Computer Graphics

- Programmable Shading in OpenGL -

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History

- **Pre-GPU graphics acceleration**
  - SGI, Evans & Sutherland
  - Introduced concepts like vertex transformation and texture mapping
- **First-generation GPUs (-1998)**
  - NVIDIA TNT2, ATI Rage, Voodoo3
  - Vertex transformation on CPU, limited set of math operations
- **Second-generation GPUs (1999-2000)**
  - GeForce 256, GeForce2, Radeon 7500, Savage3D
  - Transformation & lighting, more configurable, still not programmable
- **Third-generation GPUs (2001)**
  - GeForce3, GeForce4 Ti, Xbox, Radeon 8500
  - Vertex programmability, pixel-level configurability
- **Fourth-generation GPUs (2002)**
  - GeForce FX series, Radeon 9700 and on
  - Vertex-level and pixel-level programmability (limited)
- **Eighth-generation GPUs (2007)**
  - Geometry shaders, feedback, unified shaders, …
- **Ninth-generation GPUs (2009/10)**
  - OpenCL/DirectCompute, hull & tesselation shaders

Graphics Hardware

Gen.	Year	Product	Fab.	Transistors	Antialiasing fill rate	Polygon rate
1st	1998	RIVA TNT	0.25μ	7 M	50 M	6 M
1st	1999	RIVA TNT2	0.22μ	9 M	75 M	9 M
2nd	1999	GeForce 256	0.22μ	23 M	120 M	15 M
3rd	2001	GeForce3	0.15μ	57 M	800 M	30 M
4th	2003	GeForce FX	0.13μ	125 M	2,000 M	200 M
8th	2007	GeForce 8800 (GT100)	0.09μ	681 M	13,800 M	13,800 M
8th	2008	GeForce 280 (GT200)	0.065μ	1,400 M	19,264 M	-/-
9th	2009	GeForce 480 (GF100)	0.040μ	3,000 M	33,600 M	-/-
…		…		…	…	
12th	2016	GeForce GTX 1080 (GP104 / Pascal)	0.016μ	7,200 M	102,800 M	-/-

Shading Languages

- **Small program fragments (plug-ins)**
  - Compute certain aspects of the rendering process
  - Executing at innermost loop, must be extremely efficient
  - Executed at each intersection (in ray tracing) and other events
- **Typical shaders**
  - Material/surface shaders: compute reflected color
  - Light shaders: compute illumination from light at given position
  - Volume shader: compute interaction in a participating medium
  - Displacement shader: compute changes to the geometry
  - Camera shader: compute rays for each pixel
- **Shading languages**
  - RenderMan (the “mother of all shading languages”)
  - GPUs: HLSL (DX only), GLSL (OpenGL only), Cg (NVIDIA only)
  - Currently no portable shading format usable for exchange

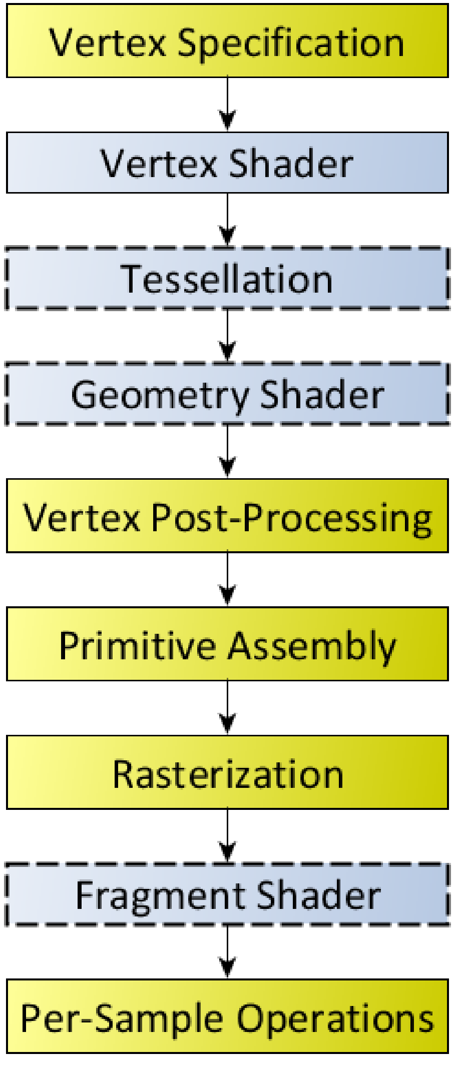
History of Shading Languages

- **Rob Cook: shade trees (1984 @ LucasFilm)**
  - Flexible connection of function blocks
- **Ken Perlin: The Image Synthesizer (1985)**
  - Deep pixels (pixels with more than data)
  - Control structures, noise function
- **Pat Hanrahan: RenderMan (1988 @ Pixar)**
  - Renderman is still the most used shading language
  - Mostly for offline and high quality rendering

- **Realtime shading languages**
  - RTSL (Stanford, lead to Cg)
  - Cg (NVIDIA, cross platform)
  - HLSL (Microsoft, DirectX)
  - GLSL (Khronos, OpenGL)
- **New contenders**
  - OpenSL (Sony, Larry Gritz)
  - Material description languages (MDL from Nvidia, shade.js from SB)

GLSL

- **OpenGL Shading Language**
- **Syntax somewhat similar to C**
- **Supports overloading**
- **Used at different stages of the rendering pipeline**



GLSL: Data Types

- **Three basic data types in GLSL:**
  - float, bool, int – just like in C, uint: unsigned int
  - Allows for constructor syntax (vec3 a = vec3(1.0, 2.0, 3.0))
- **Vectors with 2, 3 or 4 components, declared as:**
  - {, b, i, u}vec{2,3,4}: a vector of 2, 3 or 4 floats, bools, ints, unsigned
- **Matrices**
  - mat2, mat3, mat4: square matrices
  - mat2x2, mat2x3, mat2x4, mat3x2 to mat4x4: explicit size
- **Sampler (texture access)**
  - {, i, u}sampler{1D, 2D, 3D, Cube, 2DRect, 1DArray, 2DArrray, Buffer, 2DMS, 2DMSArray}
    - float, int, unsigned: texture access return type (vec4, ivec4, uvec4)
    - Different types of textures:
      - Array: texture array, MS: multi-sample, buffer: buffer texture
    - Cannot be assigned, set by OpenGL, passed to same type of parameter
- **Structures: as in C**
- **Arrays: full types**

Storage/Interpolation Qualifiers

- **Storage qualifiers**
  - const
    - Compile time constant
  - in, centroid in (read only)
    - Linkage into a shader, pass by value
    - „Centroid“ interpolates at centroids (not sample positions) in fragment shader
  - out, centroid out
    - Linkage out of a shader, pass by value
  - Uniform (read only)
    - Does not change across a primitive, passed by OpenGL
  - inout (only for function parameter)
    - Passed by reference
- **Interpolation qualifiers (for in/out)**
  - flat: no interpolation
  - smooth: perspective correct interpolation
  - nonperspective: linear in screen space

Shader Input & Output

- **Variable names and types of connected shaders must match**
  - No sampler
  - No array (except for vertex shader in)
  - Vertex shaders cannot have structures (but arrays)
  - Geometry shader must have all variables as arrays
    - Receives an entire primitive
    - “in float a[ ]” for an output “out float a” from the vertex shader
  - int and uint must be “flat” for a fragment shader (no interpolation)
  - Fragment shader cannot have matrix or structure output
- **Interface blocks**
  - in/out/uniform InterfaceName { …} instance_name;
  - Groups related variables together
  - InterfaceName is used for name lookup from OpenGL
    - InterfaceName.VariableName
- **Layout qualifiers**
  - Used to specify characteristics of geometry shaders
    - Primitive type of input and output, max number of output primitives, ...

Vertex Shader Input/Output

- **Predefined vertex shader variables**

```
in int gl_VertexID;          // Implicit index of vertex in vertex-array call
in int gl_InstanceID;        // Instance ID passed by instance calls

out gl_PerVertex
{
   vec4  gl_Position;        // Homogeneous position of vertex
   float gl_PointSize;       // Size of point in pixels
   float gl_ClipDistance[];  // Distance from clipping planes > 0 == valid
};
```

Geometry Shader Input/Output

- **Predefined geometry shader variables**

```
in gl_PerVertex
{
   vec4  gl_Position;
   float gl_PointSize;
   float gl_ClipDistance[];
} gl_in[];

in int gl_PrimitiveIDIn; // # of primitives processed so far in input

out gl_PerVertex
{
   vec4  gl_Position;
   float gl_PointSize;
   float gl_ClipDistance[];
};

out int gl_PrimitiveID;
out int gl_Layer;         // Specifies layer of frame buffer to write to
```

Fragment Shader Input/Output

- **Predefined fragment shader variables**

```
in vec4   gl_FragCoord;       // (x, y, z, 1/w) for (sub-)sample
in bool   gl_FrontFacing;     // Primitive is front facing
in float  gl_ClipDistance[];  // Linearly interpolated
in vec2   gl_PointCoord;      // 2D coords within point sprite
in int    gl_PrimitiveID;     // As before

out float gl_FragDepth;       // Computed depth value
```

GLSL Operations

- **Vector component access**
  - {x,y,z,w}, {r,g,b,a} and {s,t,p,q} provide equivalent access to vecs
  - LHS: no repetition, defines type for assignment
  - RHS: arbitrary set, defines result type
  - Example:

```
vec4 pos = vec4(1.0, 2.0, 3.0, 4.0);
vec4 swiz = pos.wzyx;     // swiz = (4.0, 3.0, 2.0, 1.0)
vec4 dup = pos.xxyy;      // dup = (1.0, 1.0, 2.0, 2.0)
pos = vec4(1.0, 2.0, 3.0, 4.0);
pos.xw = vec2(5.0, 6.0);  // pos = (5.0, 2.0, 3.0, 6.0)
pos.wx = vec2(7.0, 8.0);  // pos = (8.0, 2.0, 3.0, 7.0)
```

- **All vector and matrix operations act component wise**
  - Except multiplication involving a matrix:
    - Results in correct vec/mat, mat/vec, mat/mat multiply from LinAlg

Control Flow

- **Usual C/C++ control flow**
- **`discard`**
  - Statement allowed only in fragment shader
  - Fragment is thrown away, does not reach frame buffer

- **Everything is executed on a SIMD processor**
  - Should make sure that control flow is as similar as possible
- **Some texture functions require implicit derivatives**
  - Computed from a 2x2 pixel “quad” through divided differences
  - Require to be in control flow only containing uniform conditions
  - May be inaccurate due to movement within pixel
    - Sample must be within primitive

Functions

- **Example**

```
vec4 toonify(in float intensity)
{
    vec4 color;

    if      (intensity > 0.98) color = vec4(0.8,0.8,0.8,1.0);
    else if (intensity > 0.50) color = vec4(0.4,0.4,0.8,1.0);
    else if (intensity > 0.25) color = vec4(0.2,0.2,0.4,1.0);
    else                       color = vec4(0.1,0.1,0.1,1.0);

    return(color);
}
```

Shader Library

- **Typical math library**
  - sin, cos, pow, min/max,
  - clamp, max, dot, cross, normalize
- **Shader specific**
  - faceforward(N, I, Nref): returns N if dot(Nref, I) < 0, -N otherwise
  - reflect(I, N): reflects I at plane with normalized normal N
  - refract(I, N, eta): refracts at normalized N with refraction index eta
  - smoothstep(begin, end, x): Hermite interpolation between 0 and 1
  - mix(x, y, a): affine interpolation
  - noise1() to noise4(): Perlin-style noise
  - …

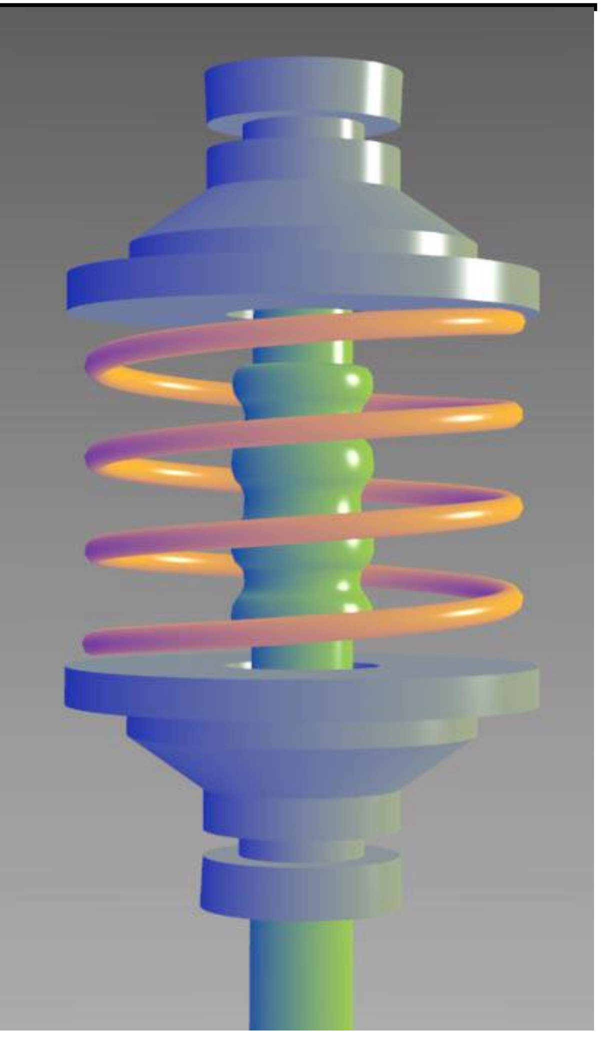
Shader Library: Texturing & Deriv.

- **Huge list of texture functions**
  - Direct and homogeneous projection sampling
  - With and without LOD (MIP-mapping)
  - With and without offset in texture coordinates
  - With and without derivatives in texture space
  - Fetch with integer coords (no interpolation/filtering)
  - Combinations of the above
- **Derivatives**
  - `dFdx(e), dFdy(e)`: derivatives with respect to window coordinates
    - Approximated with divided differences on “quads”: piecewise linear
  - `fwidth(e) = abs(dFdx(e)) + abs(dFdy(e))`
    - Approximate filter width

Ex.: Gooch Cool/Warm Shader

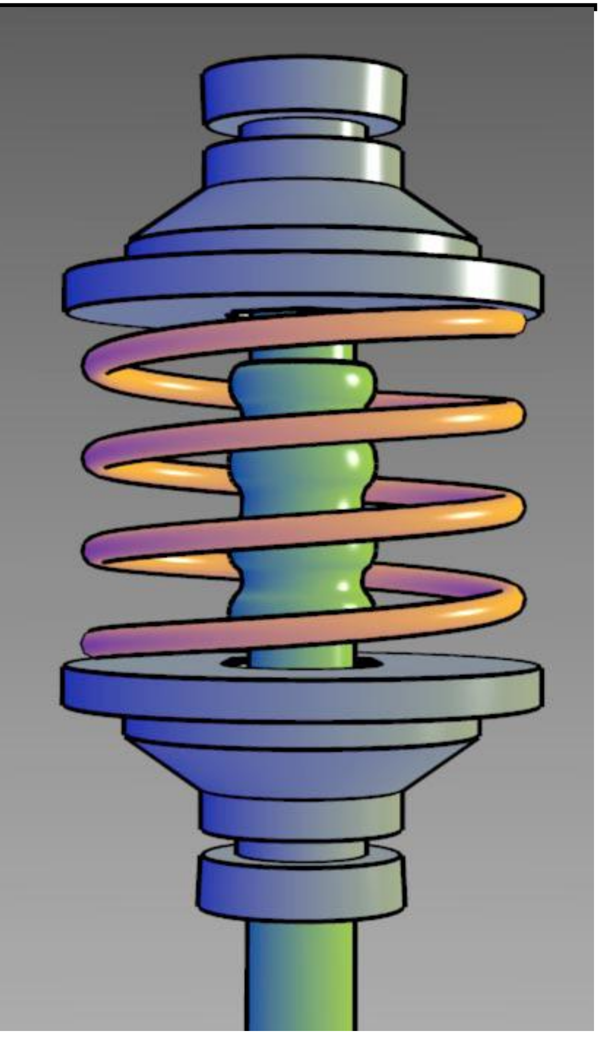
- **Vertex shader**

```
uniform vec4 lightPos;
uniform mat4x4 modelview_mat;
uniform mat4x4 modelviewproj_mat;
uniform mat4x4 normal_mat;

in vec3 P;
in vec3 N;

out vec3 normal;
out vec3 lightVec;
out vec3 viewVec;

void main()
{
   gl_Position = modelviewproj_mat * P;
   vec4 vert = modelview_mat * P;

   normal = normal_mat * N;
   lightVec = vec3(lightPos - vert);
   viewVec = -vec3(vert);
}
```



Ex.: Gooch Cool/Warm Shader

- **Fragment shader**



```
uniform Material
{
    float Ka = 1.0;
    float Kd = 0.8;
    float Ks = 0.9;
    vec3 ambient = vec3(0.2, 0.2, 0.2);
    vec3 spec_col = vec3(1.0, 1.0, 1.0);
    vec3 kCool = vec3(.88, .81, .49);  // Purple
    vec3 kWarm = vec3(.58, .10, .76);  // Orange
} m;

in vec3 normal;
in vec3 lightVec;
in vec3 viewVec;

out vec4 frag_color;

void main()
{
    vec3 norm = normalize(normal);
    vec3 L = normalize(lightVec);
    vec3 V = normalize(viewVec);
    vec3 halfAngle = normalize(L + V);
    float NdotH = clamp(dot(halfAngle, norm), 0.0, 1.0);
    float spec = pow(NdotH, 64.0);
    vec3 Cgooch = mix(mat.kWarm, mat.kCool, 0.5 * dot(L, norm) + 0.5);
    vec3 res = m.Ka * m.ambient + m.Kd * Cgooch + m.spec_col * m.Ks * spec;
    frag_color = vec4(res, 1.0);
}
```

Simple OpenGL Program

- **Discussion of critical pieces of an OpenGL program**
- **Details available at**
  - http://duriansoftware.com/joe/An-intro-to-modern-OpenGL.-Table-of-Contents.html

Simple OpenGL Program

Main program

```
#include <stdlib.h>
#include <GL/glew.h>
#include <GL/glut.h>

int main(int argc, char** argv)
{
    glutInit(&argc, argv);
    glutInitDisplayMode(GLUT_RGB|GLUT_DEPTH|GLUT_DOUBLE);
    glutInitWindowSize(400, 300);
    glutCreateWindow("Hello World");
    glutDisplayFunc(&render);
    glutIdleFunc(&update);

    // Initialize the GL Extension Wrangler Library
    glewInit();
    if (!GLEW_VERSION_2_0) {
        fprintf(stderr, "OpenGL 2.0 not available\n");
        return 1;
    }

    // Initialize data structures

    glutMainLoop();
    return 0;
}
```

Generating the buffers

```
// Called if nothing else to do
static void update (void)
{
    int ms = glutGet(GLUT_ELAPSED_TIME);
    // Do any animation control here

    glutPostRedisplay();
}

// Called if display needs to be rendered
// e.g. due to PostRedisplay() or exposure of window
static void render(void)
{
    // Should ideally just be done once
    glEnable(GL_DEPTH_TEST);
    glEnable(GL_CULL_FACE);
    glClearColor(1.0f, 1.0f, 1.0f, 1.0f);

    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);

    // real rendering code

    glutSwapBuffers();
}
```

Simple OpenGL Program

Vertex Shader

```
#version 110

uniform mat4 p_matrix, mv_matrix;

attribute vec3 position, normal;
attribute vec2 texcoord;
attribute float shininess;
attribute vec4 specular;

varying vec3 frag_position, frag_normal;
varying vec2 frag_texcoord;
varying float frag_shininess;
varying vec4 frag_specular;

void main()
{
    vec4 eye_position = mv_matrix * vec4(position, 1.0);
    gl_Position = p_matrix * eye_position;
    frag_position = eye_position.xyz;
    frag_normal   = (mv_matrix * vec4(normal, 0.0)).xyz;
    frag_texcoord = texcoord;
    frag_shininess = shininess;
    frag_specular = specular;
}
```

Fragment Shader

```
#version 110

uniform mat4 p_matrix, mv_matrix;
uniform sampler2D texture;

varying vec3 frag_position, frag_normal;
varying vec2 frag_texcoord;
varying float frag_shininess;
varying vec4 frag_specular;

const vec3 light_direction = vec3(0.408248, -0.816497, 0.408248);
const vec4 light_diffuse = vec4(0.8, 0.8, 0.8, 0.0);
const vec4 light_ambient = vec4(0.2, 0.2, 0.2, 1.0);
const vec4 light_specular = vec4(1.0, 1.0, 1.0, 1.0);

void main()
{
    vec3 mv_light_direction = (mv_matrix * vec4(light_direction, 0.0)).xyz,
         normal = normalize(frag_normal),
         eye = normalize(frag_position),
         reflection = reflect(mv_light_direction, normal);

    vec4 frag_diffuse = texture2D(texture, frag_texcoord);
    vec4 diffuse_factor
        = max(-dot(normal, mv_light_direction), 0.0) * light_diffuse;
    vec4 ambient_diffuse_factor
        = diffuse_factor + light_ambient;
    vec4 specular_factor
        = max(pow(-dot(reflection, eye), frag_shininess), 0.0)
            * light_specular;

    gl_FragColor = specular_factor * frag_specular
        + ambient_diffuse_factor * frag_diffuse;
}
```

Simple OpenGL Program

Generating shaders

```
static Gluint
make_shader(GLenum type, const char *filename)
{
    GLint length, shader_ok;
    GLchar *source = file_contents(filename, &length);
    GLuint shader;

    if (!source) return 0;
    shader = glCreateShader(type);
    glShaderSource(shader, 1,
                   (const GLchar**)&source, &length);
    free(source);
    glCompileShader(shader);
    glGetShaderiv(shader, GL_COMPILE_STATUS,
                  &shader_ok);
    if (!shader_ok) {
        fprintf(stderr,
           "Failed to compile %s:\n", filename);
        glDeleteShader(shader);
        return 0;
    }
    return shader;
}
```

Generating the shader program

```
static Gluint
make_program(GLuint vertex_shader, GLuint fragment_shader)
{
    GLint program_ok;

    GLuint program = glCreateProgram();
    glAttachShader(program, vertex_shader);
    glAttachShader(program, fragment_shader);
    glLinkProgram(program);

    glGetProgramiv(program, GL_LINK_STATUS, &program_ok);
    if (!program_ok) {
        fprintf(stderr, "Failed to link shader program:\n");
        glDeleteProgram(program);
        return 0;
    }
    return program;
}

// Getting access to the shader variables
uniform.texture= glGetUniformLocation(program, "texture");
attributes.position= glGetAttribLocation(program, "position");
// …
```

Simple OpenGL Program

Defining a texture

```
static Gluint
make_texture(const char *filename)
{
    GLuint texture;
    int width, height;
    void *pixels = read_imagefile(filename, &width, &height);

    if (!pixels) return 0;
    // Create a texture object and make it the current one
    glGenTextures(1, &texture);
    glBindTexture(GL_TEXTURE_2D, texture);

    // Set parameters
    glTexParameteri(GL_TEXTURE_2D,
      GL_TEXTURE_MIN_FILTER, GL_LINEAR);
    glTexParameteri(GL_TEXTURE_2D,
      GL_TEXTURE_MAG_FILTER, GL_LINEAR);
    glTexParameteri(GL_TEXTURE_2D,
      GL_TEXTURE_WRAP_S, GL_CLAMP_TO_EDGE);
    glTexParameteri(GL_TEXTURE_2D,
      GL_TEXTURE_WRAP_T, GL_CLAMP_TO_EDGE);

    // Upload the texture data
    glTexImage2D(
        GL_TEXTURE_2D, 0,   /* target, level of detail */
        GL_RGB8,            /* internal format */
        width, height, 0,   /* width, height, border */
        GL_BGR, GL_UNSIGNED_BYTE, /* external fmt, type */
        pixels                  /* pixel data */
    );
    free(pixels);
    return texture;
}
```

Simple OpenGL Program

Defining the scene data structure

```
struct flag_vertex {
    GLfloat position[4];
    GLfloat normal[4];
    GLfloat texcoord[2];
    GLfloat shininess;
    GLubyte specular[4];
};
```

Generating and filling the buffers

```
struct flag_vertex *vertex_data= (struct flag_vertex*)
        malloc(FLAG_VERTEX_COUNT * sizeof(struct flag_vertex));
GLushort *element_data= (GLushort*)
        malloc(element_count * sizeof(GLushort));

/* Generate the data */
GLuint vertex_buffer, element_buffer;
glGenBuffers(1, &vertex_buffer);
glGenBuffers(1, &element_buffer);

// Filling the buffers
glBindBuffer(GL_ARRAY_BUFFER, vertex_buffer);
glBufferData(GL_ARRAY_BUFFER,
    vertex_count * sizeof(struct flag_vertex),
    vertex_data, GL_STREAM_DRAW);

glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, element_buffer);
glBufferData(GL_ELEMENT_ARRAY_BUFFER,
    element_count * sizeof(GLushort),
    element_data, GL_STATIC_DRAW);
```

Simple OpenGL Program

Actual Rendering

```
static void render(void)
{
    // Beginning of rendering code (glClear)

    // Activate shader and textures from make_* calls
    glUseProgram(program);

    glActiveTexture(GL_TEXTURE0);
    glBindTexture(GL_TEXTURE_2D, texture);
    glUniform1i(uniform.texture, 0);
```

```
 glBindBuffer(GL_ARRAY_BUFFER, vertex_buffer);
 glVertexAttribPointer(attributes.position,
     3, GL_FLOAT, GL_FALSE, sizeof(struct flag_vertex),
     (void*)offsetof(struct flag_vertex, position));
glVertexAttribPointer(attributes.normal,
     3, GL_FLOAT, GL_FALSE, sizeof(struct flag_vertex),
     (void*)offsetof(struct flag_vertex, normal));
glVertexAttribPointer(attributes.texcoord,
     2, GL_FLOAT, GL_FALSE, sizeof(struct flag_vertex),
     (void*)offsetof(struct flag_vertex, texcoord));
glVertexAttribPointer(attributes.shininess,
     1, GL_FLOAT, GL_FALSE, sizeof(struct flag_vertex),
     (void*)offsetof(struct flag_vertex, shininess));
glVertexAttribPointer(attributes.specular,
     4, GL_UNSIGNED_BYTE, GL_TRUE, sizeof(struct flag_vertex),
     (void*)offsetof(struct flag_vertex, specular));

glBindBuffer(GL_ELEMENT_ARRAY_BUFFER, element_buffer);
glDrawElements(GL_TRIANGLES, element_count,
     GL_UNSIGNED_SHORT, (void*)0);
```

Demomaking

- **This is the art of creating "demos"**
- **A demo is a "non-interactive multimedia presentation"**
- **Written with DirectX, OpenGL most of the time**
- **Size restrictions (4K, 1K, 256bytes, 64bytes, 32bytes)**
  - **Intense use of procedural generation**

- Revision is the world's biggest pure Demoscene event with visitors from more than 30 countries!
- Revision 2019, April 19th to 22nd,
  Saarbrücken, Germany

Ray-marching in GLSL

- **Technique used in demos**
- **Renders objects defined by distance fields**

```
float sphere(vec3 x, vec3 center, float radius) {
   return distance(x, center) - radius;
}

float box(vec3 x, vec3 center, vec3 half_extents) {
    vec3 d = abs(x - center) - half_extents;
    return max(d.x, max(d.y, d.z));
}

float eval(vec3 x) {
     return sphere(x, vec3(0, 0, 0), 1.0);
}
```

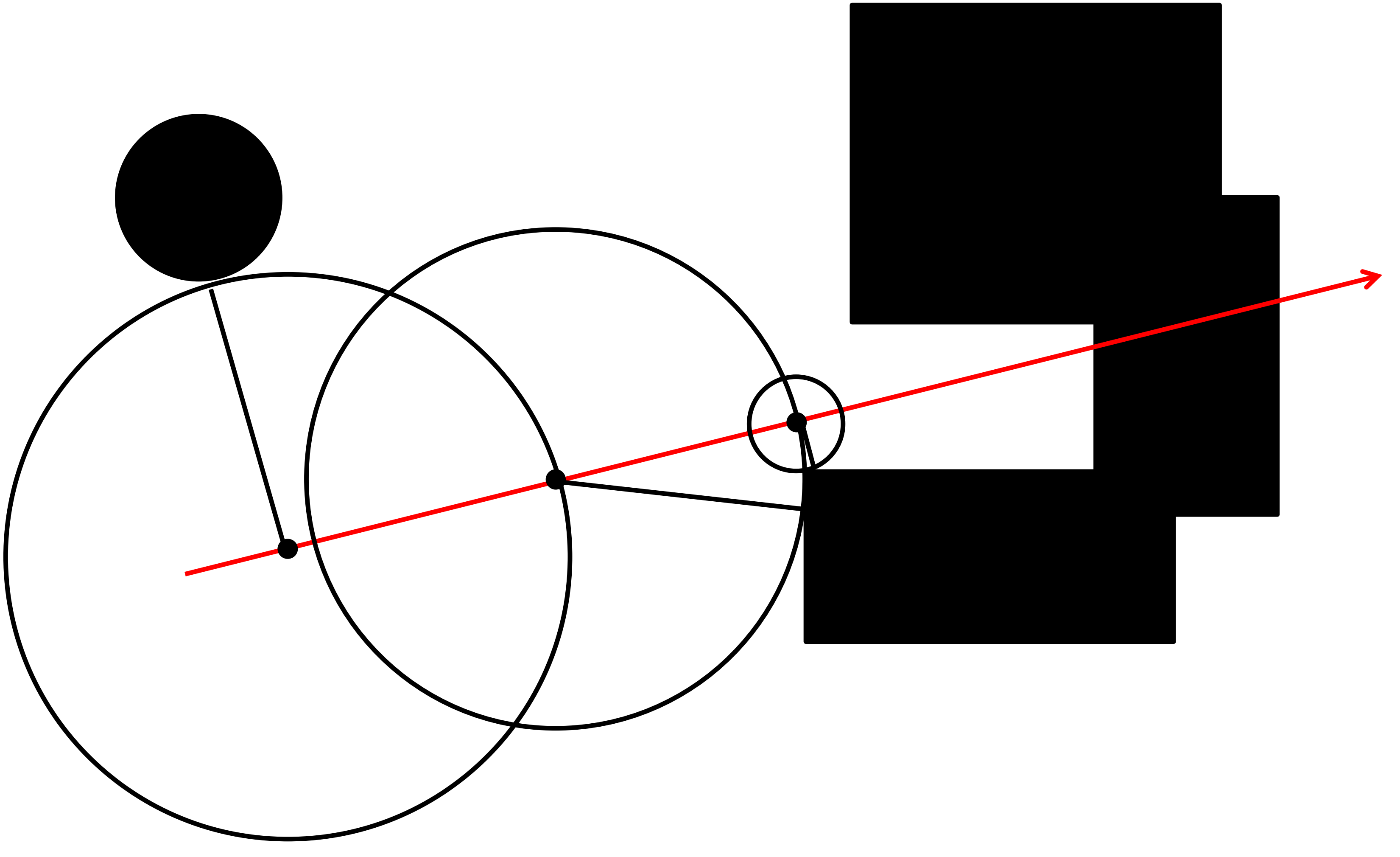
Ray-marching in GLSL

- **Naive ray-marching: constant step**

```
void mainImage(out vec4 fragColor, in vec2 fragCoord) {
    vec2 uv = fragCoord.xy / iResolution.xy - vec2(0.5);
    uv.y *= iResolution.y / iResolution.x; // Maintain image ratio

    vec3 eye = vec3(0, 0, -10);                    // Camera position
    vec3 dir = normalize(vec3(0, 0, 1) + vec3(uv, 0));      // Ray direction
    float inc = 0.1;

    vec4 color = vec4(0);

    const int max_steps = 100;
    vec3 p = eye;
    for (int i = 0; i < max_steps; i++) {
        float d = eval(p);
        if (d <= 0.0) {
            color = vec4(1);
            break;
        }
        p += inc * dir;
    }

    fragColor = color;
}
```

Raymarching in GLSL

- **Ray-marching with adaptive step**



Raymarching in GLSL

- **Ray-marching with adaptive step**

```
void mainImage(out vec4 fragColor, in vec2 fragCoord) {
    vec2 uv = fragCoord.xy / iResolution.xy - vec2(0.5);
    uv.y *= iResolution.y / iResolution.x; // Maintain image ratio

    vec3 eye = vec3(0, 0, -10);                    // Camera position
    vec3 dir = normalize(vec3(0, 0, 1) + vec3(uv, 0));      // Ray direction

    vec4 color = vec4(0);

    const int max_steps = 64;
    vec3 p = eye;
    for (int i = 0; i < max_steps; i++) {
        float d = eval(p);
        if (d <= 0.0) {
            color = vec4(1);
            break;
        }
        p += d * dir;
    }

    fragColor = color;
}
```

Distance field and visibility

- **Visibility by tracing additional rays**

- **"Fake" visibility**
  - **Take *n* points between the light and surface**
  - **Compute the corresponding distances**
  - **Blend distances with magic formula**

- **Ambient occlusion**
  - **Made cheap by evaluating *n* points close to the surface along the normal**
  - **Further away surfaces occlude less: weight decreasing with distance**

Distance fields and CSG

- **How to perform CSG operations?**
  - **Idea: use min, max**

- **Instancing possible by repeating the domain**
  - **Idea: use mod**

- **For more fun, see http://iquilezles.org/www/material/nvscene2008/nvscene2008.htm**

- **For your experiments: http://www.shadertoy.com**

- **For some inspiration: http://www.pouet.net**