Advanced Computer Graphics
Advanced Shader Programming

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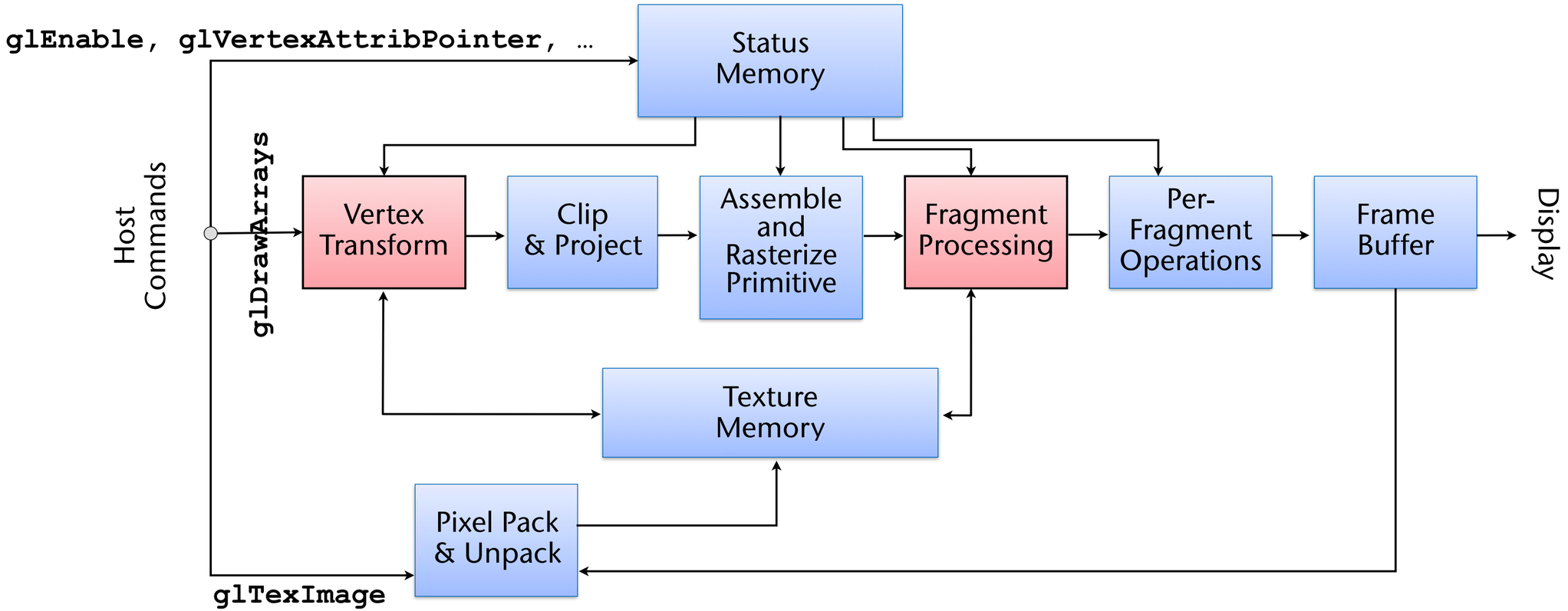
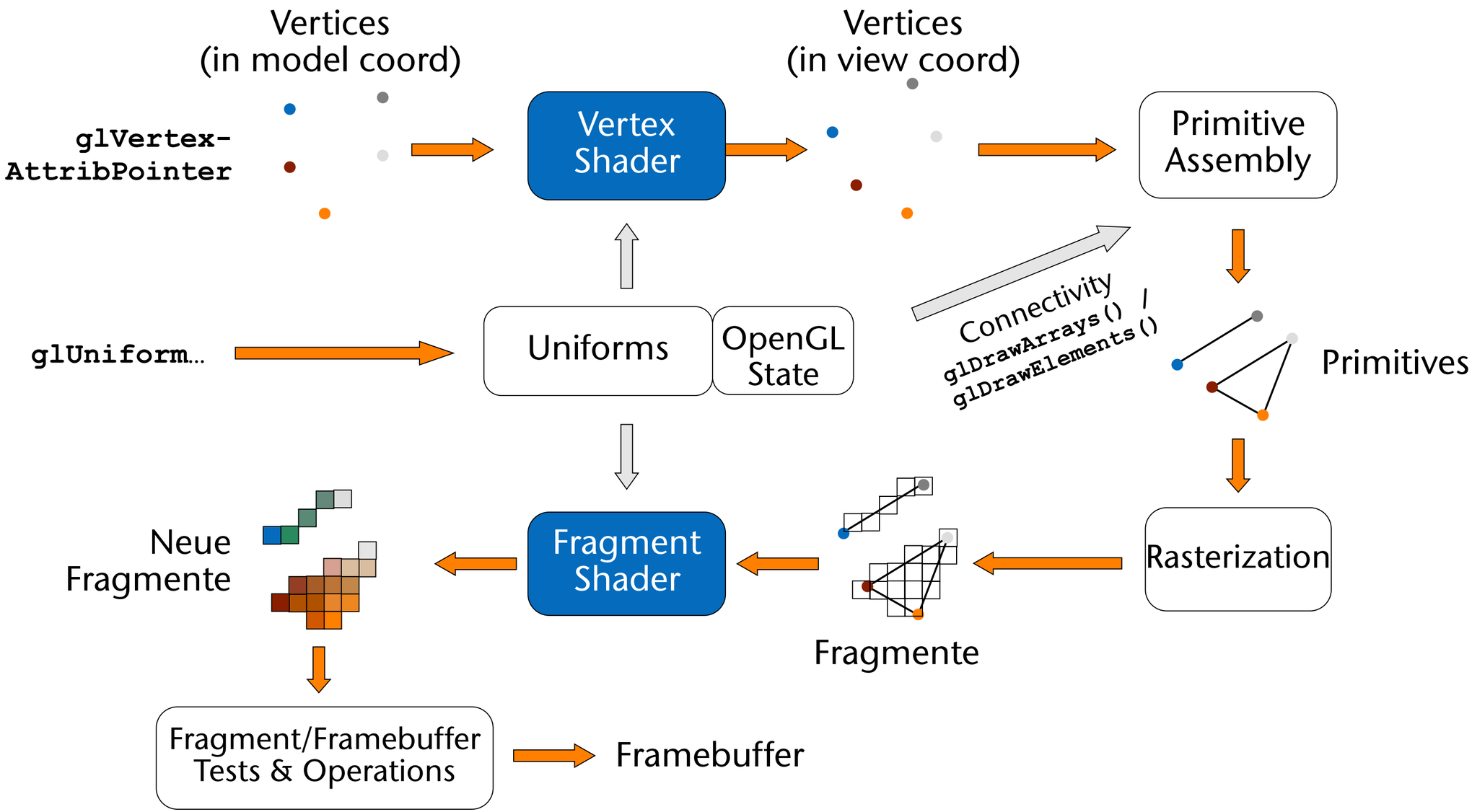
Recap (see Bachelor's *Computer Graphics* Course for more!)

- Today's GPUs contain programmable *vertex und fragment processors* (and more)
- Texture memory = general storage for any kind of data you want
- Balancing the pipeline is now the programmer's (your) job

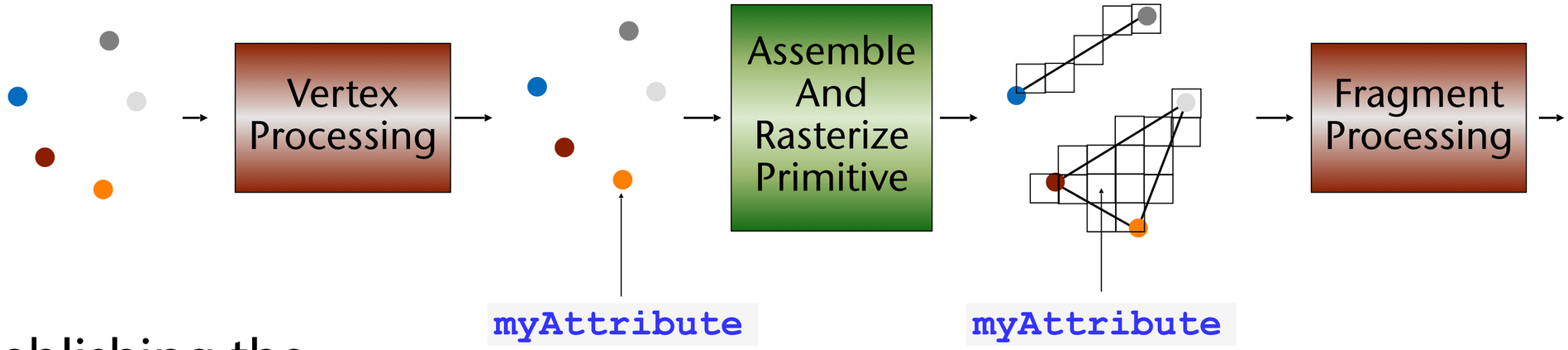


A More Abstract Overview of the Programmable Pipeline



Passing Vertex Attributes Down the Pipeline

- Vertex = set of attributes, fragment = set of attributes, rasterizer interpolates:



- Establishing the connection in modern between vertex & fragment shaders in GLSL syntax ("`#version 330`"):

Declarations in the vertex shader:

```
in vec3 vertex_modelSpace;
in vec3 normal_modelSpace;

struct vertexAttributes
{
  vec4 position_camSpace;
  vec3 normal_camSpace;
  vec4 color;
};
out vertexAttributes vertexOut;
```

Declarations in the fragment shader:

```
struct fragmentAttributes
{
  vec4 position_camSpace;
  vec3 normal_camSpace;
  vec4 color;
};
in fragmentAttributes frag;

out vec4 fragColor;
```

Just FYI

- The connection in old GLSL syntax ("**`#version 210`**" or WebGL1):

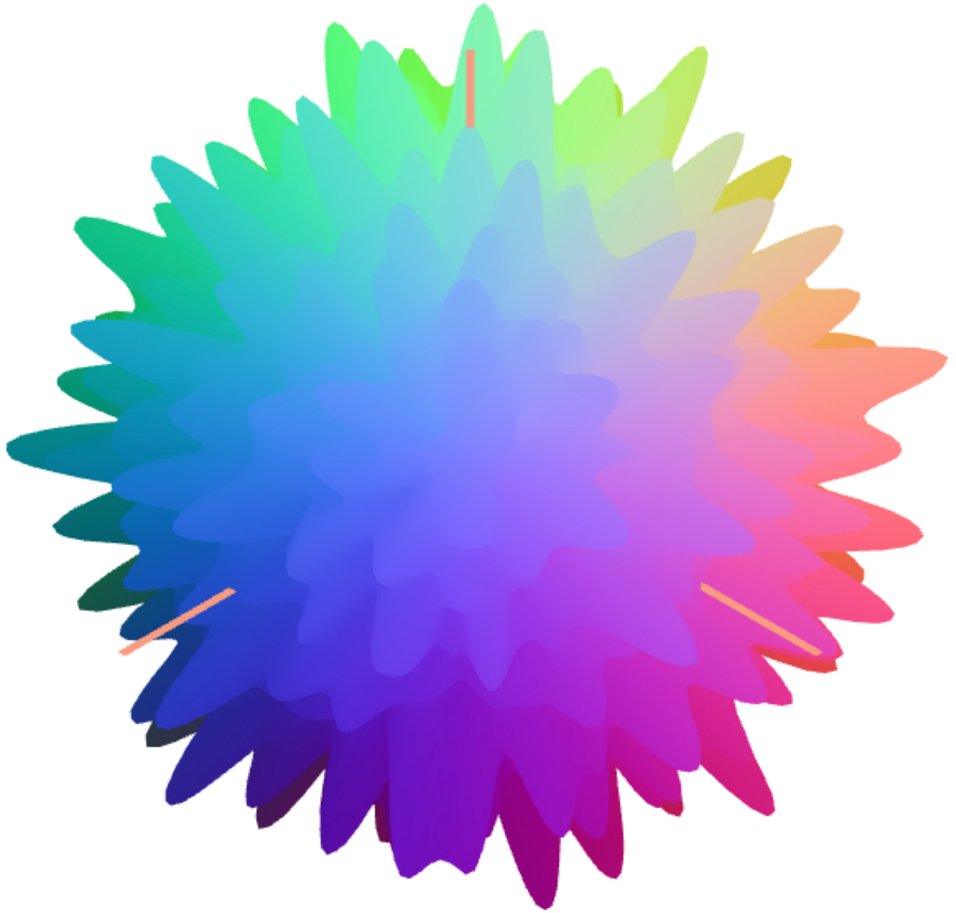
Declarations in the vertex shader:

```
attribute vec3 vertex_modelSpace;
attribute vec3 normal_modelSpace;

varying vec4 position_camSpace;
varying vec3 normal_camSpace;
varying vec4 color;
```

Declarations in the fragment shader:

```
varying vec4 position_camSpace;
varying vec3 normal_camSpace;
varying vec4 color;

// out vec4 gl_FragColor is predefined!
```

- Can you guess how this was done? What was done in which shader?



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:

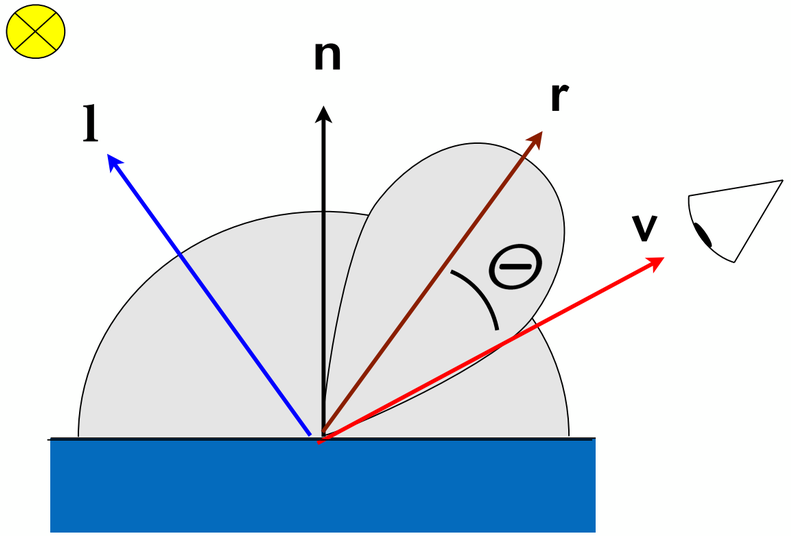
```
vec4 c = texture2D( myTex, gl_TexCoord[0].st );
```

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

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

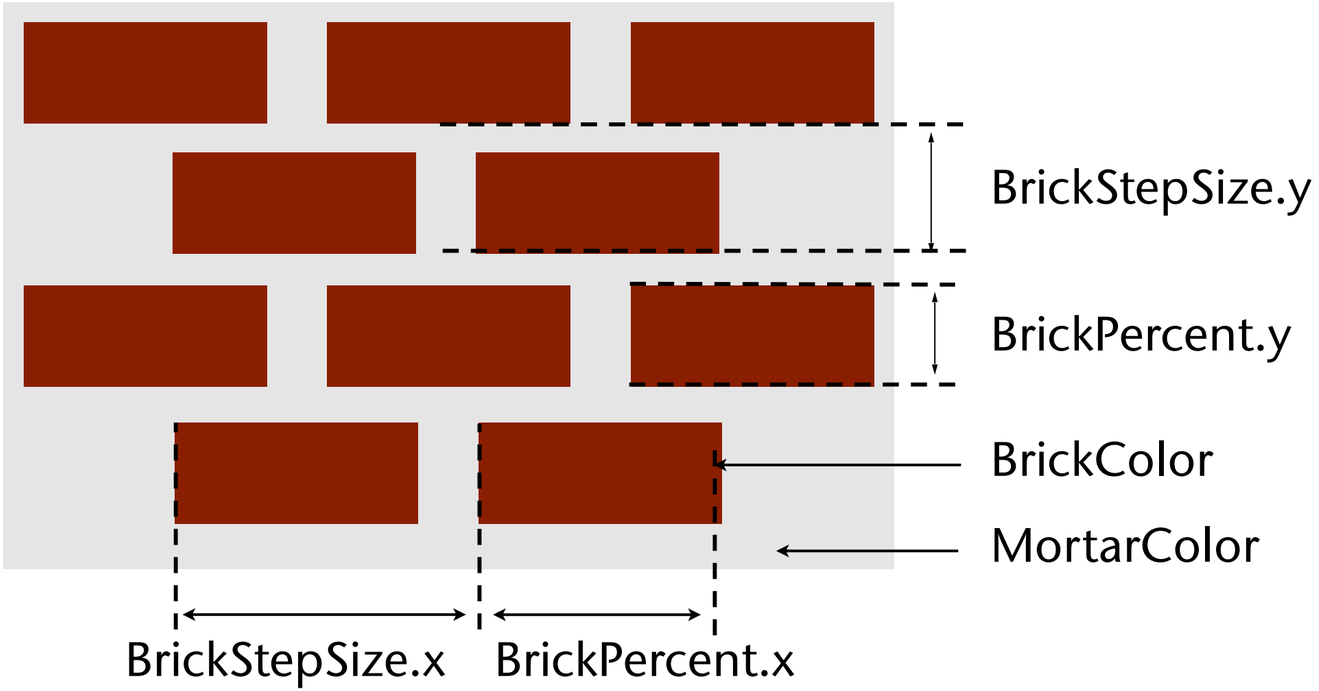
$$r_s = r_s(u, v)$$



Procedural Textures Using Shader Programming

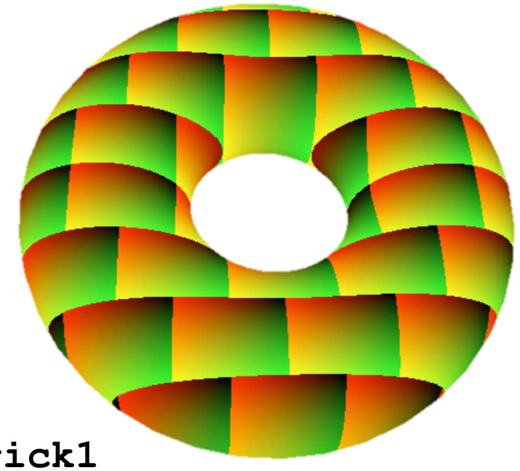
Goal: Brick texture

Simplification & parameters:

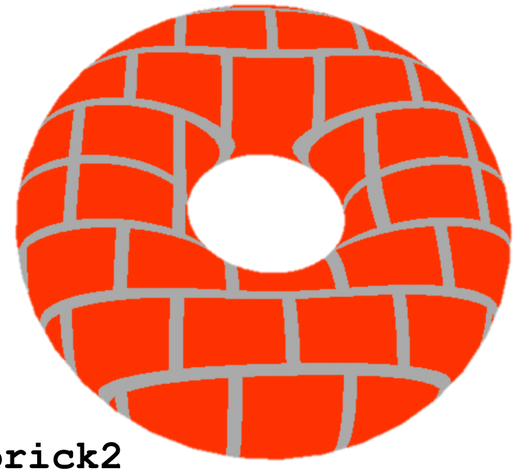


Overview of Approach

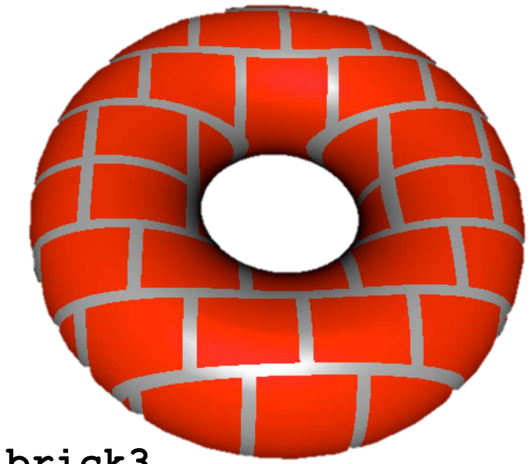
- Vertex shader: normal lighting calculation
- Fragment shader:
  - For each fragment, determine if the point lies in the brick or in the mortar on the basis of the x/y coordinates of the corresponding point in *object space(!)*
  - After that, multiply the corresponding color with intensity from lighting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



`brick1`

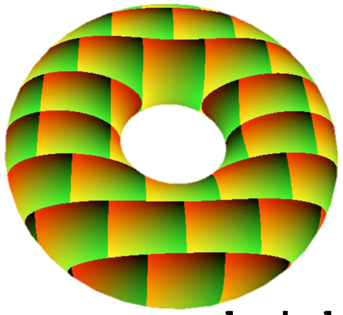


`brick2`



`brick3`

The Source Code of These Shaders

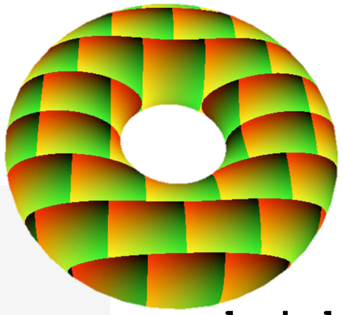


brick1

Vertex Shader Declarations

```
#version 330 core

// pre-defined by host program
uniform mat4 ModelToWorldMatrix;    // model-to-world trf
uniform mat4 CameraMatrix;          // world-to-camera trf
uniform mat4 ProjectionMatrix;      // projection matrix

// our own parameters
uniform vec3 LightPos;              // given in world coord!

// vertex attributes (pre-defined by host program)
layout (location = 0) in vec3 vPosition;
layout (location = 1) in vec3 vNormal;

// output to fragment shader (via rasterizer)
out vec3 aPosition_model;           // pos./normal of the vertex/fragment
out vec3 aNormal_model;             // in model(!) coords
out vec3 aPosition_world;           // dito in world coords
out vec3 aNormal_world;
```

Vertex Shader Main

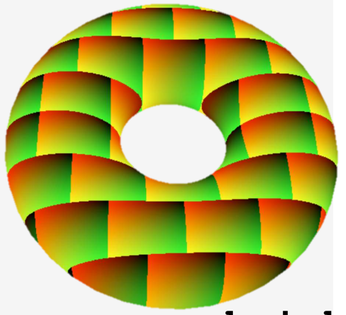


brick1

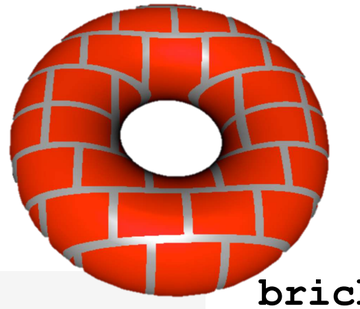
```
void main()
{
    // We need the vertex/fragment positions in object space in the
    // fragment shader, so we output them here.
    // (Traditionally, you name the out's with aAttributeName)
    aNormal_model = vNormal;
    aPosition_model = vPosition;

    // Calculate the real position of this pixel in 3d space
    aPosition_world = ( ModelToWorldMatrix * vec4( vPosition, 1.0 )).xyz;

    // Calculate the normal including the model rotation and scale, but no translation
    aNormal_world = vec3( ModelToWorldMatrix * vec4( vNormal, 0.0 ) );

    // This sets the position of the vertex in 3d space. The correct math is
    // provided below to take into account camera and object data.
    gl_Position = ProjectionMatrix * ModelToWorldMatrix * vec4( vPosition, 1.0 );
}
```

Fragment Shader

```
// same uniforms as in the vertex shader, plus ...
uniform vec2 BrickStepSize;          // size of bricks; MUST NOT BE 0!

// input from vertex shader (via rasterizer)
in vec3 aPosition_model;             // the position of the fragment
in vec3 aNormal_model;               // in model(!) coords
in vec3 aPosition_world;
in vec3 aNormal_world;

out vec4 fragColor;                 // final output color

void main()
{
    vec3 lightVector = normalize( LightPos - aPosition_world );

    // simplistic lighting here
    float brightness = clamp( dot( aNormal_world, lightVector ), 0.0, 1.0);

    vec2 rel_pos = aPosition_model.xy / BrickStepSize;    // now rel_pos is in [k,k+1] for one brick

    // shift odd brick rows left by shifting the x coord of the fragments right
    if ( mod(abs(rel_pos.y), 2.0) > 1.0 )                 // this saves conversion to int / mod
        rel_pos.x += 0.5;

    rel_pos = fract( rel_pos );                           // = rel. position within brick

    fragColor = vec4( rel_pos, 0.0 , 1.0);                // visualize the rel. position
}
```



brick1



brick3

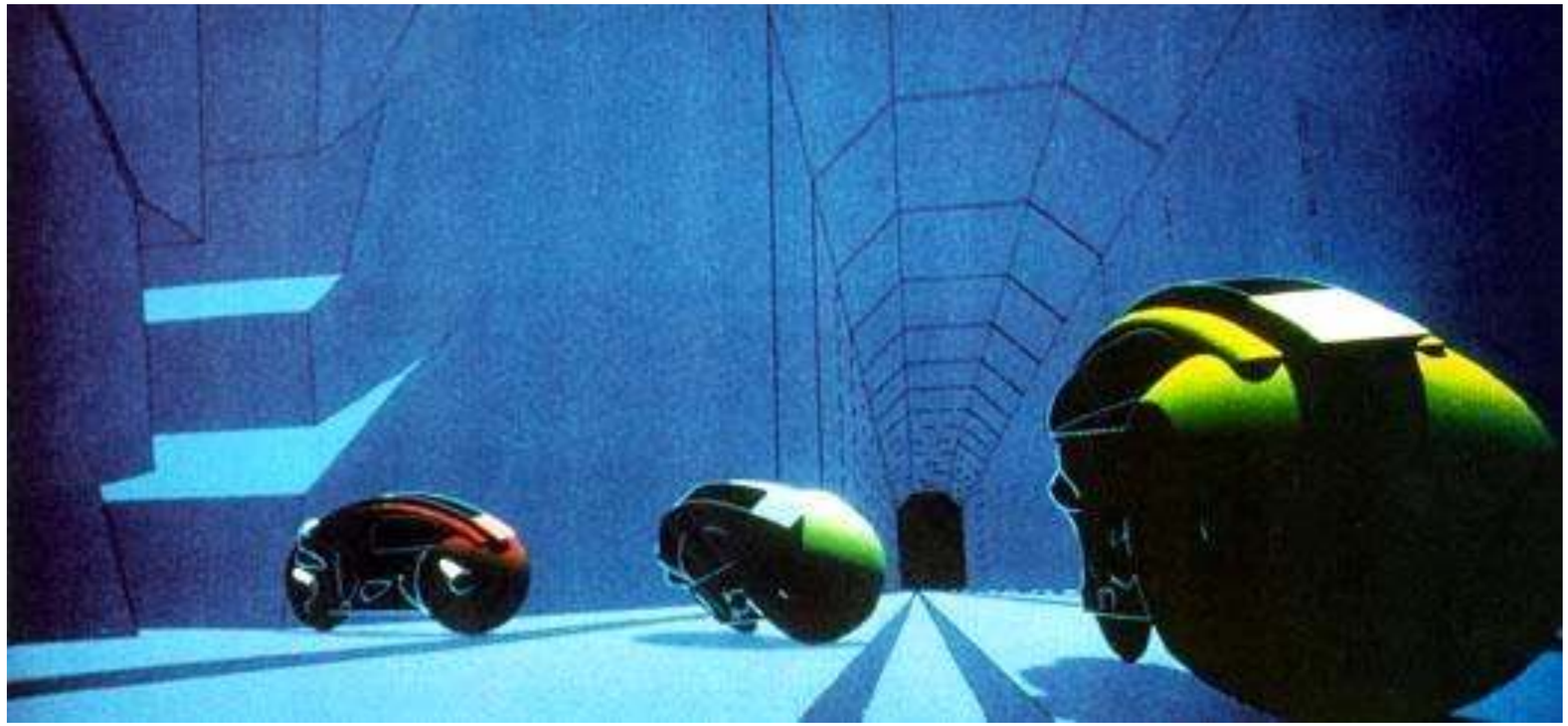
Fragment Shader

```
void main()
{
    .... as before ...

    if ( any( greaterThan(rel_pos, BrickPercent) ) ) // comparison operators for vectors
        base_color = MortarColor;
    else
        base_color = BrickColor;

    fragColor = base_color * lightingModel(normal, lightVector, viewVector, ...);
}
```

```
rel_pos.x > BrickPercent.x || rel_pos.y > BrickPercent.y
```

Noise

- Most procedural textures look too "clean"
  - Real objects show signs of dirt, grime, dents, random irregularities, etc.
- Idea: add special kinds of "randomness"



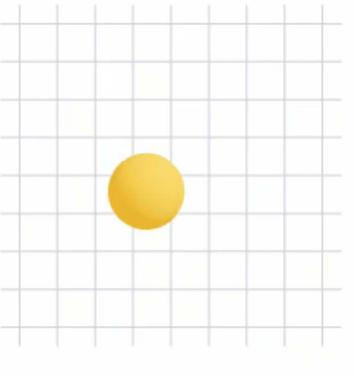
Kenn Perlin

Ideal qualities of a noise function *f*

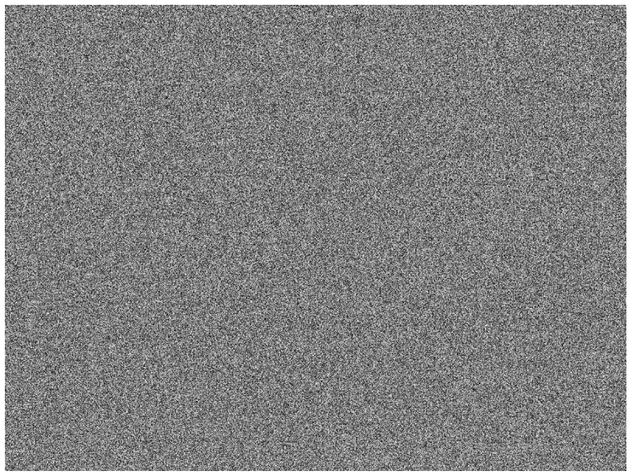
- Should *look* like random, but is not exactly random
  - **`math.random()`** doesn't work as-is
- At least C^2-continuous
- No obvious patterns or repetitions
- Repeatable (same output with the same input)
- Can be defined for 1,...,4 dimensions
- Isotropic (invariant under rotation)
- Convenient range, e.g. [-1,1] or [0,1]

position = rand()

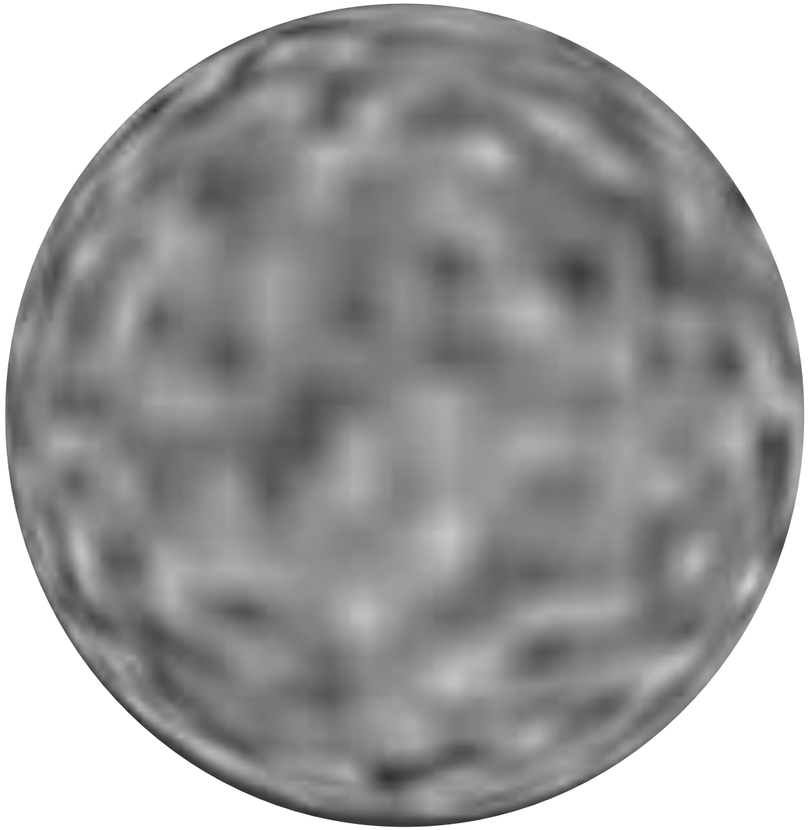
position = noise(*t*)



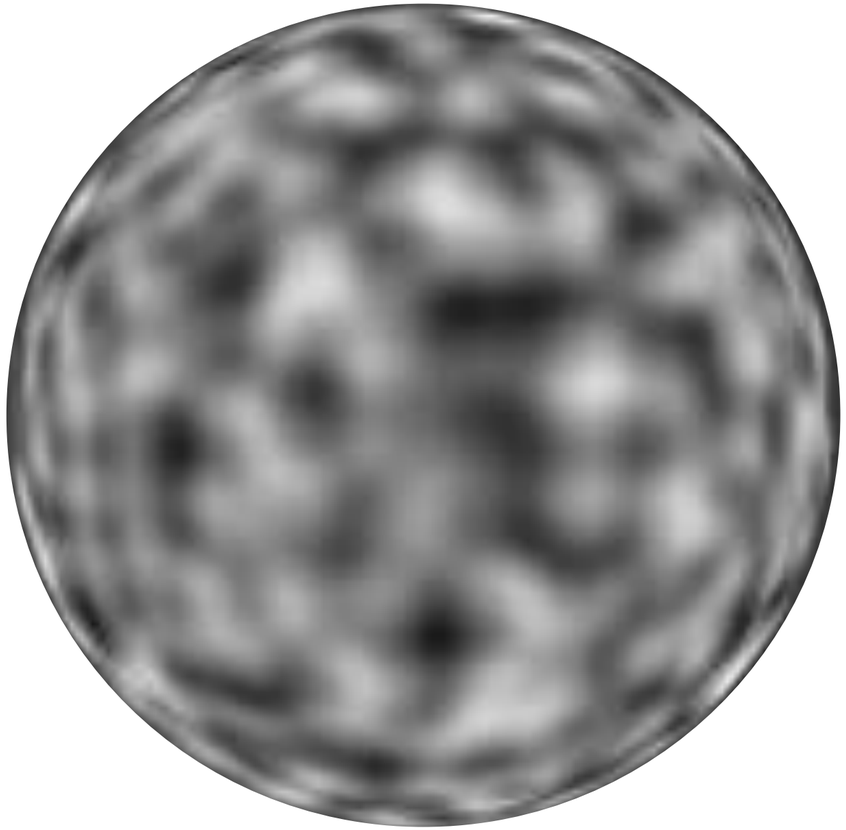
color = rand()



Why we don't just use a noise *texture*



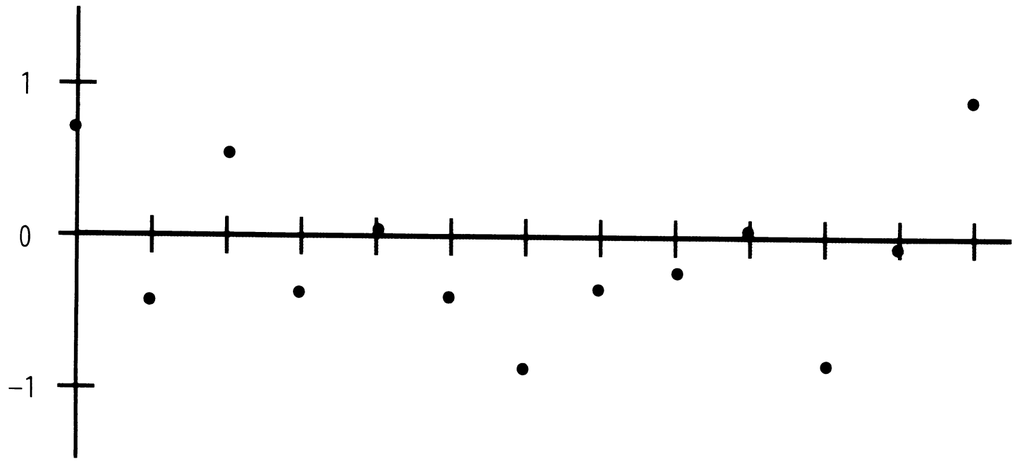
Sphere rendered with a 3D texture to provide the noise.
Notice the artifacts from linear interpolation.



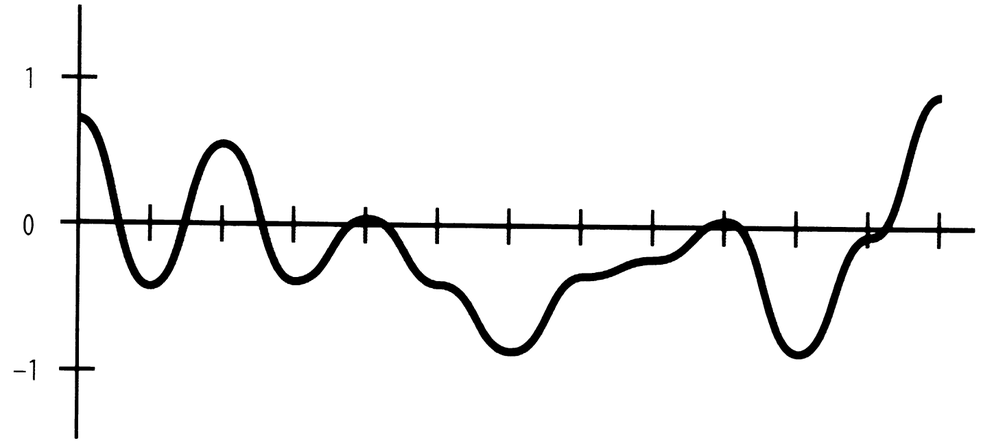
Sphere rendered with procedural noise.

Simple Idea: Value Noise

1. Choose random y-values from [-1,1] at the integer positions
   - Spacing of x-positions ⟶ "frequency"



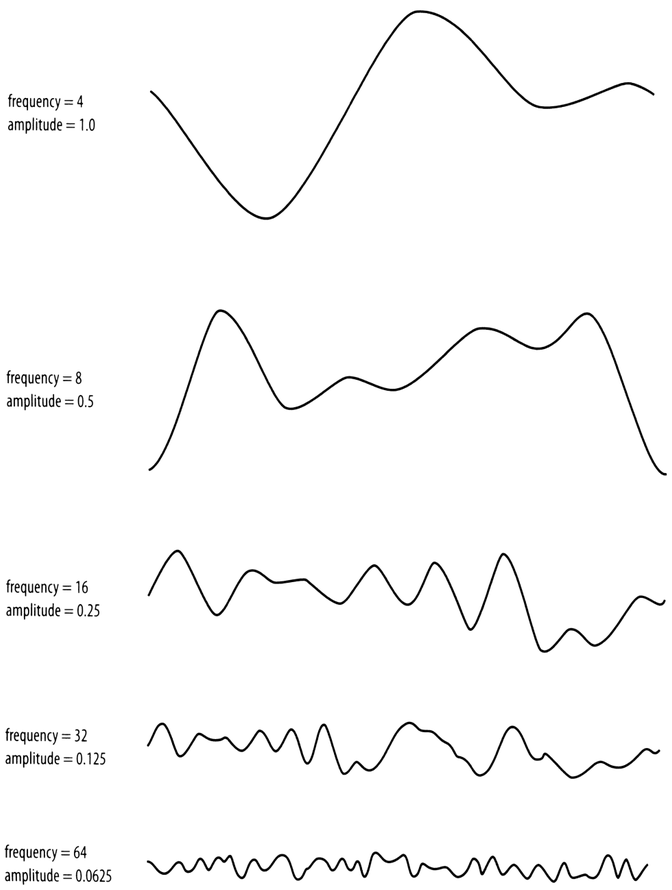
2. Interpolate in-between, e.g. cubically (linearly isn't sufficient)

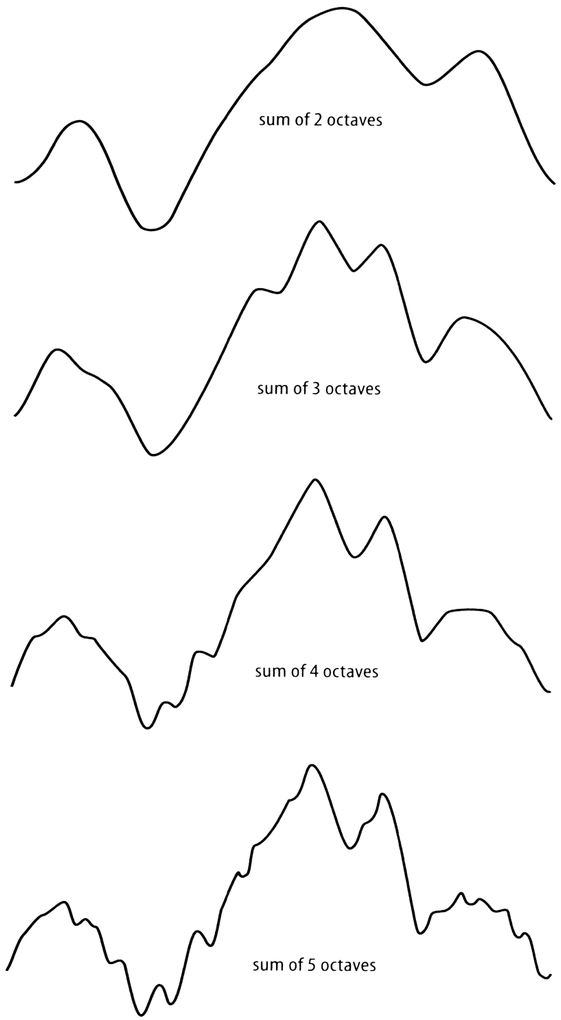


Fractal Noise

3. Generate multiple noise functions with different frequencies

4. Add them all up: produces noise at different "scales"





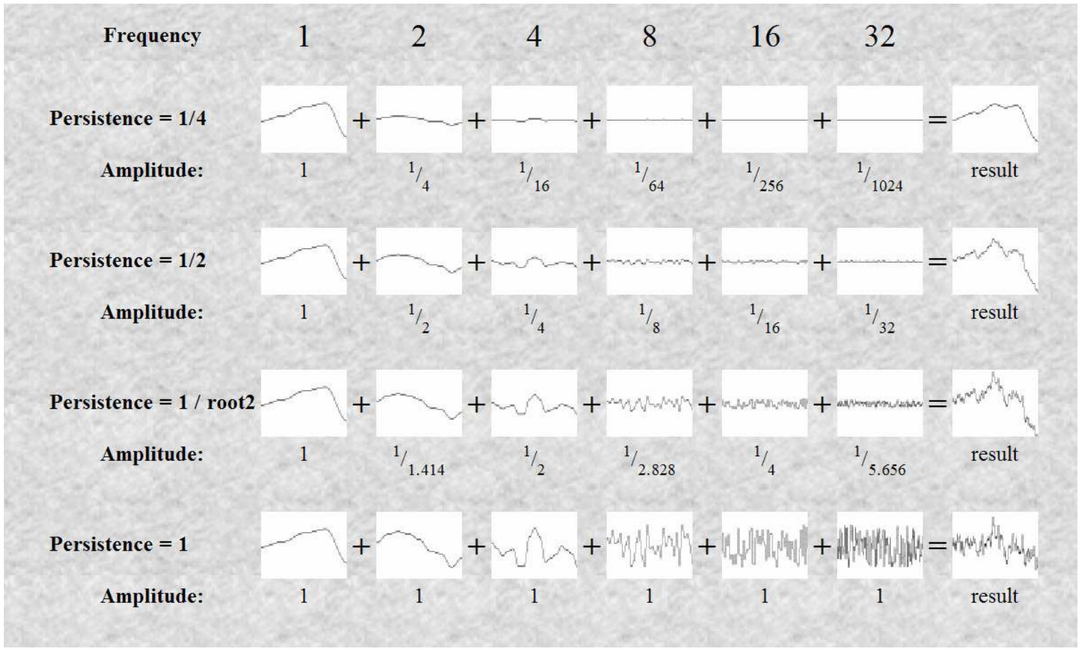
- Persistence = successive scaling of amplitude on successive octaves

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

Persistence

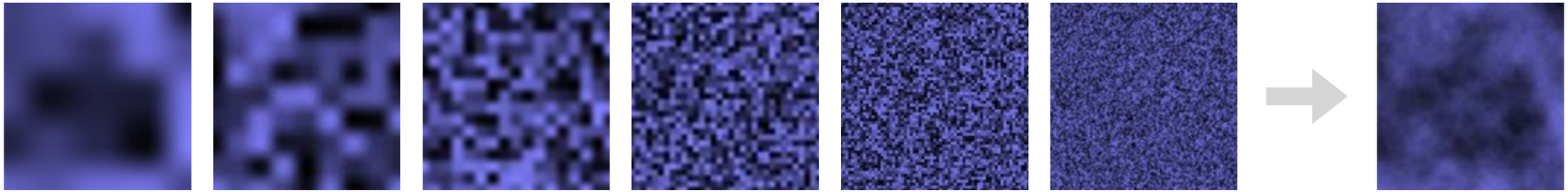
Scaling along x for octaves

- Example:



- Persistence = ½ ⟶ *pink noise,*
  persistence = 1 ⟶ *white noise*

- Same thing in 2D:

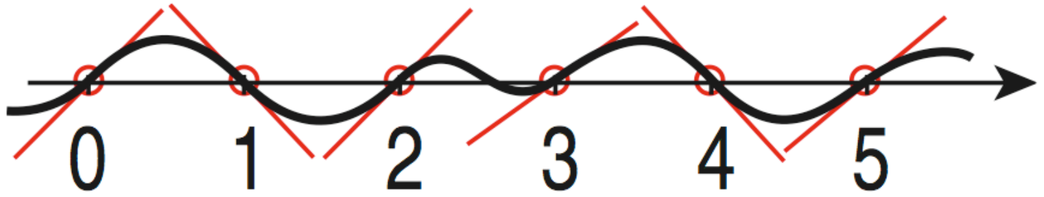


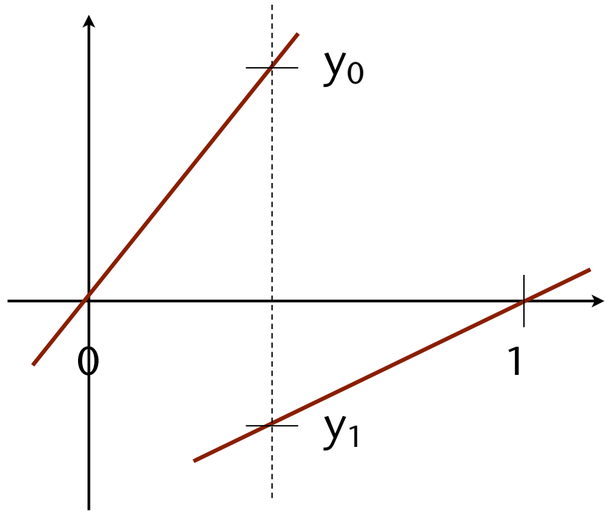
- Straight-forward generalization to higher dimensions

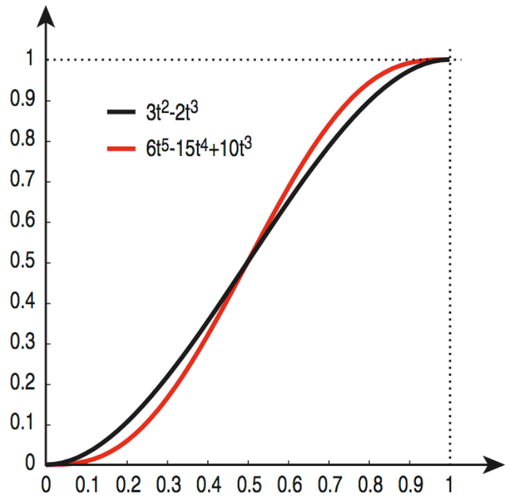
Gradient Noise

- Specify the gradients, instead of values, at integer x-points
- Interpolate to obtain values $y = f(x)$:
  - 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. $h(x) = 3x^2 - 2x^3$

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





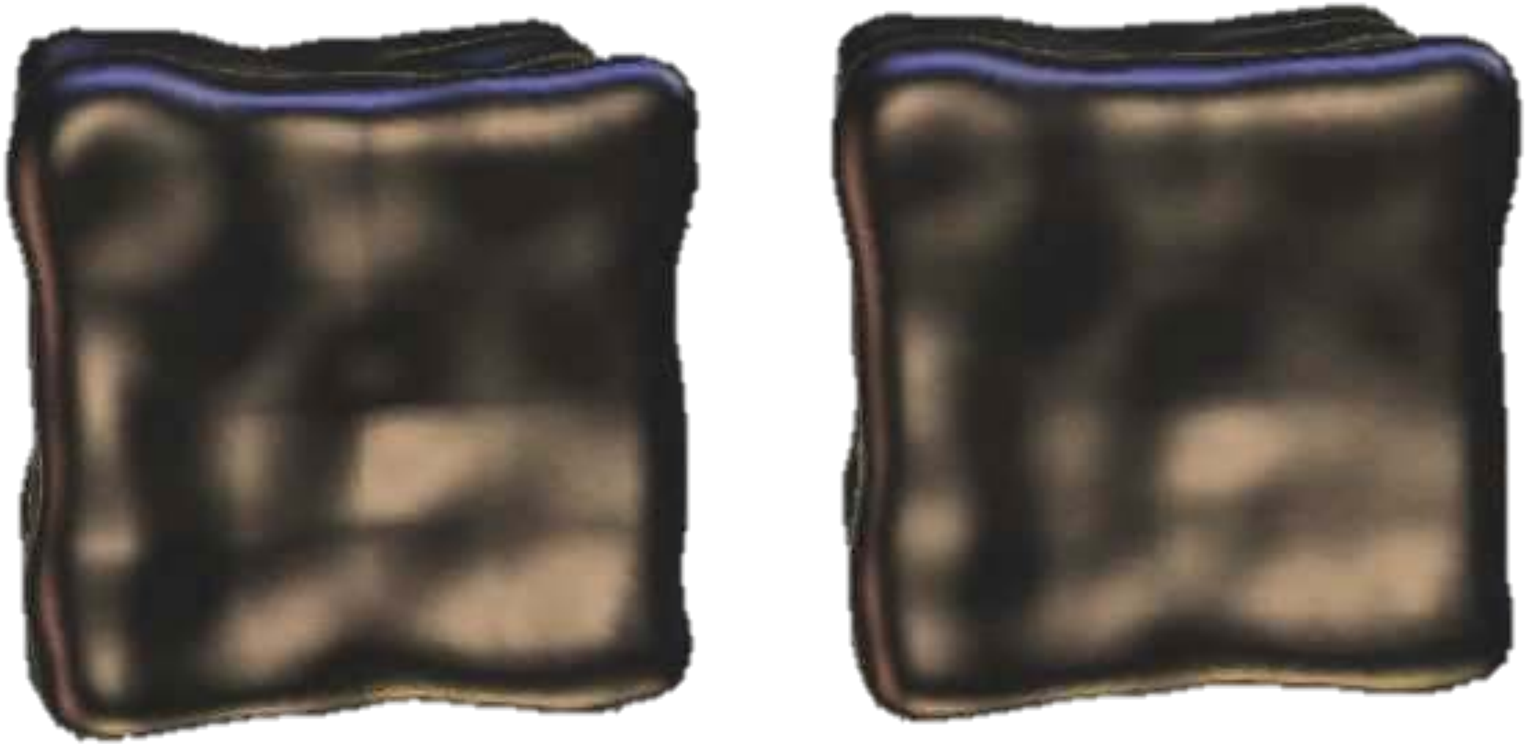


- Advantage of the quintic blending function: $q''(0) = q''(1)$

  → the entire noise function is C^2-continuous

- Example where one can easily see this:

Cubic interpolation



Quintic interpolation

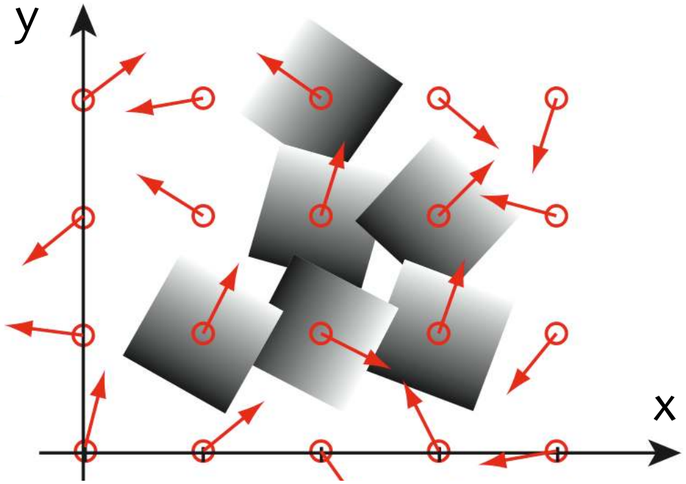
[Ken Perlin]

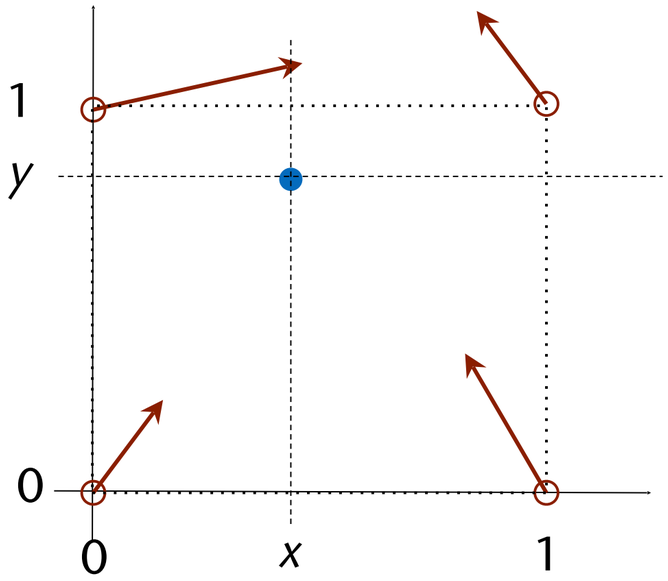
Gradient Noise in 2D, $f : \mathbb{R}^2 \to \mathbb{R}$

- Set gradients at *integer grid points*
  - *Gradient* = 2D vector (not necessarily of length 1)
- Interpolation (as in 1D):
  - Wlog., at 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 = (x,y) :

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

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



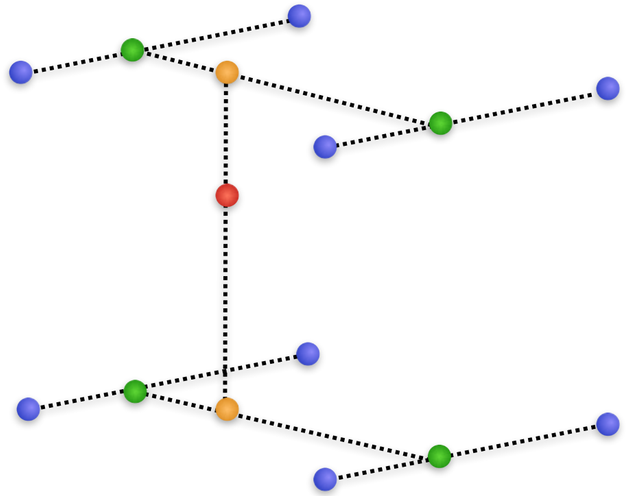


- Blending of 4 z-values through bilinear interpolation:

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

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

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



Total lerps = 4 + 2 + 1 = 7

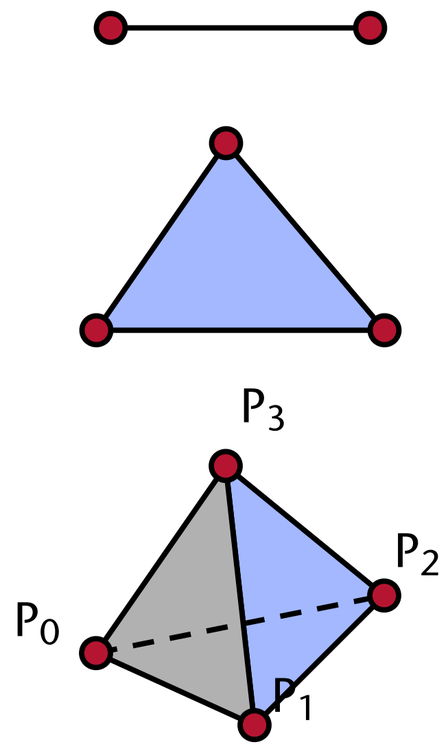
Simplex Noise

- The d-dimensional simplex :=
  barycentre 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

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

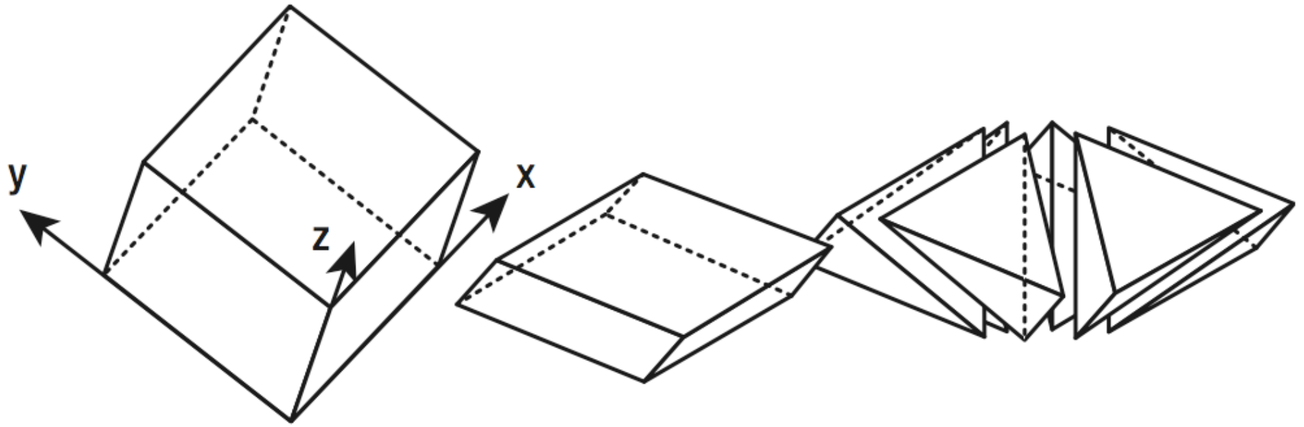
with

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



Simplicial Tesselation

- In general, the following is true: it is possible to partition *d*-dimensional space (*tessellation*) with equilateral *d*-dimensional simplices
- Using equilateral *d*-dimensional simplices, one can partition a cube that was suitably "compressed" along one of its diagonals

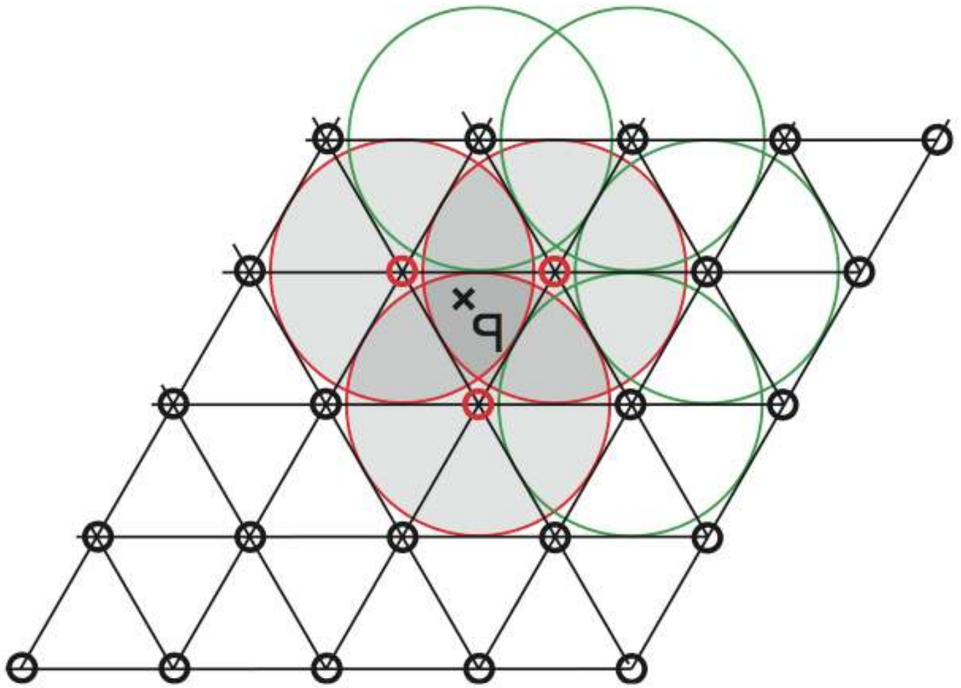


- Such a "compressed" *d*-dimensional cube contains *d*! many simplices

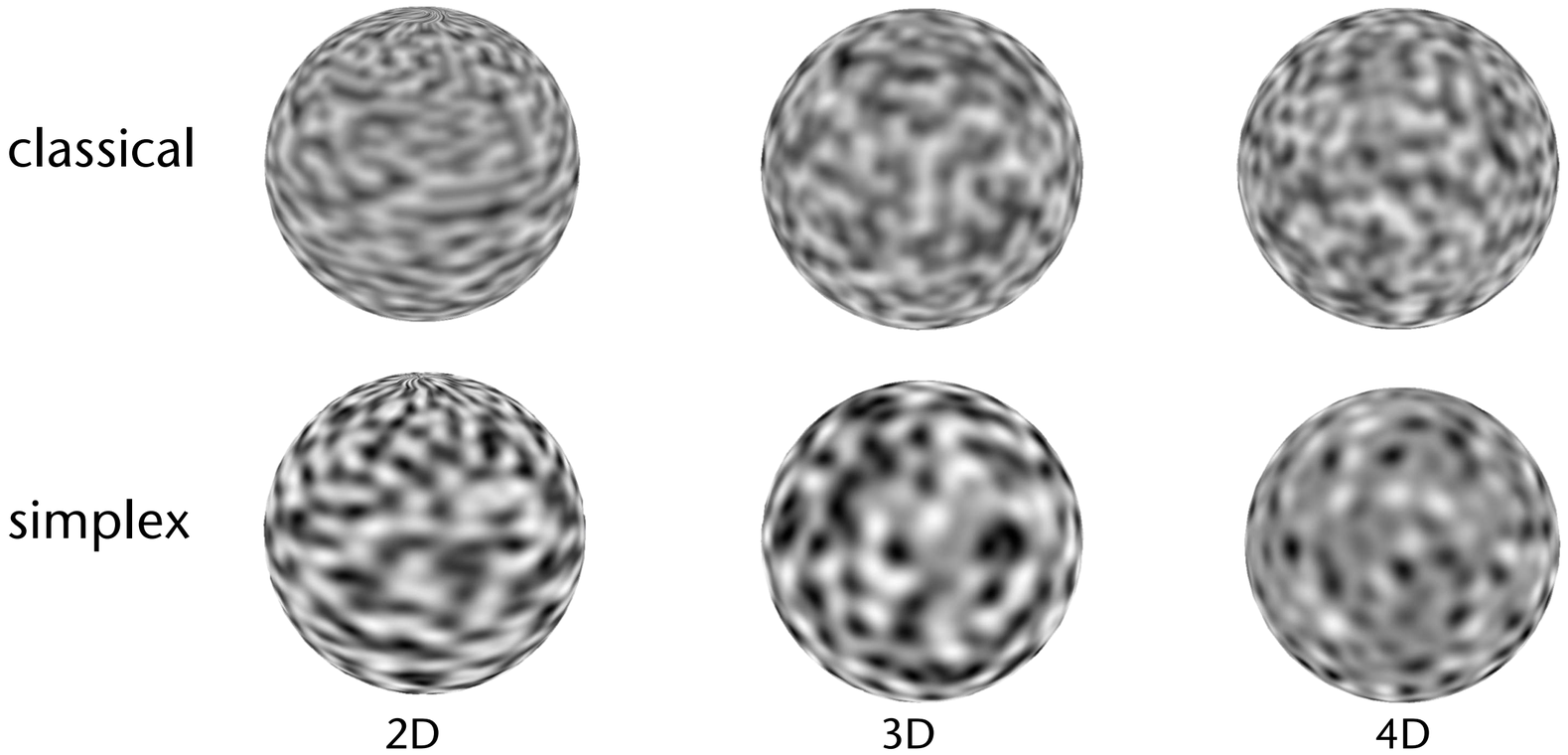
Construction of the Noise Function

- Given: a simplex tessellation (hence *"simplex noise"*) and gradients at each node/vertex

1. Determine the simplex in which a query point *P* lies
2. Determine all of its vertices and the gradients there
3. Determine (as before) the value of these "gradient ramps" in query point *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 simplices



- Advantage: has only complexity $O(d)$
- For details see "Simplex noise demystified" (on the homepage of this course)
- Comparison between classical value noise and simplex noise:



- Four noise functions are defined in the GLSL standard:

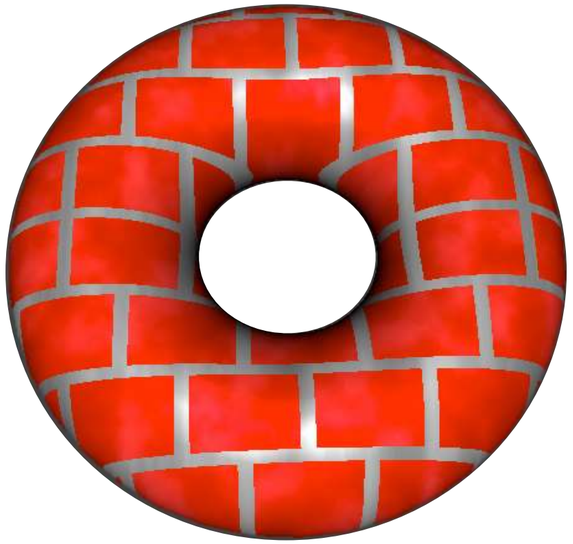
```
float noise1(gentype),  vec2 noise2(gentype),
vec3  noise3(gentype),  vec4 noise4(gentype).
```

- Calling such a noise function:

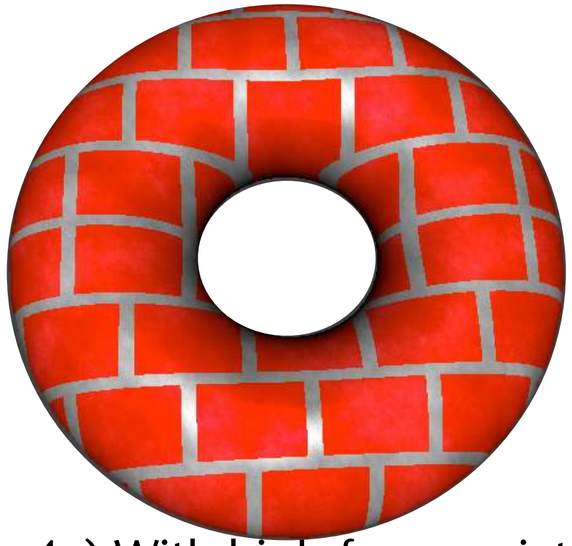
$$v = \text{noise2}(\, f*x + t,\, f*y + t\,)$$

  - With *f,* one can control the spatial frequency;
    with *t,* one can generate a shifting animation (*t*="time").
  - Analogous for 1D and 3D noise
- Caution: range is [-1,+1]!
- Cons: are not implemented everywhere
  - Often very slooooooooow ...

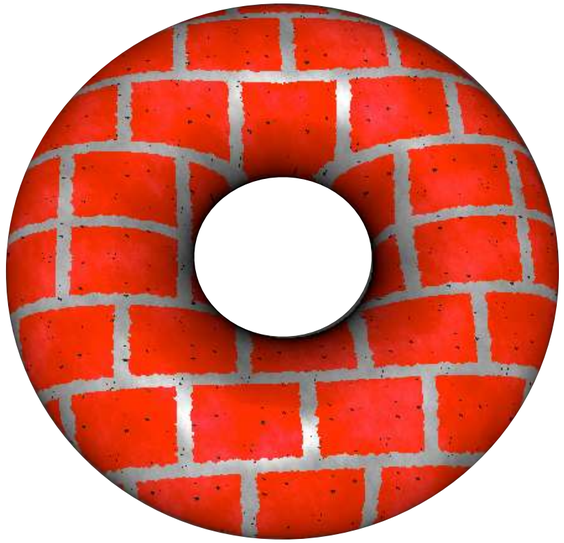
Example (cont'd): Application of Noise to our Procedural Brick Texture



4) Color var. (low freq.)



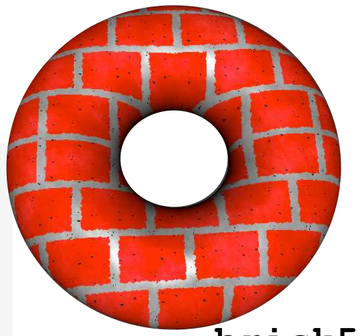
4a) With high-freq. variations
(left as exercise to you)



5) Curvy brick edges

The code for these examples is on the course's homepage; after unpacking the archive, it is in directory
`vorlesung_demos/brick shader with ShaderFrog`

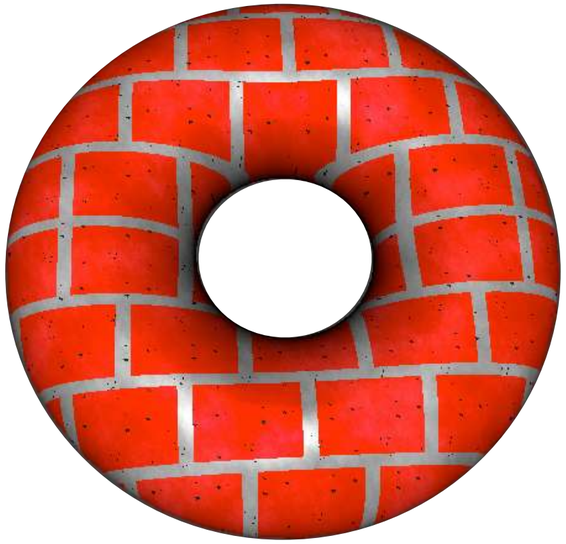
Fragment Shader for "wavy" brick borders


brick5

```
.... uniforms and "in" variables as before ...

uniform float border_freq;
uniform float border_amp;

void main()
{
    .... as before ...

    vec2 rel_pos = aPosition_model.xy / BrickStepSize;    // same as before
    ... shifting of odd rows omitted here for clarity ...
    rel_pos = fract( rel_pos );                           // dito

    // make border of bricks noisy by shifting coords
    rel_pos += border_amp * noise2( border_freq * aPosition_model );
    bool outside_brick = any( greaterThan(rel_pos, BrickPercent) ) ||
                         any( lessThan(rel_pos, vec2(0.0)      ) );
   if ( outside_brick )
    .... rest as before ...
}
```

Sparse Dot Noise (a.k.a. Spot Noise)

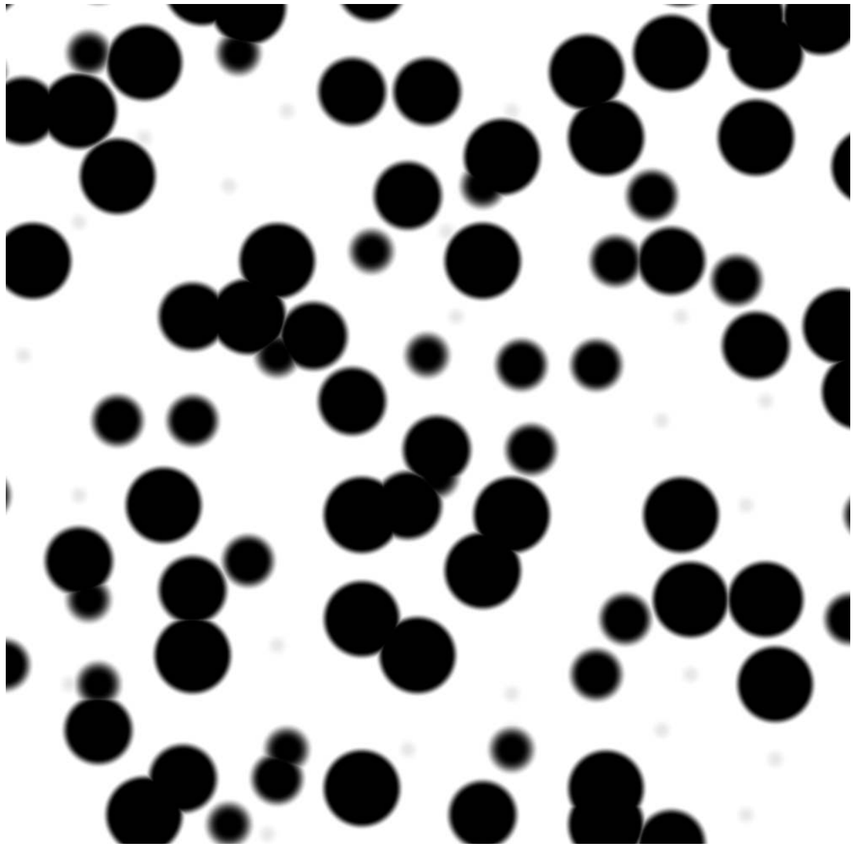
- Basic idea:
  - Create a regular grid
  - Assign 4 random numbers, r_1,..,r_4, to each grid cell
  - If r_1 > threshold, then create a dot/black circle in the cell
    - Radius = r_2, center = (r_3, r_4)
    - Fragment color = black, if (fragment - center) < radius



6) Black spots

- Challenges for you:
  - Improve it, so that the grid is not noticeable with higher frequencies/densities
  - Add per-fragment Phong lighting

Simple Example



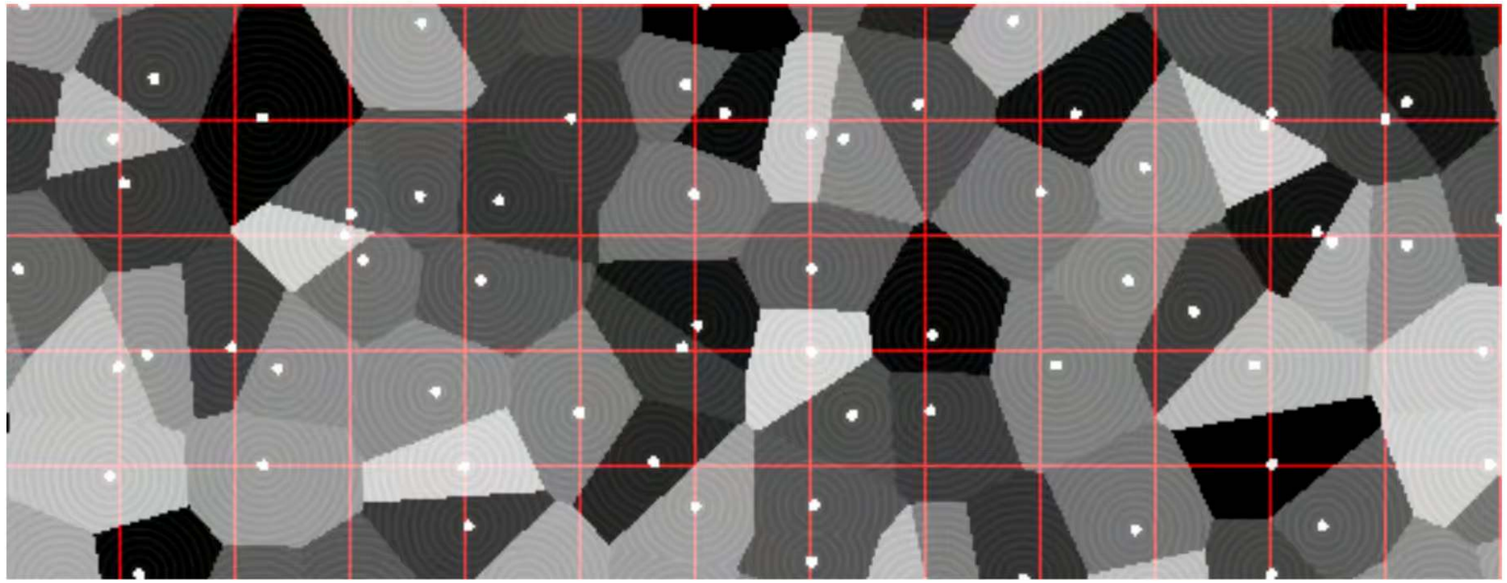
Worley Noise (aka. Cellular Noise, aka. Voronoi Noise)

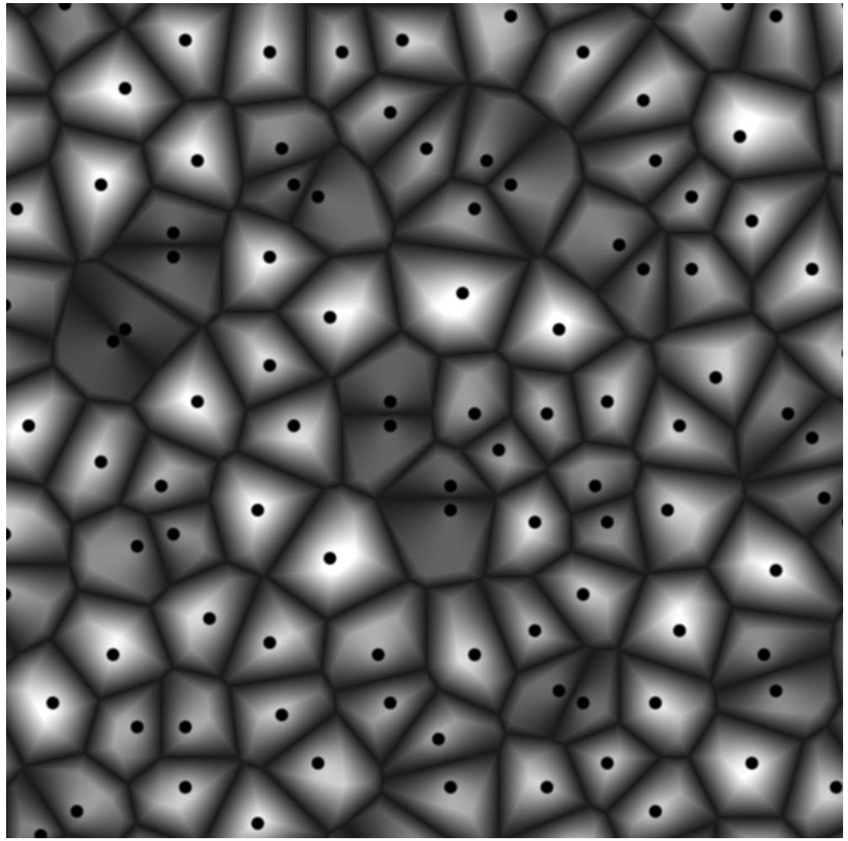
- Place feature points P_i randomly in the plane
- Define distance function

$$F_k(\mathbf{x}) = \text{distance of } \mathbf{x} \text{ to } k\text{-th closest feature point}$$

  for any point **x** in the plane
- Use the F_k as noise functions (drop-in replacement for Perlin)
- Properties of the functions F_k:
  - C^0-continuous
  - The derivative (gradient) is continuous, too, except at "borders" where the k-th closest feature point "switches"
  - The gradient points from the k-th closest feature point towards **x**
- $F_1(\mathbf{x}) \leq F_2(\mathbf{x}) \leq F_3(\mathbf{x}) \leq \ldots$

Simple Example





Variations of Worley Noise

- Or, use linear combinations

$$F(\mathbf{x}) = \sum_{i=1}^{m} \alpha_i F_i(\mathbf{x})$$

- Or, combine like fractal noise

$$G(x) = \sum_{i=1}^{m} p^i F_i(2^i x)$$

- Or, generate Worley noise functions $F_k^{(1)}, F_k^{(2)}, F_k^{(3)}, \ldots$, where each $F_k^{(i)}$ uses a different set of random points with increasing density
  - Then, overlay these kinds of "octaves":

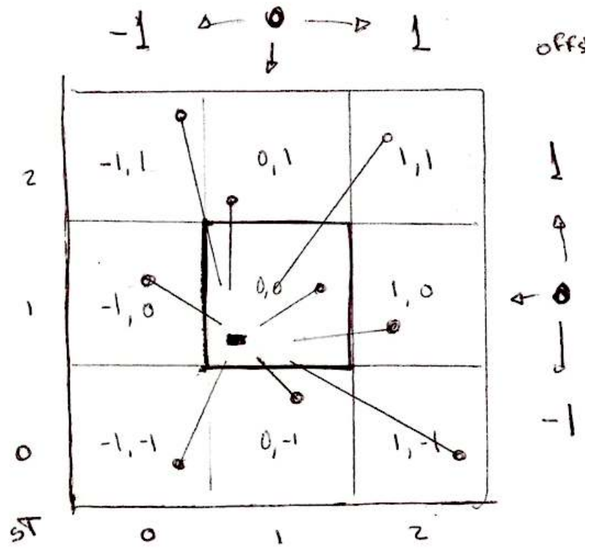
$$G(x) = \sum_{i=1}^{m} p^i F_k^{(i)}$$

How Would You Generate Sets of Random Points with Increasing Density?

https://www.menti.com/al4mfvjgaq3k

Computing $F_k(\mathbf{x})$

- Conceptually, sample the plane using jittered sampling (stratification)
  - One (or several) random points per grid cell
  - Either store them as fixed array
  - Or, generate them on-the-fly using a hash function as a *deterministic* PRNG: cell coords $(i,j) \longrightarrow$ hash fct $\longrightarrow$ integer $\longrightarrow$ float
  - Both ways, the set of random pts is *repeatable*
- Convert **x** to cell coords (i,j)
- Do breadth-first-search from cell (i,j) outwards until k-th closest P_i is found

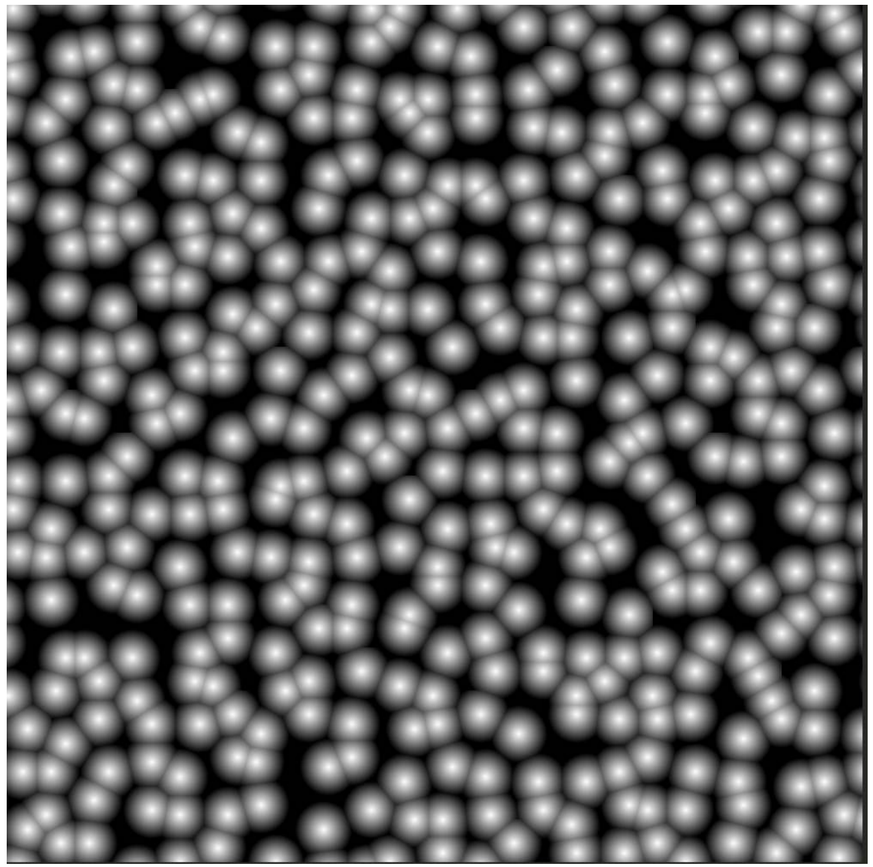


Sufficient for F_1

GLSL code snippet for F_1 (in fragment shader)

```
vec2 st = gl_FragCoord.xy / u_resolution.xy;          // convert to normalized space

vec2 int_st = floor(st);                              // tile the space
vec2 frac_st = frac(st);                              // note: st = int_st + frac_st

float m_dist = 3.0;                                   // minimum distance

for (int y= -1; y <= 1; y++)
    for (int x= -1; x <= 1; x++)
    {
        vec2 neighbor = vec2( float(x),float(y) );    // neighbor place in the grid
        vec2 point = random( int_st + neighbor );     // random, yet deterministic pos.
        vec2 diff = neighbor + point - frac_st;
        // note: (neighbor+point+int_st) - st = neighbor+point - frac_st
        float dist = length( diff );
        m_dist = min( m_dist, dist );                 // keep the closer dist. (avoid if!)
    }
```

How Was This Generated?



Example in Movies

If you look closely, you can see yellowed printed material, little scratches, and paint worn off metal surfaces that tell you this collection is old but well-maintained.

Other Examples for the Applications of Noise

Ken Perlin's famous solid textured marble vase, 1985

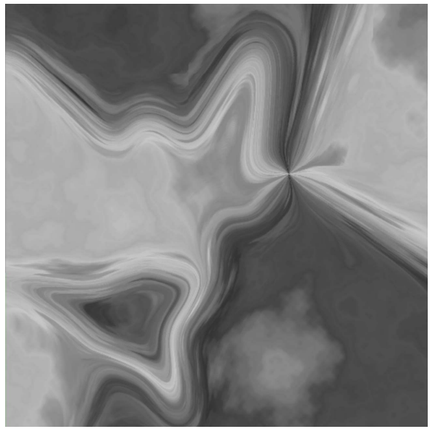
Procedural bump mapping, done by computing noise in the pixel shader and using that for perturbing the surface normal

g = a * perlin(x,y,z)
grain = g - int(g)

Warped Noise

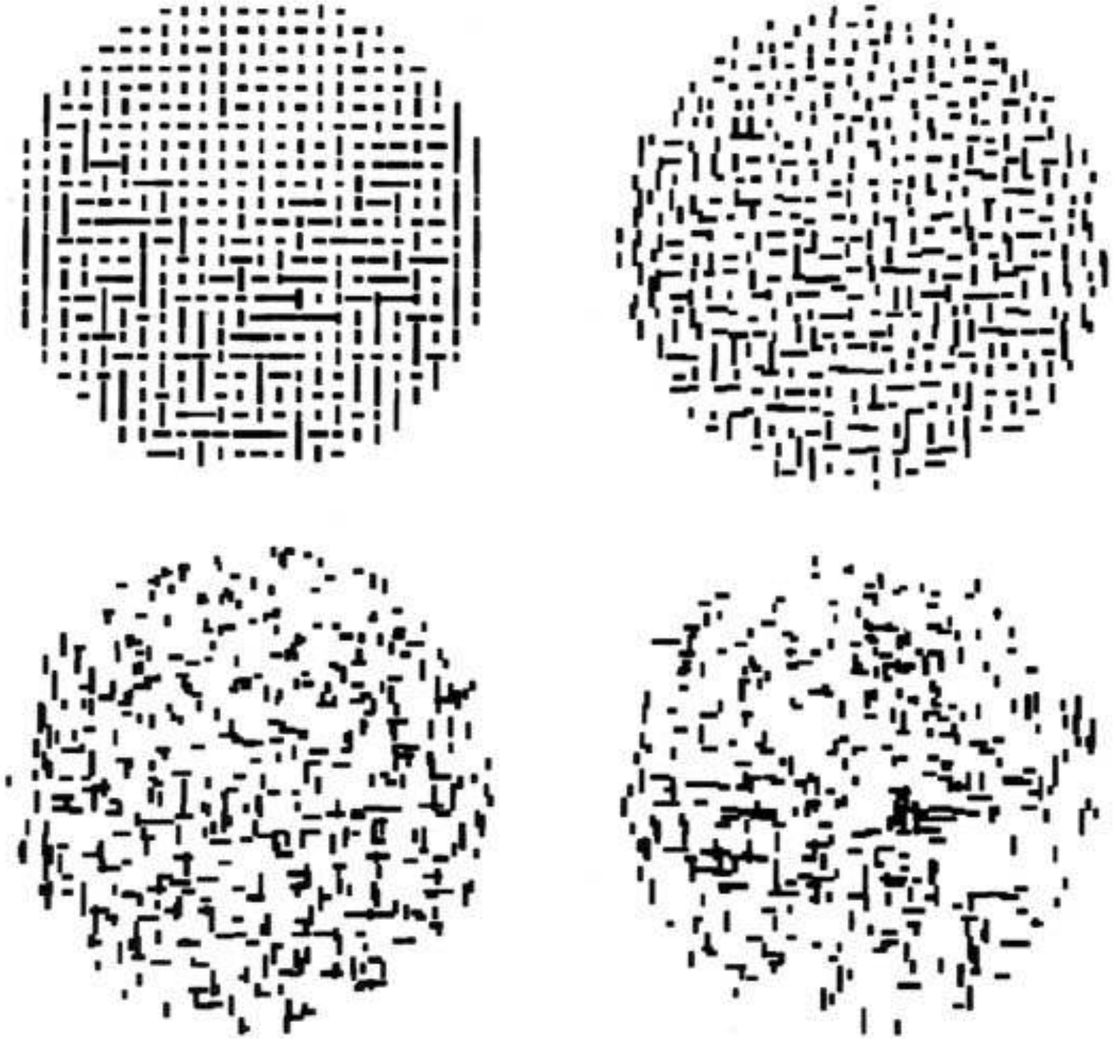
FYI

- Sometimes, you need different frequencies in different parts of the noise image/domain
- General idea: perform image warping
- Method:
  - Define polylines where noise image should "contract" (increases frequency)
  - Use generalized barycentric coordinates to move original pixels closer to "borders"



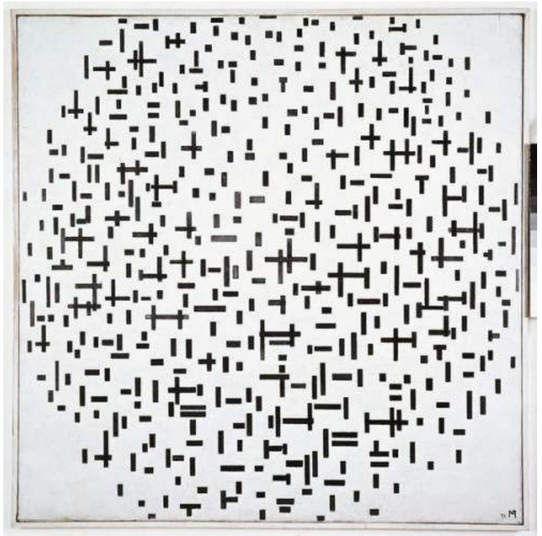
Digression on Randomness

FYI

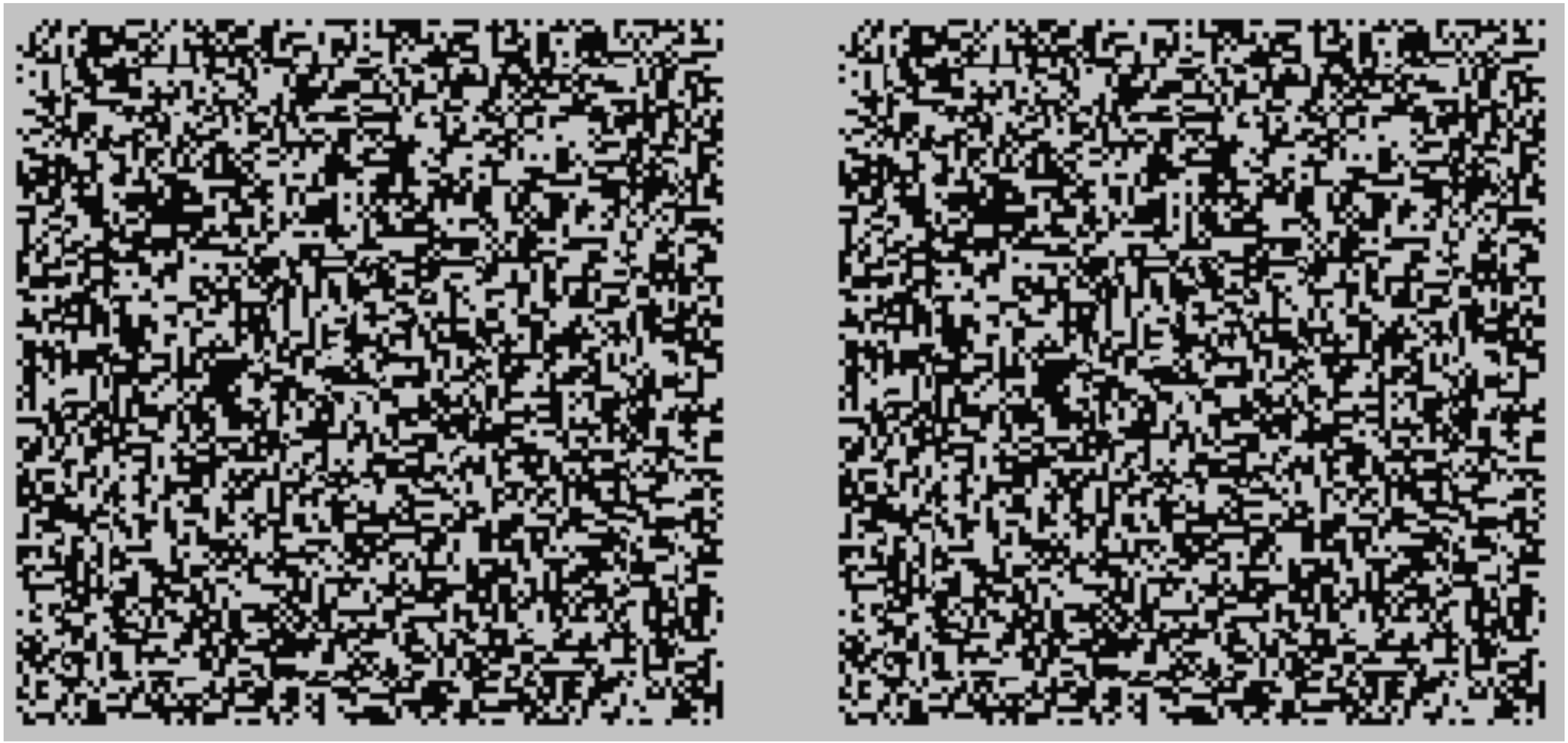


Michael Noll, 1962:
Computer Composition with Lines
Based on Piet Mondrian's
Composition with Lines

Piet Mondiran, 1917

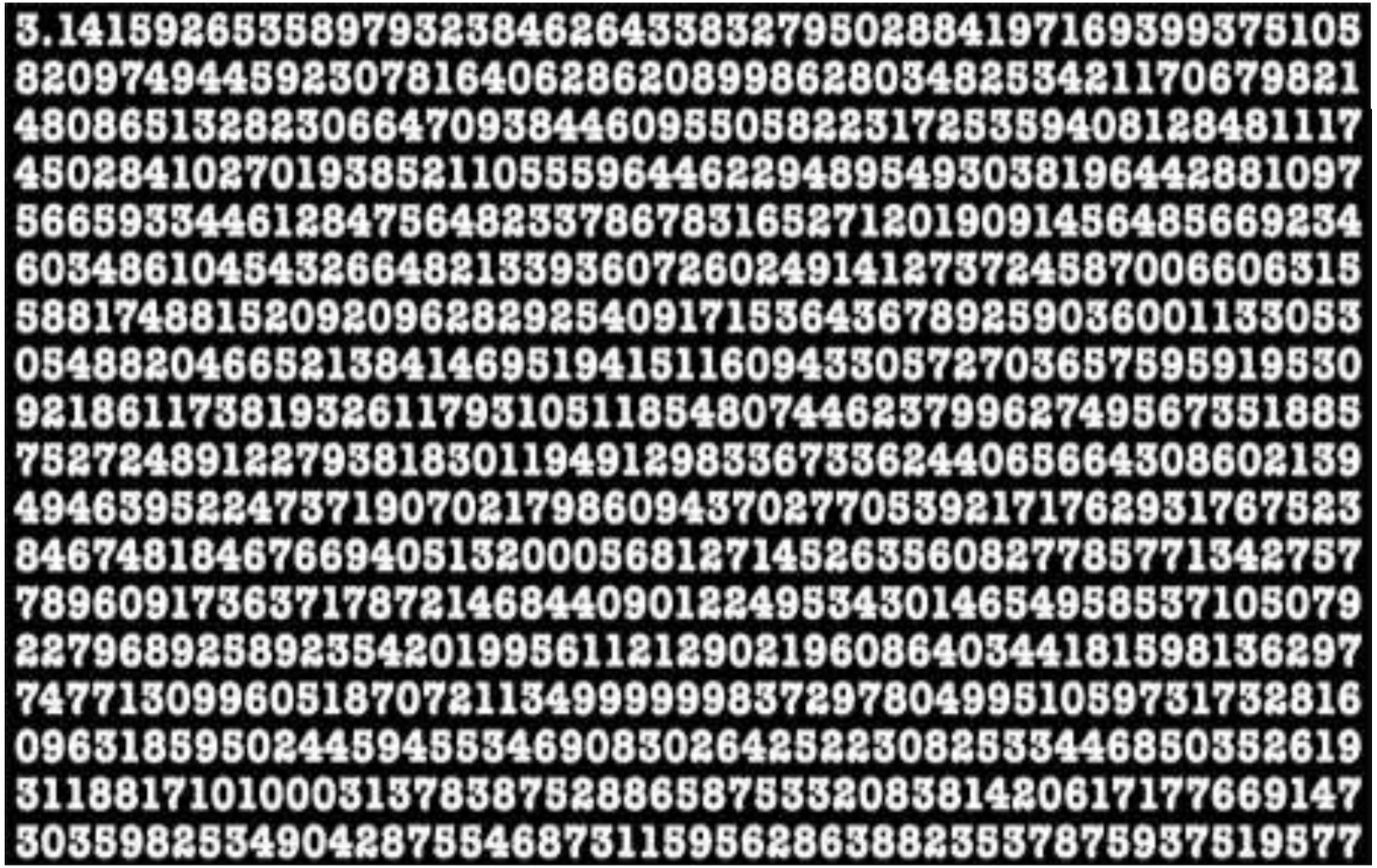


FYI



Random-dot stereograms. 3D object hidden in random images.
[Bela Julesz, Hungarian psychologist]

FYI

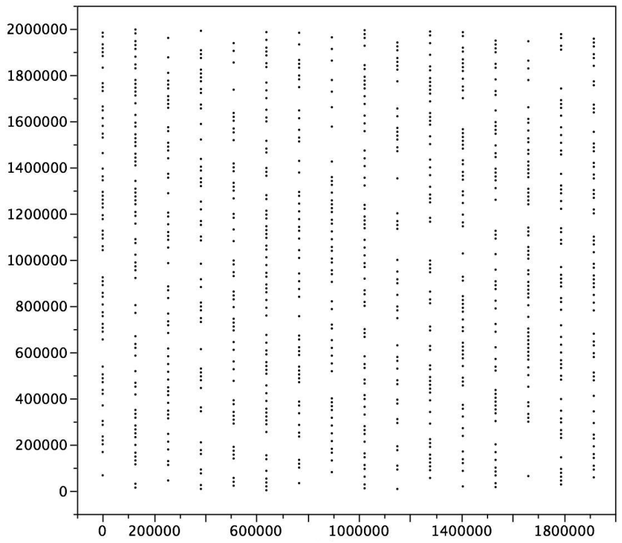


Is it random? What makes it random?

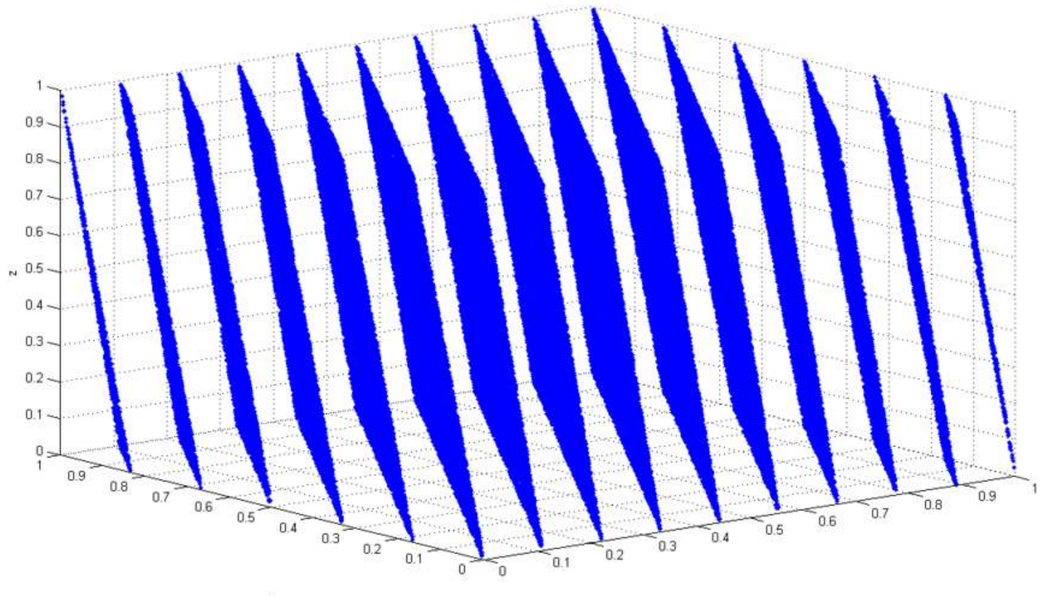
Is Your Random Number Generator Random?

FYI

- Spectral test:
  - Calculate x_i = rand(), for $i = 1, \ldots, N$ (N large)
  - Create 2D scatter plot of all points (x_i, x_{i+1})
    - Or in 3D using (x_i, x_{i+1}, x_{i+2})



Apple's rand() function in C



IBM's RANDU function

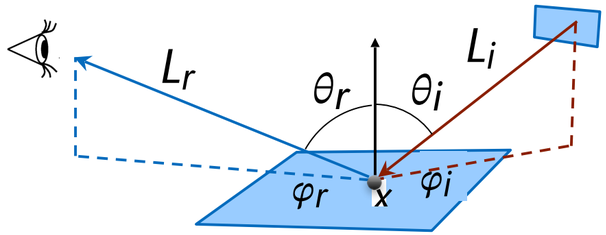
FYI

Eudaemons = Name of a group of physics graduates from University of Santa Cruz who understood that roulette wheels obey Newtonian physics, but is just very sensitive to initial conditions.
Using miniaturized computers, hidden in special shoes, they could capture the state of the ball and the wheel, and could increase their odds by 44%.

[Thomas A. Bass : *The Eudaemonic Pie*, 1985]

Ambient Occlusion

- Motivation:
  - Remember the rendering equation



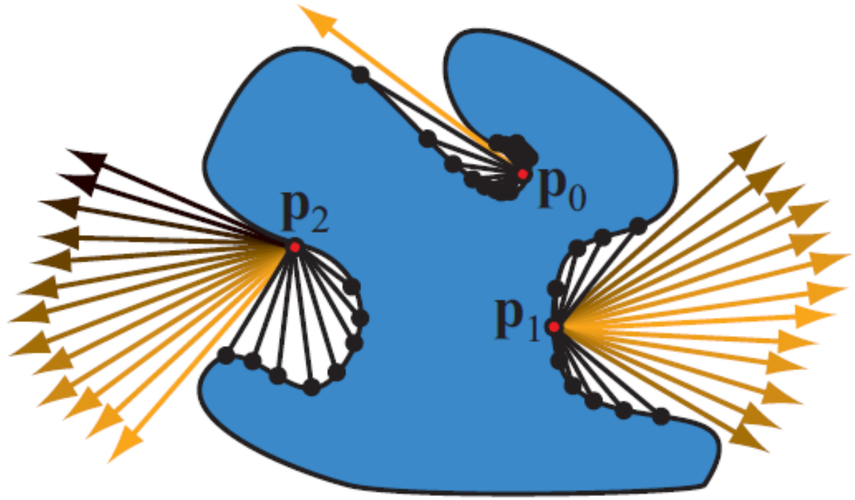
$$L_r(x,\omega_r) = \int_\Omega \rho(x,\omega_r,\omega_i) L_i(x,\omega_i) \cos(\theta_i) d\omega_i$$

  - Assume that ρ and incoming light is constant (if any) from/in every direction $\longrightarrow$ ambient occlusion (should be called ambient lighting):

$$A(\mathbf{x}) = \rho L_i \int_\Omega v(\mathbf{x},\omega_i)\, \mathbf{n}\cdot\omega_i \, d\omega_i$$

where $v(x,\omega) = \{0, 1\}$ = visibility in direction ω

- Further simplification: only check for self-occlusion ⟶ object-space ambient occlusion
- Can be pre-computed per object as kind of a "light map" (as a factor in the lighting model)
  - Independent of light direction and other objects in the scene
  - Can be multiplied with texture at run-time per fragment



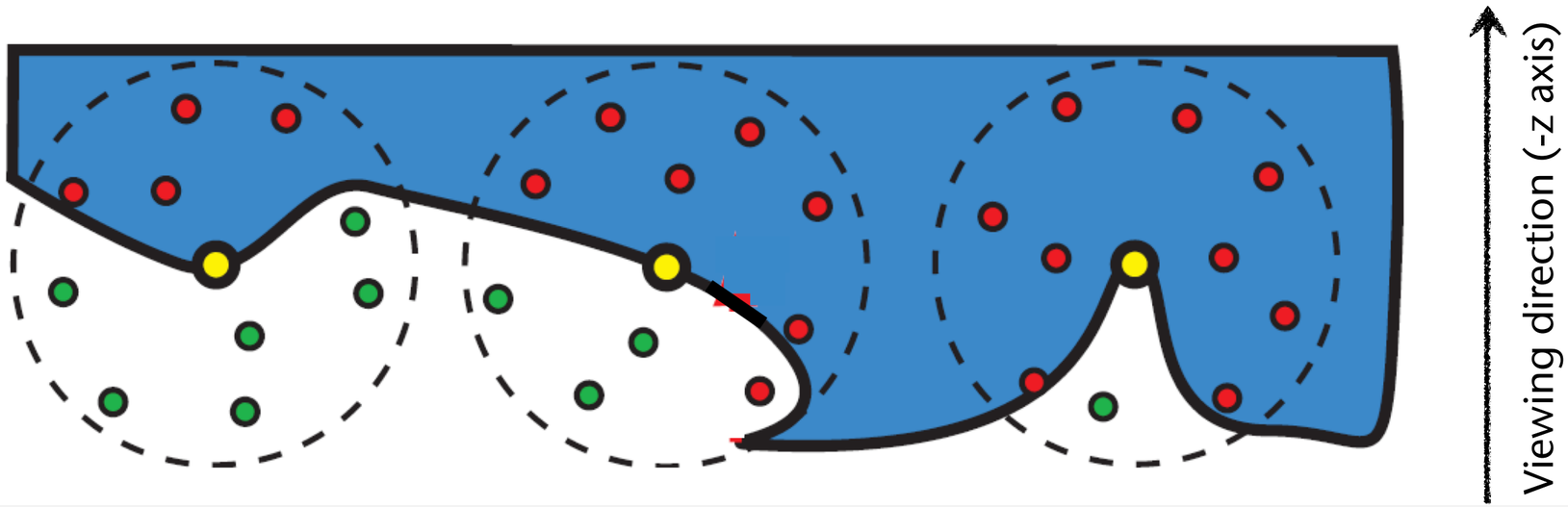
"Occlusion Feelers"

Ambient Occlusion Effect Depends on Length of Occlusion Feelers

(a) Ray length: 160 units (b) Ray length: 40 units (c) Ray length: 10 units (d) Ray length: 2 units

Screen-Space Ambient Occlusion (SSAO)

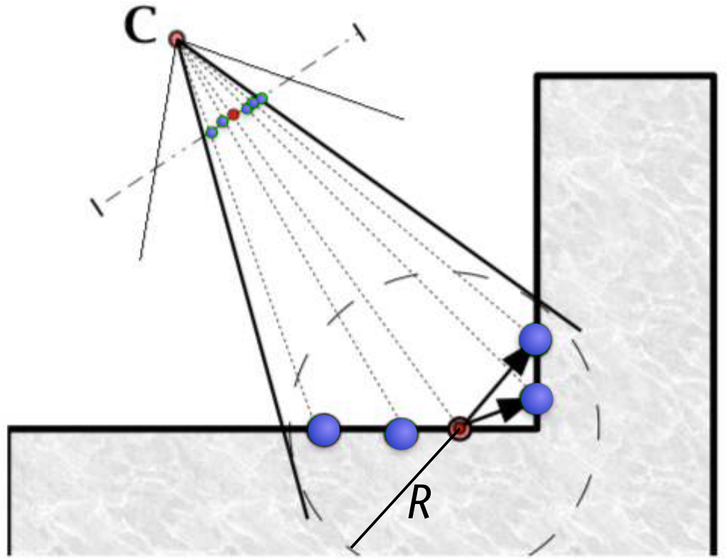
- Principle idea: sample neighborhood around each point on a surface, calculate ambient occlusion term, use in the lighting model as a factor
- One solution: use deferred shading, i.e., render into G-buffer in first pass
  - In second pass: for each receiver (= fragment), use z-buffer to check visibility of sample points $\mathbf{v}_i$ around receiver (wrt. viewpoint!)
  - Approximate the occlusion term $A \approx \frac{1}{\#\text{ samples } \mathbf{v}_i} \sum_{\text{green } \mathbf{v}_i} \mathbf{n} \cdot \omega_i$
  - Then evaluate lighting model

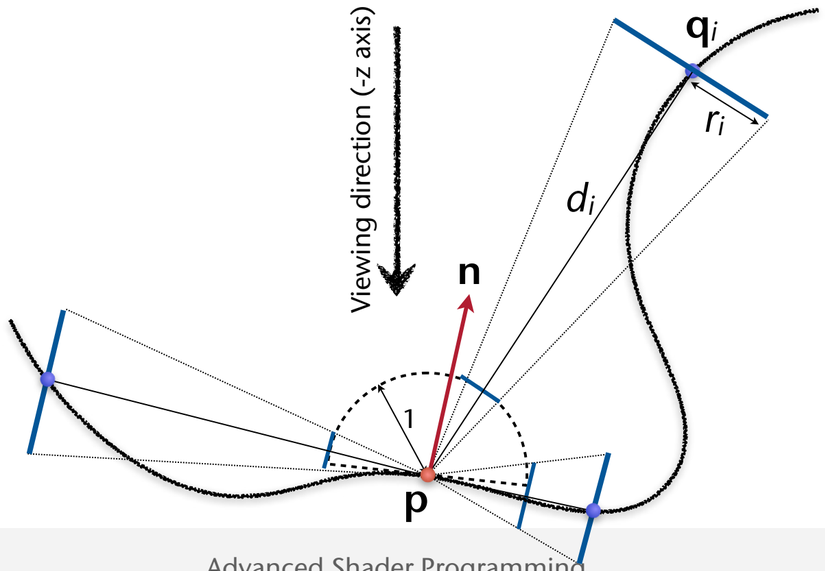


Method 2

- Re-project every pixel in frame buffer to the 3D point (in camera space!) ⟶ receiver point **p**
- Convert neighborhood radius R to radius on screen, consider all pixels within, reproject ⟶ sample points $\mathbf{q}_i$
- Approximate surface around sample points by disks, F_i, with radius r_i, oriented towards receiver
- Project onto hemisphere around receiver ⟶ F_i'
- Accumulate

$$A \approx \sum_{|\mathbf{q}_i - \mathbf{p}| < R} F_i' \mathbf{n} \cdot (\mathbf{q}_i - \mathbf{p}) = \sum_{|\mathbf{q}_i - \mathbf{p}| < R} \frac{F_i}{d_i^2} \mathbf{n} \cdot (\mathbf{q}_i - \mathbf{p})$$

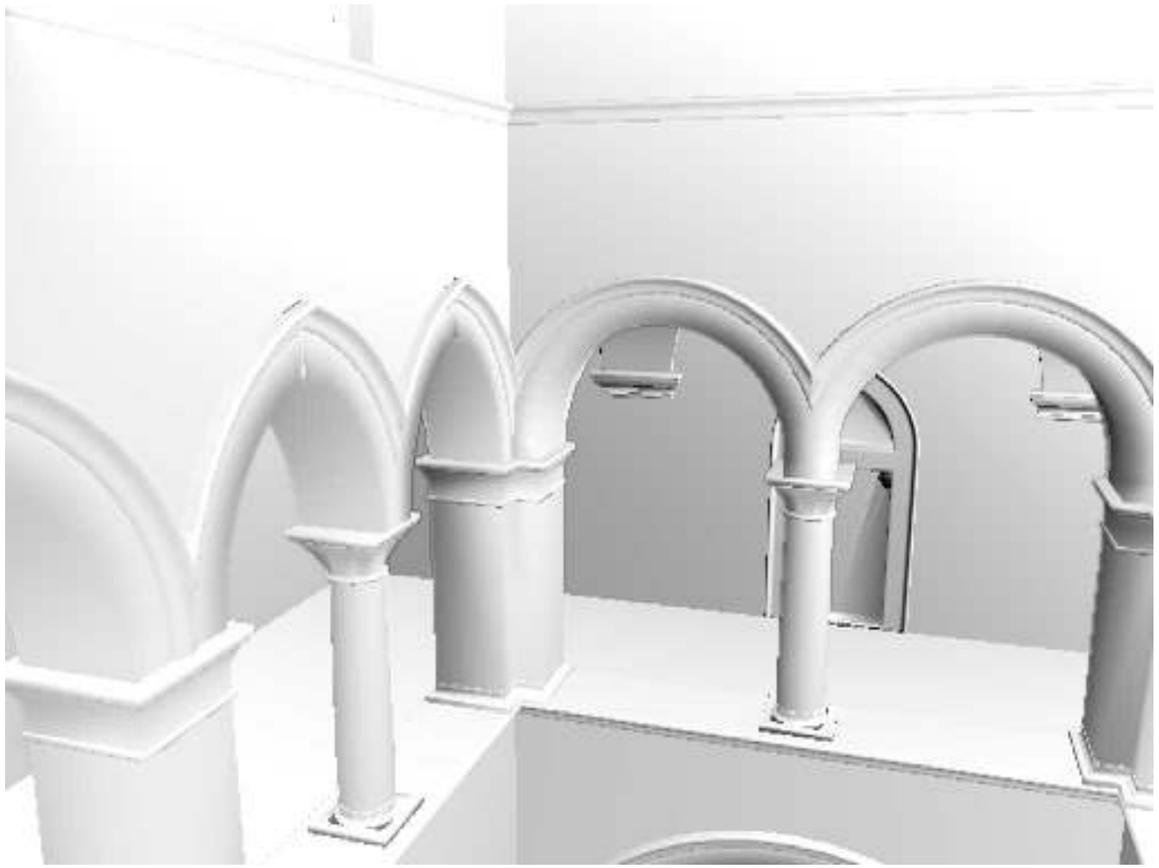


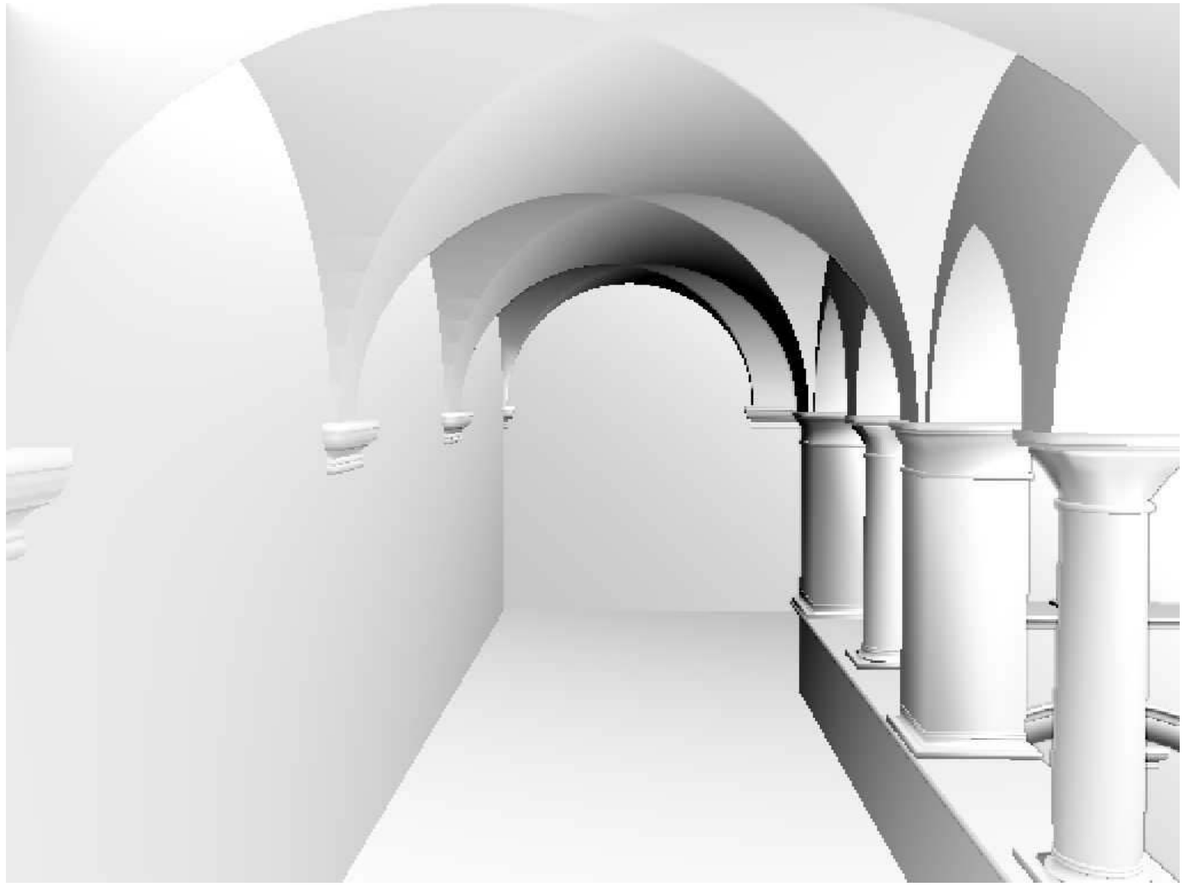


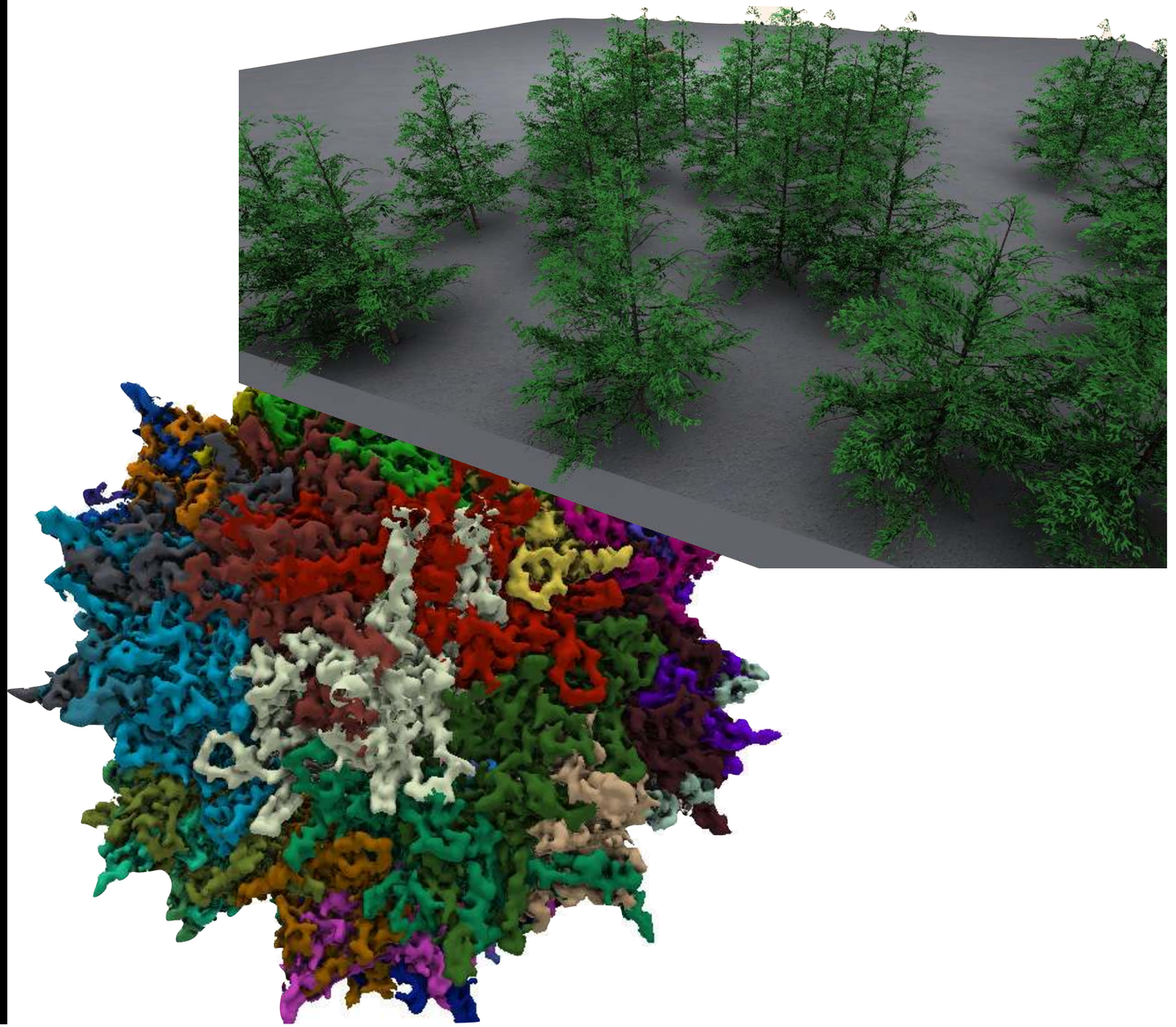
Experiment!

- Change parameters: size of neighborhood R, radius of disks r_i
- Specifically for method 2:
  - Place spheres around samples? (project these onto hemi-sphere of receiver point)
  - Should radius of sample disks/spheres depend on distance d_i?
  - Compute area of spherical cap on hemi-sphere covered by sample disks (don't just scale area F_i of the disks)
  - Orient disks perpendicular to normal in sample points, not towards receiver pt?
  - How to account for parts of surface around $\mathbf{p}$ that are visible from $\mathbf{p}$, but invisible from viewpoint?
- Does method 1 or method 2 produce more aesthetically pleasing results?

Results

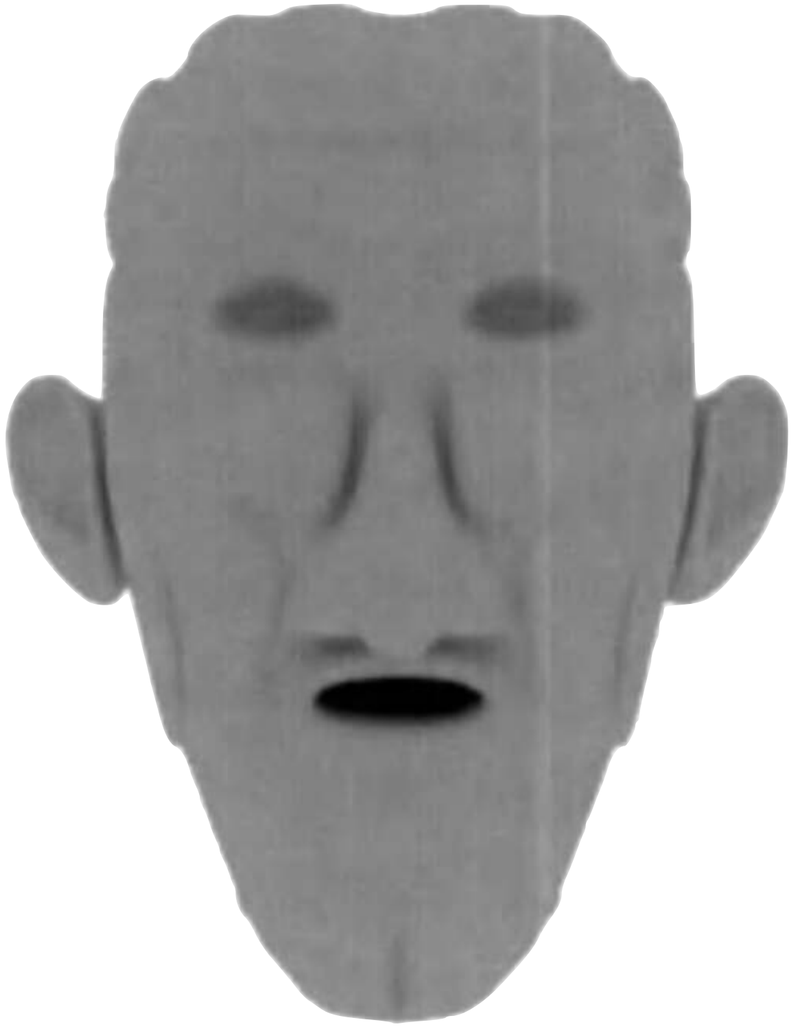






Effects Appear Usually Exaggerated Compared to Global Illumination

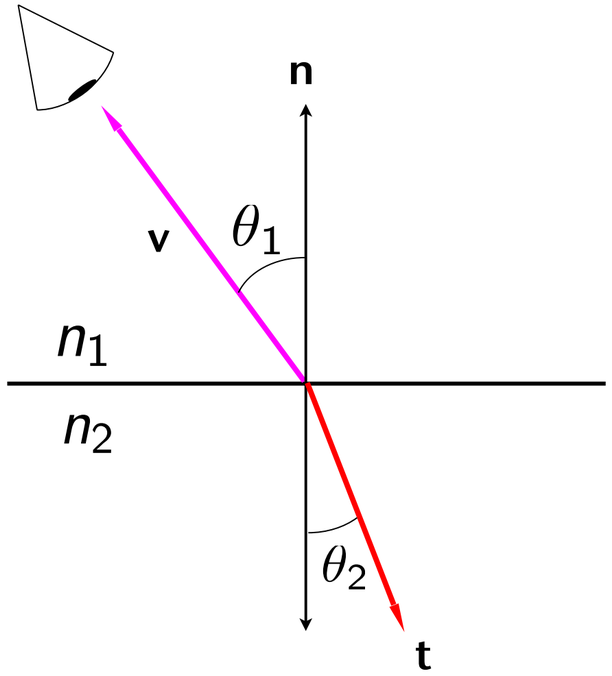
Ambient Occlusion

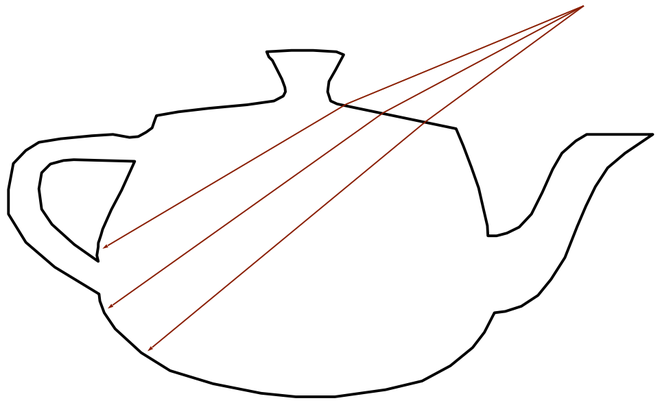


Full Global Illumination

Light Refraction

- With shaders, one can implement simple approximations of global effects
- Example: light refraction
- What do we need to calculate the refracted ray?
  - Snell's Law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$
  - Needed: **n**, **v**, 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 points of the refracted ray, one needs the entire geometry!



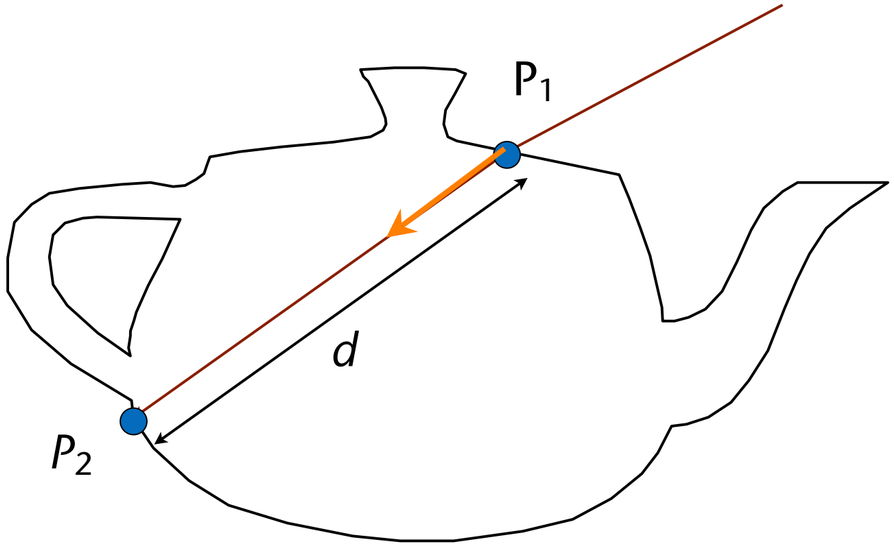


- Approximation: one entry point, one exit point out of transparent object (or vice versa)

1. step: determine the exit point

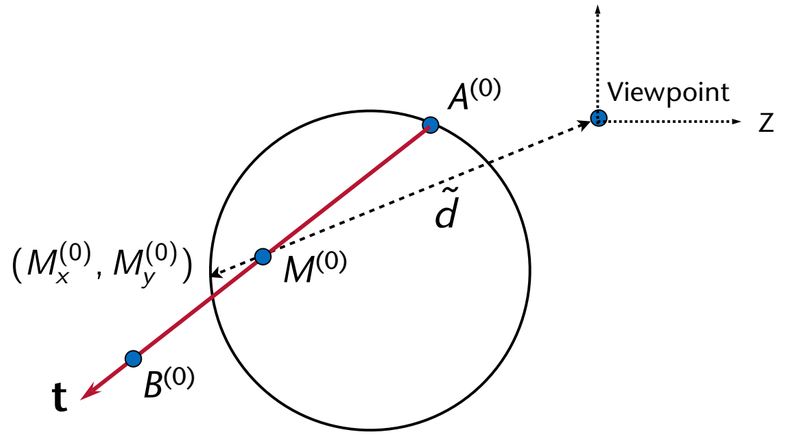
$$P_2 = P_1 + d\mathbf{t}$$

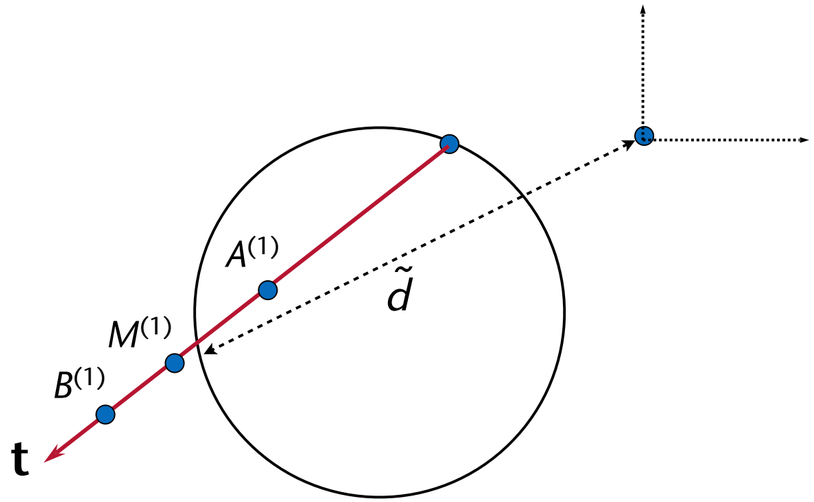
  - Idea: approximate d
  - To do that, render a depth map of the back-facing polygons in the first pass, from the viewpoint
  - Use binary search to find a good approximation of d (ca. 5 iterations suffice)



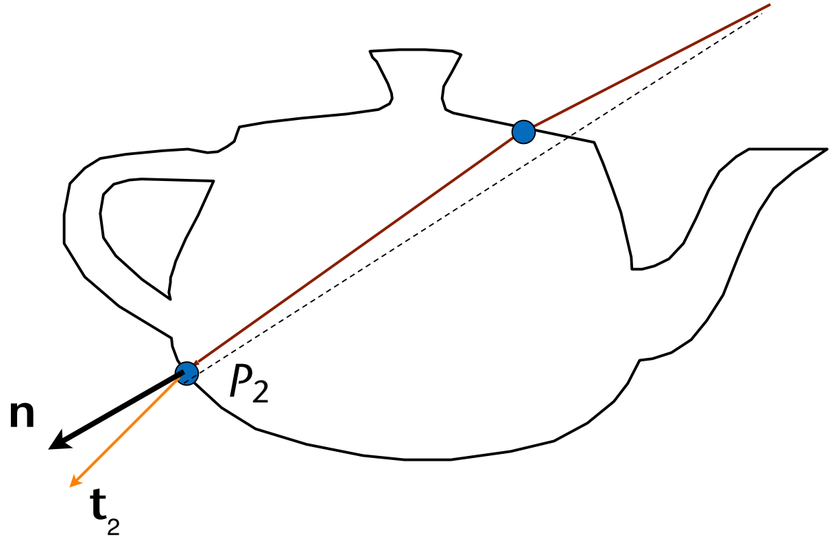
Details on the binary search for finding the distance between P_1 and P_2

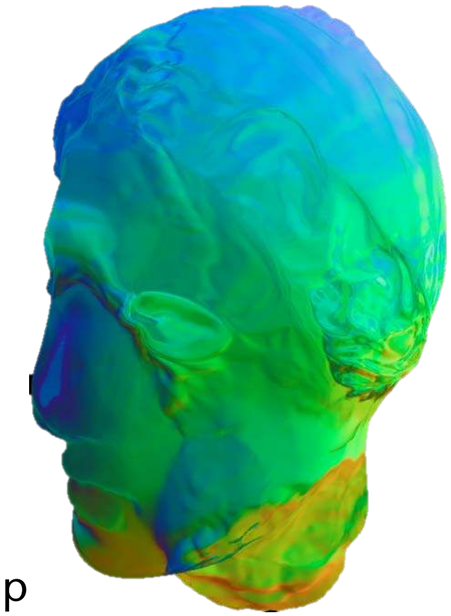
- Situation: given a ray **t**, with $t_z < 0$, and two "bracket" points $A^{(0)}$ and $B^{(0)}$ (in *camera space*!), between which the intersection point must be; and a precomputed depth map
- Compute midpoint $M^{(0)}$
- Use $(M_x^{(0)}, M_y^{(0)})$ to index the depth map $\longrightarrow \tilde{d}$
- If $\tilde{d} > M_z^{(0)} \Rightarrow$ set $A^{(1)} = M^{(0)}$
- If $\tilde{d} < M_z^{(0)} \Rightarrow$ set $B^{(1)} = M^{(0)}$
- Repeat until convergence or max iterations
- Warning: my drawing is simplified! (for clarity)





2. Step: 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
3. Step:
   - Determine $\mathbf{t}_2$
   - Index an environment map

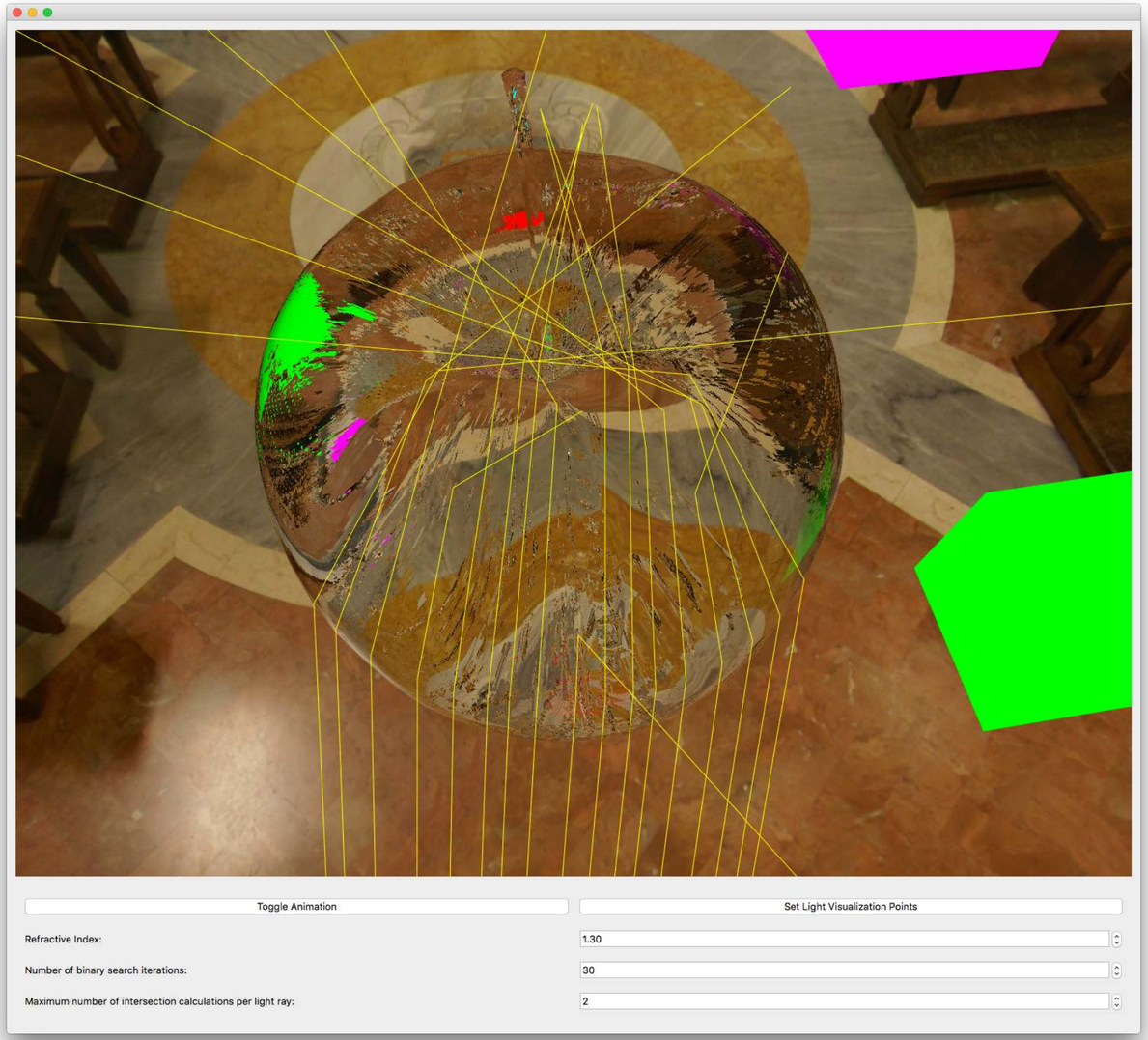




Normal map

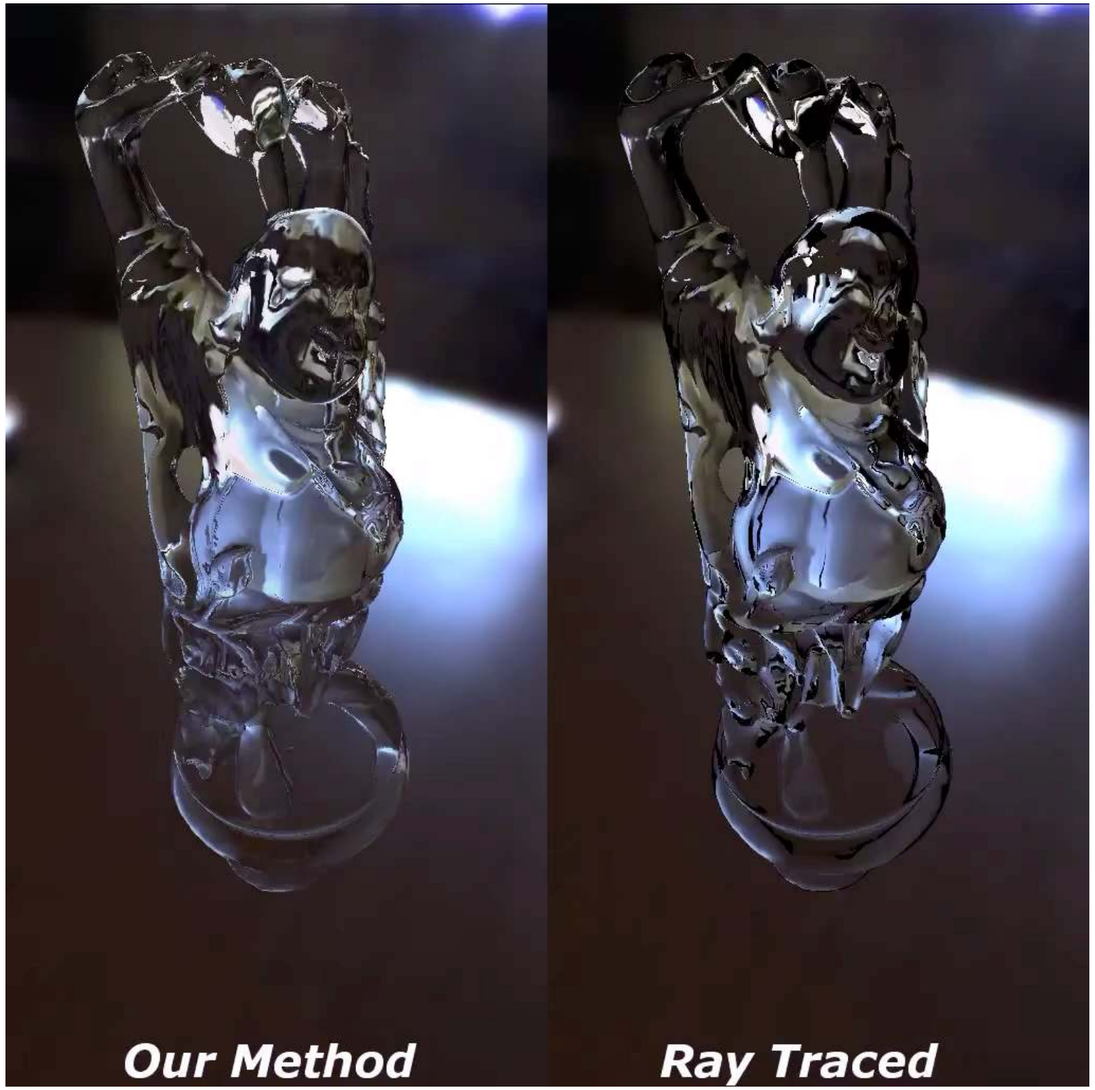
- Many open challenges:
  - When *depth complexity* > 2:
    - Which normal/which depth value should be stored in the depth/normal maps?
  - Approximation of distance
    - If object is highly non-convex, the approximation method can fail
  - Combination of reflected and refracted rays with Fresnel terms
  - Aliasing

[Jonathan Bronson, U Maryland, 2007]


Toggle Animation
Set Light Visualization Points
Refractive Index:
1.30
Number of binary search iterations:
30
Maximum number of intersection calculations per light ray:
2


Refraction
File
Toggle Animation
Set Light Visualization Points
Refractive Index:
1,30
Number of binary search iterations:
20
Maximum number of intersection calculations per light ray:
2

Examples



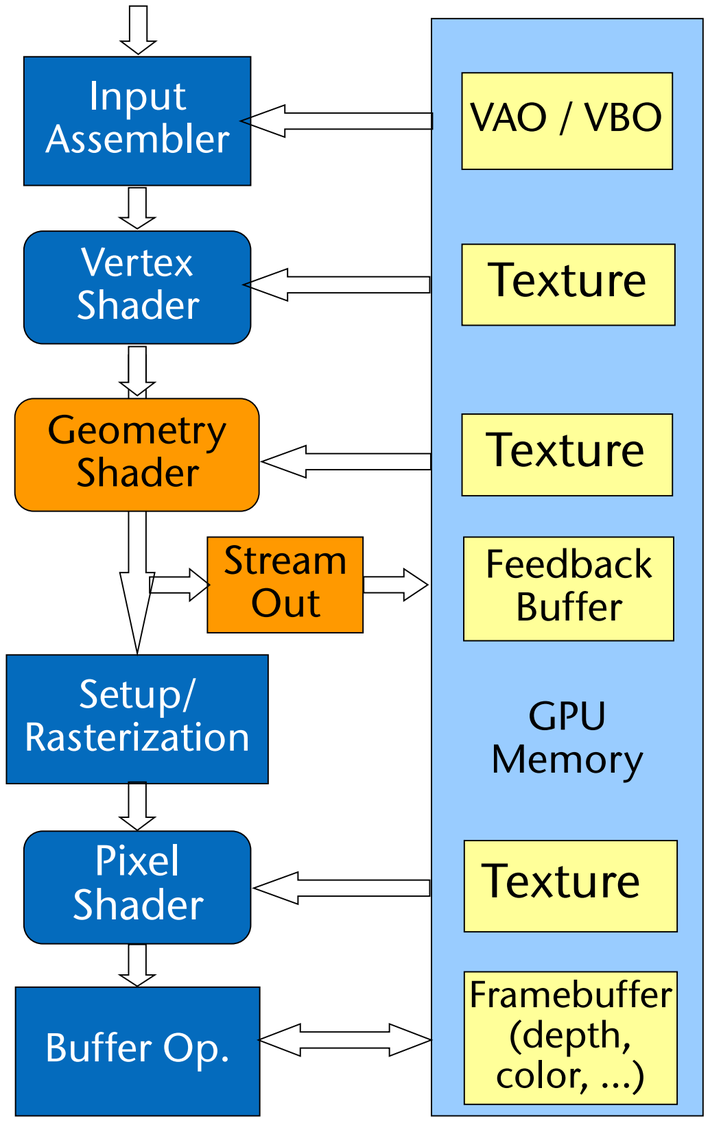
With large number (5?) of internal reflections

[Chris Wyman]

With different number of internal reflections

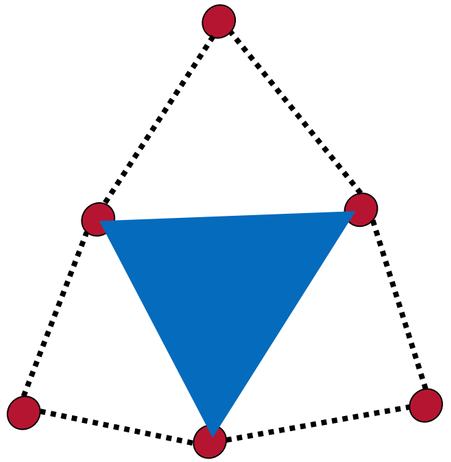
The Geometry Shader

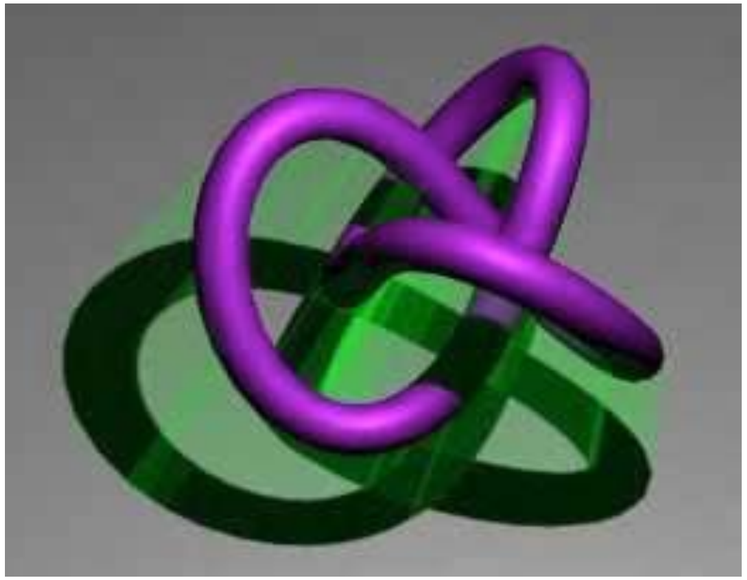
- Situated between vertex shader and rasterizer
- Essential difference to other shaders:
  - Per-*primitive* processing
  - The geometry shader can produce *variable-length* output!
  - 1 primitive in, *k* primitives out
  - Is optional (not necessarily present on all GPUs)
- Note on the side: features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



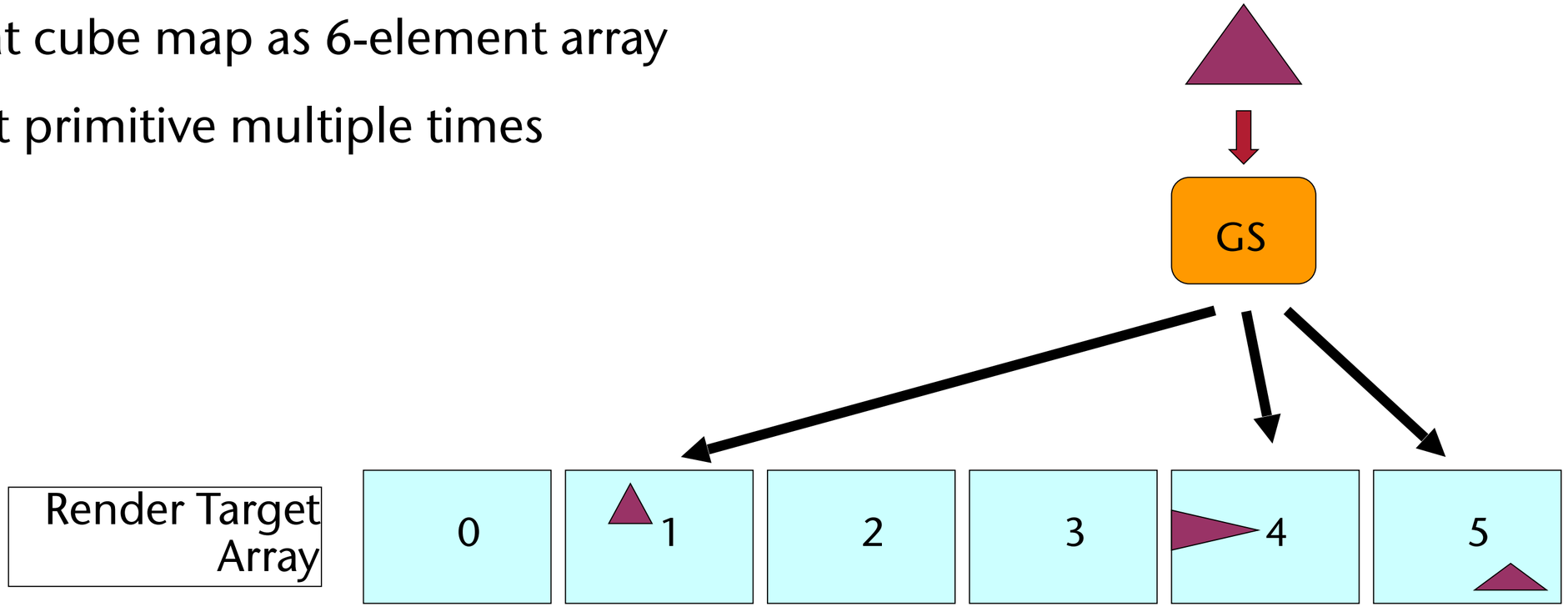
Features / Purposes of the Geometry Shader

- The geometry shader's principle function:
  - In general "amplify geometry"
  - More precisely: can create (or destroy) primitives *on the GPU*
  - Input = one complete primitive (optionally with adjacency)
  - Output: zero or more primitives (max 1024)
- Example application:
  - Silhouette extrusion for shadow volumes



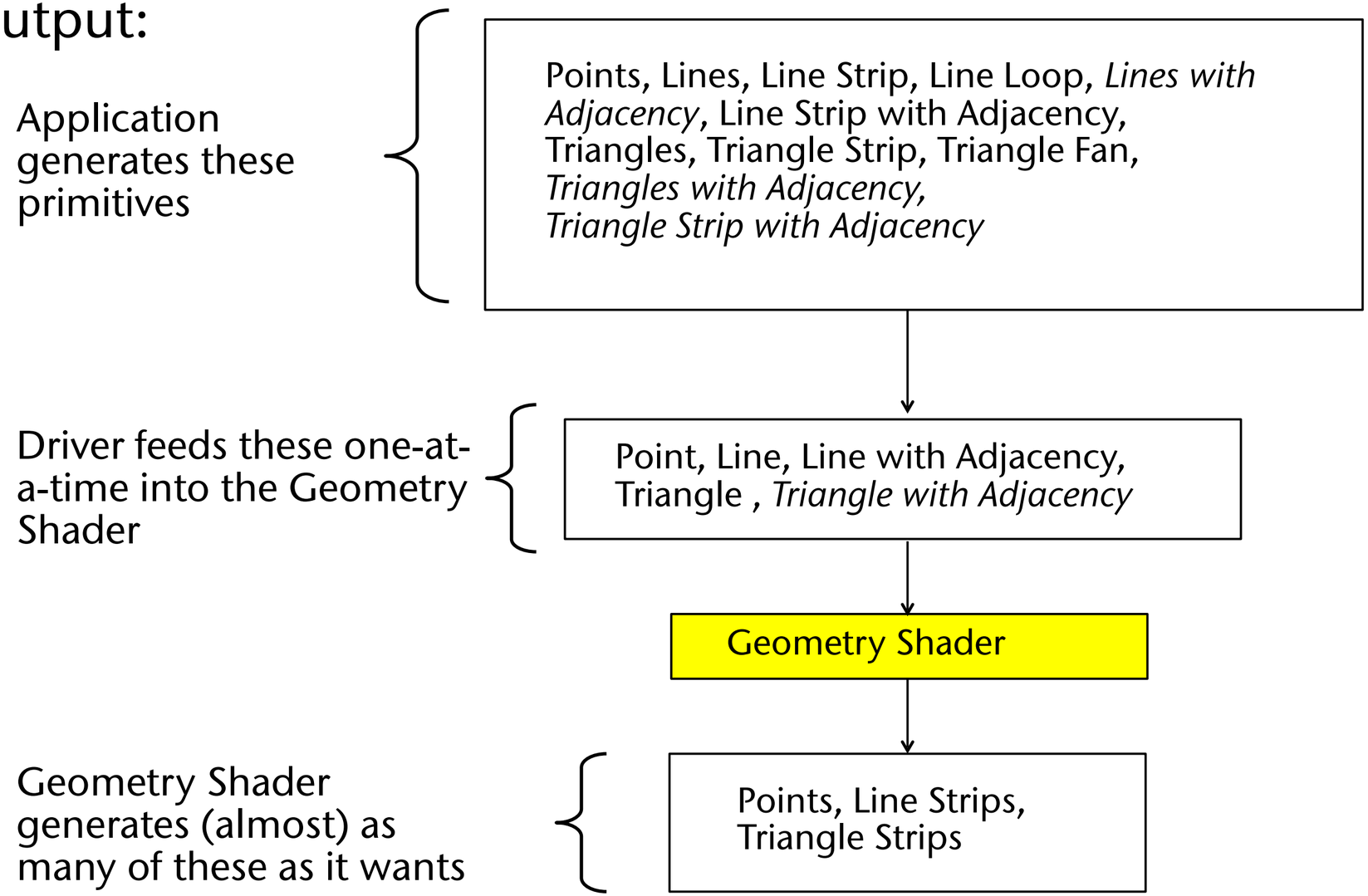


- Another feature of geometry shaders: can render the same geometry to multiple targets
- E.g., render to cube map in a single pass:
  - Treat cube map as 6-element array
  - Emit primitive multiple times



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 );
```

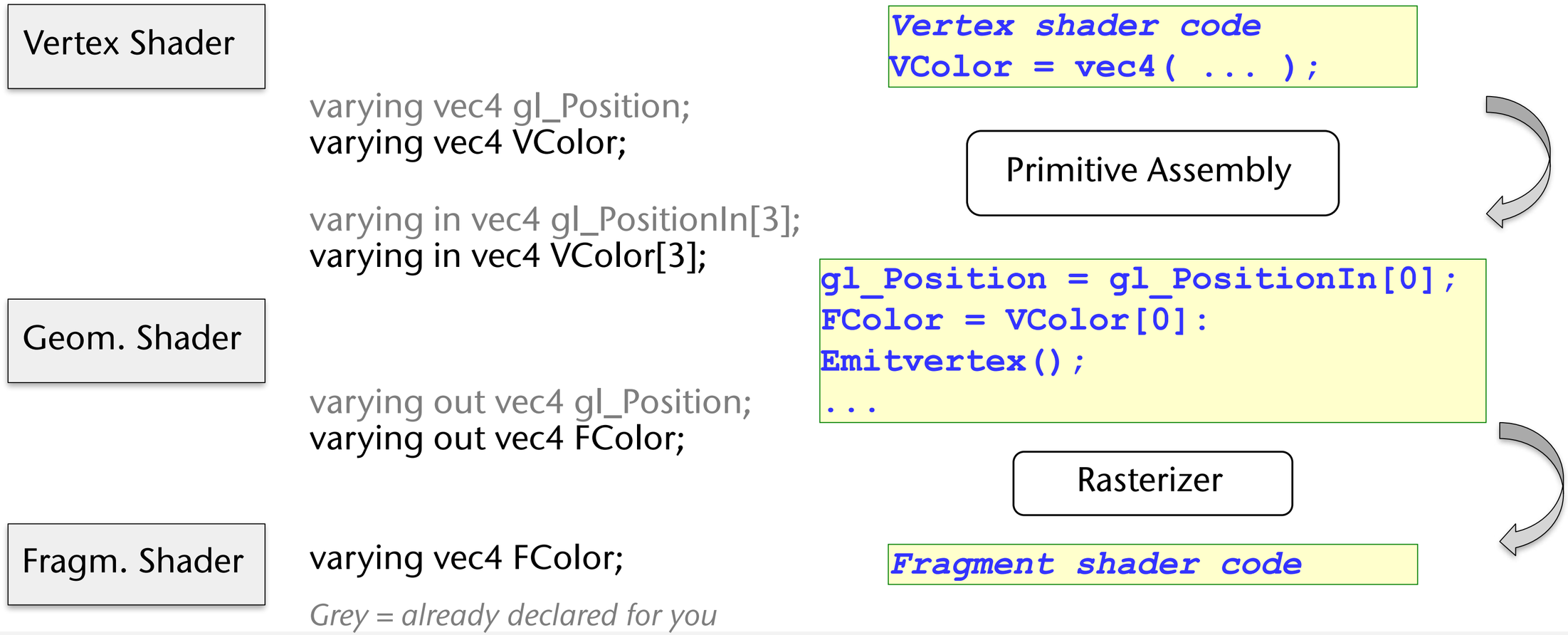
  - **`value`** = primitive type that this geometry shader will output
  - Possible values: GL_POINTS, GL_LINE_STRIP, GL_TRIANGLES_STRIP

Data Flow of the Principle Predefined Varying Variables

If a Vertex Shader writes variables as:		then the Geometry Shader will read them as:		and will write them to the Fragment Shader as:
gl_Position	→	gl_PositionIn[▪]	→	gl_Position
gl_TexCoord[▪]	→	gl_TexCoordIn[▪]	→	gl_TexCoord[▪]
gl_FrontColor	→	gl_FrontColorIn[▪]	→	gl_FrontColor
myAttrib	→	myAttrib[▪]	→	myAttrib
"varying"		"varying in"		"varying out"

- gl_VerticesIn

- 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:



Caveats

- 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 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 previous EndPrimitive() call

A Very Simple Geometry Shader Program

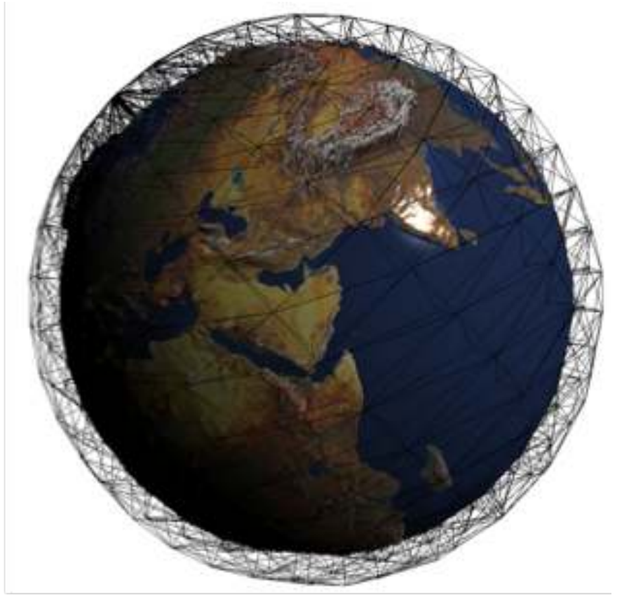
```
#version 120
#extension GL_EXT_geometry_shader4 : enable void
main(void)
{
  float d = 0.04;
  gl_Position = gl_PositionIn[0] + vec4(0.0, d, 0.0, 0.0);
  gl_FrontColor = vec4(1.0, 0.0, 0.0, 1.0);
  EmitVertex();
  gl_Position = gl_PositionIn[0] + vec4(d, -d, 0.0, 0.0);
  gl_FrontColor = vec4(0.0, 1.0, 0.0, 1.0);
  EmitVertex();
  gl_Position = gl_PositionIn[0] + vec4(-d, -d, 0.0, 0.0);
  gl_FrontColor = vec4(0.0, 0.0, 1.0, 1.0);
  EmitVertex();
  EndPrimitive();
}
```

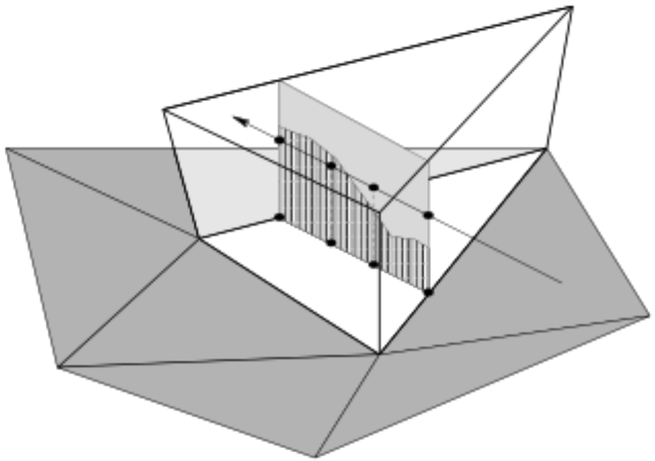
Examples

- 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

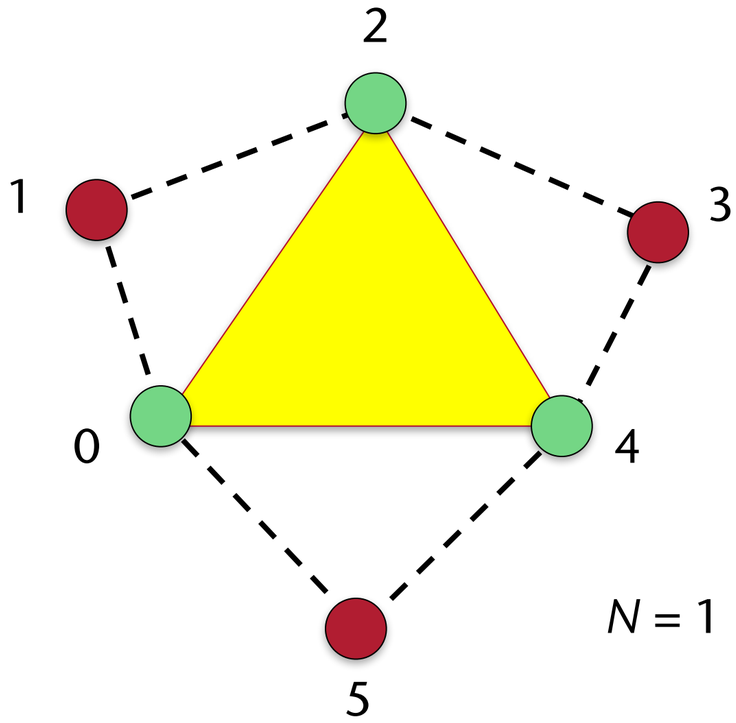




Intermezzo: Adjacency Information

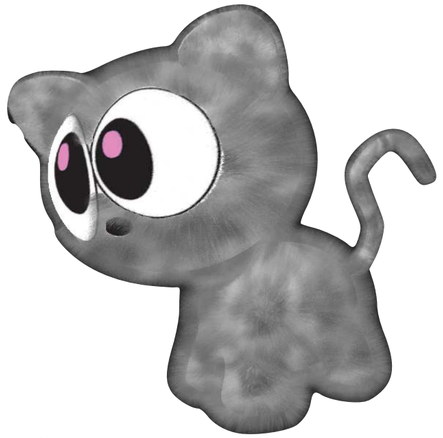
- In addition to the conventional primitives (GL_TRIANGLE et al.), a few new primitives were introduced with geometry shaders
- The most frequent one: GL_TRIANGLES_WITH_ADJACENCY

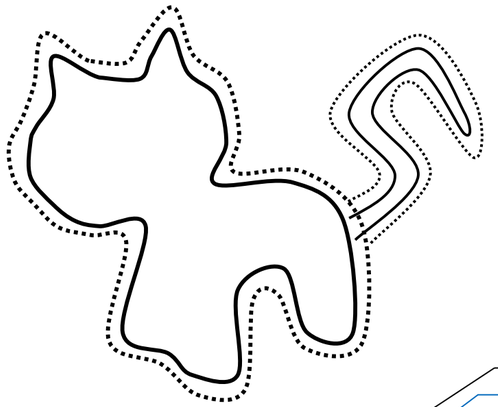
6N vertices are given
(where *N* is the number of triangles to draw).
Points 0, 2, and 4 define the triangle.
Points 1,3, and 5 tell where adjacent triangles are.

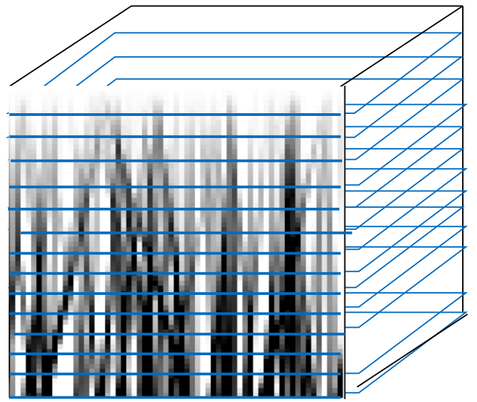


Shells & Fins

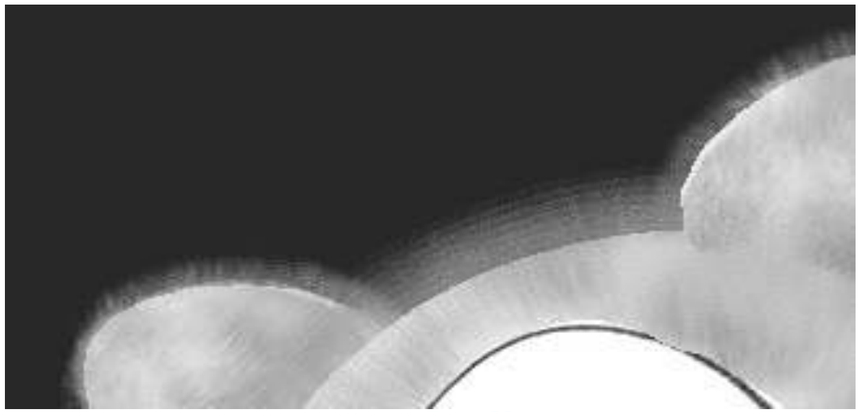
- Suppose, we want to generate a "fluffy", ghost-like character like this
- Idea:
  - Render several shells (offset surfaces) around the original polygonal geometry
    - Can be done easily using the vertex shader
  - Put different textures on each shell to generate a volumetric, yet "gaseous" shell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





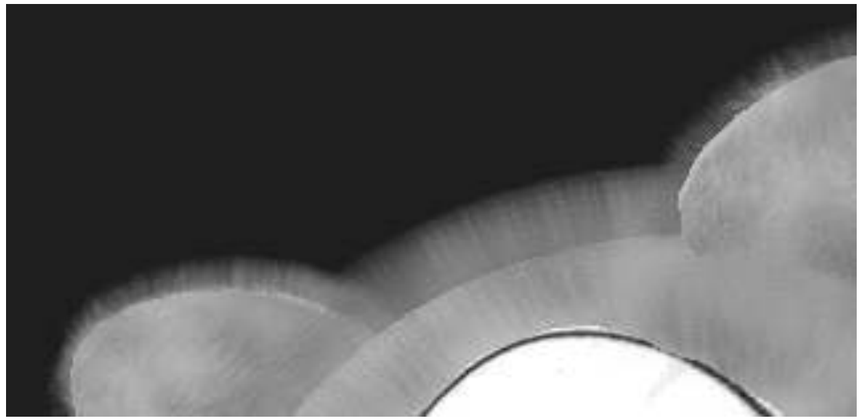


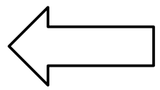
- Problem at the silhouettes:
- Solution: add "fins" at the silhouette
  - Fin = polygon standing on the edge between 2 silhouette polygons
- Makes problem much less noticeable

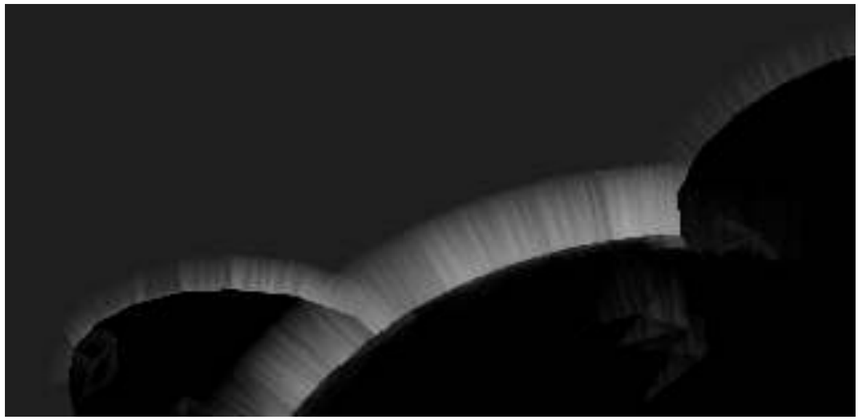


8 shells

+





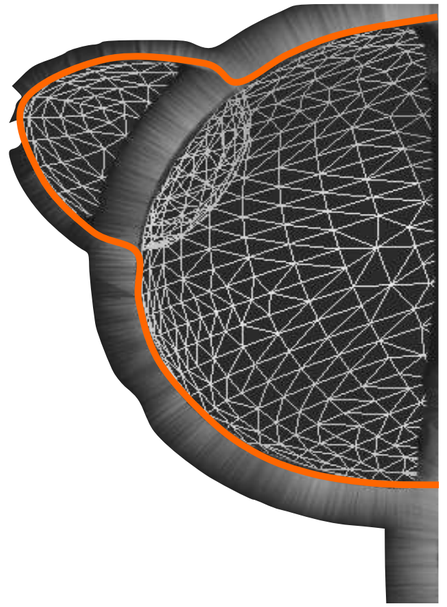


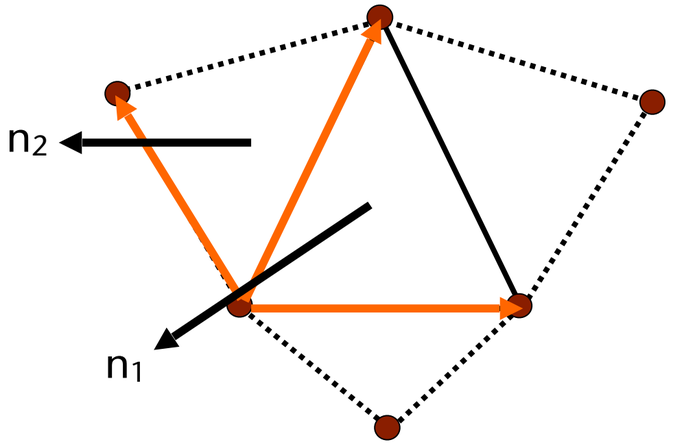
fins

- 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:

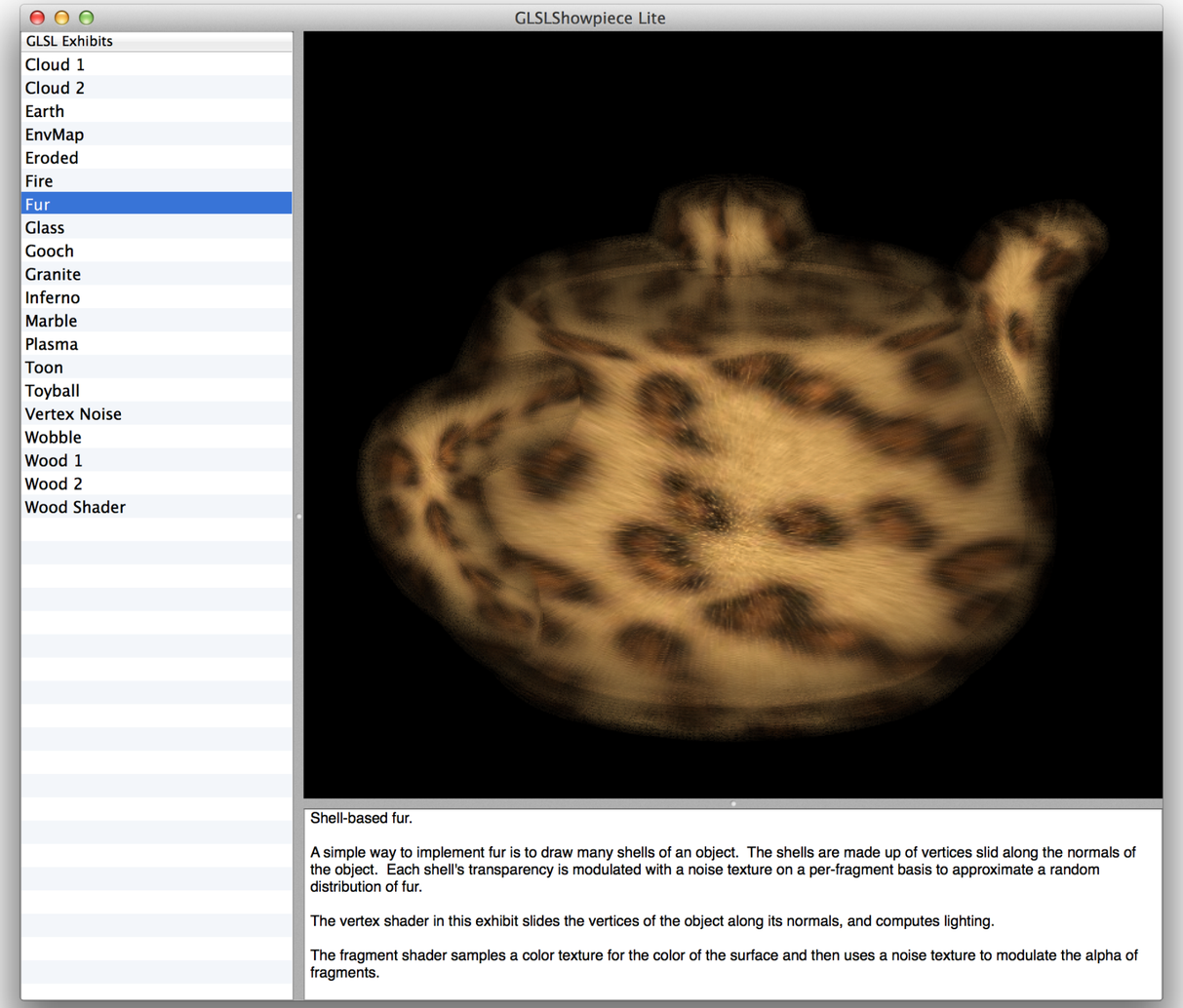
$$\text{silhouette} \Leftrightarrow \mathbf{en}_1 > 0 \wedge \mathbf{en}_2 < 0$$

    where **e** = eye vector, from edge to eye
  - If edge = silhouette edge, then the geometry shader emits a fin polygon *and* the input polygon
  - Else, it just emits the input polygon
  - Do we need to check the "other orientation" of signs?





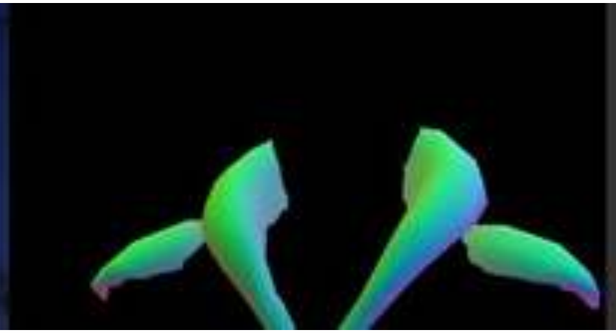
Demo


GLSLShowpiece Lite
GLSL Exhibits
Cloud 1
Cloud 2
Earth
EnvMap
Eroded
Fire
Fur
Glass
Gooch
Granite
Inferno
Marble
Plasma
Toon
Toyball
Vertex Noise
Wobble
Wood 1
Wood 2
Wood Shader
Shell-based fur.
A simple way to implement fur is to draw many shells of an object. The shells are made up of vertices slid along the normals of the object. Each shell's transparency is modulated with a noise texture on a per-fragment basis to approximate a random distribution of fur.
The vertex shader in this exhibit slides the vertices of the object along its normals, and computes lighting.
The fragment shader samples a color texture for the color of the surface and then uses a noise texture to modulate the alpha of fragments.

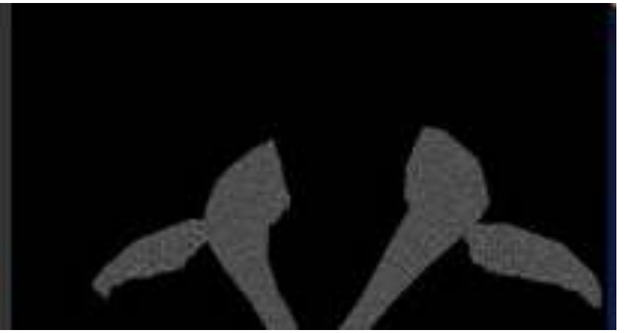
Example Application: Lost Planet Extreme Condition

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

Texture for color



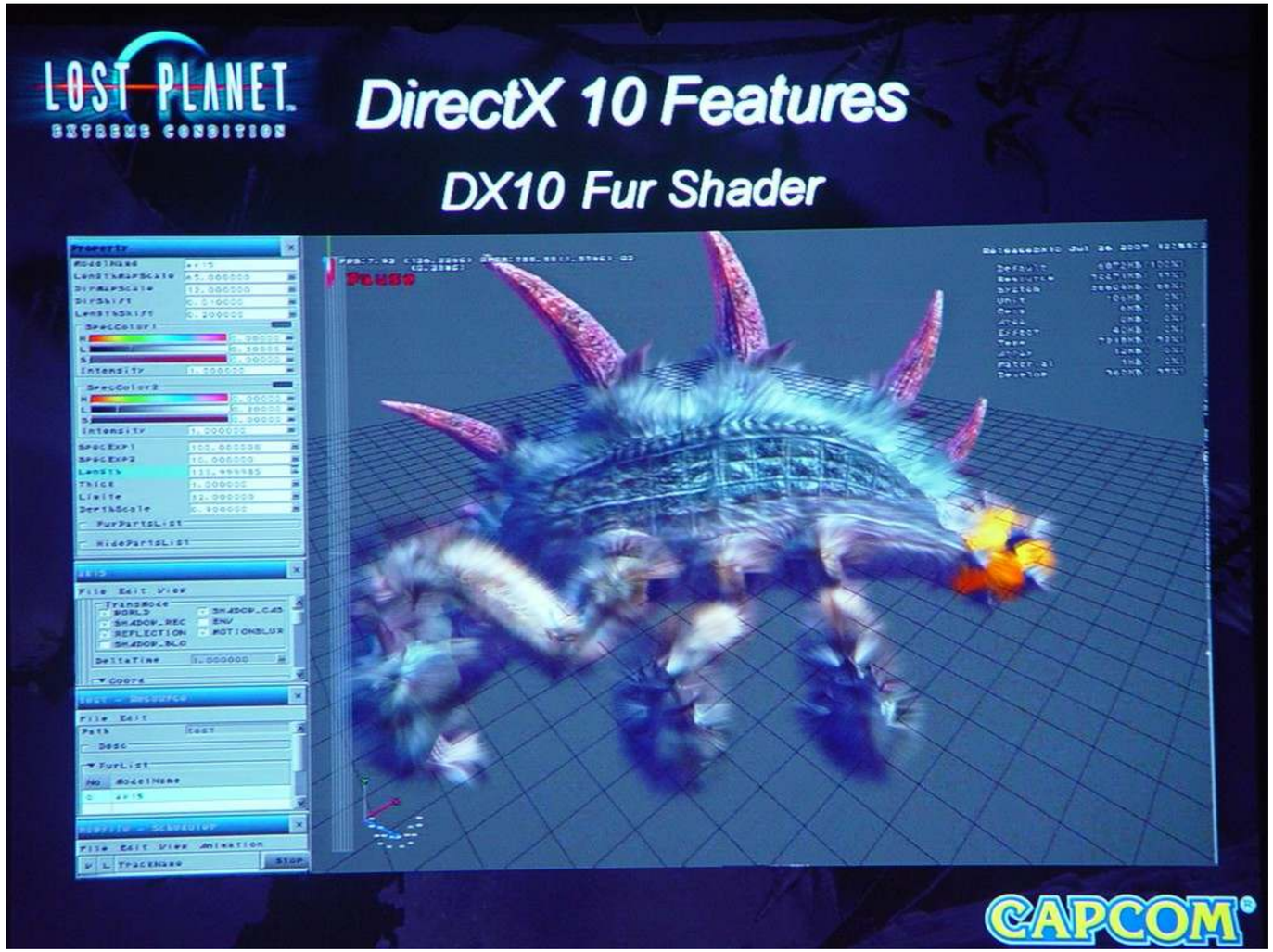
Texture for angle of fur hairs



Noise texture for length of fur hairs

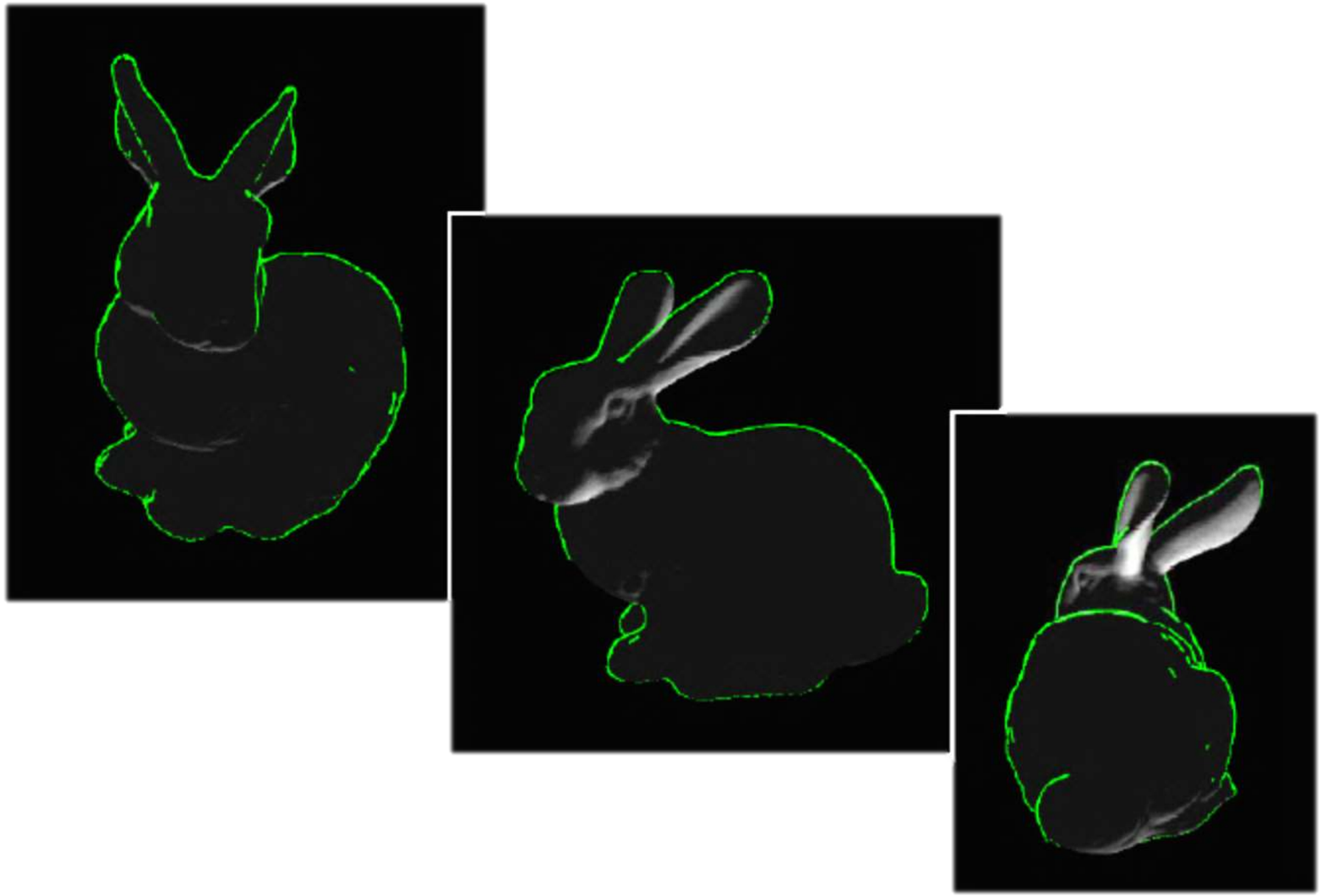
Furthermore, one should try to render self-shadowing of strands of fur hairs ...

- 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 they can determine the best look



Silhouette Rendering

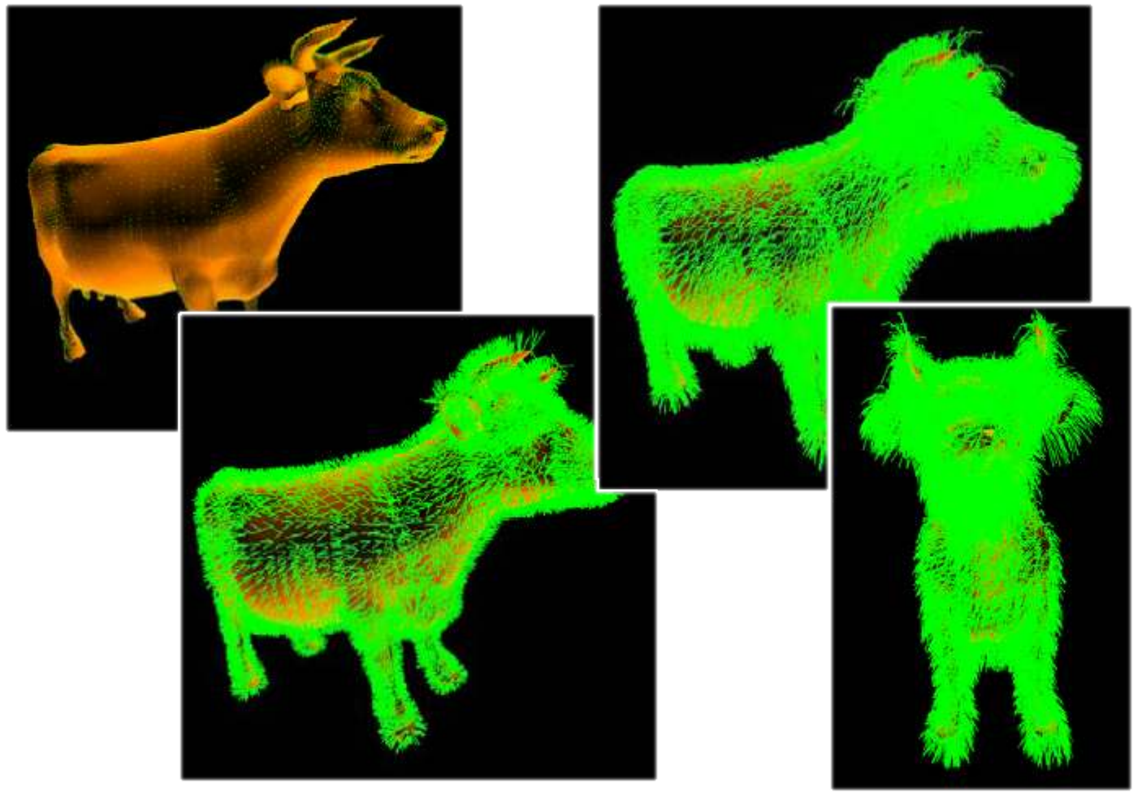
- Goal:

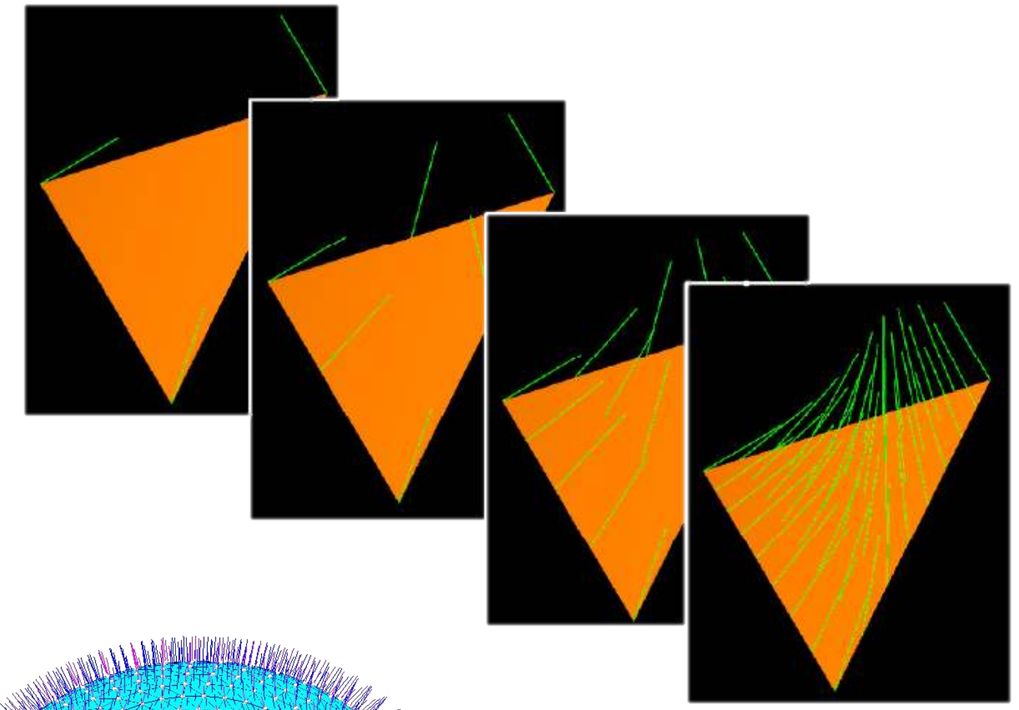


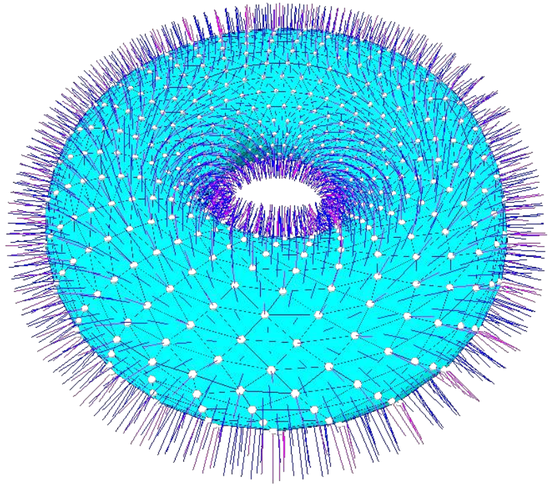
Technique: 2-pass rendering

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
     - With tolerance to make silhouette thicker
   - If yes $\longrightarrow$ output line
   - If no $\longrightarrow$ output no geometry

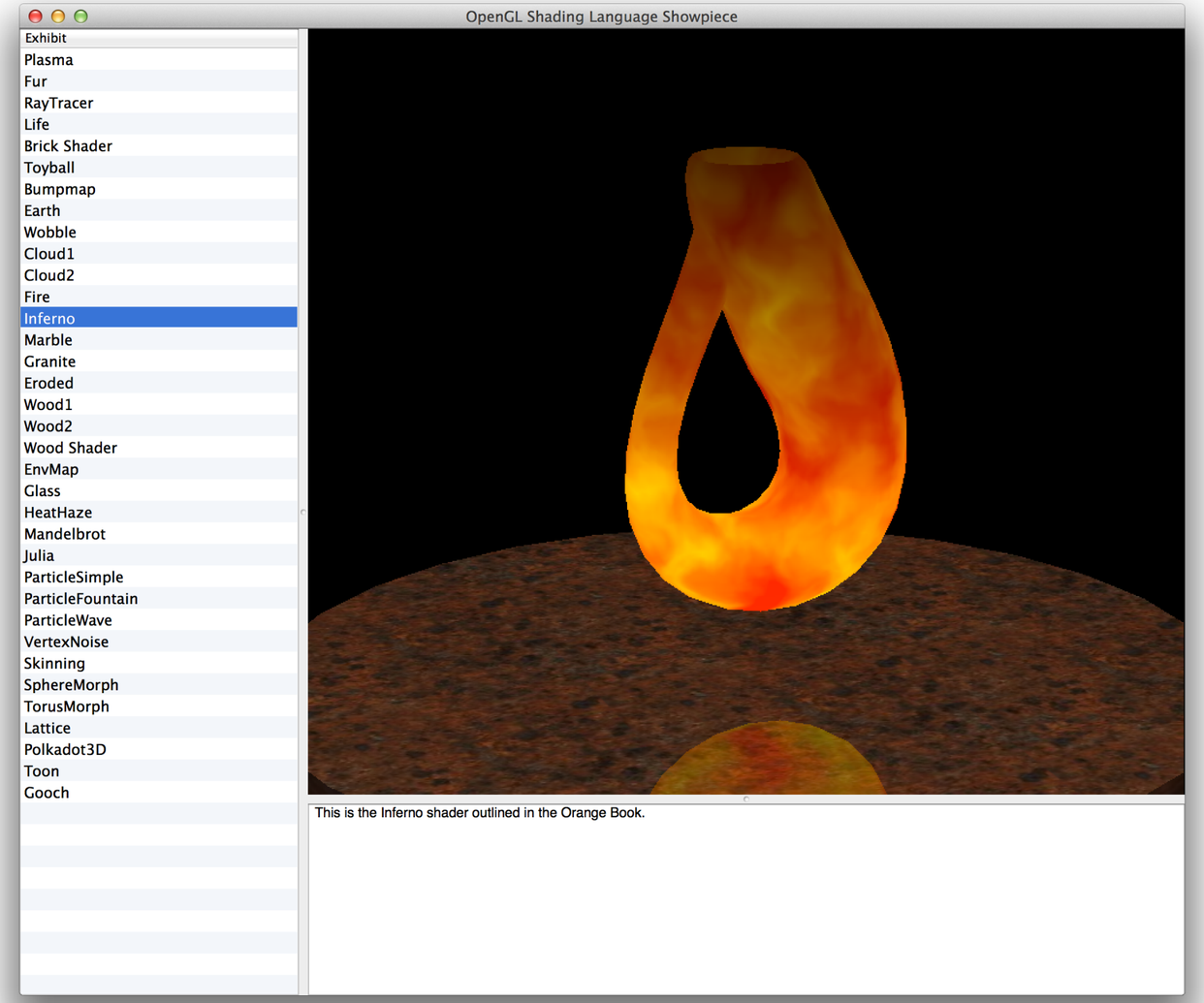
Hedgehog Plots



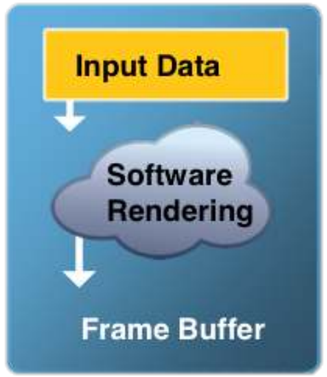




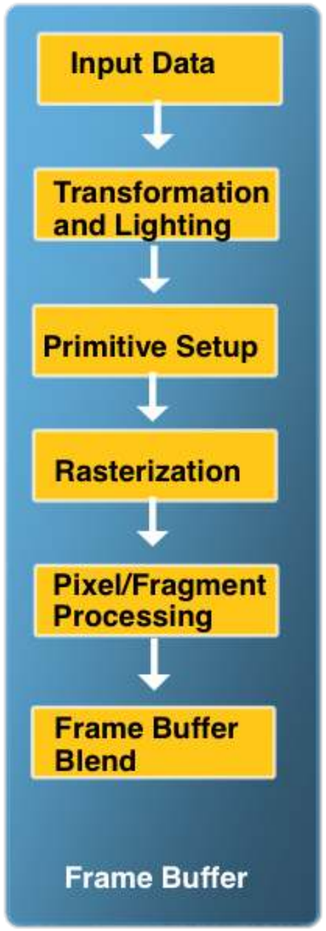
Concluding Demos



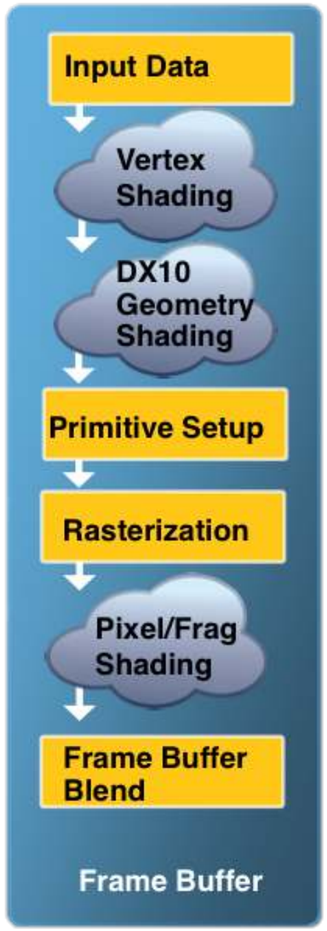
The Future of Polygonal Rendering on GPUs?



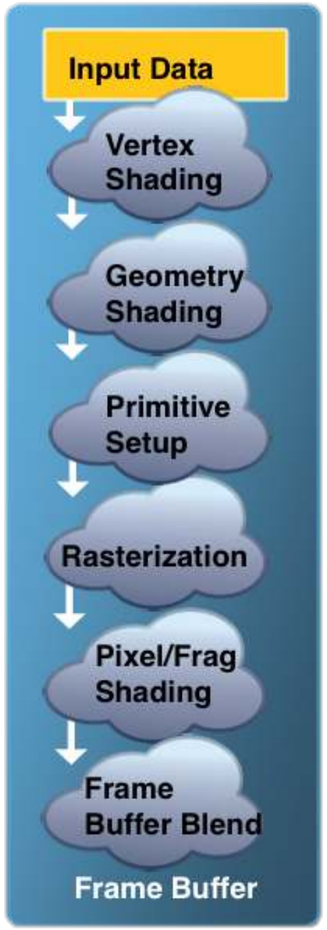
Pre 1986: pure software rendering



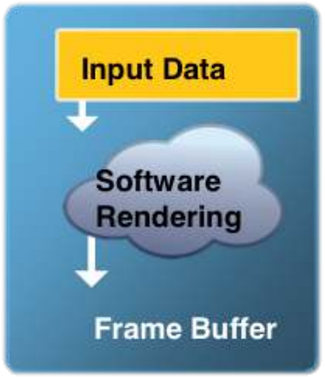
Pre 2001: complete, efficient HW pipeline



OpenGL 3.x: first real programmability



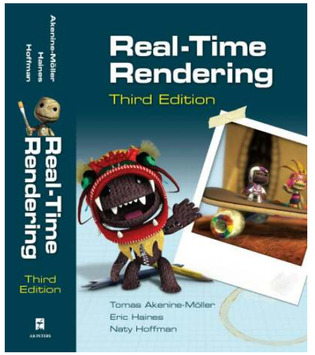
No fixed function any more?



Pure software rendering?

Resources on Shaders

- Real-Time Rendering; 3rd edition



- The tutorial on this course's home page

- OpenGL Shading Language Reference:
  https://www.khronos.org/opengl/
- On the geometry shader in particular:
  https://www.khronos.org/opengl/wiki/Geometry_Shader