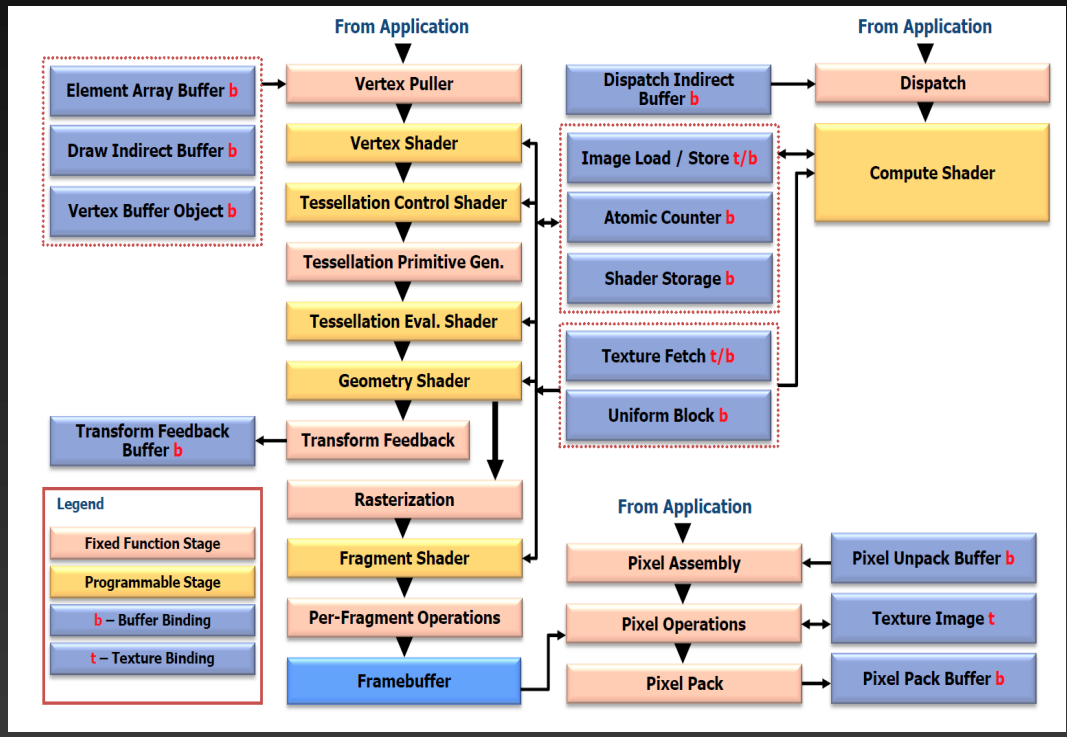
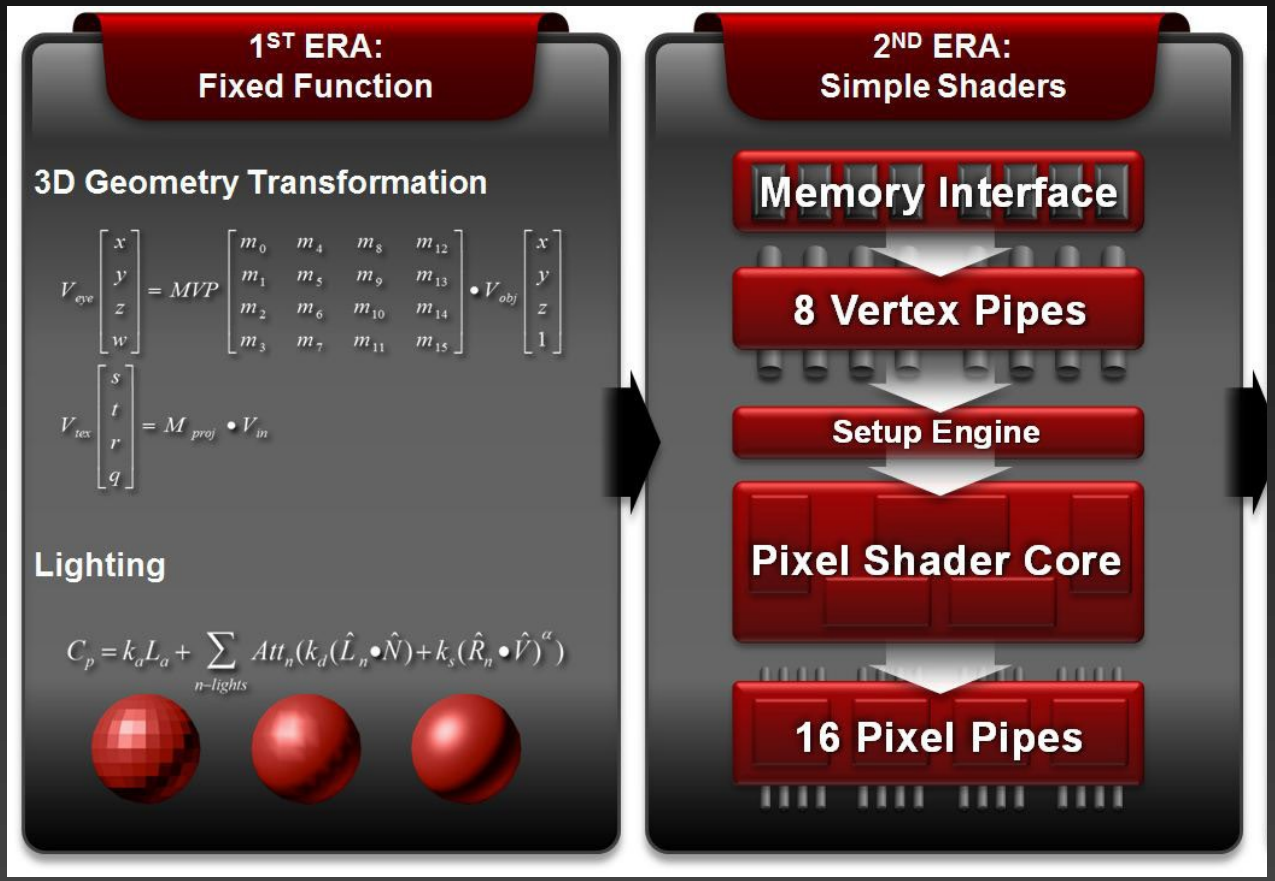
Shaders

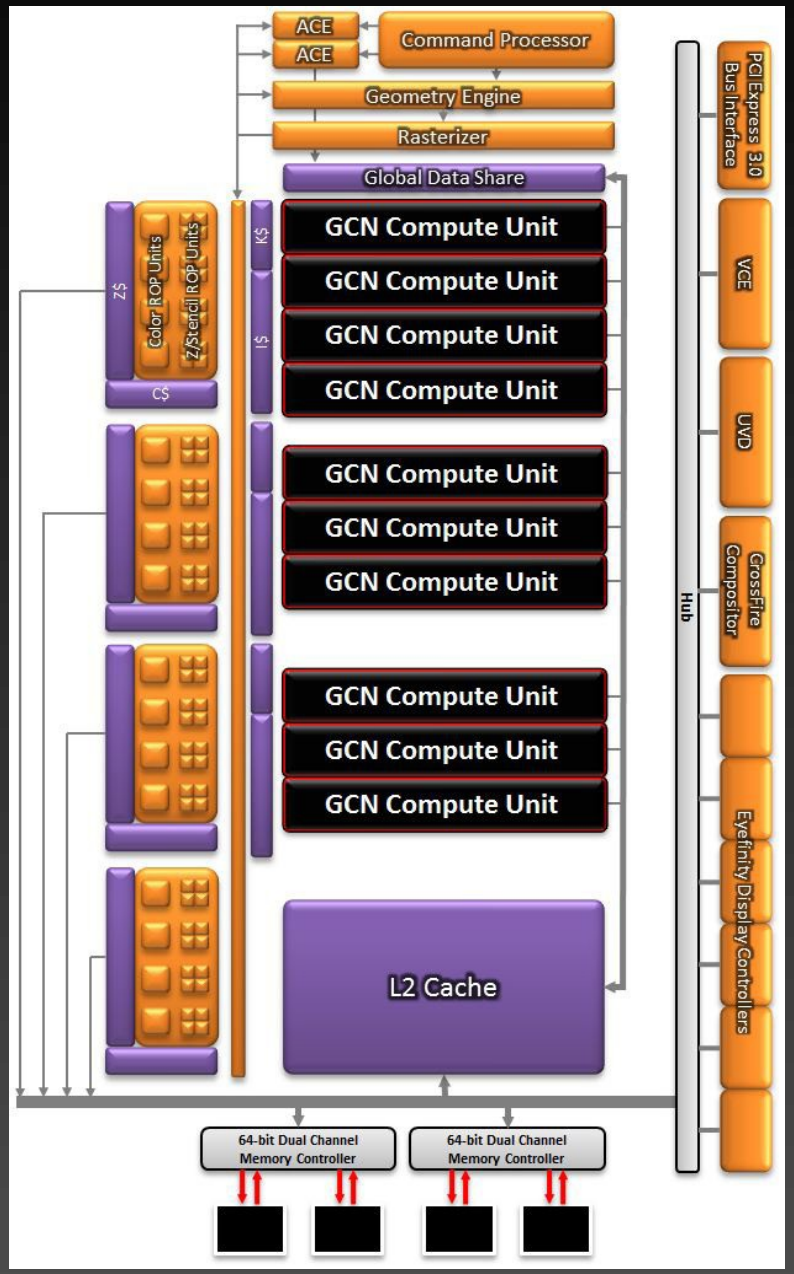
What Is a Shader?

- Shader = small program, executed directly on GPU for each vertex (fragment)
- Shader defines function of the pipeline
- Usually cooperation of at least two programs
  - vertex shader and fragment shader



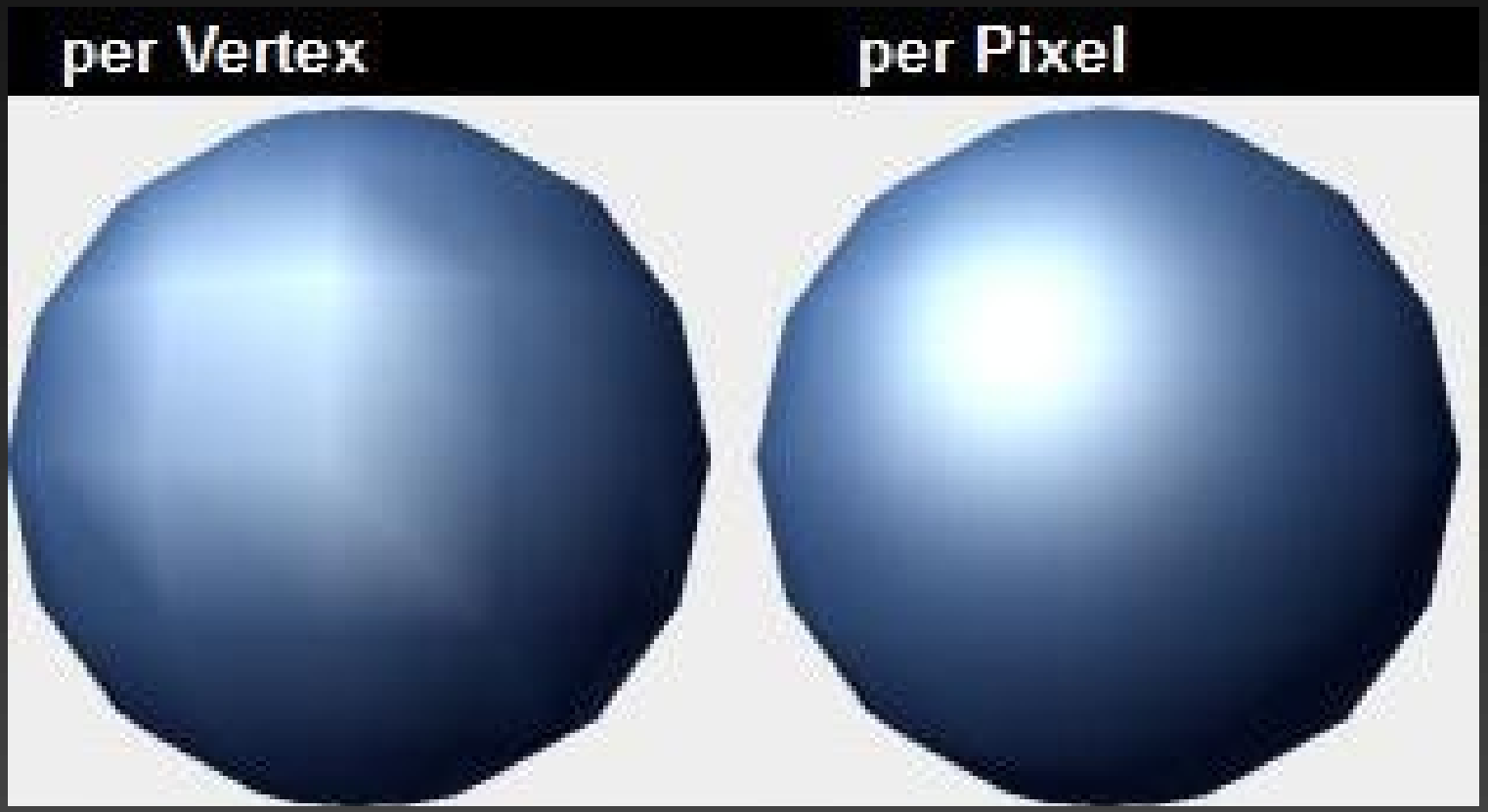
Evolution of hardware





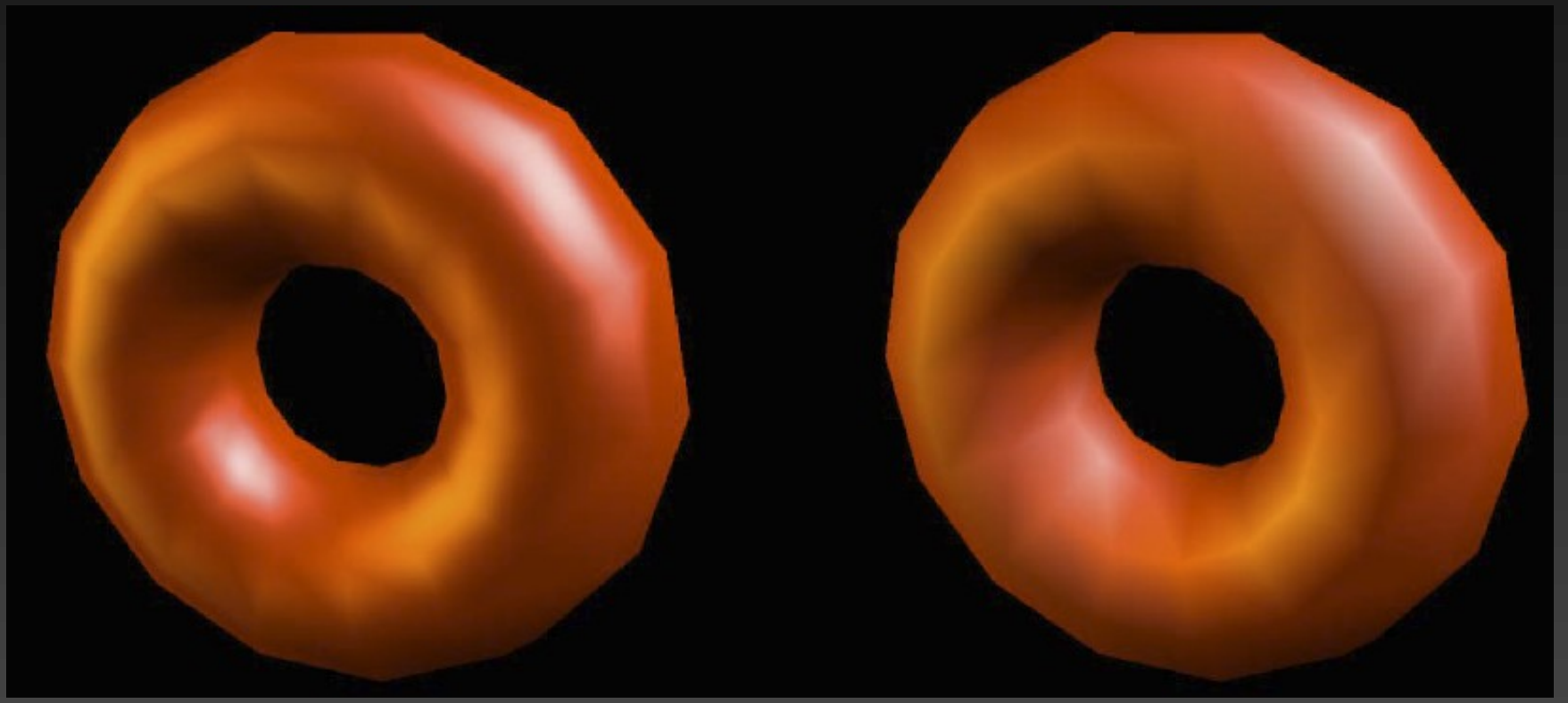
Example

- Gouraud vs. Per-fragment



Example

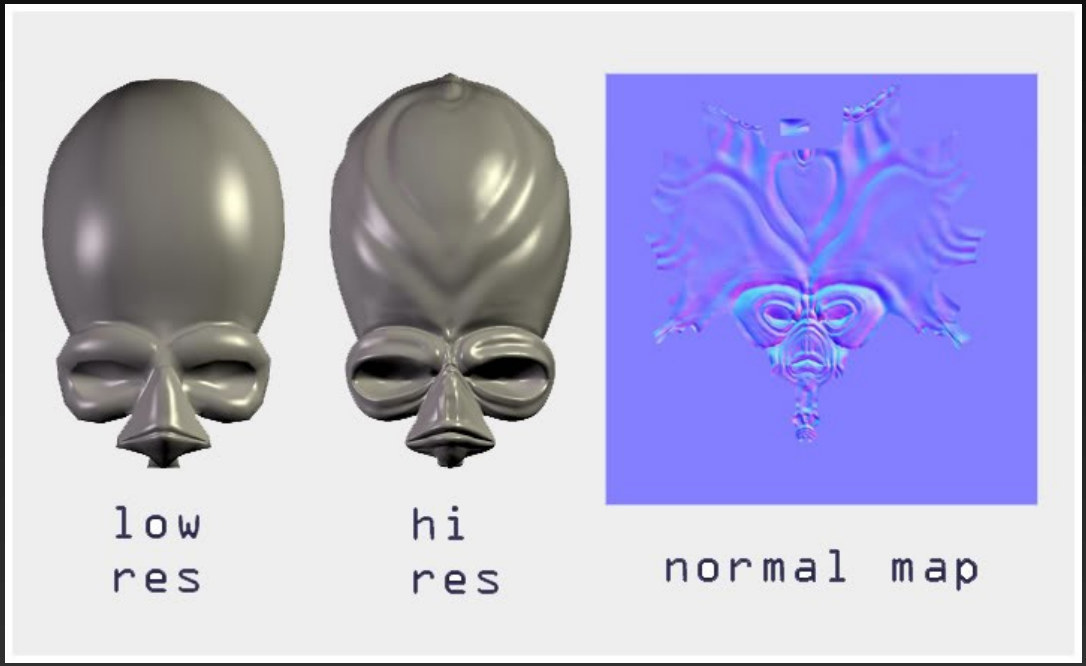
- Per-fragment vs. Gouraud

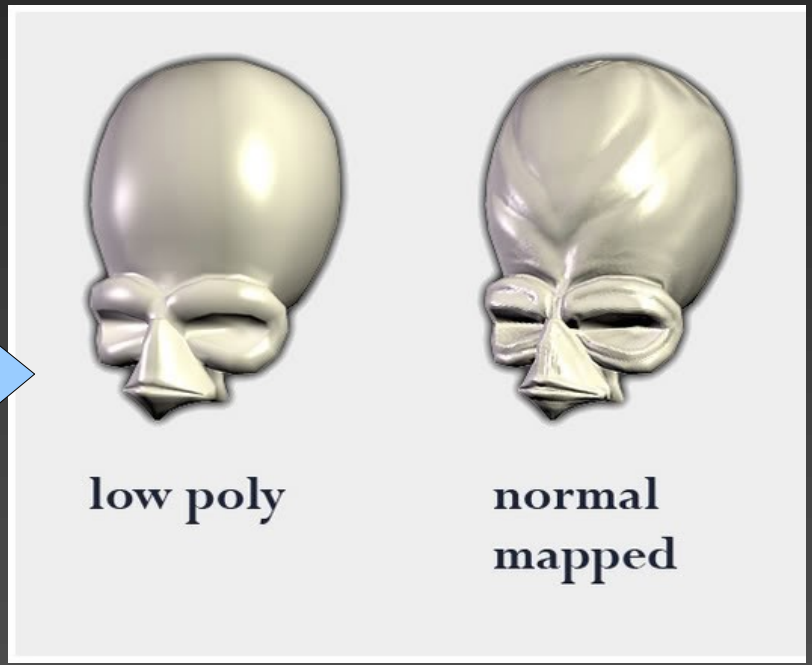


Example

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

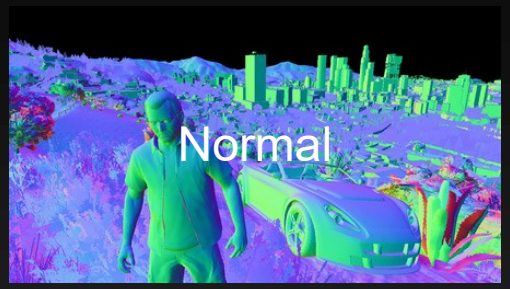
Example

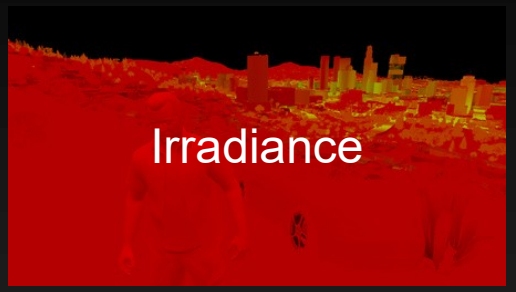




GTA-V


Diffuse


Normal


Irradiance


Specular + Shadow

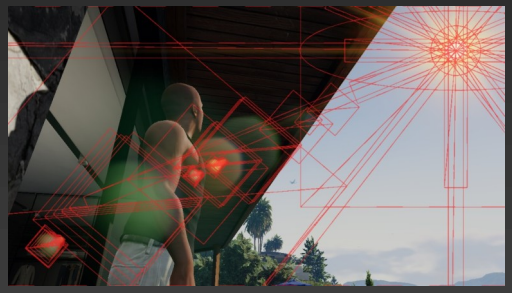

Depth

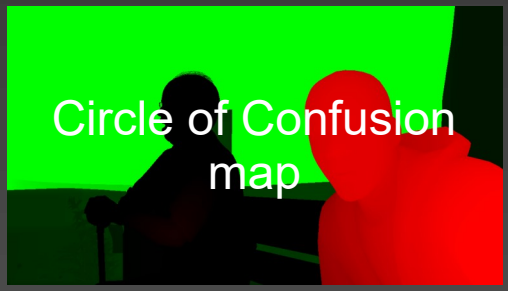

tencil


SSAO


Reflection


Cube
128x128




Circle of Confusion
map

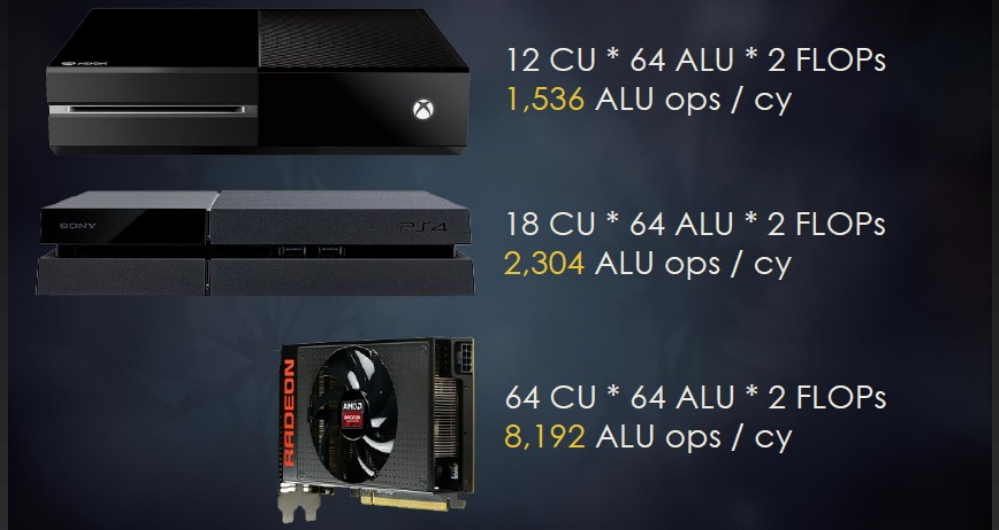
Why shaders?


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
UBM


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?

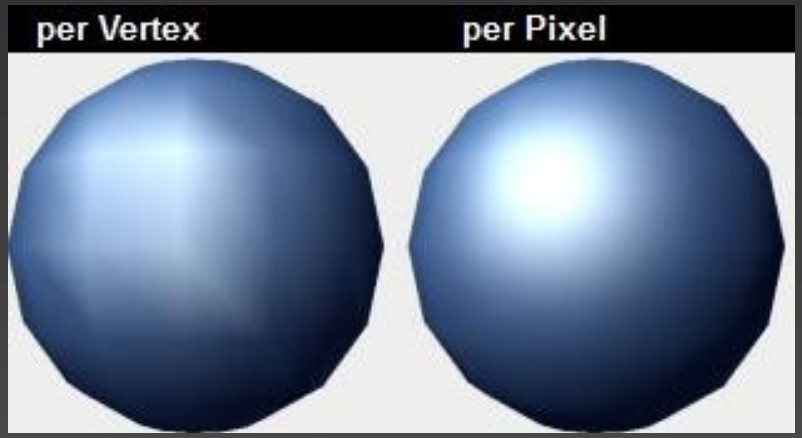
- Used mostly for lighting and shading
- Lighting – compute intensity and color in point of scene, as viewed by user
  - function of scene geometry (model, lights, camera and their positions) and material properties
  - per vertex/fragment = vertex or fragment shader
- Shading – process of interpolation 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, …

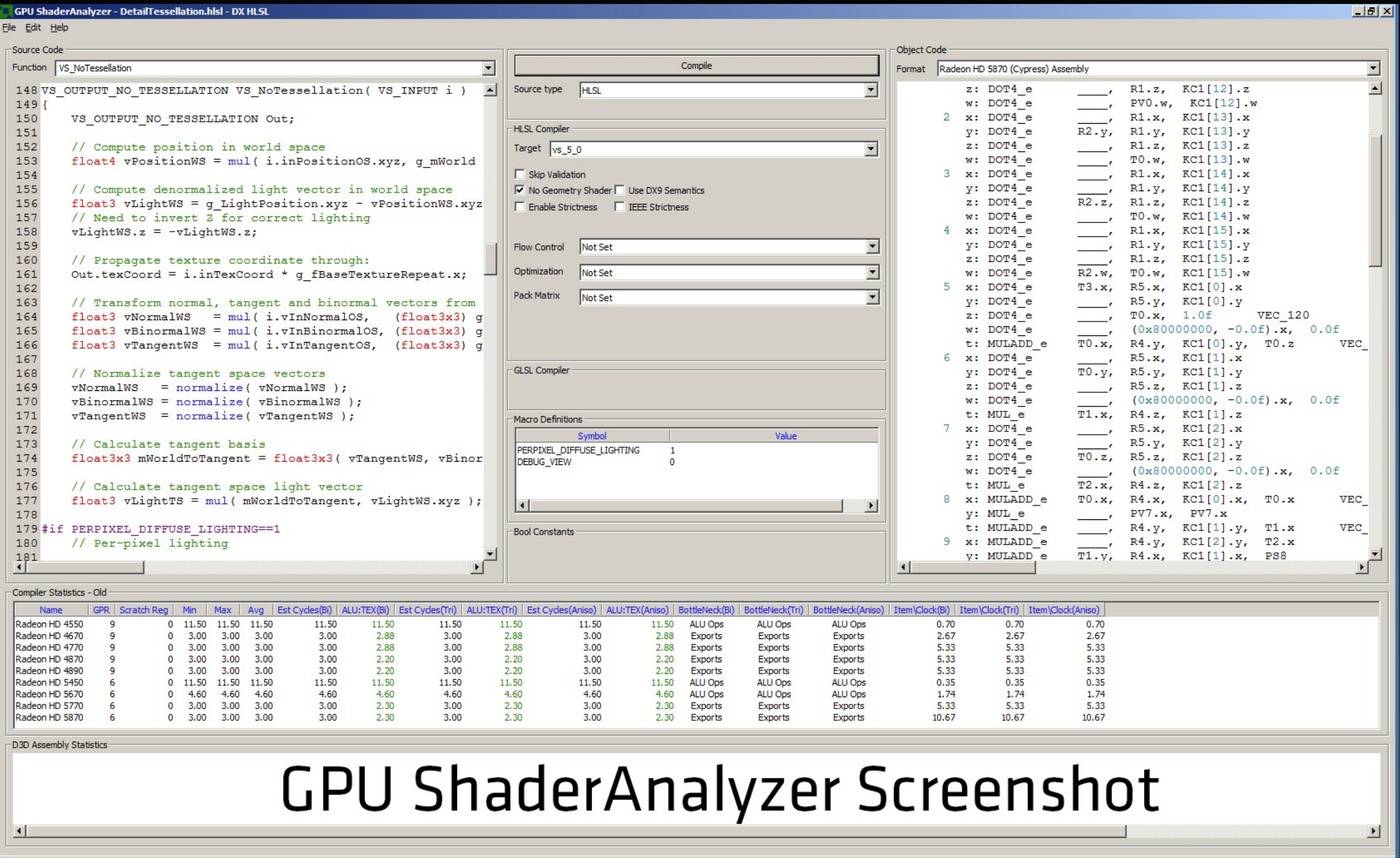


Literature

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

Shader language

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


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) { … }

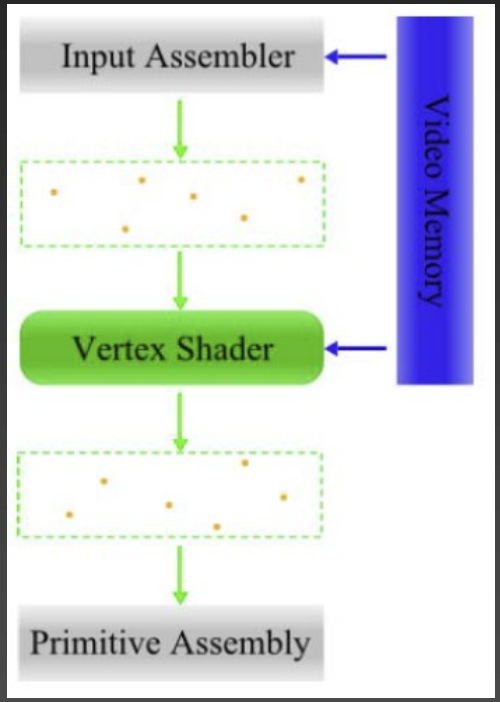
- … but more restrictions
  - parameters passed only by value, function returns direct value, non-existent pointers (automatic memory management by GPU drivers)
  - strong typing, no automatic conversion (float x int etc.)
- Default internal variables for input and output
  - starting with gl_
- Data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

Shader types

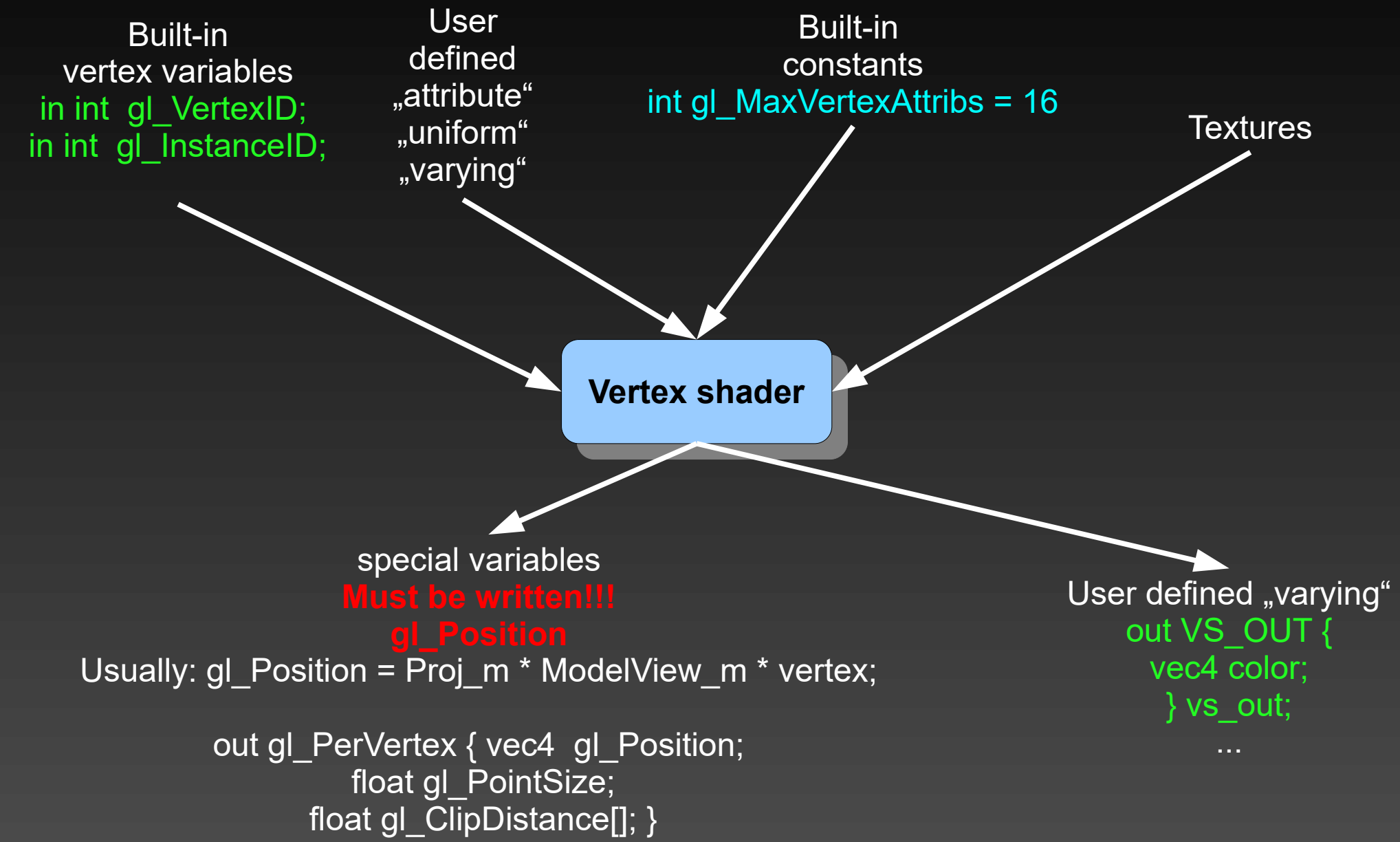
- Most common
  - Vertex shader
    - manipulation with single vertex
  - Fragment shader
    - fragment coloring
- Less common
  - Geometry shader
    - can create/drop vertices and primitives
- Least common
  - Tesseleation control shader
  - Tesselation evaluation shader
  - Compute shader
  - mesh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

Vertex shader

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



Vertex shader

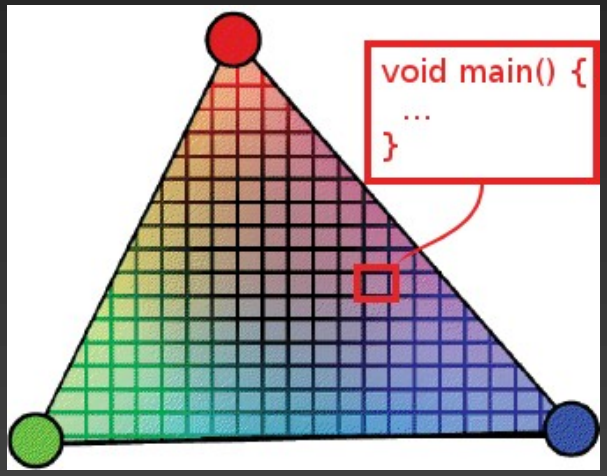


Vertex Shader Example

```
#version 430 core
// shading language version specifier: must be the first

in vec4 position, color; // input variables

out VS_OUT                    // output variables, grouped to structure
{
     vec4 color;
} vs_out;

uniform mat4 mv_m,projection_m;  // uniform variables

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

Fragment Shader (dx3d = pixel shader)

- Usualy does
  - 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, ...



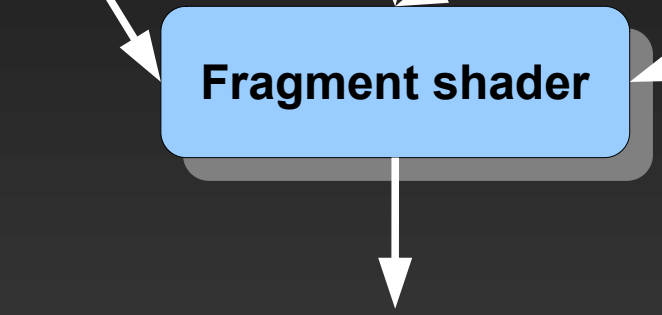
Fragment shader

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“
(not 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 Example

```
#version 430 core
// shading language version specifier: must be the first

out vec4 color; // mandatory output variable: fragment color

in VS_OUT {        // input variables grouped to structure, passed from vertex shader
    vec4 color;
} fs_in;

// FS main function
void main( void ) {
    // Pass color – color is „varying“,
    // i.e. it is already interpolated between values set in vertices
    color = fs_in.color;
}
```

Shader Use 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);

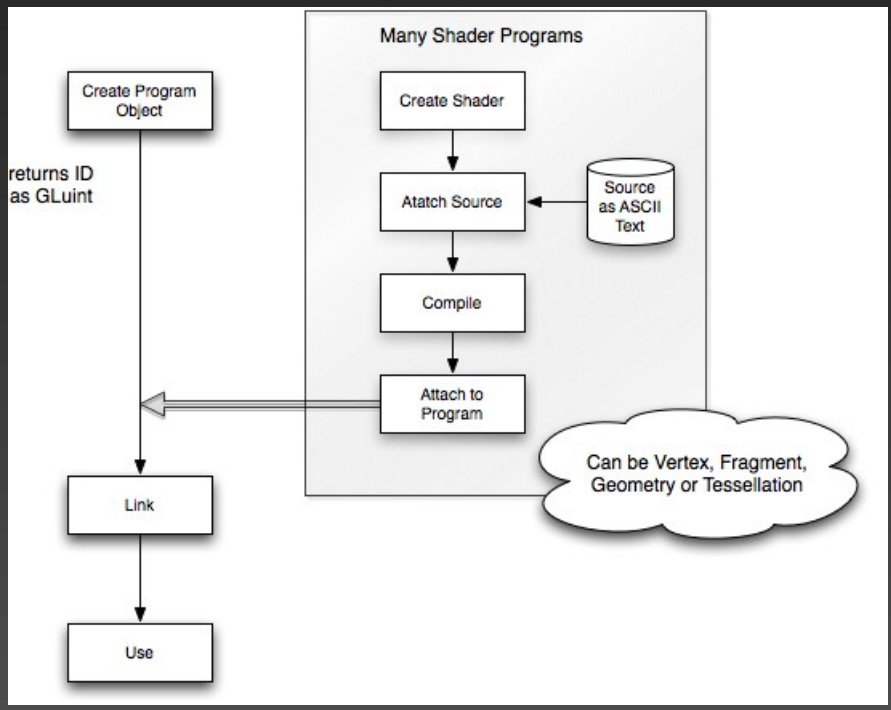
4) prog_h = glCreateProgram();

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

6) glLinkProgram(prog_h);

7) glUseProgram(prog_h);

8) (glDeleteShader(), glDeleteProgram())



GLSL 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_rgba);


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

[[smooth/flat] in/out/uniform/const] [float/vec3/mat4/...]

- „in“
  - Input to a shader stage
  - Usually internally as vec4 → group scalars together
  - „smooth in“ = „in“ = varying, default
    - variable for data transfer into fragment shader, only float (+vector, matrix)
    - in FS automatically interpolated in polygon including perspective
      eg.: in vec3 lightVec;
  - „flat in“
    - Non-interpolated input into FS
- „out“
  - Output from a shader to next pipeline stage

GLSL Type Modifiers II/II

- „uniform“
  - set as a parameter by CPU application
  - constant in whole primitive and all shaders

  eg.: uniform bool lightsOn;

- „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 the variable

    GLint location = glGetUniformLocation(GLint prog, char * varName)
  - set value to handle
  - 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)

```
// C++ program

int main()
{
  // …
  glm::vec4 rgba = ...;
  // …
  while (!glfwWindowShouldClose(window))
  {
    // …
    glUseProgram(my_prog);
    GLint h = glGetUniformLocation(prog_ID, “myrgba“);
    glUniform4fv(h, 1, glm::value_ptr(rgba));
    // …
  }
  // …
}
```

```
#version 430 core
out vec4 color;

uniform vec4 myrgba;

void main( void ) {
      color = myrgba;
}
```

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

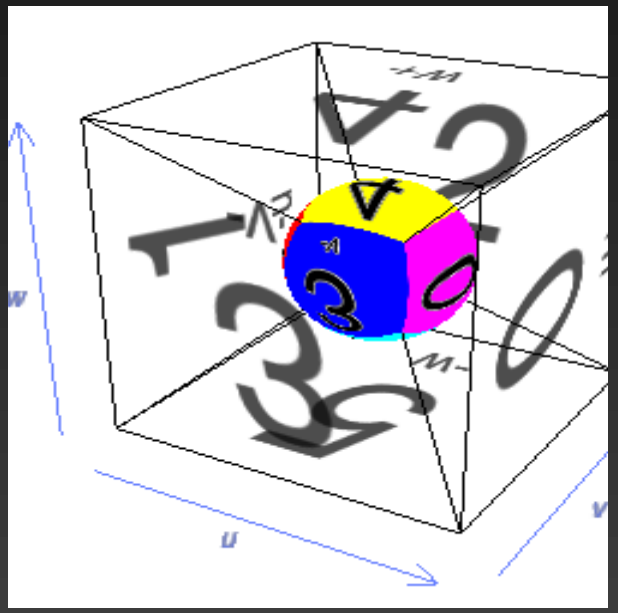
Functions

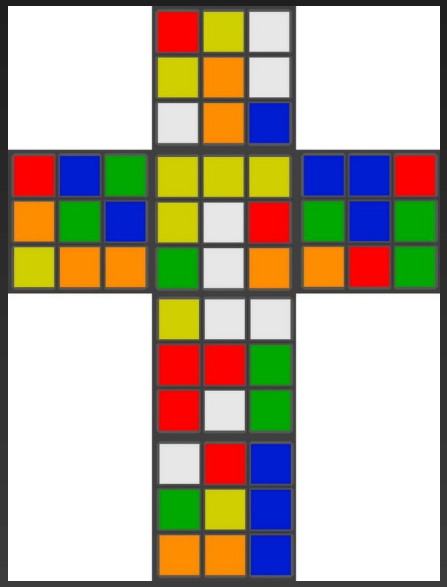
return_type *func*(**[in/out/inout]** type param1)

- one value returned via return_type
- no pointers – how to return more values?
  - define & return structure
  - or with type modifier
    - 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

```
// C++ program

int main()
{
  // …
  while (!glfwWindowShouldClose(window))
  {

    // …

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

    // …

  }
  // …
}
```

```
#version 430 core

// FS

in vec2 texcoord;
out vec4 out_color;
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

Create Shaders: example, no error checking

```
// 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

```
// load text file
#include <iostream>
#include <fstream>
#include <sstream>
#include <filesystem>

std::string textFileRead(const std::filesystem::path& fn) {
      std::ifstream file(fn);
      if (!file.is_open())
            throw std::exception("Error opening file.\n");

      std::stringstream ss;
      ss << file.rdbuf();
      return ss.str();
}

// get shader compilation errors
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;
}

// get shader linker errors
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);

const char* VS_string =
                  textFileRead(source_file_VS).c_str();
const char* FS_string =
                  textFileRead(source_file_FS).c_str();

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

glCompileShader(VS_h);
{ // check compile result, display error (if any)
    GLint cmpl_status;
    glGetShaderiv(VS_h, GL_COMPILE_STATUS, &cmpl_status);
    if (cmpl_status == GL_FALSE) {
        std::cerr << getShaderInfoLog(VS_h);
        throw std::exception("Shader compilation err.\n");
    }
}

glCompileShader(FS_h);
{ … glGetShaderiv(FS_h, GL_COMPILE_STATUS, &cmpl_status);
  … }

prog_h = glCreateProgram();
glAttachShader(prog_h, VS_h);
glAttachShader(prog_h, FS_h);
glLinkProgram(prog_h);
{ // check link result, display error (if any)
    GLint status;
    glGetProgramiv(prog_h, GL_LINK_STATUS, &status);
if (isLinked == GL_FALSE) {
        std::cerr << getProgramInfoLog(prog_h);
        throw std::exception("Link err.\n");
    }
}

glUseProgram(prog_h);
```