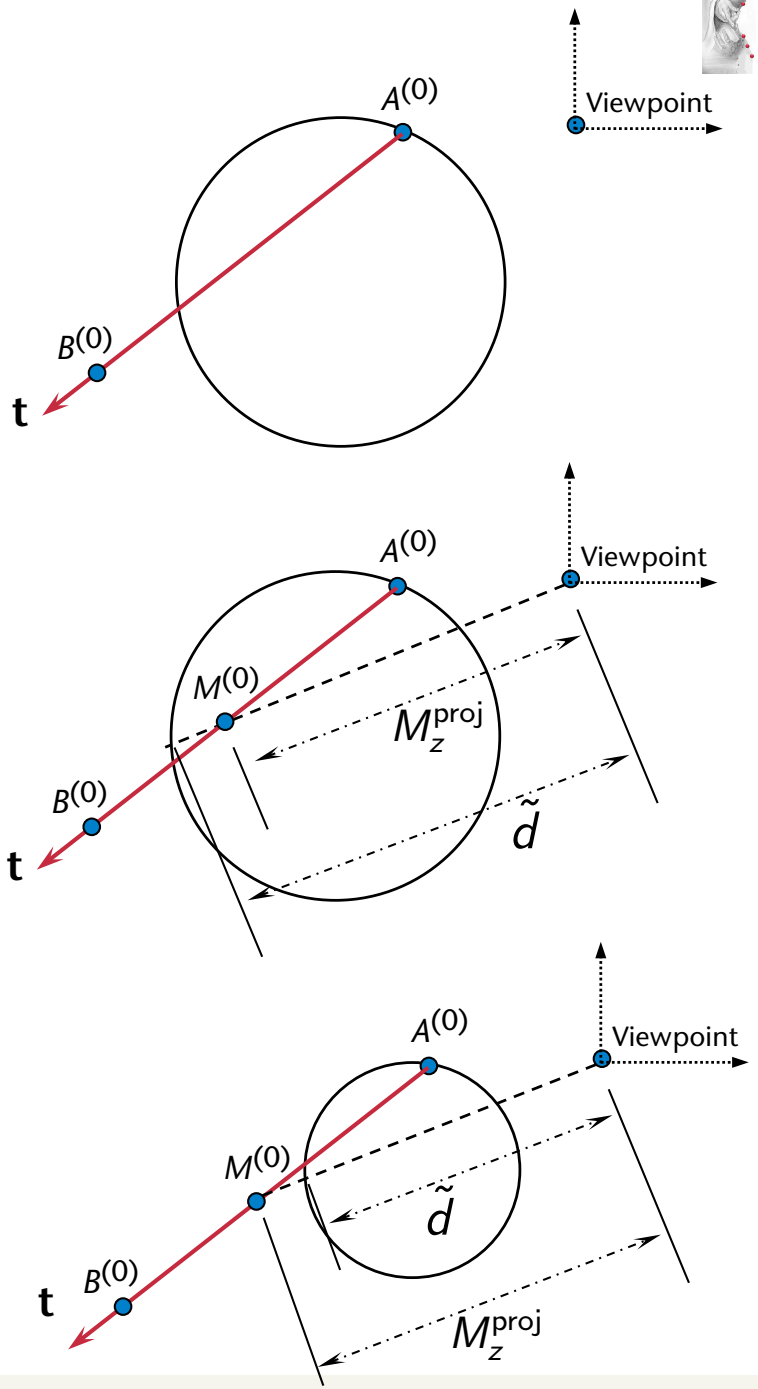
  - Idea: approximate *d*
  - To do that, render a depth map of the back-facing polygons in a previous pass, from the viewpoint
  - Use binary search to find a good approximation of the depth (ca. 5 iterations suffice)



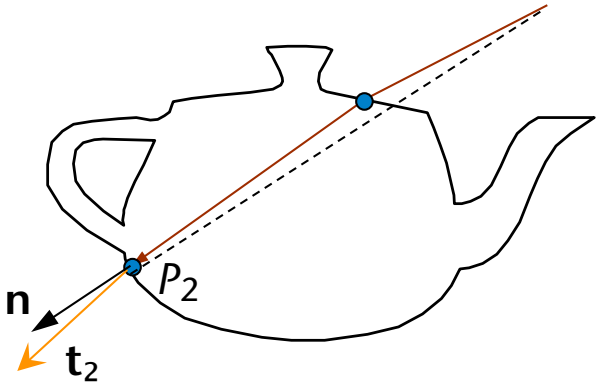


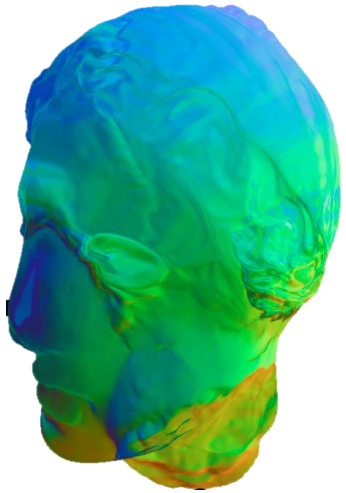


- On the binary search for finding the depth between P_1 and P_2:
  - Situation: given a ray **t**, with $t_z < 0$, and two "bracket" points $A^{(0)}$ and $B^{(0)}$, between which the intersection point must be; and a precomputed depth map
  - Compute midpoint $M^{(0)}$
  - Project midpoint with projection matrix $\longrightarrow M^{\text{proj}}$
  - Use $(M_x^{\text{proj}}, M_y^{\text{proj}})$ to index the depth map $\longrightarrow \tilde{d}$
  - If $\tilde{d} > M_z^{\text{proj}} \Rightarrow$ set $A^{(1)} = M^{(0)}$
  - If $\tilde{d} < M_z^{\text{proj}} \Rightarrow$ set $B^{(1)} = M^{(0)}$



- Step 2: determine the normal in P_2
  - To do that, render a normal map of all back-facing polygons from the viewpoint (yet another pass before the actual rendering)
  - Project P_2 with respect to the viewpoint into screen space
  - Index the normal map
- Step 3:
  - Determine $\mathbf{t}_2$
  - Index an environment map

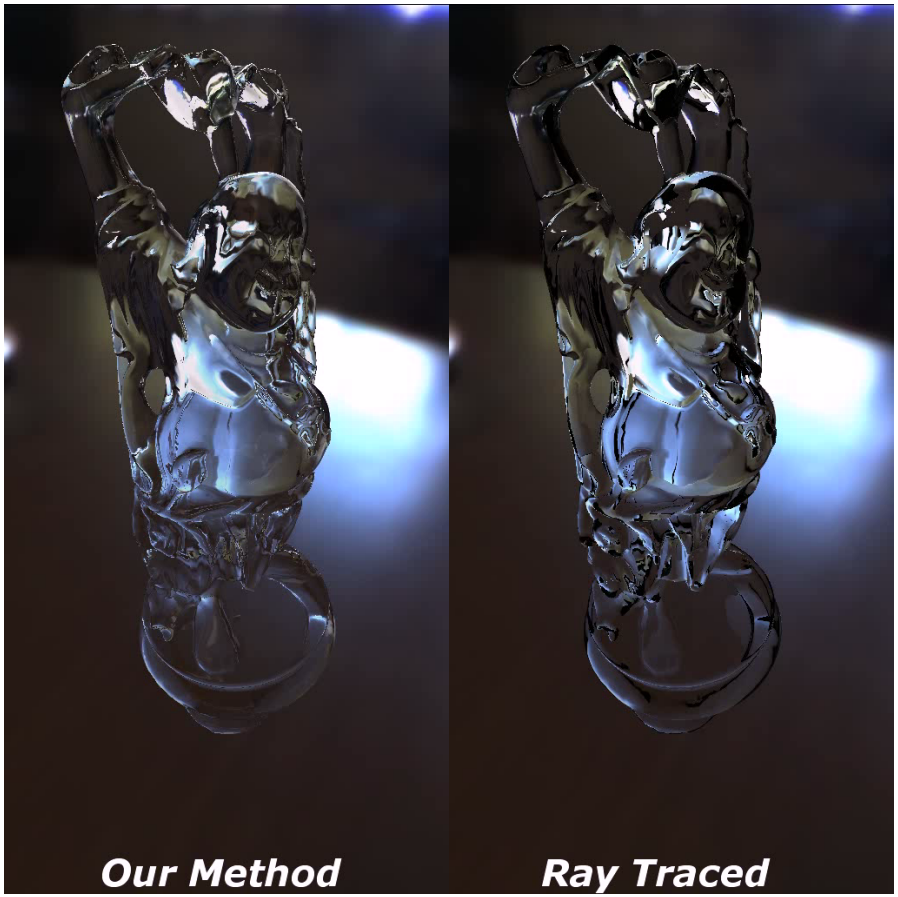




Normal map

- Many open challenges:
  - When *depth complexity* > 2:
    - Which normal/which depth value should be stored in the depth/normal maps?
  - Approximation of distance
  - Aliasing

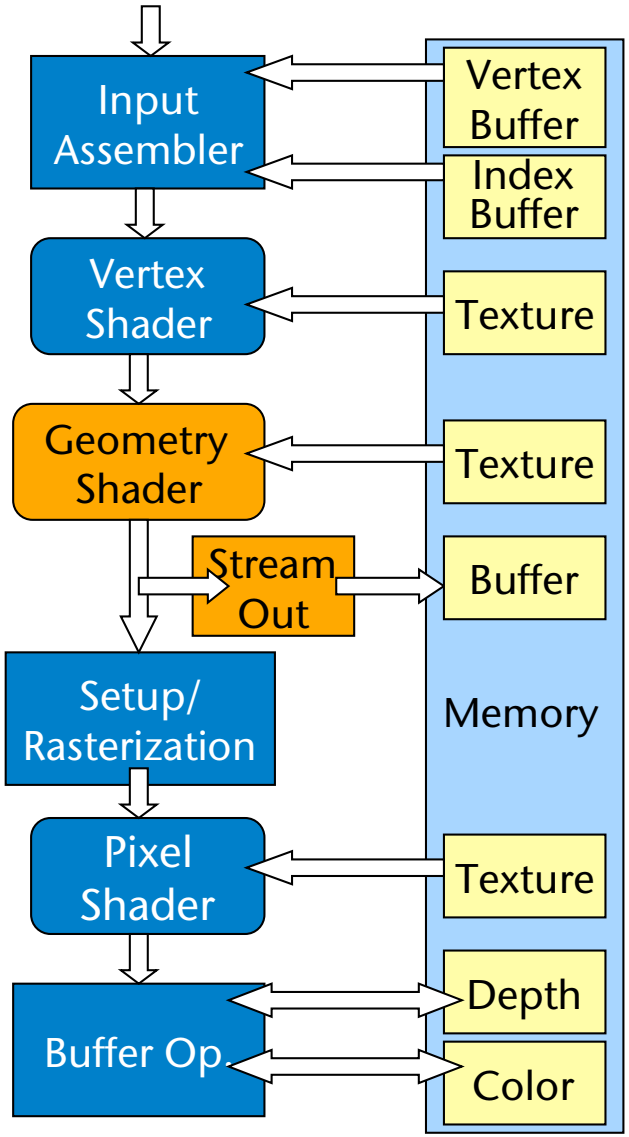
Examples

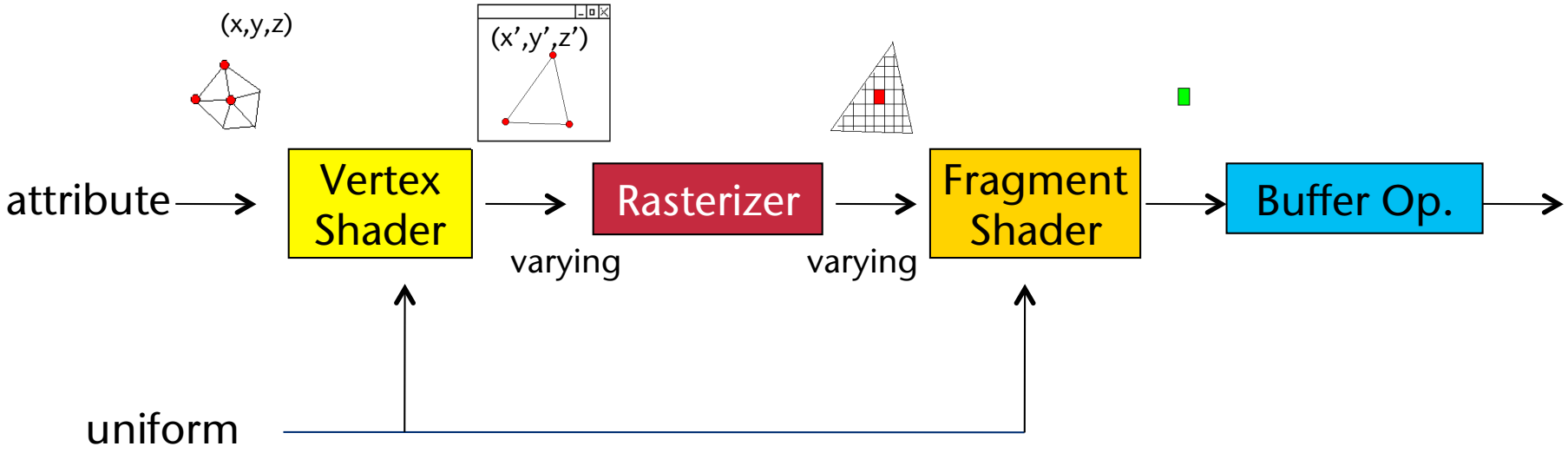


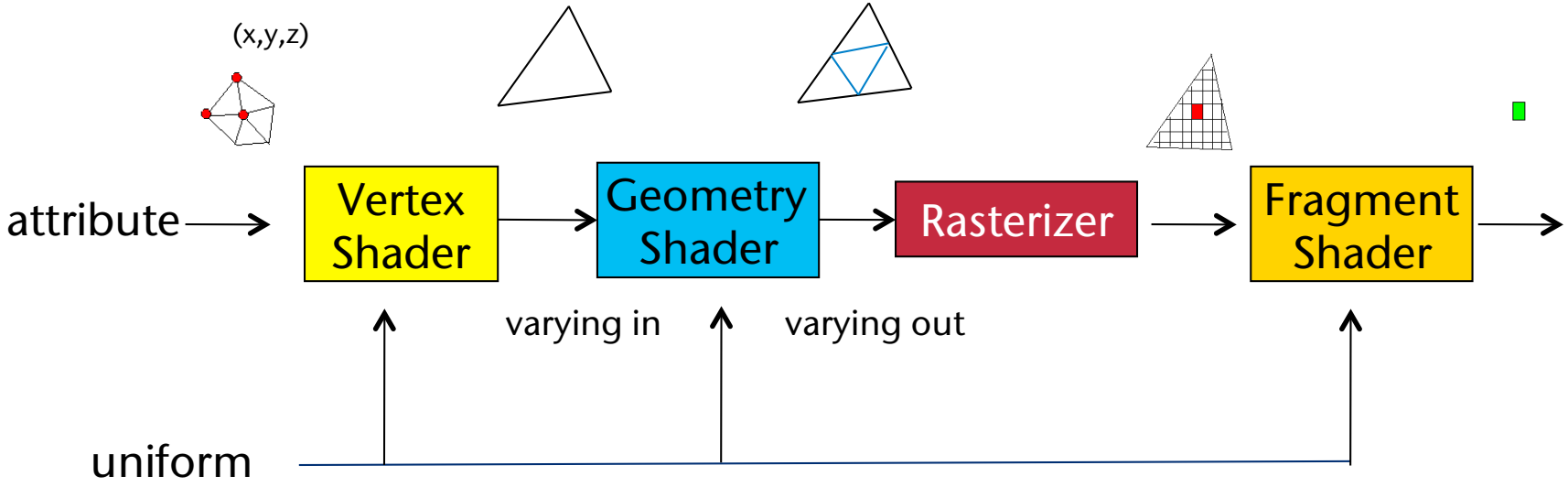
With internal reflection

The Geometry Shader

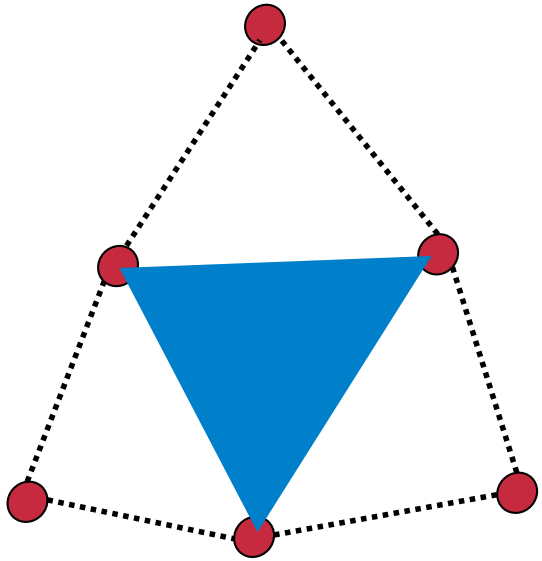
- Situated between vertex shader and rasterizer
- Essential difference to other shaders:
  - Per-*primitive* processing
  - The geometry shader can produce variable-length output!
  - 1 primitive in, *k* prims out
  - Is optional (not necessarily present on all GPUs)
- Note on the side: features stream out
  - New, fixed-function
  - Divert primitive data to buffers
  - Can be transferred back to the OpenGL prog ("Transform Feedback")

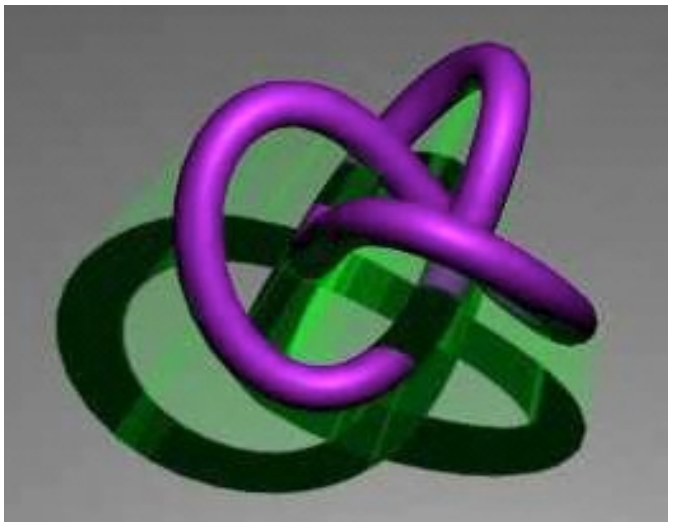



(x,y,z)
(x',y',z')
attribute
Vertex Shader
Rasterizer
Fragment Shader
Buffer Op.
varying
varying
uniform

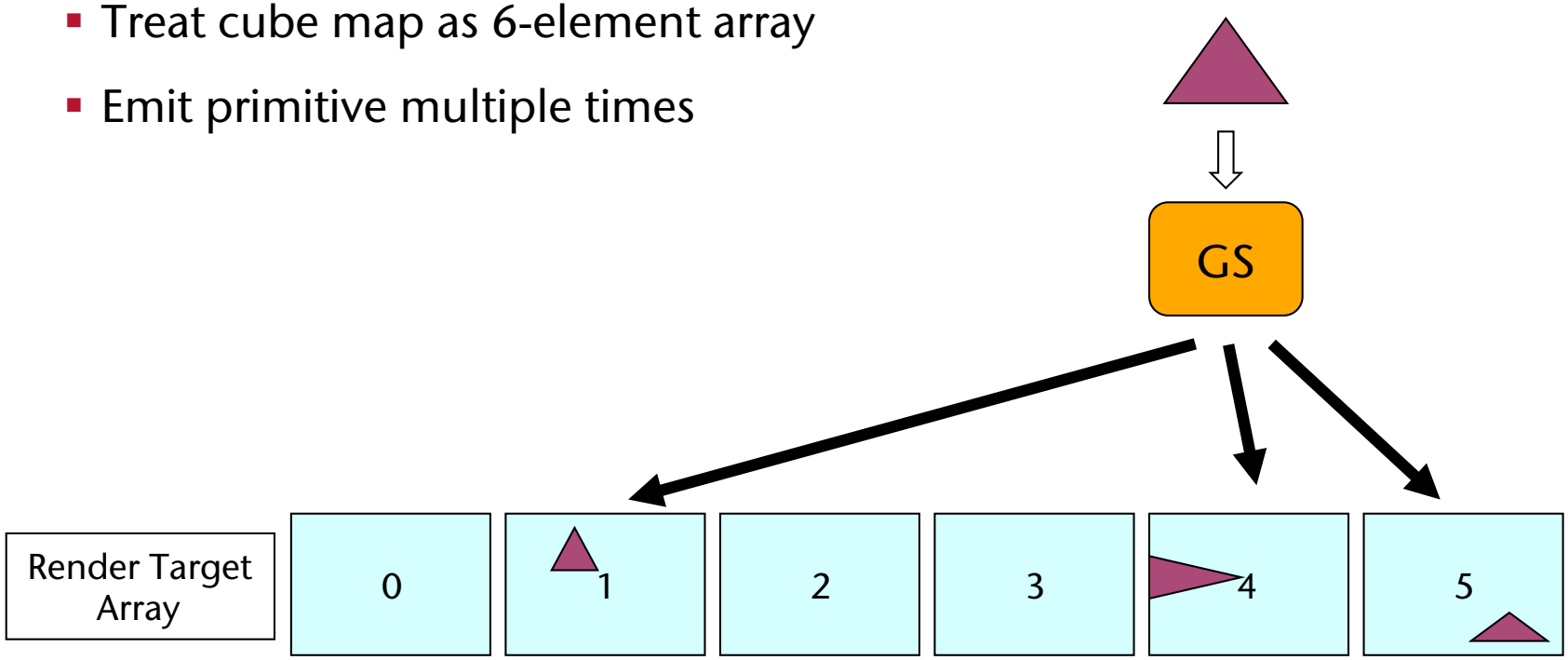

(x,y,z)
attribute
Vertex Shader
Geometry Shader
Rasterizer
Fragment Shader
varying in
varying out
uniform

- The geometry shader's principle function:
  - In general "amplify geometry"
  - More precisely: can create or destroy primitives *on the GPU*
  - Entire primitive as input (optionally with adjacency)
  - Outputs zero or more primitives
    - 1024 scalars out max
- Example application:
  - Silhouette extrusion for shadow volumes



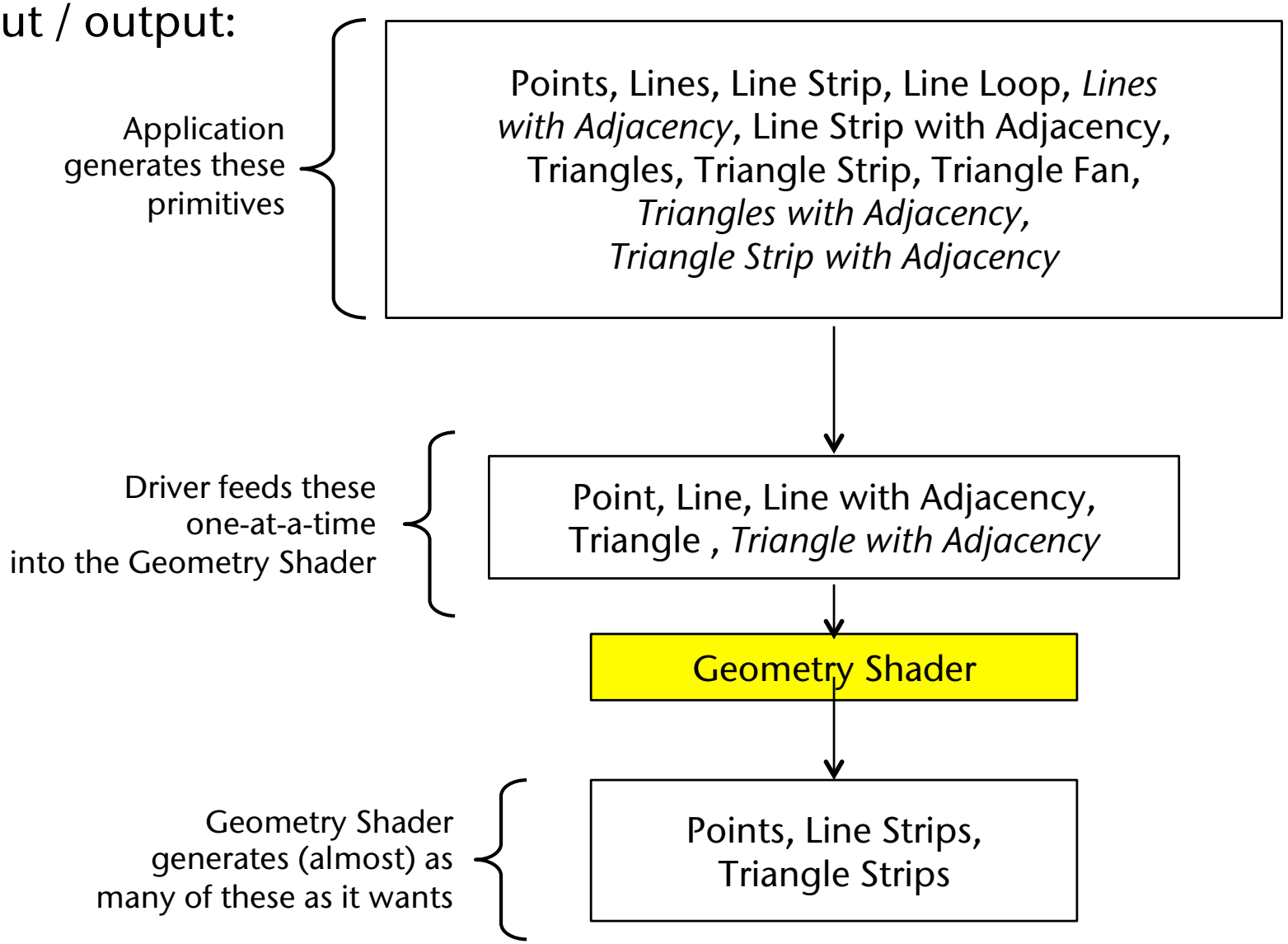


- Another feature of geometry shaders: can render the same geometry to multiple targets
- E.g., render to cube map in a single pass:
  - Treat cube map as 6-element array
  - Emit primitive multiple times



Some More Technical Details

- Input / output:



- In general, you must specify the type of the primitives that will be input and output to and from the geometry shader
  - These need not necessarily be the same type
- Input type:

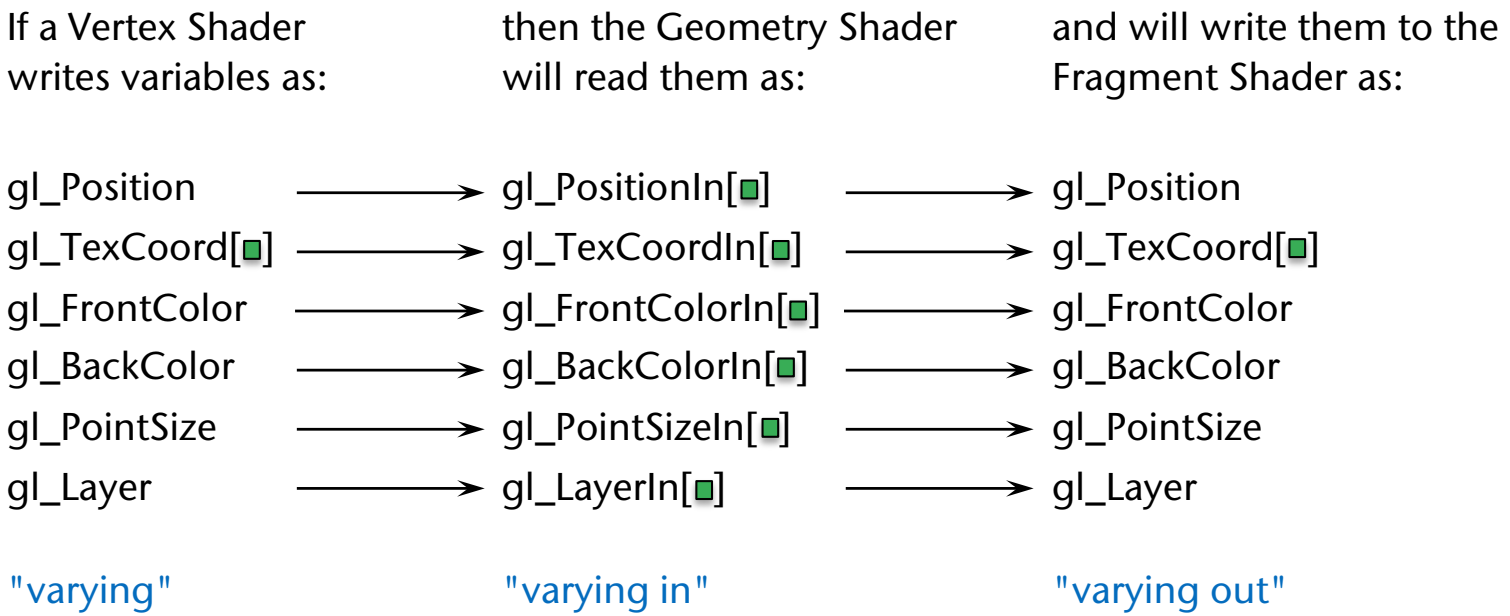
```
glProgramParameteri( shader_prog_name,
                     GL_GEOMETRY_INPUT_TYPE, int value );
```

  - **value** = primitive type that this geometry shader will be receiving
  - Possible values: GL_POINTS, GL_TRIANGLES, … (more later)
- Output type:

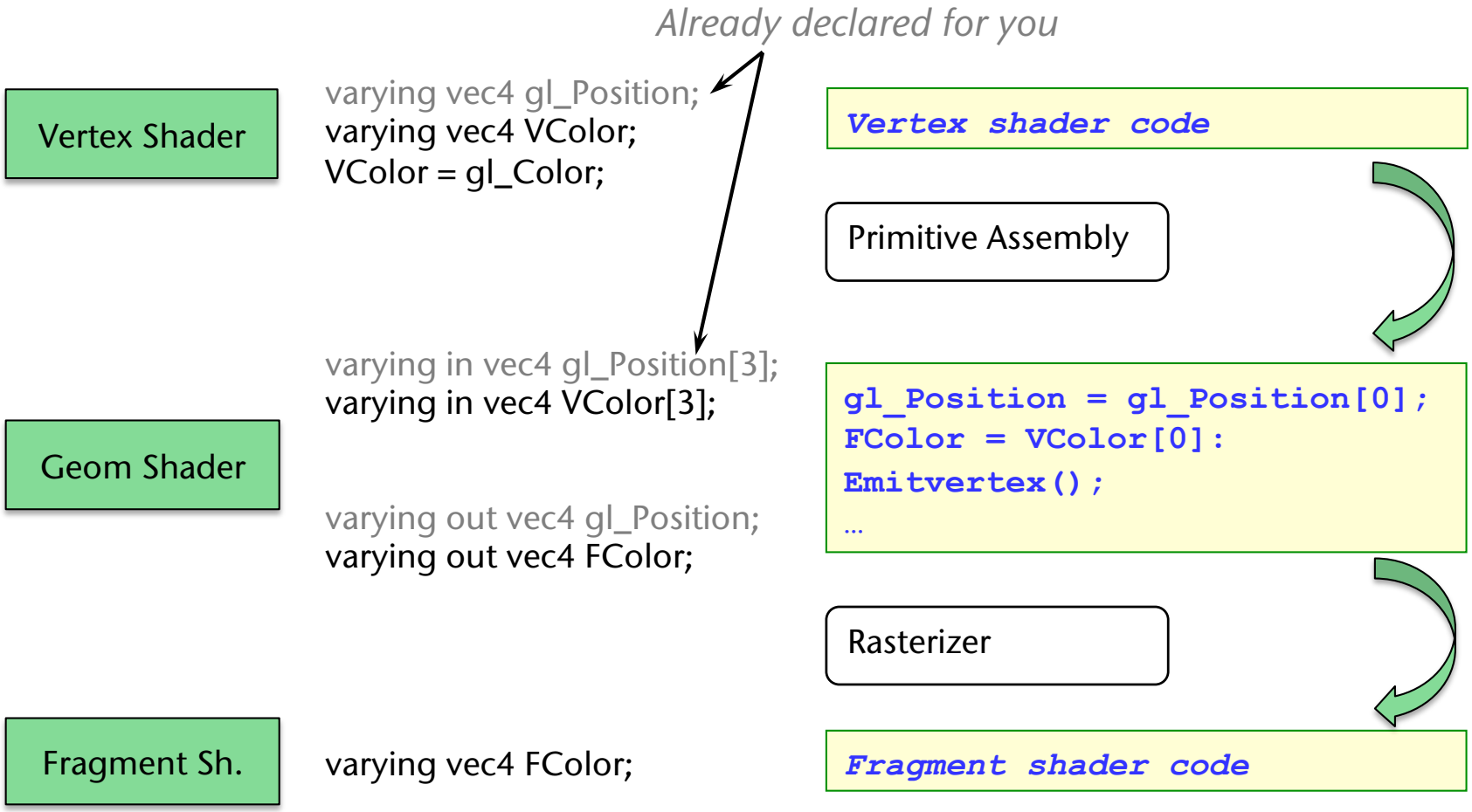
```
glProgramParameteri( shader_prog_name,
                     GL_GEOMETRY_OUTPUT_TYPE, int value );
```

  - **value** = primitive type that this geometry shader will output
  - Possible values: GL_POINTS, GL_LINE_STRIP, GL_TRIANGLES_STRIP

Data Flow of the Principle Varying Variables



- If a geometry shader is part of the shader program, then passing information from the vertex shader to the fragment shader can only happen via the geometry shader:



- Since you may not emit an unbounded number of points from a geometry shader, you are required to let OpenGL know the maximum number of points any instance of the shader will emit
- Set this parameter *after* creating the program, but *before* linking:

```
glProgramParameteri( shader_prog_name,
                     GL_GEOMETRY_VERTICES_OUT, int n );
```

- A few things you might trip over, when you try to write your first geometry shader:
  - It is an error to attach a geometry shader to a program without attaching a vertex shader
  - It is an error to use a geometry shader without specifying GL_GEOMETRY_VERTICES_OUT
  - The shader will not compile correctly without the #version and #extension pragmas

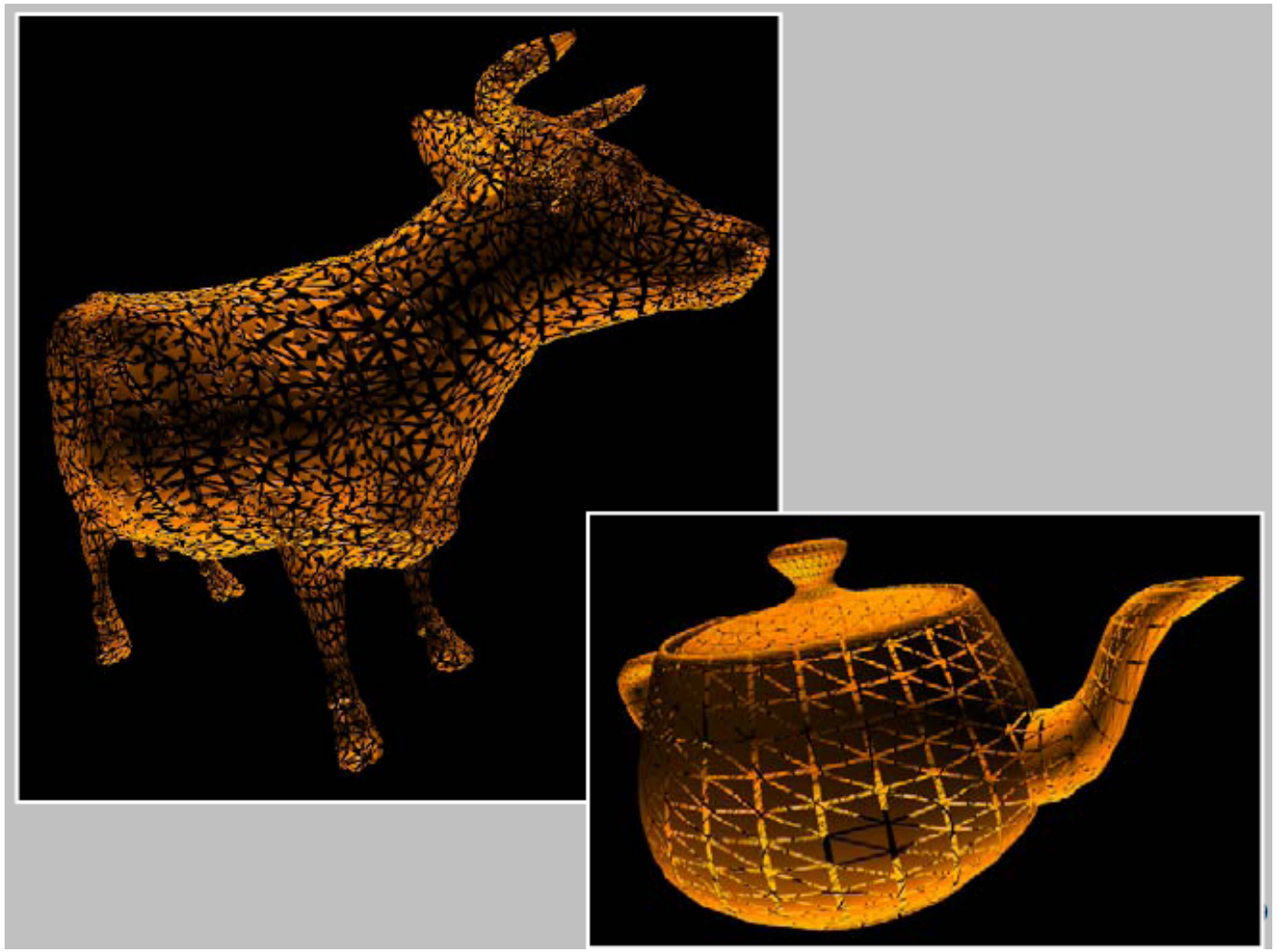
- The geometry shader generates geometry by repeatedly calling **`EmitVertex()`** and **`EndPrimitive()`**
- Note: there is no BeginPrimitive() routine. It is implied by
  - the start of the Geometry Shader, or
  - returning from the **`EndPrimitive()`** call

A Very Simple Geometry Shader Program

```
#version 120

#extension GL_EXT_geometry_shader4 : enable void

main(void)
{
   gl_Position = gl_PositionIn[0] + vec4(0.0, 0.04, 0.0, 0.0);
   gl_FrontColor = vec4(1.0, 0.0, 0.0, 1.0);
   EmitVertex();

   gl_Position = gl_PositionIn[0] + vec4(0.04, -0.04, 0.0, 0.0);
   gl_FrontColor = vec4(0.0, 1.0, 0.0, 1.0);
   EmitVertex();

   gl_Position = gl_PositionIn[0] + vec4(-0.04, -0.04, 0.0, 0.0);
   gl_FrontColor = vec4(0.0, 0.0, 1.0, 1.0);
   EmitVertex();

   EndPrimitive();

}
```

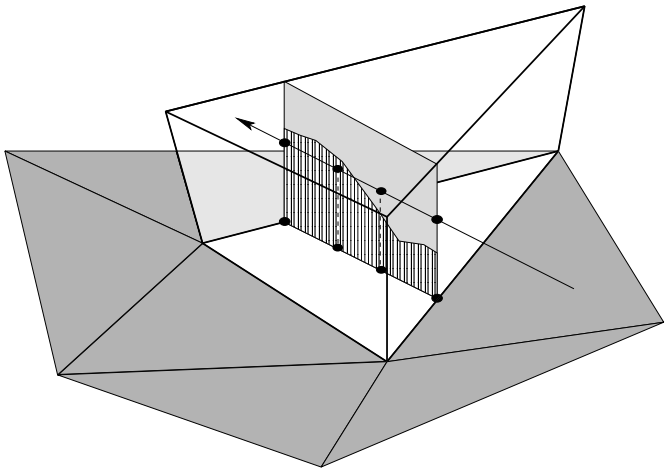
Examples

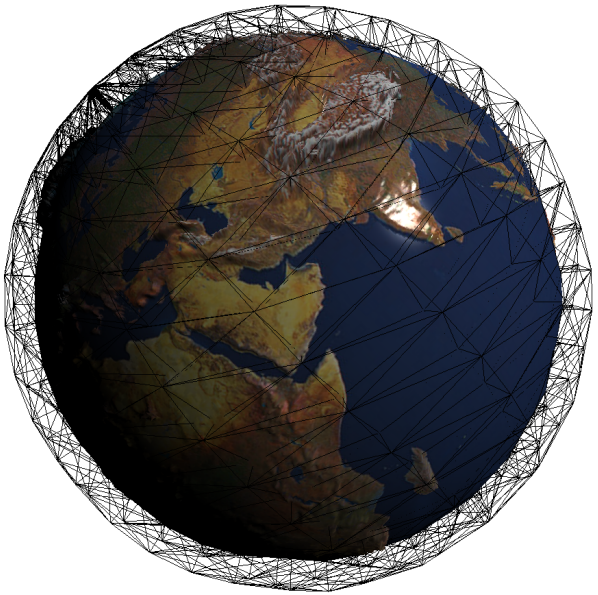
- Shrinking triangles:



Displacement Mapping

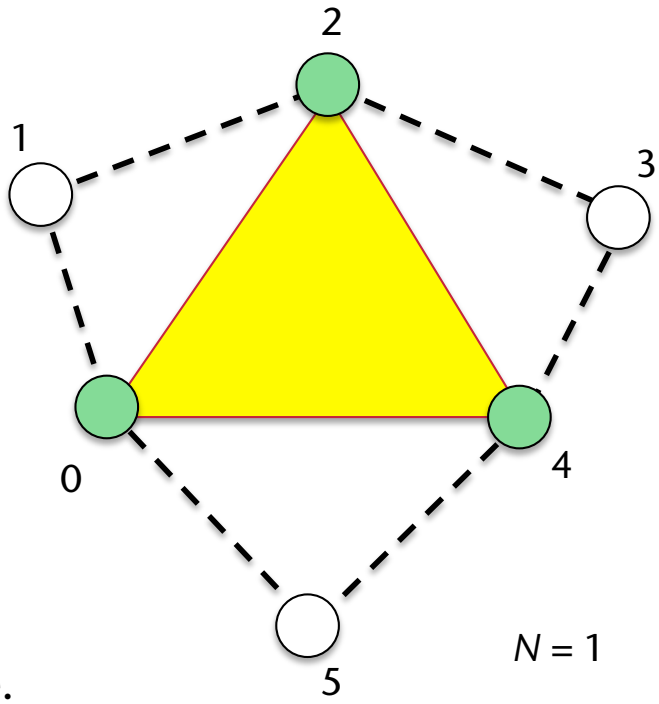
- Geometry shader extrudes prism at each face
- Fragment shader ray-casts against height field
- Shade or discard pixel depending on ray test





Intermezzo: Adjacency Information

- In addition to the conventional primitives (GL_TRIANGLE et al.), a few new primitives were introduced with geometry shaders
- The most frequent one: GL_TRIANGLES_WITH_ADJACENCY

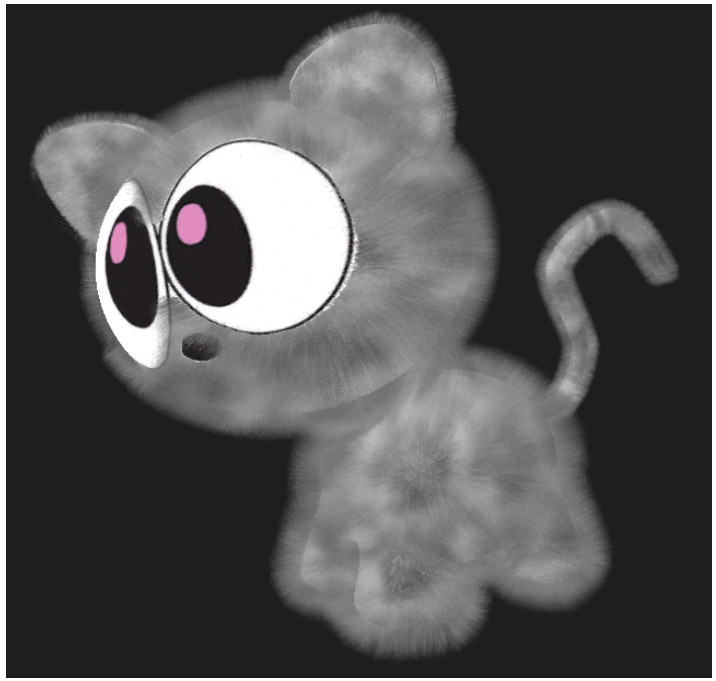


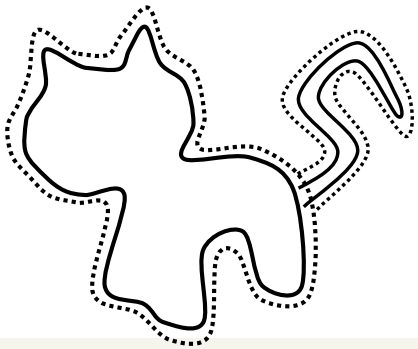
Triangles with Adjacency

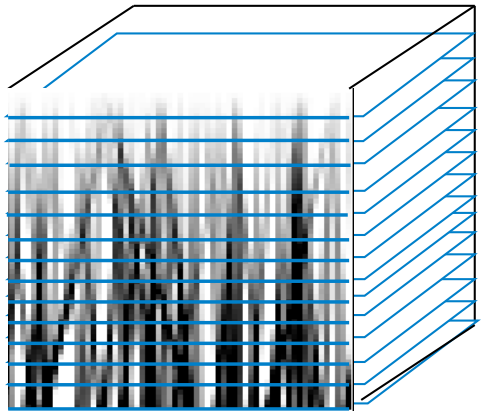
6N vertices are given
(where *N* is the number of triangles to draw).
Points 0, 2, and 4 define the triangle.
Points 1,3, and 5 tell where adjacent triangles are.

Shells & Fins

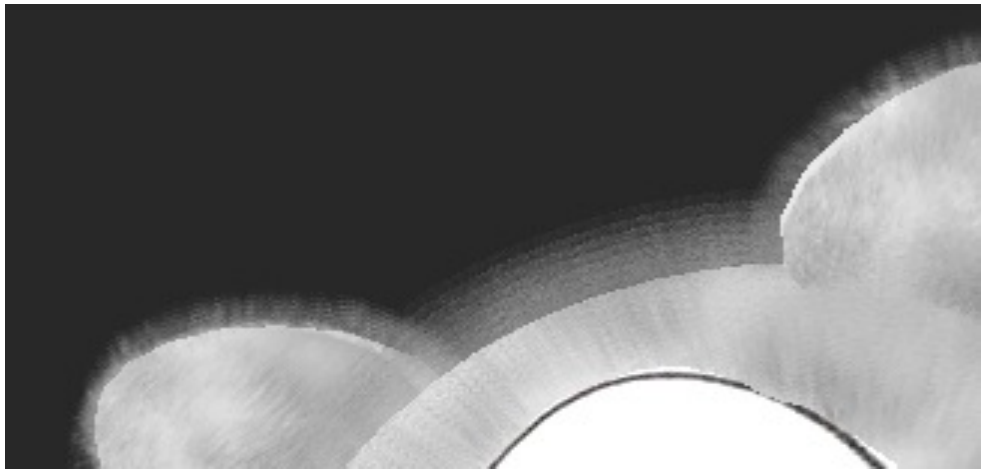
- Suppose, we want to generate a "fluffy", ghostly character like this
- Idea:
  - Render several shells (offset surfaces) around the original polygonal geometry
    - Can be done easily using the vertex shader
  - Put different textures on each shell the generate a volumetric, yet "gaseous" shell appearance





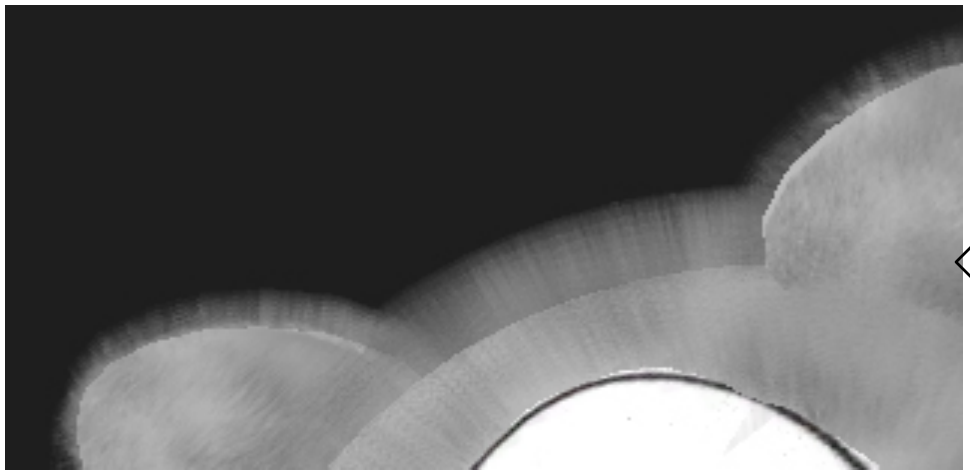


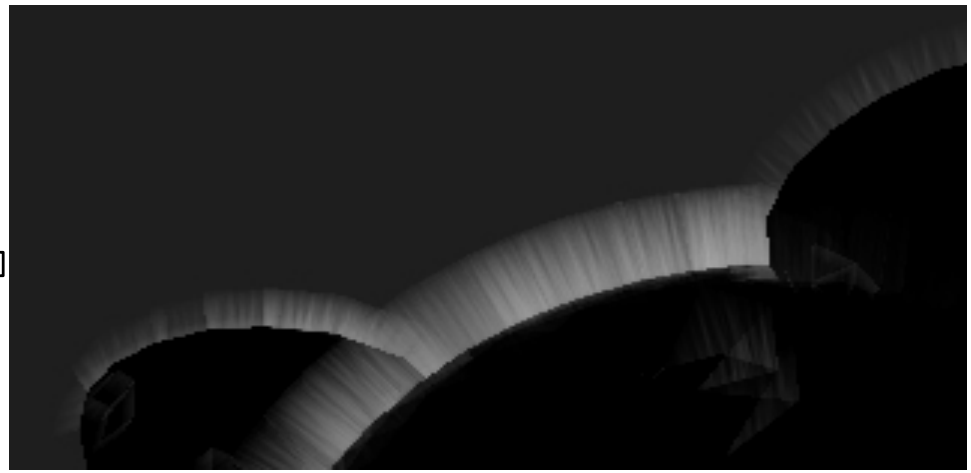
- Problem at the silhouettes:
- Solution: add "fins" at the silhouette
  - Fin = polygon standing on the edge between 2 silhouette polygons
- Makes problem much less noticeable



8 shells

+



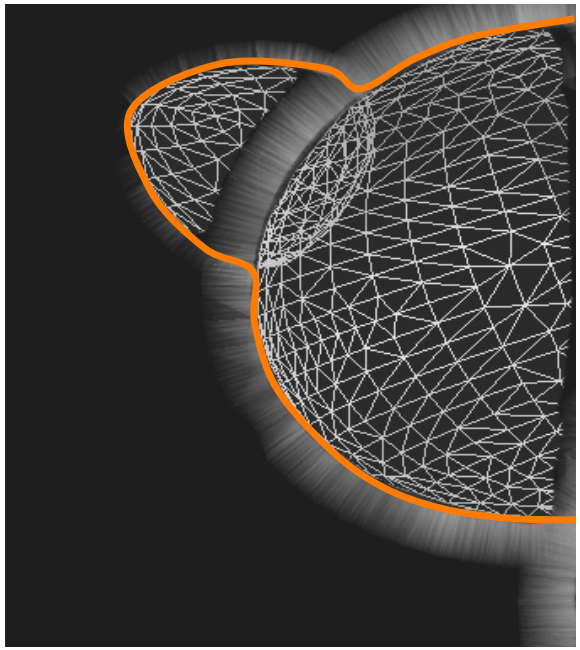


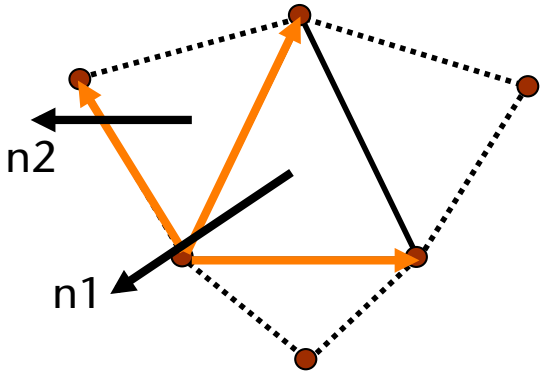
fins

- Idea: fins can be generated in the geometry shader
- How it works:
  - All geometry goes through the geometry shader
  - Geometry shader checks whether or not the polygon has a silhouette edge:

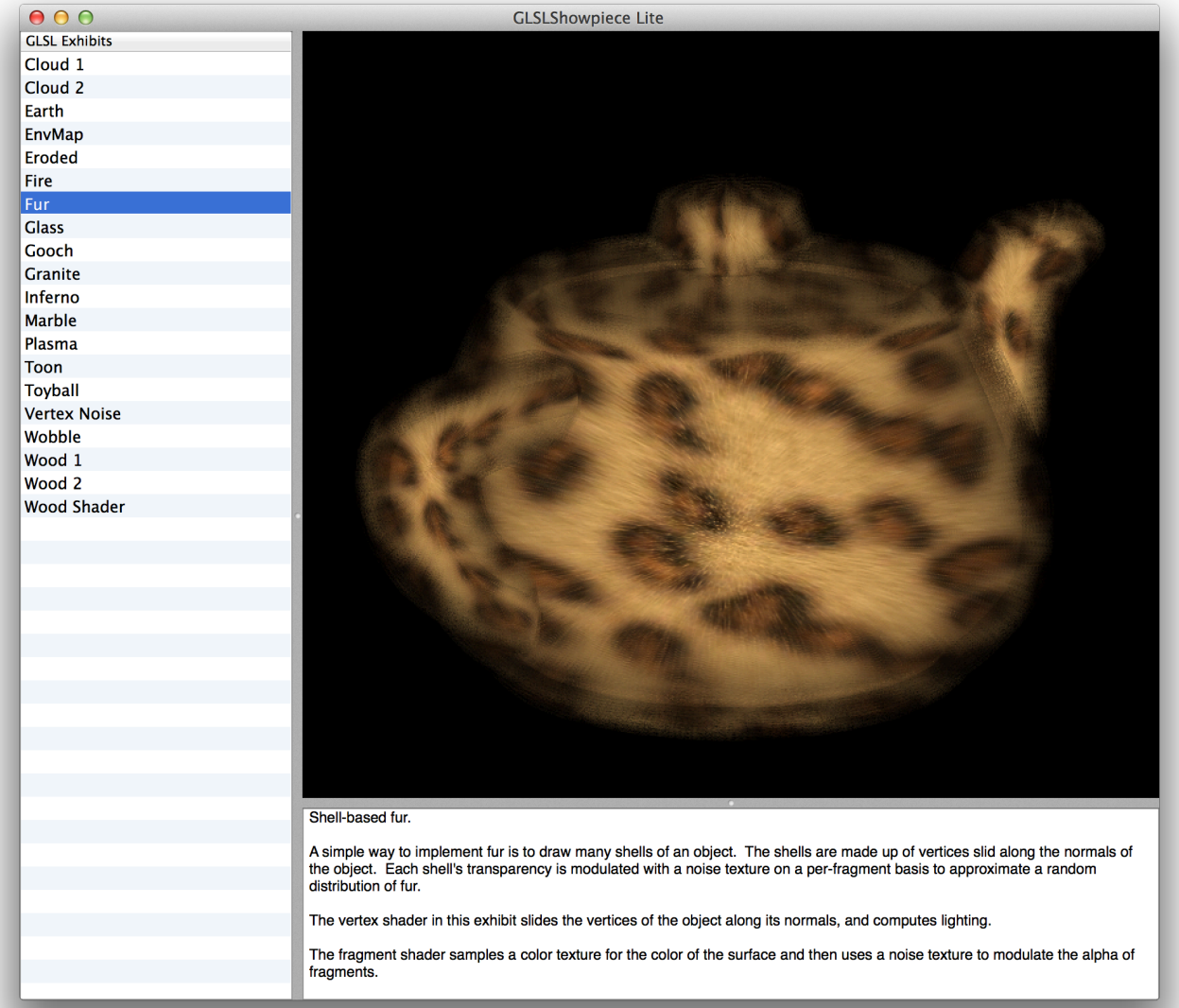
    silhouette $\Leftrightarrow$ $\mathbf{en}_1 > 0 \wedge \mathbf{en}_2 < 0$ or $\mathbf{en}_1 < 0 \wedge \mathbf{en}_2 > 0$

    where **e** = eye vector
  - If one edge = silhouette, then the geometry shader emits a fin polygon, and the input polygon
  - Else, it just emits the input polygon





Demo

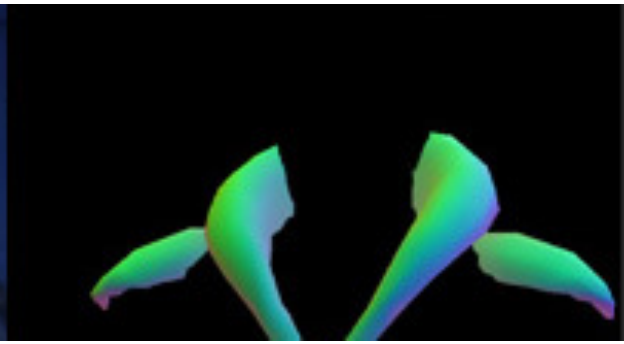


demos/shader/GLSLShowpieceLite/

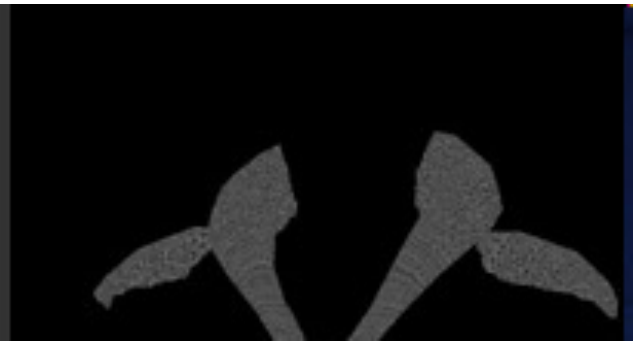
Example Application: Lost Planet Extreme Condition

- More tricks are usually needed to make it look really good:

Texture for color



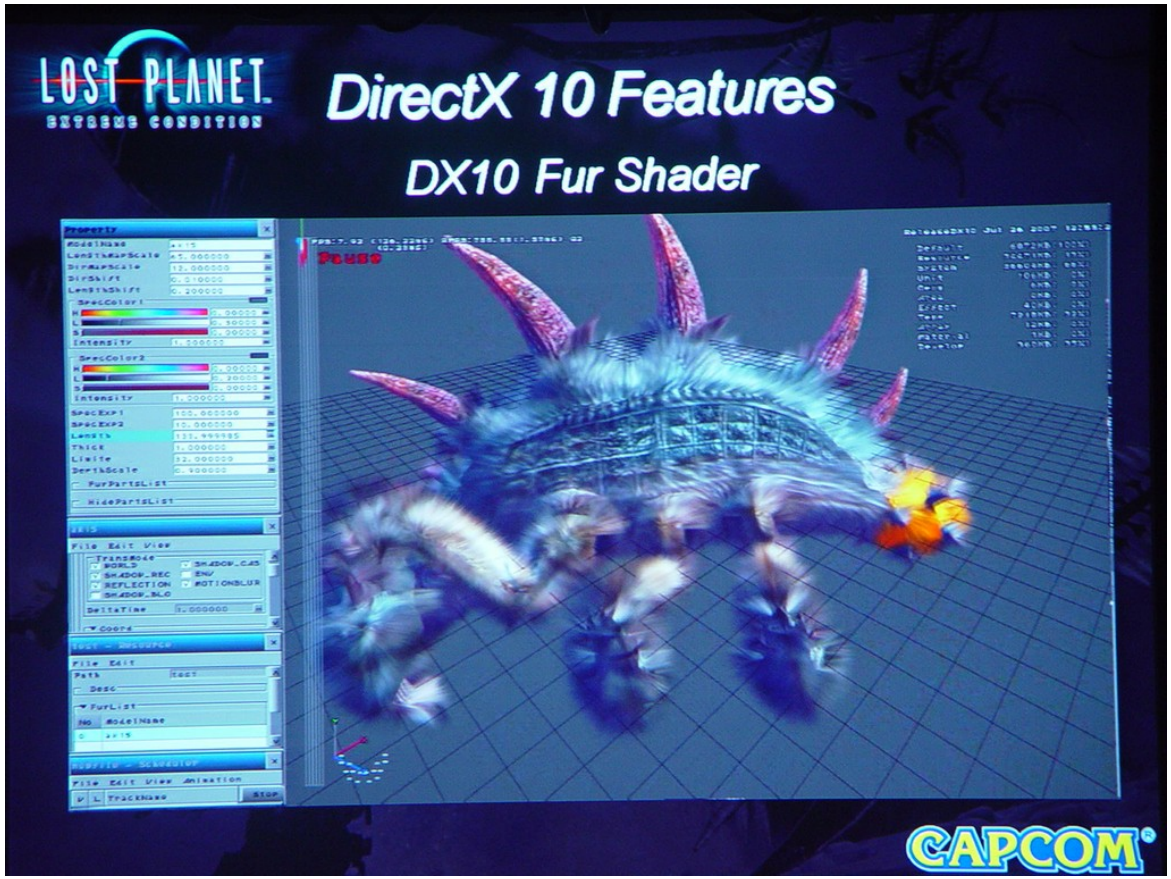
Texture for angle of fur hairs



Noise texture for length of fur hairs

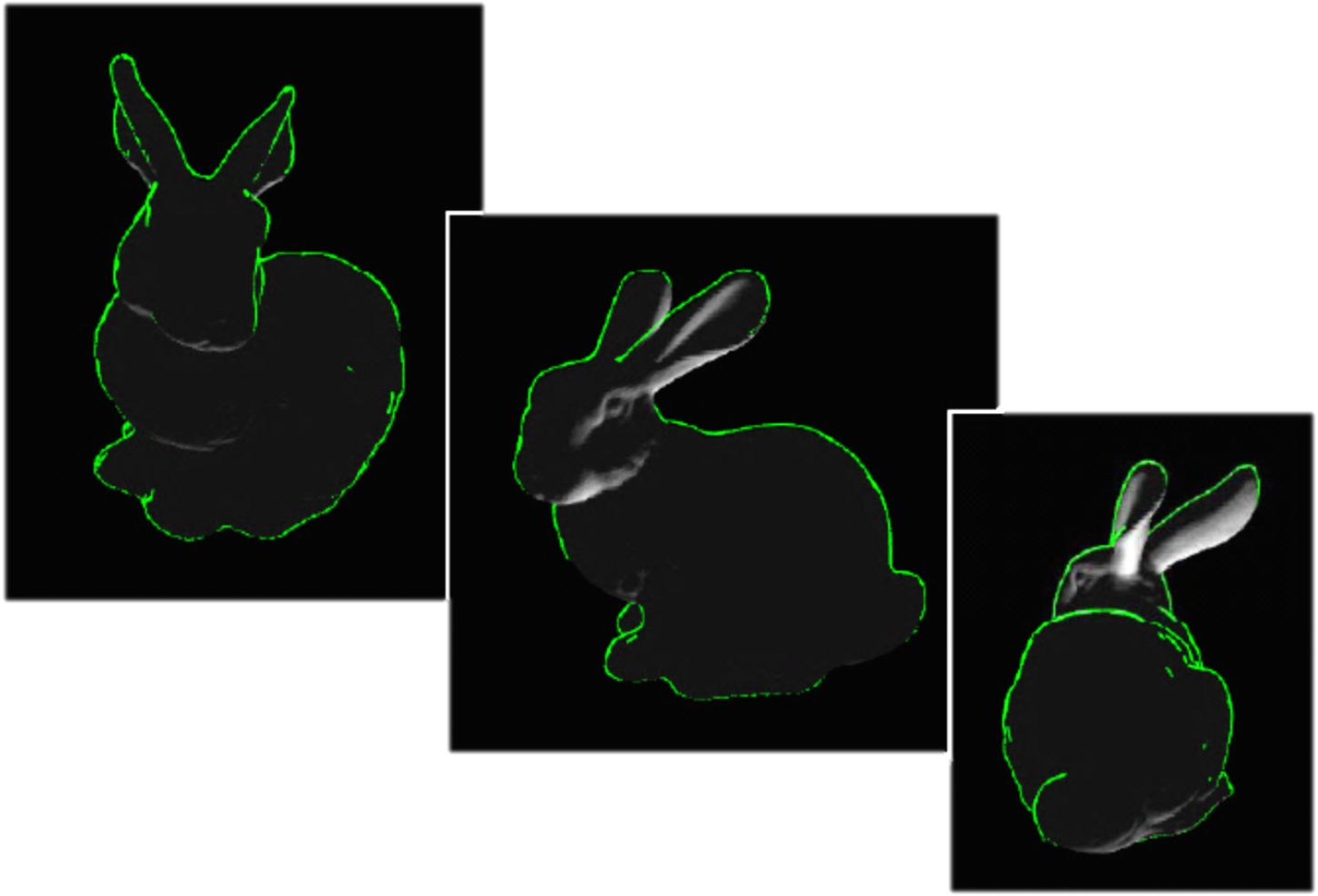
Furthermore, one should try to render self-shadowing of strands of fur hairs ...

- Typically, what you as a programmer need to do is to write the shader and expose the parameters via a GUI to the artists, so that they can determine the best look



Silhouette Rendering

- Goal:

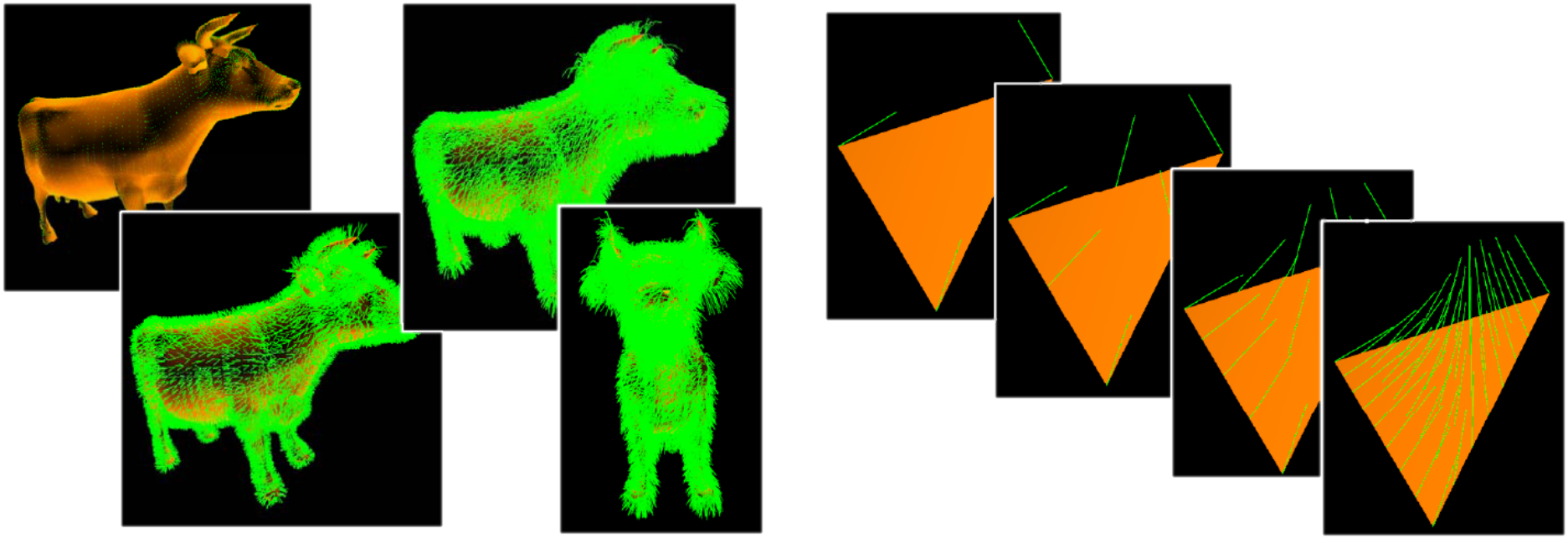


- Technique: 2-pass rendering

1. Pass: render geometry regularly
2. Pass: switch on geometry shader for silhouette rendering
   - Switch to green color for all geometry (no lighting)
   - Render geometry again
   - Input of geometry shader = triangles
   - Output = lines
   - Geometry shader checks, whether triangle contains silhouette edge
   - If yes ⟶ output line
   - If no ⟶ output no geometry
- Geometry shader input = GL_TRIANGLE_WITH_ADJACENCY
  output = GL_LINE_STRIP

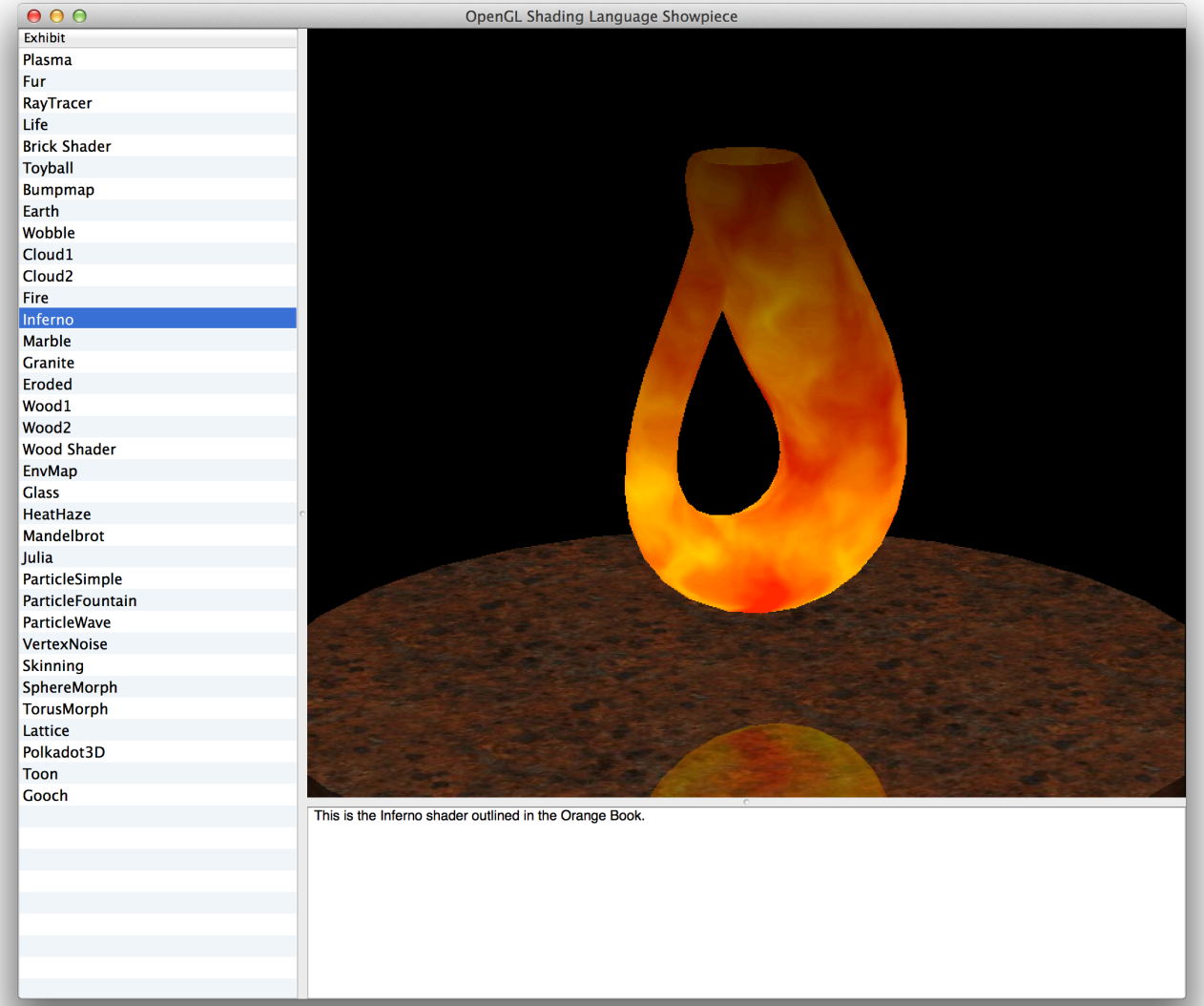
More Applications of Geometry Shaders

- Hedgehog Plots:



Shader Trees

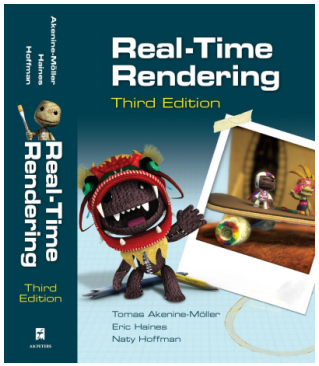
Concluding Demos



demos/shader/GLSLShowpiece/GLSLShowpiece.app
→ Inferno, Granite, Eroded, Glass, HeatHaze, Julia, ParticleFountain, VertexNoise, TorusMorph

Resources on Shaders

- Real-Time Rendering; 3rd edition

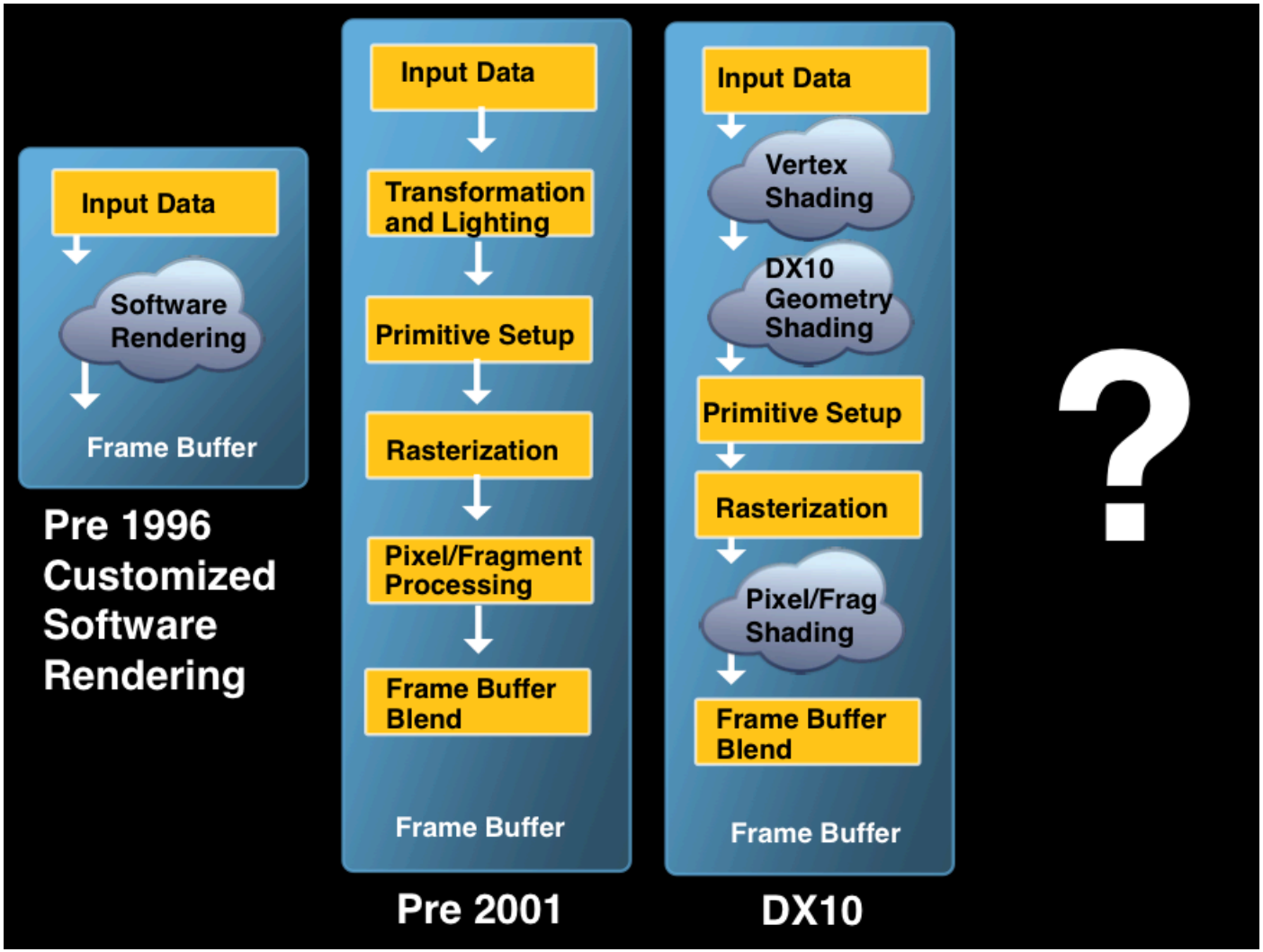


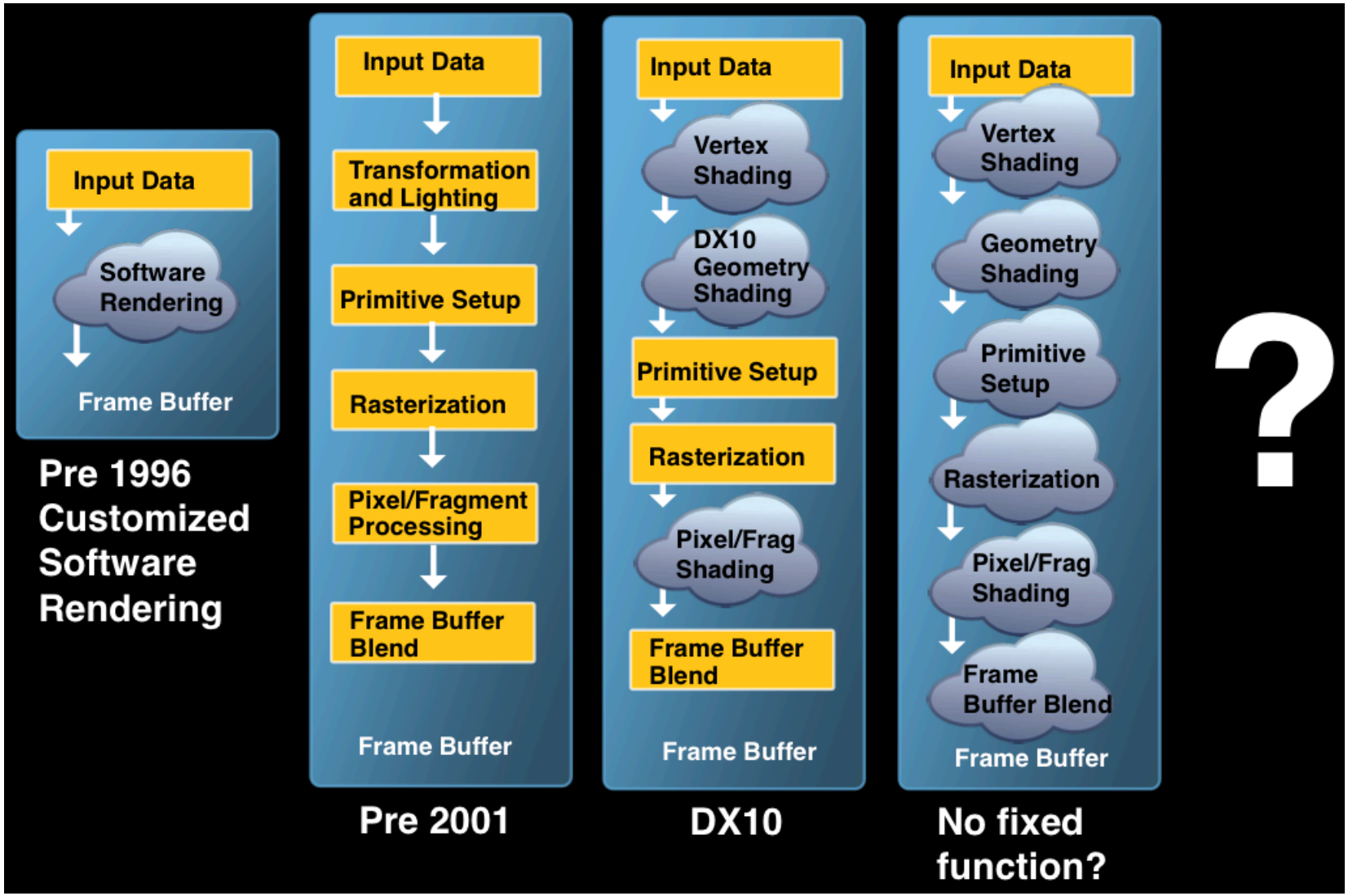
- The tutorial on the course home page

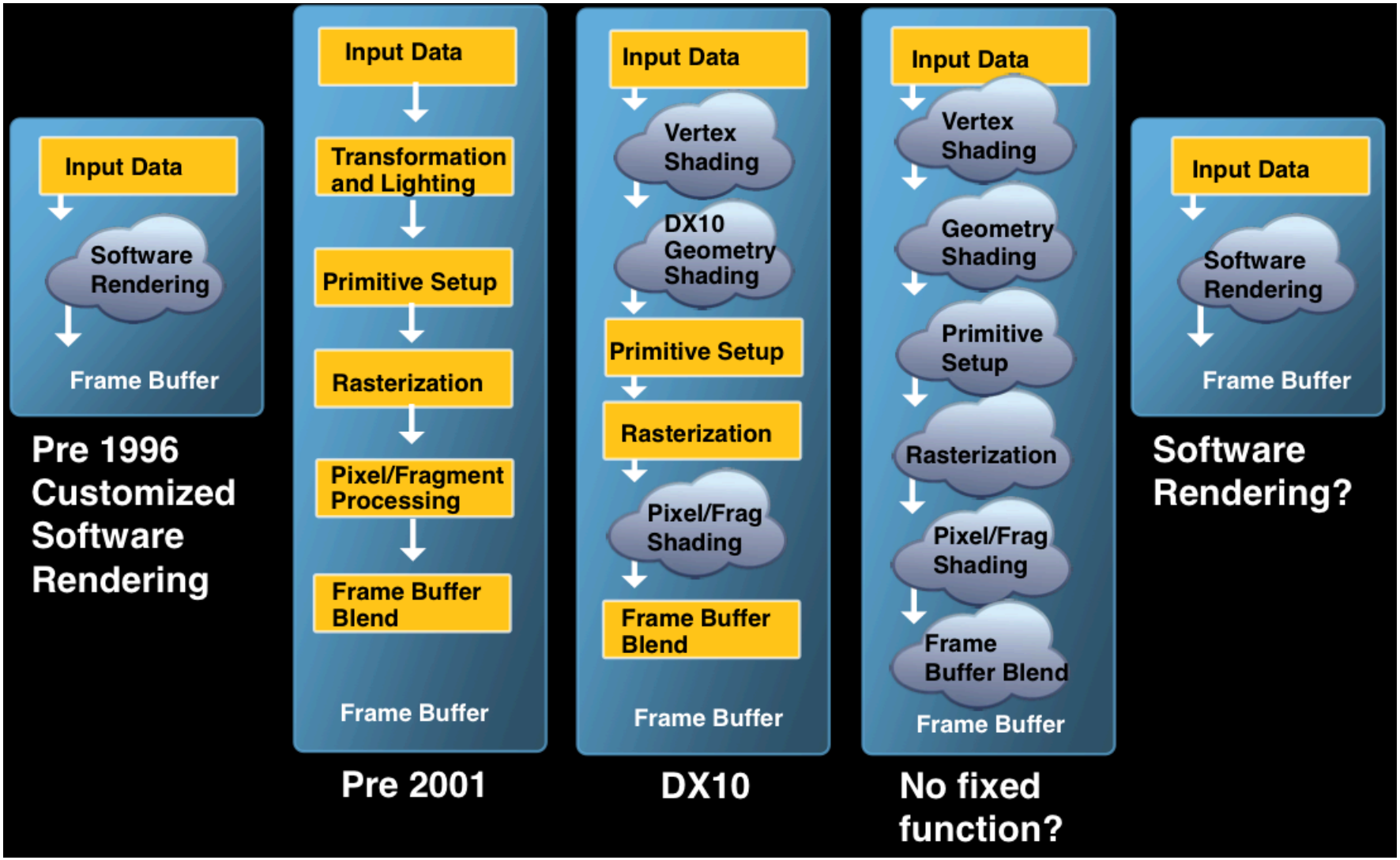
- OpenGL Shading Language Reference:
  http://www.opengl.org/documentation/glsl/

- On the geometry shader in particular:
  www.opengl.org/registry/specs/ARB/geometry_shader4.txt

The Future of GPUs?




Input Data
Software Rendering
Frame Buffer
Pre 1996 Customized Software Rendering
Input Data
Transformation and Lighting
Primitive Setup
Rasterization
Pixel/Fragment Processing
Frame Buffer Blend
Frame Buffer
Pre 2001
Input Data
Vertex Shading
DX10 Geometry Shading
Primitive Setup
Rasterization
Pixel/Frag Shading
Frame Buffer Blend
Frame Buffer
DX10
Input Data
Vertex Shading
Geometry Shading
Primitive Setup
Rasterization
Pixel/Frag Shading
Frame Buffer Blend
Frame Buffer
No fixed function?
?


Input Data
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Software Rendering
Frame Buffer
Software Rendering?