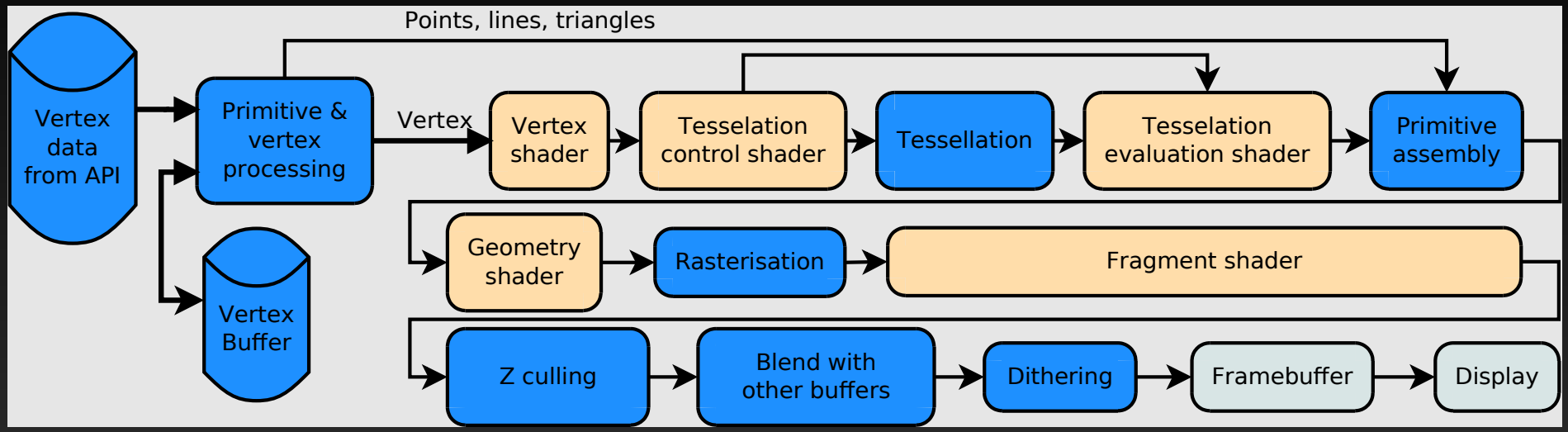
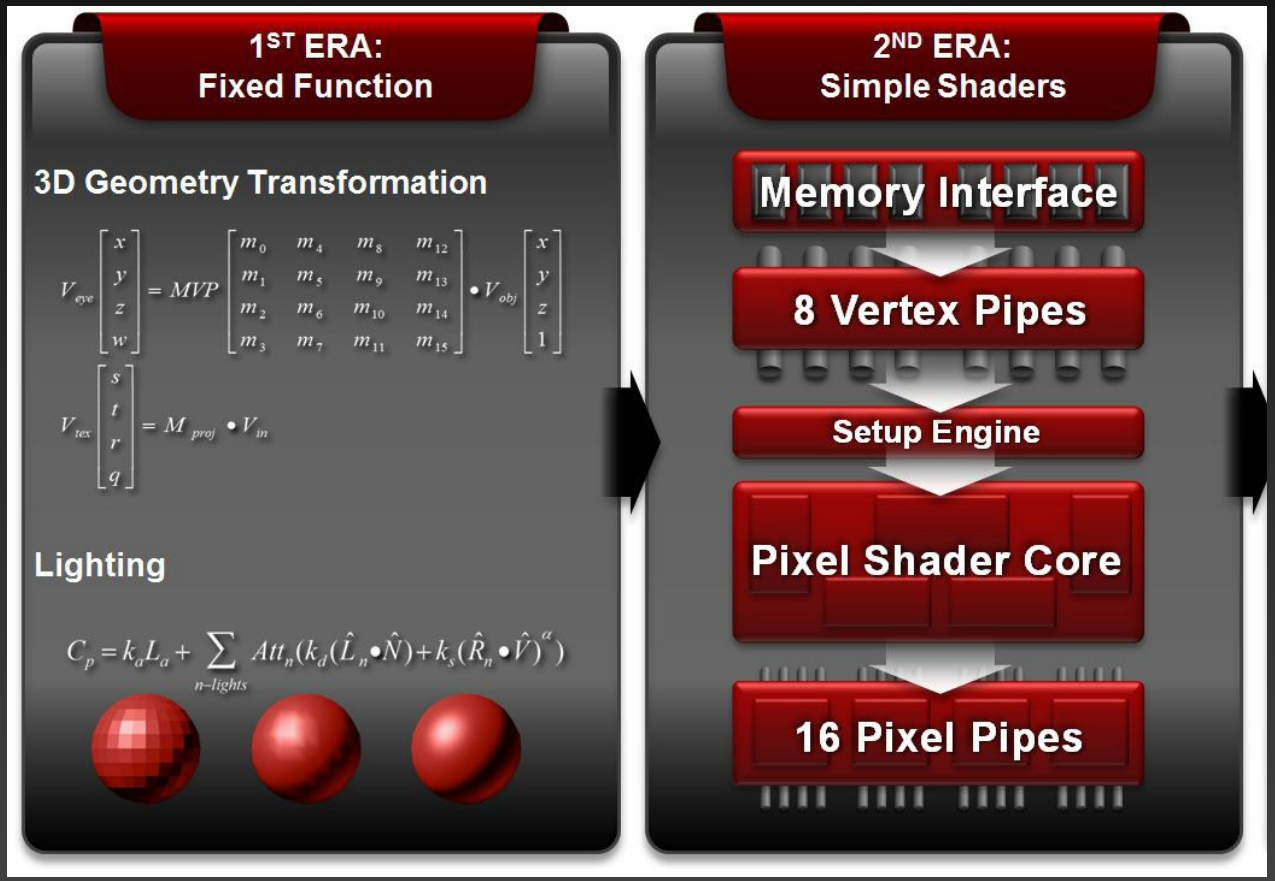
Shaders

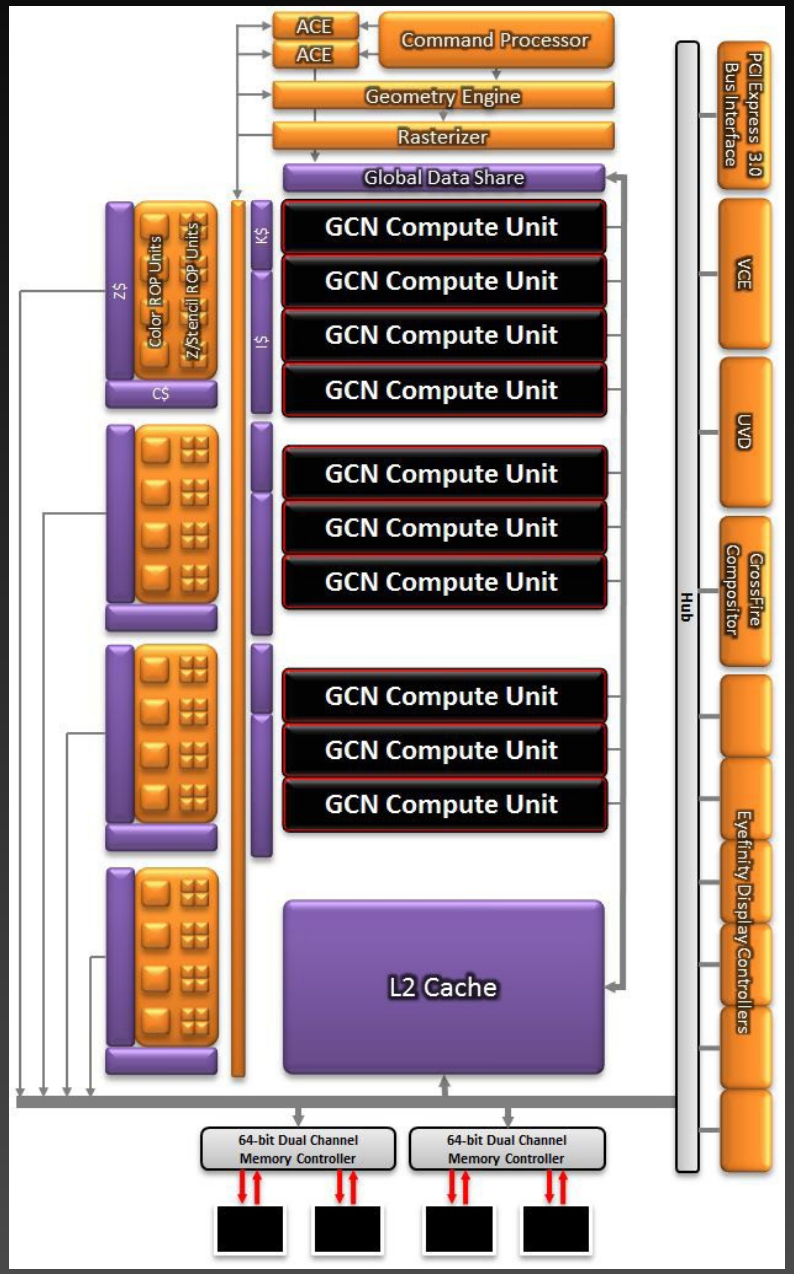
Programmable pipeline



- Programmable and fixed pipeline can NOT be combined at one moment!
- Shader = small program, executed directly on GPU for each vertex (fragment)
- Usually cooperation of at least two programs
  - vertex shader and fragment shader

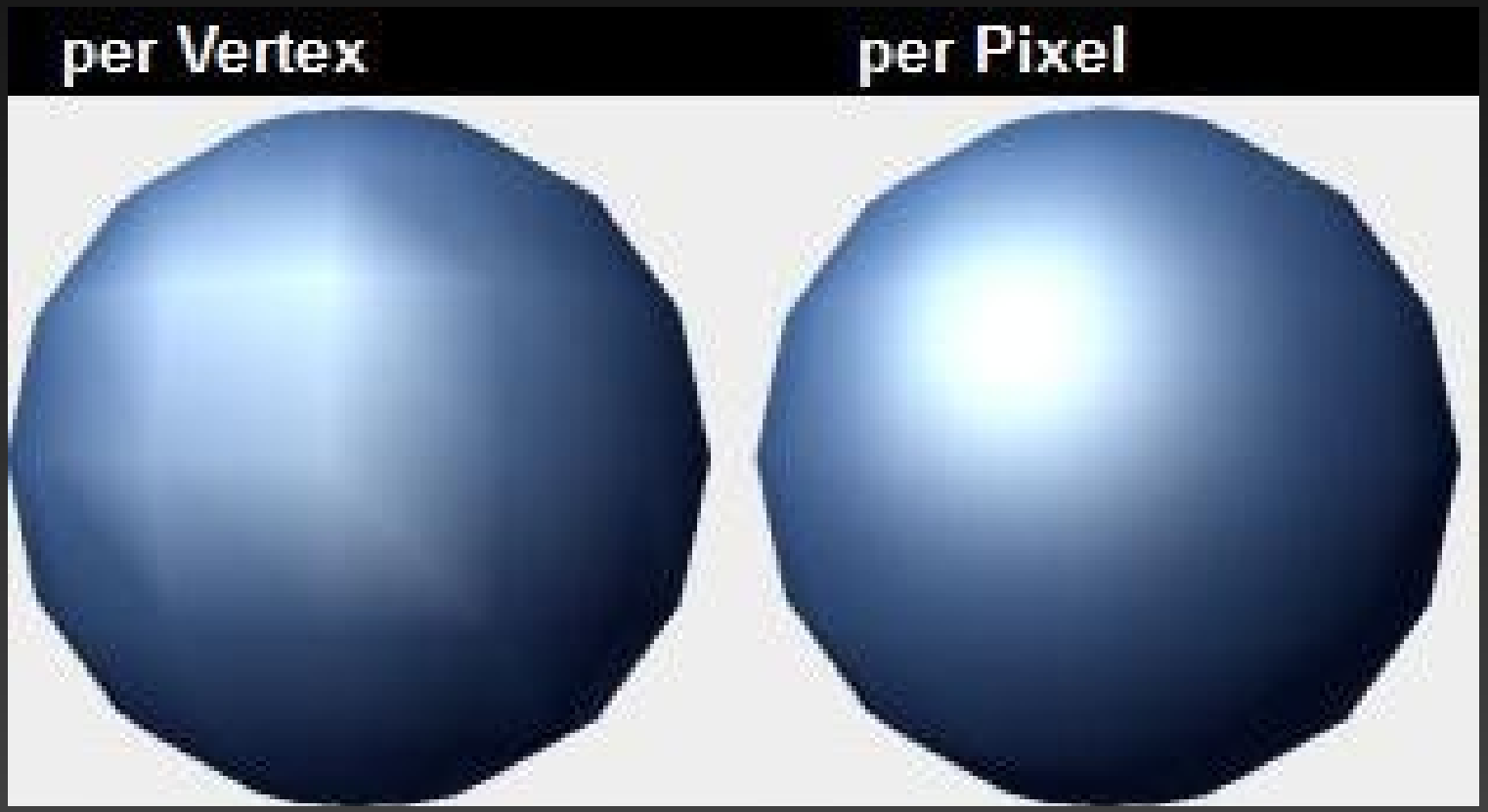
Evolution of hardware





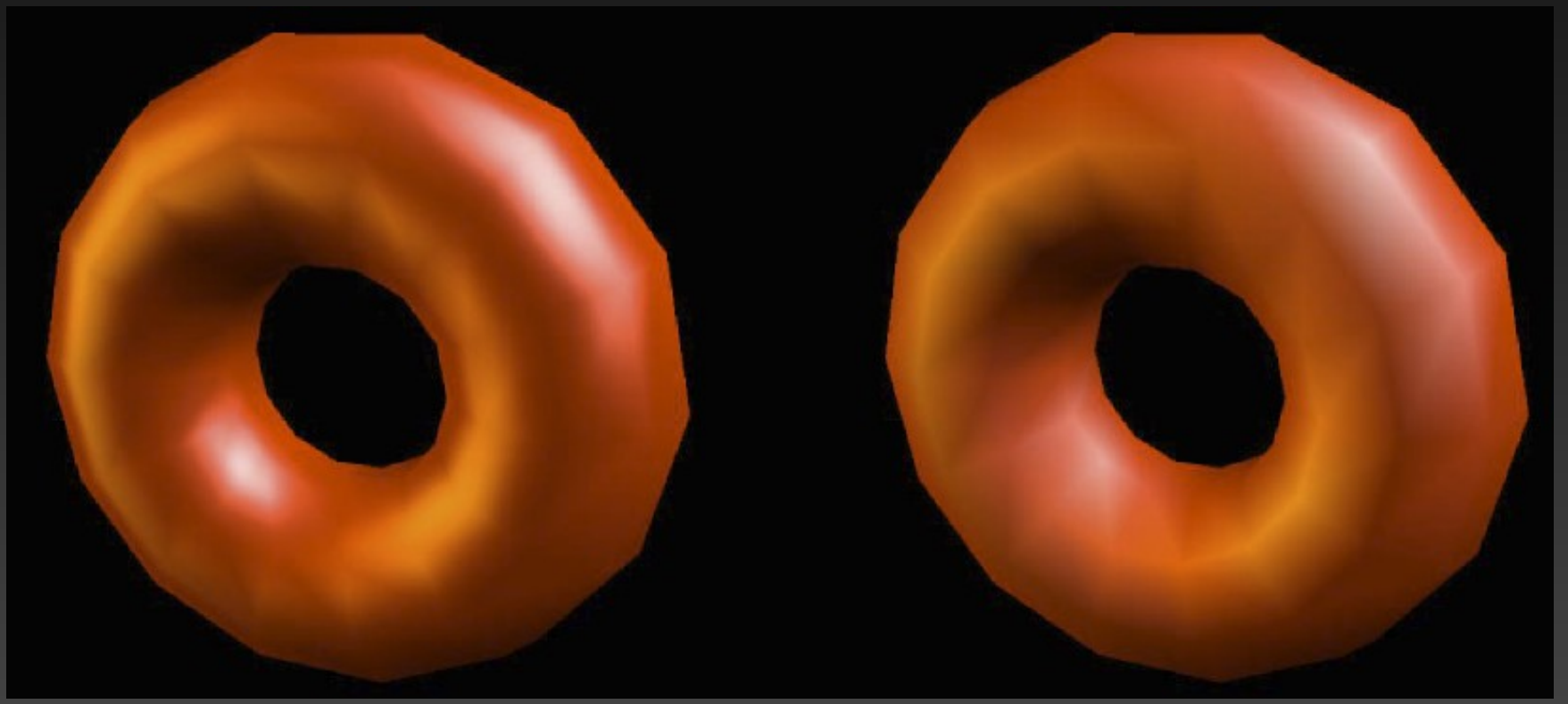
Example

- Gouraud vs. Per-fragment



Example

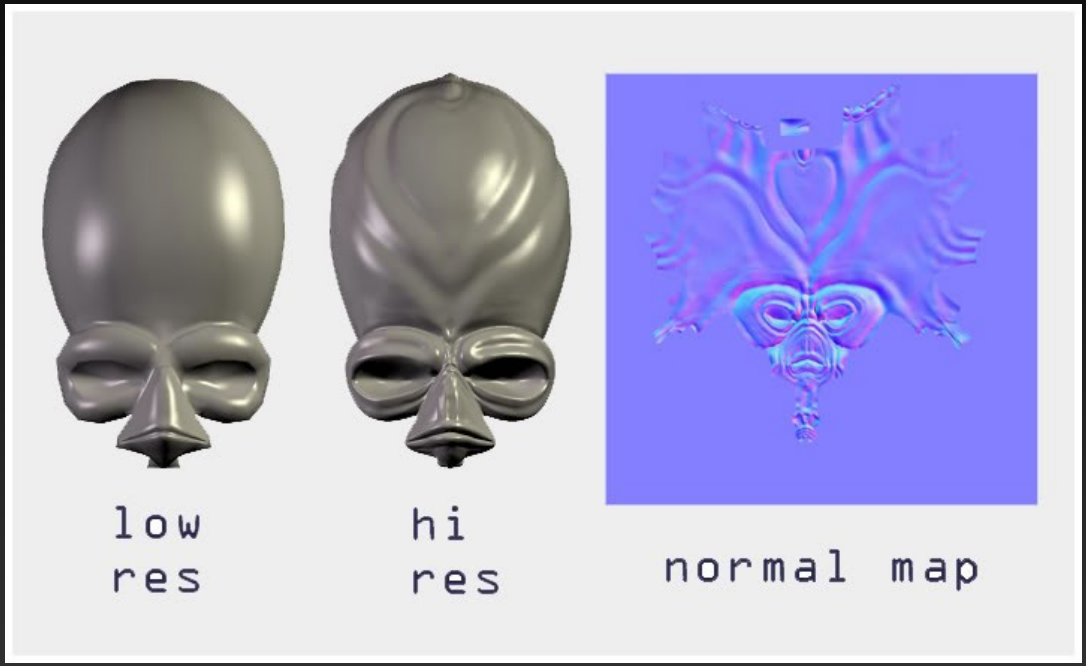
- Per-fragment vs. Gouraud

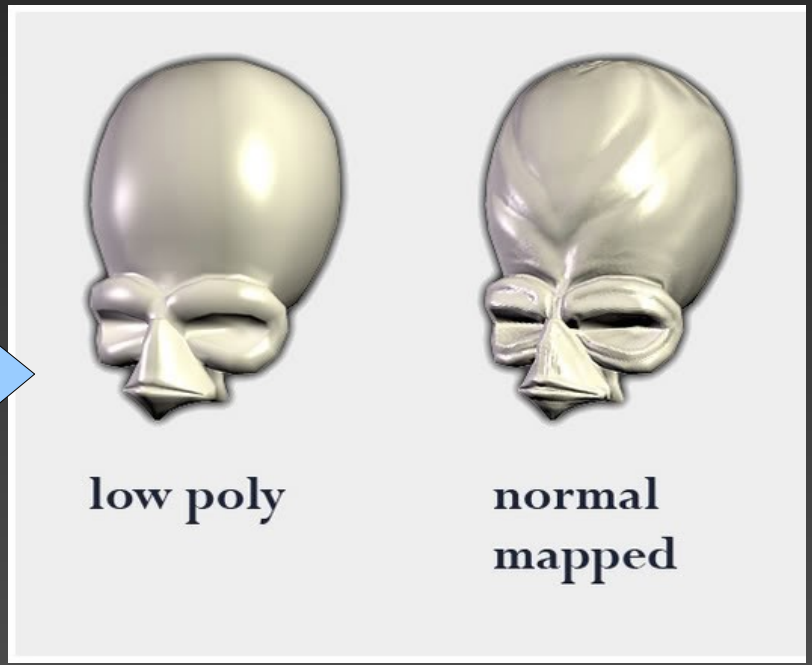


Example

- Bump maps and normal normálové maps
  - Use additional texture as per-fragment definition of normals for definition of fake geometry details

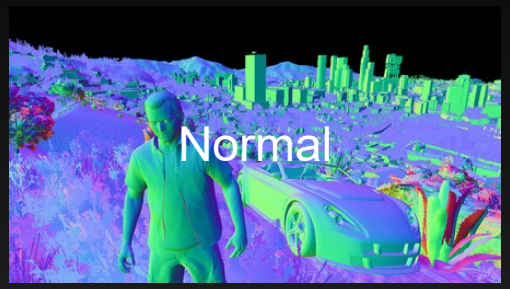
Example

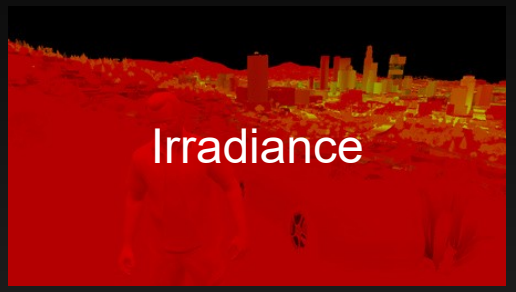




GTA-V


Diffuse


Normal

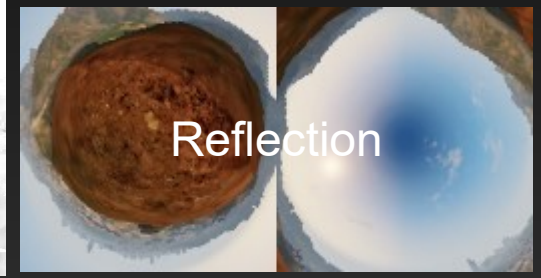

Irradiance


Specular + Shadow

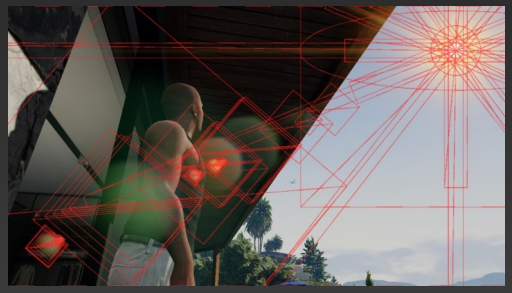

Depth

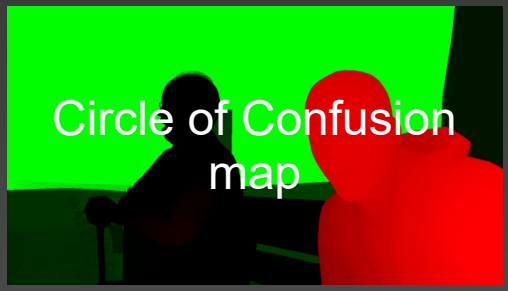

Stencil


SSAO


Reflection


Cube
128x128




Circle of Confusion
map

Why shaders?


GDC
Optimizing the Graphics Pipeline with Compute
Graham Wihlidal
Sr. Rendering Engineer, Frostbite
GAME DEVELOPERS CONFERENCE March 14–18, 2016 · Expo: March 16–18, 2016 #GDC16


FROSTBITE™3

Why shaders?


/ clock
/ clock
/ clock


12 CU * 64 ALU * 2 FLOPs
1,536 ALU ops / cy
18 CU * 64 ALU * 2 FLOPs
2,304 ALU ops / cy
64 CU * 64 ALU * 2 FLOPs
8,192 ALU ops / cy


1,536 ALU ops / 2 engines
768 ALU ops per triangle
2,304 ALU ops / 2 engines
1,017 ALU ops per triangle
8,192 ALU ops / 4 engines
2,048 ALU ops per triangle


768 ALU ops / 2 ALU per cy
= 384 instruction limit
1,017 ALU ops / 2 ALU per cy
= 508 instruction limit
2,048 ALU ops / 2 ALU per cy
= 1024 instruction limit

Why shaders?

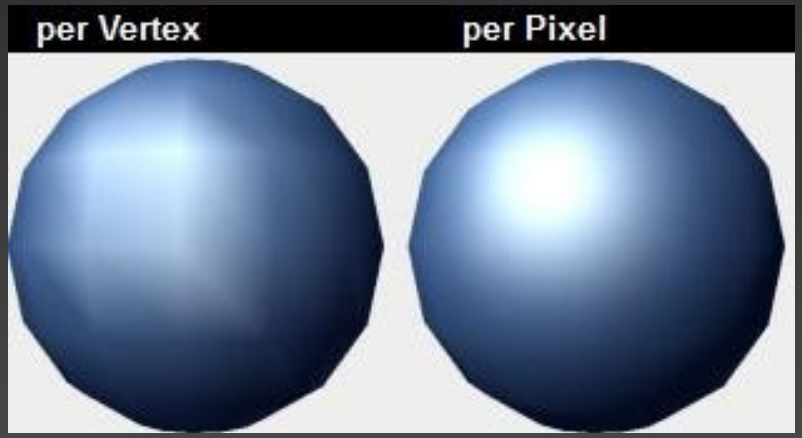
- Used mostly for lighting and shading
- Lighting – compute intensity and color in point of scene, as viewed by user
  - function of scene geometry (model, lights, camera and their positions) and material properties
  - per vertex/fragment = vertex or fragment shader
- Shading – process of interpolation of color and intensity between point, where exact lighting has been computed
  - mostly in real-time graphics (trade-off between quality and speed)
  - per fragment = fragment shader

Vertex shading (fixed pipeline default)

- few vertices, lots of fragments – almost every triangle is larger than single fragment
  - compute light only for vertex → save computations
- compute lighting in vertex, interpolate for fragments
  - Gouraud – linear interpolation
  - flat – constant fill

Fragment shading

- compute lighting in every fragment – per-pixel lighting
  - Phong shading
    - more precise, time consuming, better reflections
- Gouraud – for same quality would be necessary to increase polygon count → tesselation, …

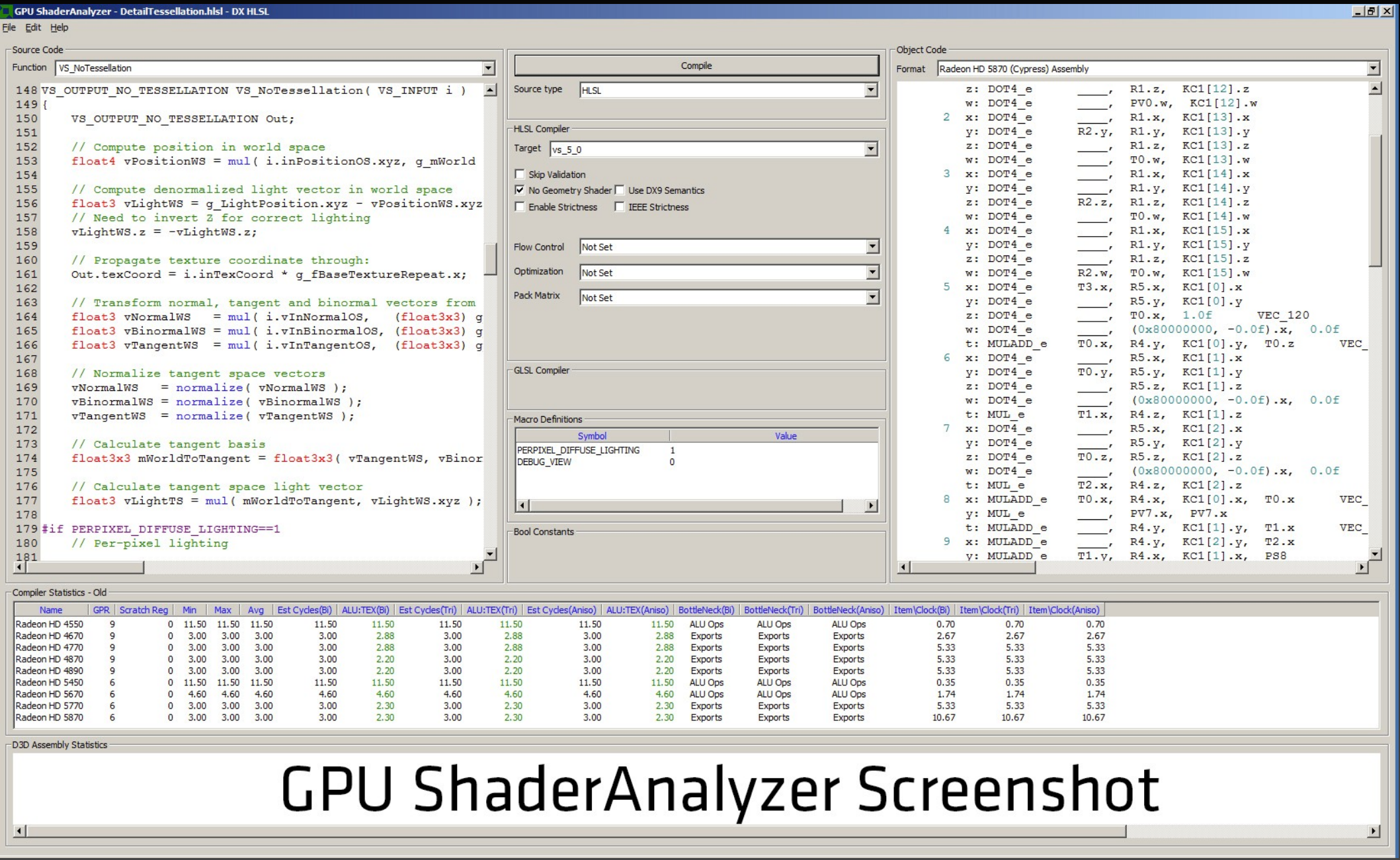


Literature

- OpenGL Programming Guide
  - Ninth edition
- OpenGL Superbible
  - Seventh edition
- www.shadertoy.com
  - online WebGL shader development

Shader language

- 4 possibilities
  - assembler of target device
    - almost unusable and unused
  - HLSL (High Level Shading Language)
    - Microsoft Direct3D 8+ (r. 2000)
  - GLSL (OpenGL Shading Language)
    - part of OpenGL since version 1.5 (r. 2003)
    - part of OpenGL ES since version 1.0 (r. 2003)
  - Cg (C for graphics)
    - Nvidia + Microsoft
  - RSL (Renderman Shading Language)
  - …


GPU ShaderAnalyzer - DetailTessellation.hlsl - DX HLSL
File Edit Help
Source Code
Function VS_NoTessellation
148 VS_OUTPUT_NO_TESSELLATION VS_NoTessellation(VS_INPUT i)
149 {
150 VS_OUTPUT_NO_TESSELLATION Out;
151
152 // Compute position in world space
153 float4 vPositionWS = mul(i.inPositionOS.xyz, g_mWorld
154
155 // Compute denormalized light vector in world space
156 float3 vLightWS = g_LightPosition.xyz - vPositionWS.xyz
157 // Need to invert Z for correct lighting
158 vLightWS.z = -vLightWS.z;
159
160 // Propagate texture coordinate through:
161 Out.texCoord = i.inTexCoord * g_fBaseTextureRepeat.x;
162
163 // Transform normal, tangent and binormal vectors from
164 float3 vNormalWS = mul(i.vInNormalOS, (float3x3) g
165 float3 vBinormalWS = mul(i.vInBinormalOS, (float3x3) g
166 float3 vTangentWS = mul(i.vInTangentOS, (float3x3) g
167
168 // Normalize tangent space vectors
169 vNormalWS = normalize(vNormalWS);
170 vBinormalWS = normalize(vBinormalWS);
171 vTangentWS = normalize(vTangentWS);
172
173 // Calculate tangent basis
174 float3x3 mWorldToTangent = float3x3(vTangentWS, vBinor
175
176 // Calculate tangent space light vector
177 float3 vLightTS = mul(mWorldToTangent, vLightWS.xyz);
178
179 #if PERPIXEL_DIFFUSE_LIGHTING==1
180 // Per-pixel lighting
181
Compile
Source type HLSL
HLSL Compiler
Target vs_5_0
Skip Validation
No Geometry Shader
Use DX9 Semantics
Enable Strictness
IEEE Strictness
Flow Control Not Set
Optimization Not Set
Pack Matrix Not Set
GLSL Compiler
Macro Definitions
Symbol Value
PERPIXEL_DIFFUSE_LIGHTING 1
DEBUG_VIEW 0
Bool Constants
Object Code
Format Radeon HD 5870 (Cypress) Assembly
z: DOT4_e ____, R1.z, KC1[12].z
w: DOT4_e ____, PV0.w, KC1[12].w
2 x: DOT4_e ____, R1.x, KC1[13].x
y: DOT4_e R2.y, R1.y, KC1[13].y
z: DOT4_e ____, R1.z, KC1[13].z
w: DOT4_e ____, T0.w, KC1[13].w
3 x: DOT4_e ____, R1.x, KC1[14].x
y: DOT4_e ____, R1.y, KC1[14].y
z: DOT4_e R2.z, R1.z, KC1[14].z
w: DOT4_e ____, T0.w, KC1[14].w
4 x: DOT4_e ____, R1.x, KC1[15].x
y: DOT4_e ____, R1.y, KC1[15].y
z: DOT4_e ____, R1.z, KC1[15].z
w: DOT4_e R2.w, T0.w, KC1[15].w
5 x: DOT4_e T3.x, R5.x, KC1[0].x
y: DOT4_e ____, R5.y, KC1[0].y
z: DOT4_e ____, T0.x, 1.0f VEC_120
w: DOT4_e ____, (0x80000000, -0.0f).x, 0.0f
t: MULADD_e T0.x, R4.y, KC1[0].y, T0.z VEC_
6 x: DOT4_e ____, R5.x, KC1[1].x
y: DOT4_e T0.y, R5.y, KC1[1].y
z: DOT4_e ____, R5.z, KC1[1].z
w: DOT4_e ____, (0x80000000, -0.0f).x, 0.0f
t: MUL_e T1.x, R4.z, KC1[1].z
7 x: DOT4_e ____, R5.x, KC1[2].x
y: DOT4_e ____, R5.y, KC1[2].y
z: DOT4_e T0.z, R5.z, KC1[2].z
w: DOT4_e ____, (0x80000000, -0.0f).x, 0.0f
t: MUL_e T2.x, R4.z, KC1[2].z
8 x: MULADD_e T0.x, R4.x, KC1[0].x, T0.x VEC_
y: MUL_e ____, PV7.x, PV7.x
t: MULADD_e ____, R4.y, KC1[1].y, T1.x VEC_
9 x: MULADD_e ____, R4.y, KC1[2].y, T2.x
y: MULADD_e T1.y, R4.x, KC1[1].x, PS8
Compiler Statistics - Old
Name GPR Scratch Reg Min Max Avg Est Cycles(Bi) ALU:TEX(Bi) Est Cycles(Tri) ALU:TEX(Tri) Est Cycles(Aniso) ALU:TEX(Aniso) BottleNeck(Bi) BottleNeck(Tri) BottleNeck(Aniso) Item\Clock(Bi) Item\Clock(Tri) Item\Clock(Aniso)
Radeon HD 4550 9 0 11.50 11.50 11.50 11.50 11.50 11.50 11.50 11.50 11.50 ALU Ops ALU Ops ALU Ops 0.70 0.70 0.70
Radeon HD 4670 9 0 3.00 3.00 3.00 3.00 2.88 3.00 2.88 3.00 2.88 Exports Exports Exports 2.67 2.67 2.67
Radeon HD 4770 9 0 3.00 3.00 3.00 3.00 2.88 3.00 2.88 3.00 2.88 Exports Exports Exports 5.33 5.33 5.33
Radeon HD 4870 9 0 3.00 3.00 3.00 3.00 2.20 3.00 2.20 3.00 2.20 Exports Exports Exports 5.33 5.33 5.33
Radeon HD 4890 9 0 3.00 3.00 3.00 3.00 2.20 3.00 2.20 3.00 2.20 Exports Exports Exports 5.33 5.33 5.33
Radeon HD 5450 6 0 11.50 11.50 11.50 11.50 11.50 11.50 11.50 11.50 11.50 ALU Ops ALU Ops ALU Ops 0.35 0.35 0.35
Radeon HD 5670 6 0 4.60 4.60 4.60 4.60 4.60 4.60 4.60 4.60 4.60 ALU Ops ALU Ops ALU Ops 1.74 1.74 1.74
Radeon HD 5770 6 0 3.00 3.00 3.00 3.00 2.30 3.00 2.30 3.00 2.30 Exports Exports Exports 5.33 5.33 5.33
Radeon HD 5870 6 0 3.00 3.00 3.00 3.00 2.30 3.00 2.30 3.00 2.30 Exports Exports Exports 10.67 10.67 10.67
D3D Assembly Statistics
GPU ShaderAnalyzer Screenshot

GLSL – OpenGL Shading Language

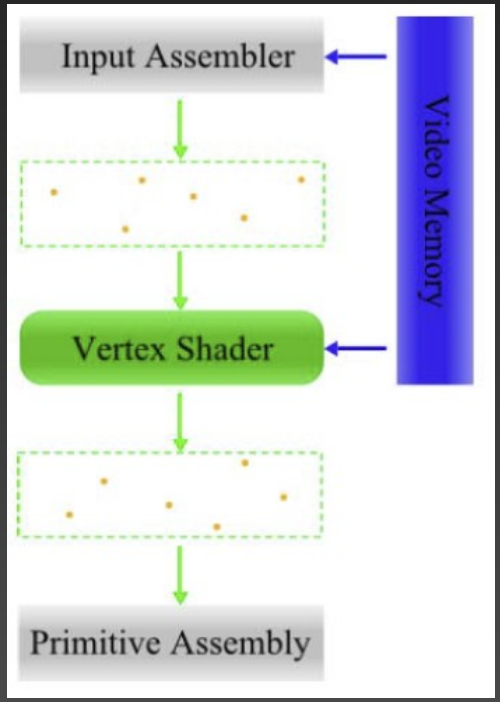
- Similar to C, same syntax, commands ...
  - void main(void) { … }
- … but more restrictions
  - parameters passed only by value, function returns direct value, non-existent pointers (automatic memory management by GPU drivers)
  - strong typing, no automatic conversion (float x int etc.)
- Default internal variables for input and output
  - starting with gl_
- Data types for matrices and vectors
  - and operations with them: item order, dot(), normalize(), length(), distance(), clamp(), sin(), cos(), pow(),…

Shader types

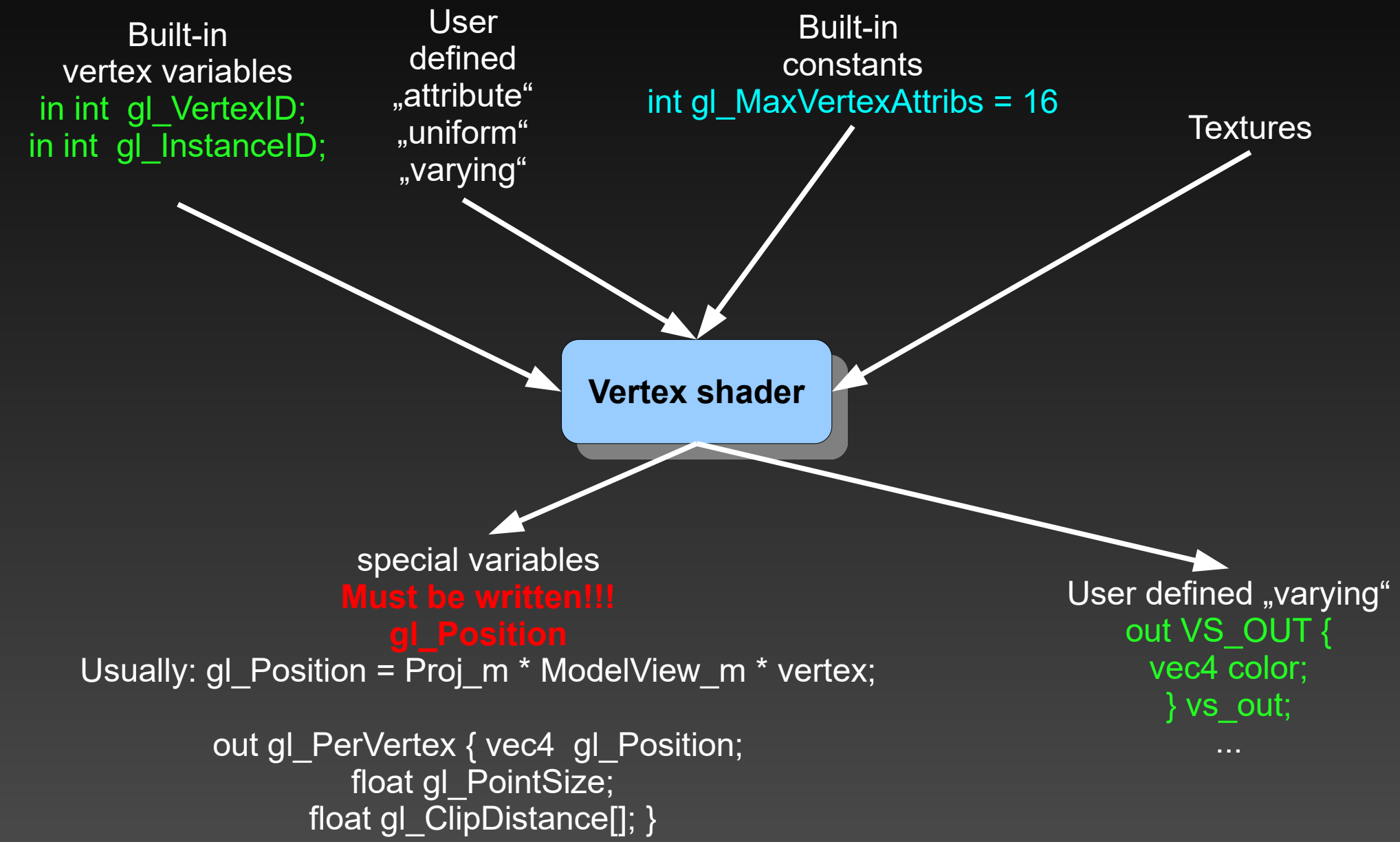
- Most common
  - Vertex shader
    - manipulation with single vertex
  - Fragment shader
    - fragment coloring
- Less common
  - Geometry shader
    - can create/drop vertices and primitives
- Least common
  - Tesseleation control shader
  - Tesselation evaluation shader
  - Compute shader

Vertex shader

- Replace fixed vertex processor functions
- Usually does (can)
  - transformations of vertex, normals, texture coordinates
  - create texture coordinates
  - compute lighting in vertex
  - set values for interpolation in next stage (fragment shader)
- Can NOT know anything about:
  - graphic primitives (!!!)
  - perspective, viewport
  - clipping planes



Vertex shader



Vertex shader

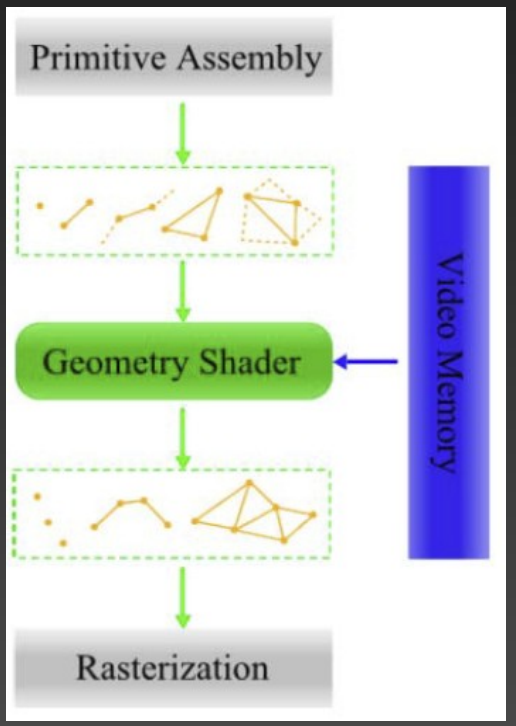
```
// Smallest VS
#version 430 core
in vec4 position, color;
out VS_OUT
{
    vec4 color;

} vs_out;

uniform mat4 mv_m,projection_m;
// VS main func
void main( void ) {
    // pass color
    vs_out.color = color;
    // transform and pass vertex position
    gl_Position = projection_m * mv_m * position;
}
```

Geometry shader

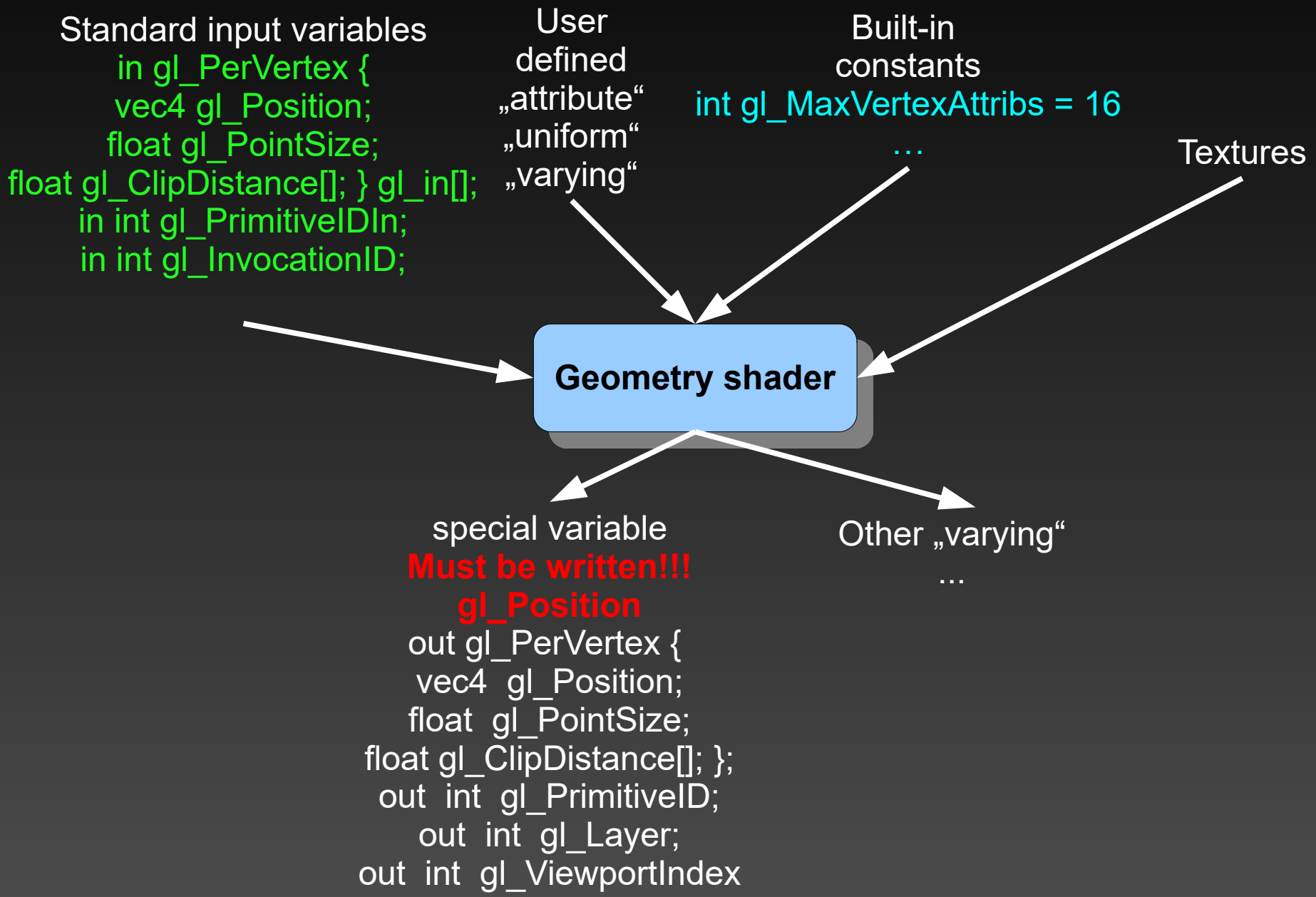
- Input is single complete graphic primitive
  - output is 0 or more primitives
- Can create new vertices and primitives
  - EmitVertex(), EmitStreamVertex()
  - EndPrimitive(), EndStreamPrimitive()



Geometry shader

- Used optionally (in contrast to VS and FS)
  - GL_ARB_geometry_shader4
    - since version 3.2, otherwise EXT
- Geometry instancing
  - Multiplying geometry on different places in scene
    - grass, leaves, trees, rocks, …
      (few types, many instances)
  - Output only: points, line-strip, triangle-strip
    - Must be same or simpler primitive as input primitive

Geometry shader

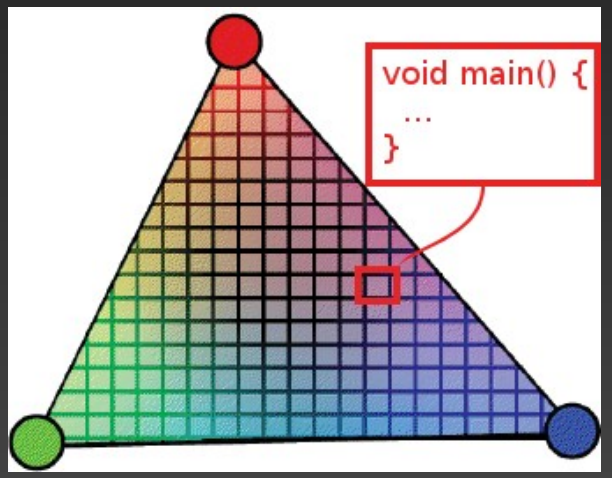


Geometry shader

```
// Smallest GS – pass through for triangles
#version 430 core
layout (triangles) in;
layout (triangle_strip) out;
layout (max_vertices = 3) out;
// GS main func
void main( void ) {
    // Iterate over all vertices of input primitive
    for ( int i = 0; i < gl_in.length(); ++i ) {
        //Pass position
        gl_Position = gl_in[i].gl_Position;
        //Pass vertex
        gl_EmitVertex();
    }
    //Primitive done
    EndPrimitive();
}
```

Fragment shader (dx3d = pixel shader)

- Replace fixed functionality of fragment processor
- Usualy does (can)
  - set fragment color – can use automatically interpolated data from vertex shader
  - fetch color form texture, multitexturing, bump maps, …
  - compute fog and similar
  - procedural draw
- Can not
  - change fragment coordinates [x, y] (can change z)
  - write to textures
  - infuence stencil, alpha, Z test, dithering, ...



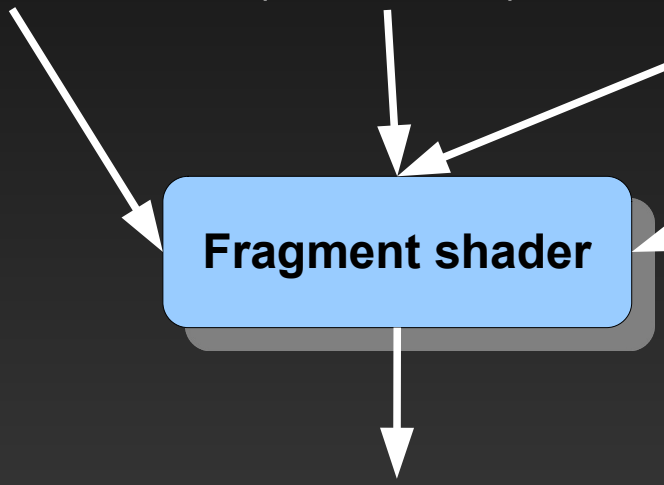
Fragment shader

Standard input variables
in vec4 gl_FragCoord;
in bool gl_FrontFacing;
in float gl_ClipDistance[];
in vec2 gl_PointCoord;
in int gl_PrimitiveID;
in int gl_SampleID;
in vec2 gl_SamplePosition;
in int gl_SampleMask[];
in int gl_Layer;
in int gl_ViewportIndex

User
defined
„uniform“
„varying“
(už ne attrib)

Built-in
constants
int gl_MaxVertexAttribs = 16
…

Textures



out vec4 my_out_color
special variables
out float gl_FragDepth;
out int gl_SampleMask[];
can call
discard;

Fragment shader

```
// Smallest FS
#version 430 core
out vec4 color;
in VS_OUT {
    vec4 color;
} fs_in;
// FS main func
void main( void ) {
    //Pass color – color is „varying“, i.e. it is already
interpolated between values in vertices
    color = fs_in.color;
}
```

Shader HOWTO

1) Create shader

   Allocate handle for each shader.

2) Specify shader

   Pass shader source code as a string.

3) Compile shader

   Driver really does compilation, checking syntax etc. Result is a binary object, that must be linked into a program. DO check compilation return code and compiler log!

4) Create program object

   Compiled shaders will be linked into that.

5) Attach shaders to the program object

   Attach already compiled binary shader objects using handles.

6) Link all compiled shaders to the final program

   That means, that you can use single compiled shader in many different programs = shared libraries. DO check linker return code and linker log!!

7) Enable linked program

   Since now the program will be used.

Shader HOWTO

0) GLuint VS_h, FS_h, prog_h;

1) VS_h = glCreateShader(GL_VERTEX_SHADER);
   FS_h = glCreateShader(GL_FRAGMENT_SHADER);

2) glShaderSource(VS_h, 1, &VS_string, NULL);
   glShaderSource(FS_h, 1, &FS_string, NULL);

3) glCompileShader(VS_h);
   glCompileShader(FS_h);

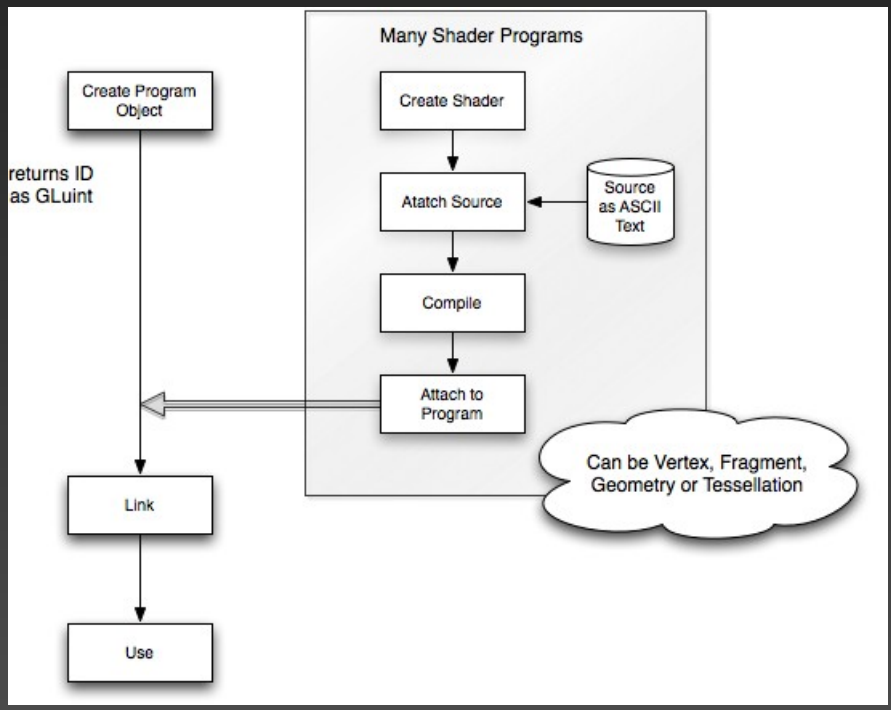
4) prog_h = glCreateProgram();

5) glAttachShader(prog_h, VS_h);
   glAttachShader(prog_h, FS_h);

6) glLinkProgram(prog_h);

7) glUseProgram(prog_h);

8) (glDeleteShader(), glDeleteProgram())



Shader details

Data types

- Simple
  - void, float, double int, uint, bool – limits and bit precision NOT specified!
- Compound
  - fp: vec2, vec3, vec4, mat2, mat3, mat4, dvec{2..4}, dmat{2..4}, mat2x3, mat3x2, …
  - int: ivec2, ivec3, ivec4, uvec{2..4}
  - bool: bvec2, bvec3, bvec4
  - arrays (one-dimensional), structures
- Samplers
  - for accessing textures
  - sampler{1D..3D}, image{1D..3D}, sampler2Drect, samplerCube, samplerBuffer, …
- Variable declaration as in C++
  - not only at the beginning of code block

Variable initialization

float f = 10;

- error – STRONG TYPING (or warning in later vers.)

int i = 10;

float f = float(i);

- similar for bool(a), int(a), float(a)

  vec3 accel = vec3(0.0, -9.81, 0.0)

- shortening, enlarging

  vec4 color_rgba; vec3 color_rgb = vec3(color);

  vec3 bila_barva = vec3(1.0);

Matrix initialization

- Item enumeration
  - 4, 9 or 16 items
- diagonal matrix

  mat3 diamat = mat3(1.0)

$$\begin{pmatrix} 1.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 1.0 \end{pmatrix}$$

- Columns enumeration

  vec3 col1 = vec3(1.0, 0.0, 0.0)

  vec3 col2 = vec3(0.0, 1.0, 0.0)

  vec3 col3 = vec3(0.0, 0.0, 1.0)

  - mat3 diamat = mat3(col1,col2,col3)

Vector items swizzle

- vector is like structure – items are accessible using „.“, usable to change items order
- three possibilities: .xyzw, .rgba, .stpq

```
vec4 v4;
v4.rgba   //same as v4
v4.rgb    //result is vec3
v4.b      //result is scalar float
v4.xy     //result is vec2
v4.xgba   //error, items not from same set
v4.arrr   //result is vec4, items can repeat or change order
```

GLSL Type Modifiers I/II

- „in“
  - Input to a shader stage
  - Usually internally as vec4 → group scalars together
- „out“
  - Output from a shader to next pipeline stage
- „uniform“
  - entered as a parameter by application
  - constant in whole primitive and all shaders
  - uniform bool lightsOn;

GLSL Type Modifiers II/II

- „smooth in“ = „in“
  - = varying
  - variable for data transfer into fragment shader, only float (+vector, matrix)
  - in FS automatically interpolated in polygon including perspective
    in vec3 lightVec;
- „flat in“
  - Non-interpolated input into FS
- „const“
  - constant value
- „buffer“
  - Data accessible by shader and CPU
- „shared“
  - Compute shaders, data shared in workgroup

Accessing uniforms

- CPU can not write to GPU directly
  - get handle of variable and write using GL

    GLint glGetUniformLocation(GLint prog, char * varName)
  - void glUniform{234}{if}(GLint location, TYPE value)
    void glUniform{234}{if}v(GLint location, GLsizei cnt, TYPE values)
    void glUniformMatrix{234}fv(GLint location, GLsizei cnt,
    GLboolean transpose, const float * values)
- In shader:

  uniform vec4 myrgba;
- In application:

  h = glGetUniformLocation(prog_h,“myrgba“);
  glUniform4f(h,rgba);

Accessing attributes

- CPU can not write to GPU directly
  - get handle of variable and write using GL

    GLint glGetAttribLocation(GLint prog, char * varName)

    void glVertexAttrib{1234}{sfd}{v}(GLuint location, TYPE value, …)

    ...
  - attributes usually grouped to vec4 during transfer
- Use eg. with glVertexAttribPointer(...) + glEnableVertexAttribArray(...) + glDrawArrays() etc.

Vector and matrix operations

- multiplication is overloaded, dimensions must match
- matrix multiply is not comutative!
  - mat = mat*mat
  - vec = vec*mat
- Examples
  - vec = vec * vec // component-wise
  - vec = dot(vec, vec) // scalar product
  - vec = cross(vec, vec) // vector product
  - mat = matrixCompMult(mat,mat) // component-wise

Flow control

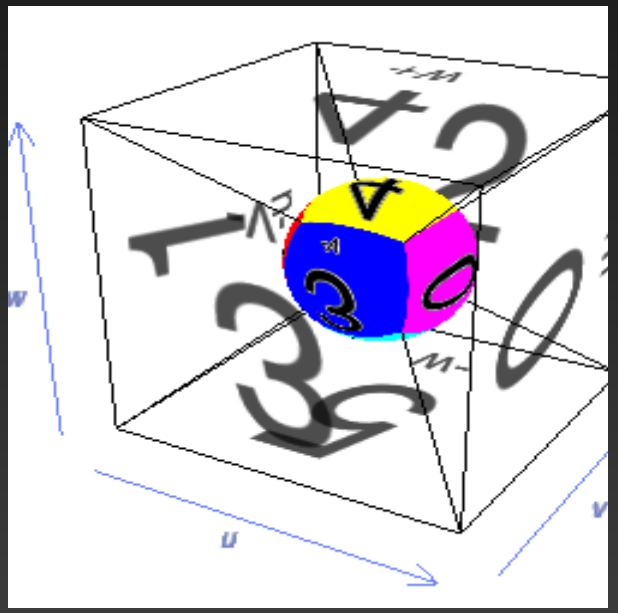
- Like standard C++
  - if – else
  - for, while, do – while
  - break, continue, functions + return
- In fragment shader
  - discard – discard fragment output and may (or may NOT) end shader execution

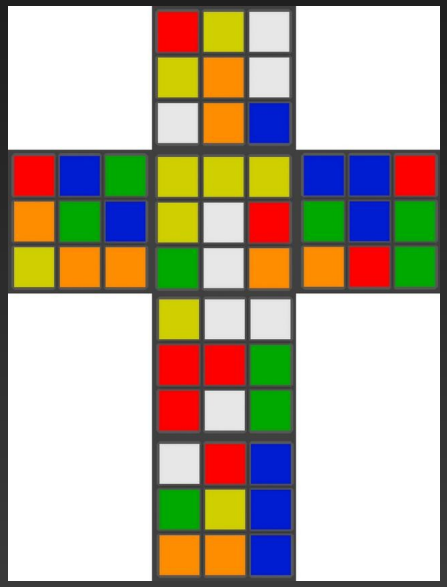
Functions

- return_type func(type param1, type param2)
- no pointers – how to return more values?
  - one via return value
  - or with parameter
    - in = input variable (default)
    - const in = constant input (read-only)
    - out = value copied out after execution finished (write-only)
    - inout = copied in and out (read-write)

Accessing textures

- Mostly in FS (rarely in VS or others)
- sampler{1D..3D}





- samplerCube
  - cube maps
- sampler1DShadow, sampler2DShadow
  - shadow textures

Accessing textures

- Bind texture unit and sampler

```
GLint texSampler_h; //handle to „tex“ variable
texSampler_h = glGetUniformLocation(FS_h, „tex“);
glUniform1i(texSampler_h, 2); //use GL_TEXTURE2
```

- FS:

```
in vec2 texcoord;
uniform sampler2D tex;
void main( void ) {
    out_color = texture(tex, in_texcoord);
}
```

Summary

- allow full pipeline control
  - user specified vertex, tesselation, geometry & fragment program allow non-standard effects
    → higher quality
  - all math & control must be programmed manually by user
    → more complicated
  - unnecessary steps can be fully eliminated
    → can be faster

shaders: simple

```
// create and use shaders
    GLuint VS_h, FS_h, prog_h;

    VS_h = glCreateShader(GL_VERTEX_SHADER);
    FS_h = glCreateShader(GL_FRAGMENT_SHADER);

    glShaderSource(VS_h, 1, &VS_string, NULL);
    glShaderSource(FS_h, 1, &FS_string, NULL);

    glCompileShader(VS_h);
    glCompileShader(FS_h);

    prog_h = glCreateProgram();

    glAttachShader(prog_h, VS_h);
    glAttachShader(prog_h, FS_h);

    glLinkProgram(prog_h);

    glUseProgram(prog_h);
```

shaders: with error checking

```
std::string textFileRead(const std::string fn) {
    std::ifstream file;
    file.exceptions(std::ifstream::badbit);
    std::stringstream ss;
    try {
        file.open(fn);
        std::string content;
        ss << file.rdbuf();
    }
    catch (const std::ifstream::failure& e) {
        std::cerr << "Error opening file: " << fn <<
std::endl;
        exit(EXIT_FAILURE);
    }
    return std::move(ss.str());
}

std::string getShaderInfoLog(const GLuint obj) {
    int infologLength = 0;
    std::string s;
    glGetShaderiv(obj, GL_INFO_LOG_LENGTH, &infologLength);
    if (infologLength > 0) {
        std::vector<char> v(infologLength);
        glGetShaderInfoLog(obj, infologLength, NULL,
v.data());
        s.assign(begin(v), end(v));
    }
    return s;
}

std::string getProgramInfoLog(const GLuint obj) {
    int infologLength = 0;
    std::string s;
    glGetProgramiv(obj, GL_INFO_LOG_LENGTH, &infologLength);
    if (infologLength > 0) {
        std::vector<char> v(infologLength);
        glGetProgramInfoLog(obj, infologLength, NULL,
v.data());
        s.assign(begin(v), end(v));
    }
    return s;
}
```

```
// create and use shaders
 GLuint VS_h, FS_h, prog_h;

 VS_h = glCreateShader(GL_VERTEX_SHADER);
 FS_h = glCreateShader(GL_FRAGMENT_SHADER);

 std::string VSsrc = textFileRead(source_file_VS);
 const char* VS_string = VSsrc.c_str();
 std::string FSsrc = textFileRead(source_file_FS);
 const char* FS_string = FSsrc.c_str();

 glShaderSource(VS_h, 1, &VS_string, NULL);
 glShaderSource(FS_h, 1, &FS_string, NULL);

 glCompileShader(VS_h);
 getShaderInfoLog(VS_h);

 glCompileShader(FS_h);
 getShaderInfoLog(FS_h);

 prog_h = glCreateProgram();
 glAttachShader(prog_h, VS_h);
 glAttachShader(prog_h, FS_h);
 glLinkProgram(prog_h);
 getProgramInfoLog(prog_h);

 glUseProgram(prog_h);
```