Working with shaders

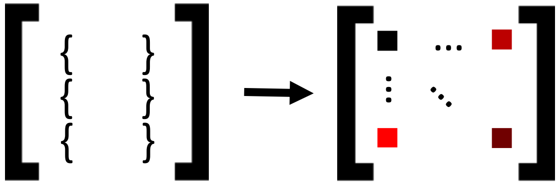
Patrick SARDINHA

What’s a shader?

Small programs that run on the GPU

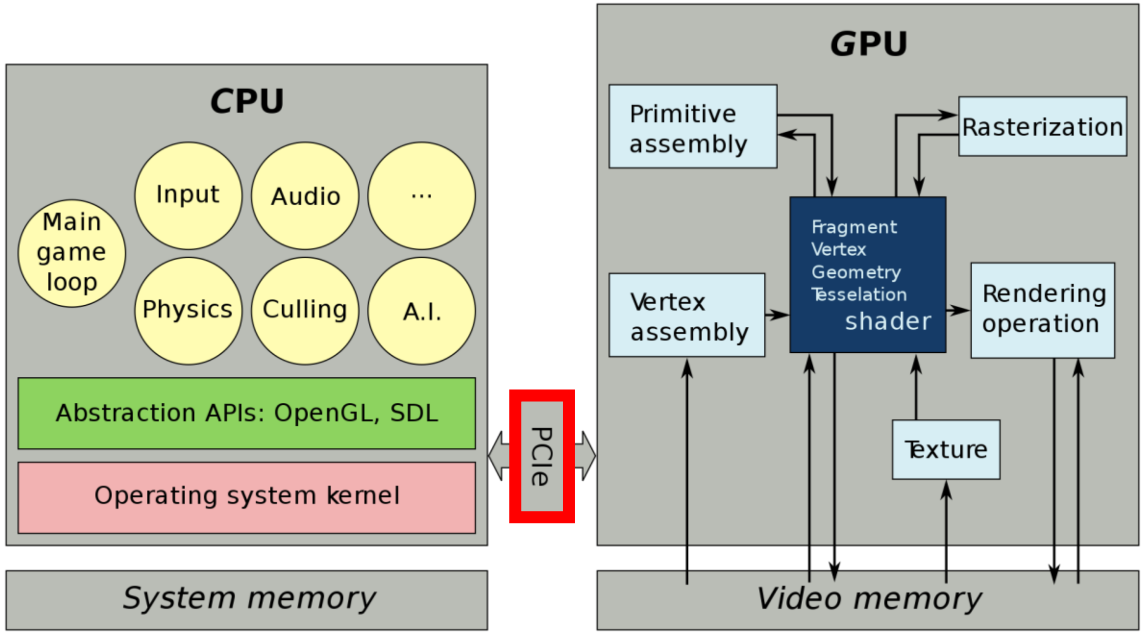
Executed for each specific section of the graphics pipeline

Isolated and not allowed to communicate with each other



It works with geometric primitives, lights, textures, ...

Shaders in the Graphics Processing Unit



Shaders are executed by the GPU & are good to be executed in parallel

Sending data to the GPU goes through the PCI, it is relatively slow & CPU/GPU must be synchronized

Different languages

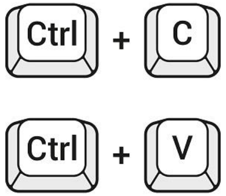
DirectX High-Level Shader Language

Cg Shader Language

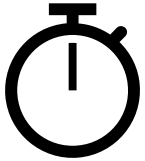
OpenGL Shading Language (GLSL)

Problem

In GLSL, there are no real data structures to easily get the attributes of a primitive (matrices, vectors, ...)



The construction of shaders is very repetitive which implies a lot of copy and paste



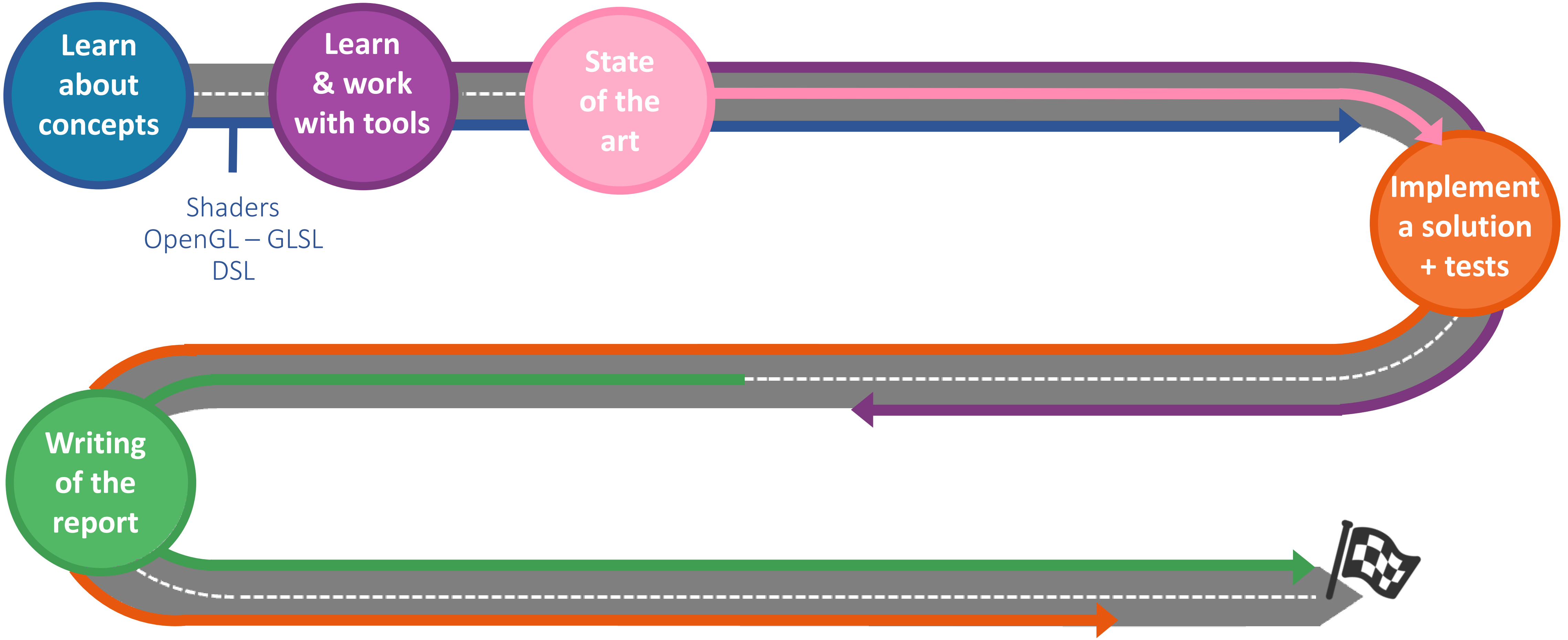
Must reduce the data sent in the PCI to avoid multiple synchronizations between CPU & GPU

Goal of the project

Work with the representation of the data
& abstract the types

Construct a DSL for shaders

Road map



Learn about concepts
Learn & work with tools
State of the art
Shaders
OpenGL – GLSL
DSL
Implement a solution + tests
Writing of the report

3D space to 2D screen space

The process of transforming 3D coordinates to 2D pixel is done by the graphics pipeline

First big part: transforms 3D coordinates into 2D coordinates

Second big part: transforms the 2D coordinates into actual colored pixels

Graphics pipeline

Input & Output Data

3 different shaders processing units

Vertex Shader

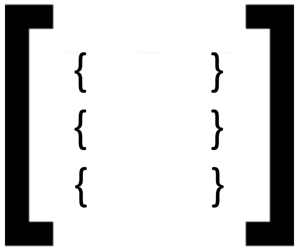
Geometry Shader

Fragment/Pixel Shader

Some others processes

Tessellation, Rasterization, Color blending

Input Data



Take as input a Vertex (or Vertices) [] which is a data structure that describes geometric primitives with certain attributes like:

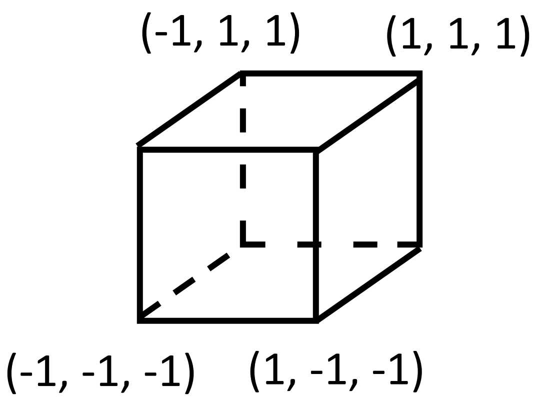
Position (2D, 3D coordinates)

Color (RGB, …)

Texture coordinates

Example

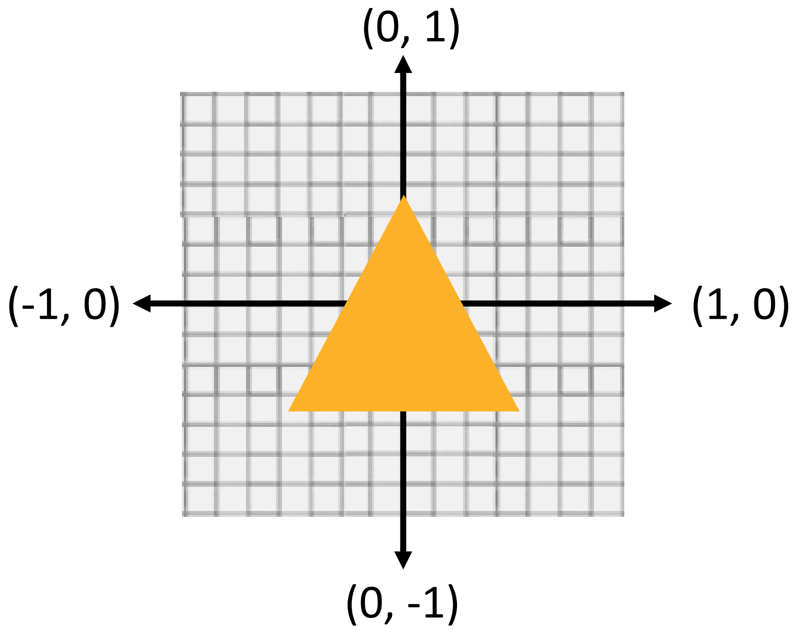
In OpenGL, only the Normalize Device Coordinates (NDC) are visible on the screen



To render a single 2D triangle:

3D position (NDC) of each vertex

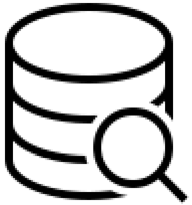
```
float vertices[] = {
    -0.5f, -0.5f, 0.0f,
     0.5f, -0.5f, 0.0f,
     0.0f,  0.5f, 0.0f
};
```



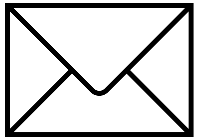
Linking vertex attributes

The input data will compose a Vertex Buffer Object (VBO) which can store a large number of vertices in the GPU memory

Then, we specify how the vertex data should be interpreted



Finally, it will be sent to the Vertex Shader



Example

Triangle with position attributes:

```
float vertices[] = {
    -0.5f, -0.5f, 0.0f,
     0.5f, -0.5f, 0.0f,
     0.0f,  0.5f, 0.0f
};
```

Copy our vertices array in a buffer

ID of the buffer which must be bind

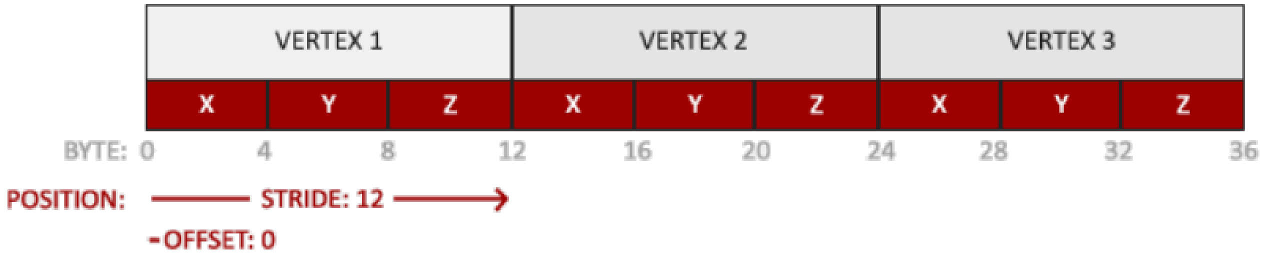
Specifies the target buffer object

```
glBindBuffer(GL_ARRAY_BUFFER, VBO);
glBufferData(GL_ARRAY_BUFFER, sizeof(vertices), vertices, GL_STATIC_DRAW);
```

Size of the buffer object

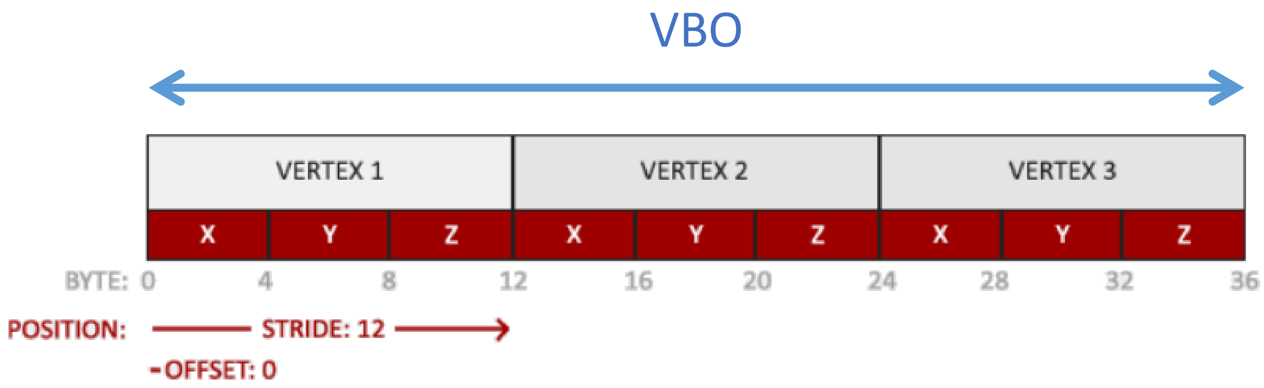
Pointer to data

VBO



Example (Cont.)

Define how the vertex data should be interpreted



The size of the vertex attribute

Specifies which vertex attribute

Normalized data or not

Offset of where the position data begins in the buffer

```
glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 3 * sizeof(float), (void*)0);
glEnableVertexAttribArray(0);
```

Enable the vertex attribute

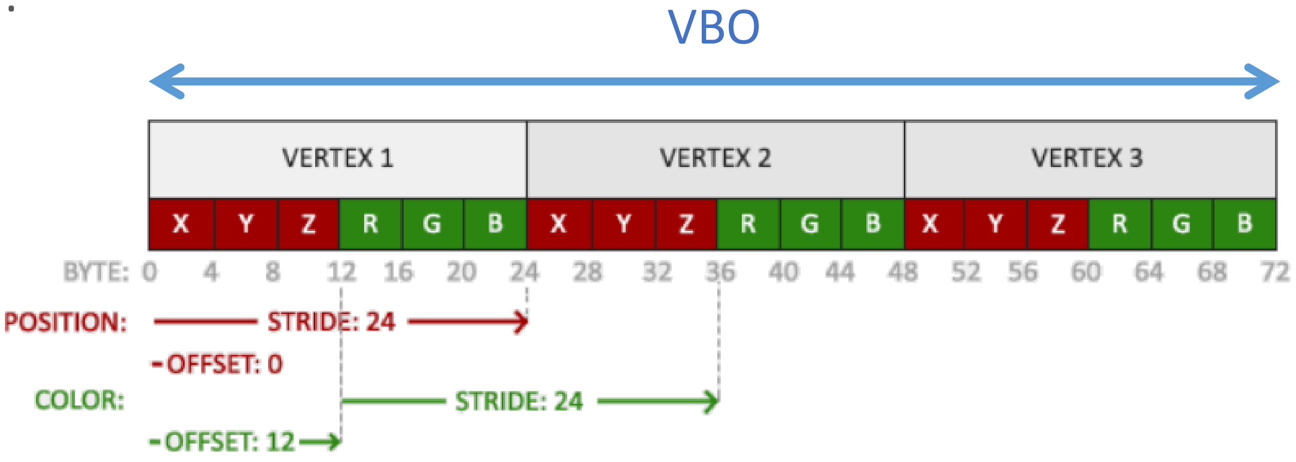
Type of the data

Stride: Space between consecutive vertex attributes

Example (Cont.)

Triangle with position & color attributes:

```
float vertices[] = {
    // positions          // colors
     0.5f, -0.5f, 0.0f,  1.0f, 0.0f, 0.0f,
    -0.5f, -0.5f, 0.0f,  0.0f, 1.0f, 0.0f,
     0.0f,  0.5f, 0.0f,  0.0f, 0.0f, 1.0f
};
```



Position offset

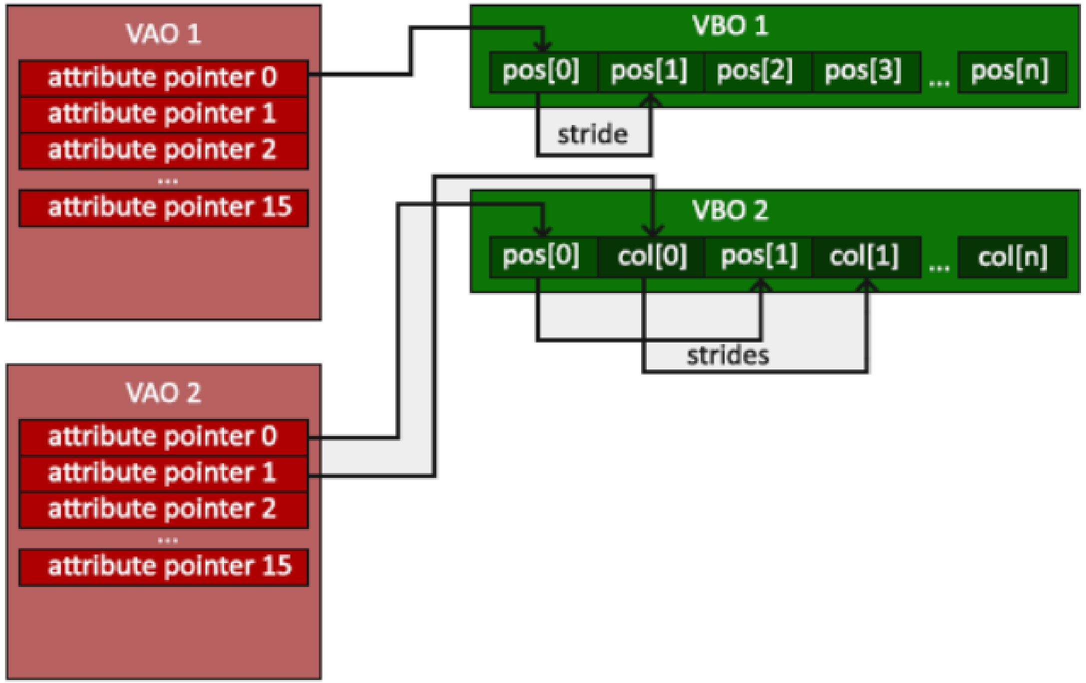
```
// position attribute
glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 6 * sizeof(float), (void*)0);
glEnableVertexAttribArray(0);
// color attribute
glVertexAttribPointer(1, 3, GL_FLOAT, GL_FALSE, 6 * sizeof(float), (void*)(3* sizeof(float))
glEnableVertexAttribArray(1);
```

Stride

Color offset

Vertex Array Object (VAO)

Allows to configure vertex attribute pointers more easily



To draw an object, just bind the corresponding VAO

We generate a VAO like a VBO

```
unsigned int VAO;
glGenVertexArrays(1, &VAO);
```

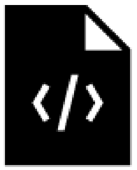
Summary

```
// 1. bind Vertex Array Object
glBindVertexArray(VAO);

// 2. copy our vertices array in a buffer for OpenGL to use
glBindBuffer(GL_ARRAY_BUFFER, VBO);
glBufferData(GL_ARRAY_BUFFER, sizeof(vertices), vertices, GL_STATIC_DRAW);

// 3. then set our vertex attributes pointers
glVertexAttribPointer(0, 3, GL_FLOAT, GL_FALSE, 3 * sizeof(float), (void*)0);
glEnableVertexAttribArray(0);

// (render loop)
// 4. draw the object
glUseProgram(shaderProgram);
glBindVertexArray(VAO);
someOpenGLFunctionThatDrawsOurTriangle();
```

Source: https://learnopengl.com/Getting-started/Hello-Triangle

Render & draw an object

The idea now is to render and draw an object.
To do that we will have to:

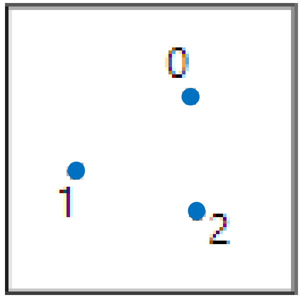


Set up a Vertex & a Fragment Shader

Compile these shaders

Link them to a shader program

Vertex Shader



Compute the projection of the vertices of primitives from 3D space into a different 3D space (NDC)

Input data: some properties of the vertices (position, color or texture coordinates)

Output data: the corresponding properties in the new space

Sample code

Shader's version (here 3.3)

All the input vertex attributes

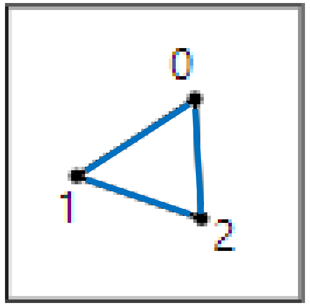
```
#version 330 core
layout (location = 0) in vec3 aPos;

void main()
{
    gl_Position = vec4(aPos.x, aPos.y, aPos.z, 1.0);
}
```

Specifically set the location of the input variable

(x, y, z) + w component

Output of the vertex shader

Primitives Assembly



This process takes all the vertex given by the step before and assemble them in order to create a geometric shape

Starting index in the array

Sample code:

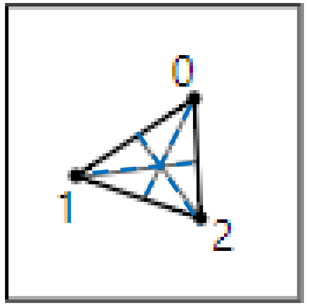
```
glDrawArrays(GL_TRIANGLES, 0, 3);
```

OpenGL function that draws a shape

Kind of primitive to render

Number of vertices to render

Tessellation

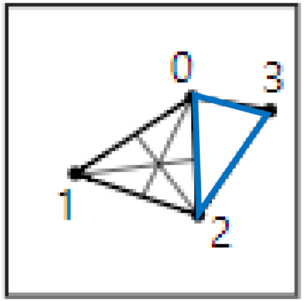


In 3D, the surfaces are built with triangular tiles

Tessellation allows to double triangles on a given surface and therefore increase the level of details

Geometry Shader

An unnecessary step

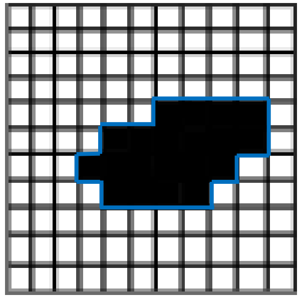


Allows to modify the geometry of each polygon and allows to create new polygons by emitting new vertices

Input data: data of a geometric primitive

Output data: data of one or more geometric primitive

Rasterization

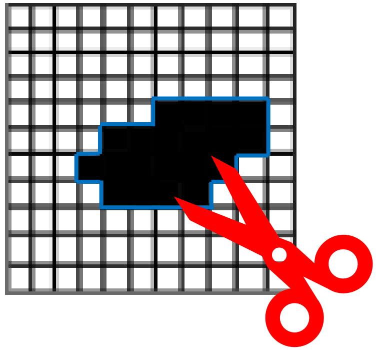


Method of converting a vector image into a raster image to be displayed on a screen

Vector image
composed of geometric objects

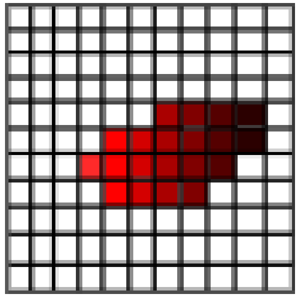
Raster image or Bitmap
composed of pixels

Clipping



This step discard all fragments (which is the required data to render a single pixel) that are outside the view, increasing the performance

Fragment/Pixel Shader



Calculates the final color of a pixel

Input data: pixel data
(position, texture coordinates, color)

Output data: the pixel color

Sample code

Shader's version (here 3.3)

```
#version 330 core
out vec4 FragColor;

void main()
{
    FragColor = vec4(1.0f, 0.5f, 0.2f, 1.0f);
}
```

Output variable which is the final color output

RGB + alpha component

Compile a Shader

First, we store the code in a string constant

```
const char *vertexShaderSource = "#version 330 core\n"
    "layout (location = 0) in vec3 aPos;\n"
    "void main()\n"
    "{\n"
    "   gl_Position = vec4(aPos.x, aPos.y, aPos.z, 1.0);\n"
    "}\0";
```

Then, we store and create the shader

```
unsigned int vertexShader;
vertexShader = glCreateShader(GL_VERTEX_SHADER);
```

Type of shader we want to create

Finally, we link the source code to the object and compile it

```
glShaderSource(vertexShader, 1, &vertexShaderSource, NULL);
glCompileShader(vertexShader);
```

Shader program

First, we create a program object

```
unsigned int shaderProgram;
shaderProgram = glCreateProgram();
```

We attach the previously compiled shaders to the program object and link them

```
glAttachShader(shaderProgram, vertexShader);
glAttachShader(shaderProgram, fragmentShader);
glLinkProgram(shaderProgram);
```

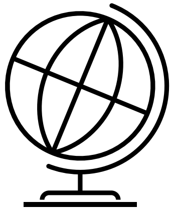
We can now activate this program to render and draw an object

```
glUseProgram(shaderProgram);
```

Final step is to delete our shader objects

```
glDeleteShader(vertexShader);
glDeleteShader(fragmentShader);
```

Uniforms variables



Useful to pass data from the application on the CPU to the shaders on the GPU

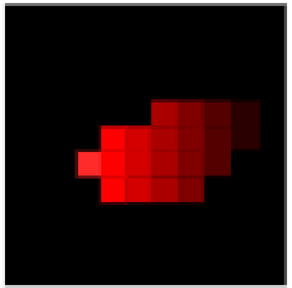
These are global variables

Sample code:

Usage of uniform keyword

```
#version 330 core
out vec4 FragColor;

uniform vec4 ourColor;

void main()
{
    FragColor = ourColor;
}
```

Alpha test



Checks the corresponding depth value of a fragment to see if the resulting fragment is in front or behind another one

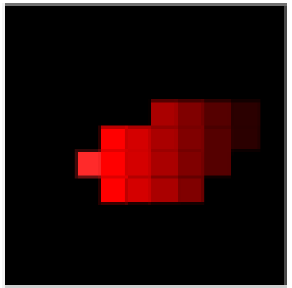
NOT DISCARDED ← in front | behind → DISCARDED

Done with the depth testing using a Z-buffer (in which the depth value of the fragments is stored)

```
glEnable(GL_DEPTH_TEST);
```

Then, checks for alpha values (opacity of an object) & blends the objects

Color Blending



The technique of gently blending two or more colors to create a gradual transition

Example of a blending function

First, we have to enable the OpenGL functionality

```
glEnable(GL_BLEND);
```

Then, blending can follow this equation:

$$\bar{C}_{result} = \bar{C}_{source} * F_{source} + \bar{C}_{destination} * F_{destination}$$

Final color of the fragment

Color output of the fragment shader

Impact of the alpha value

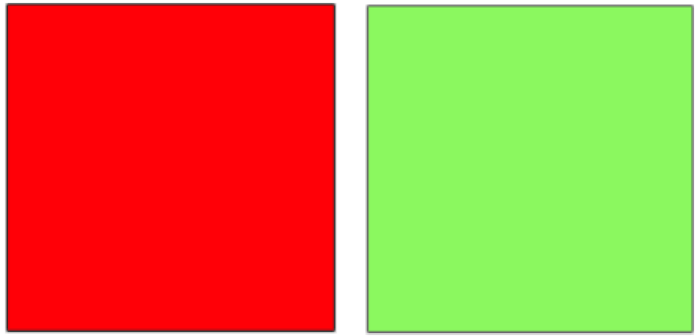
Color currently stored in the color buffer

Impact of the alpha value

Example (Cont.)

$$\bar{C}_{result} = \bar{C}_{source} * F_{source} + \bar{C}_{destination} * F_{destination}$$

$\bar{C}_{destination}$ $\bar{C}_{source}$

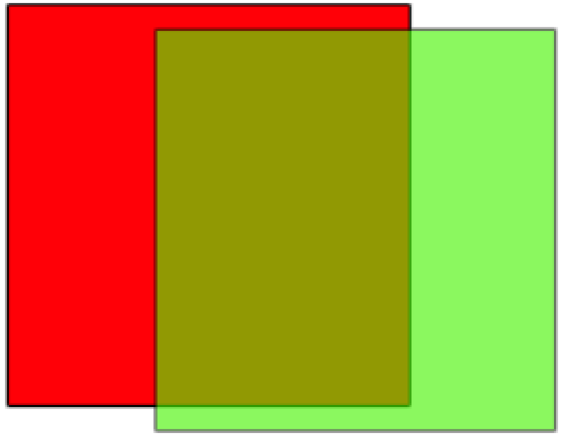


(1.0, 0.0, 0.0, 1.0) (0.0, 1.0, 0.0, 0.6)

Alpha value ($F_{destination}$)

Alpha value (F_{source})

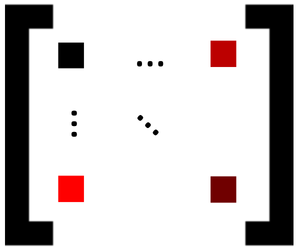
$$\bar{C}_{result} = \begin{pmatrix} 0.0 \\ 1.0 \\ 0.0 \\ 0.6 \end{pmatrix} * 0.6 + \begin{pmatrix} 1.0 \\ 0.0 \\ 0.0 \\ 1.0 \end{pmatrix} * (1 - 0.6)$$



(0.4, 0.6, 0.0, 0.76)

Resulting color then stored in the color buffer

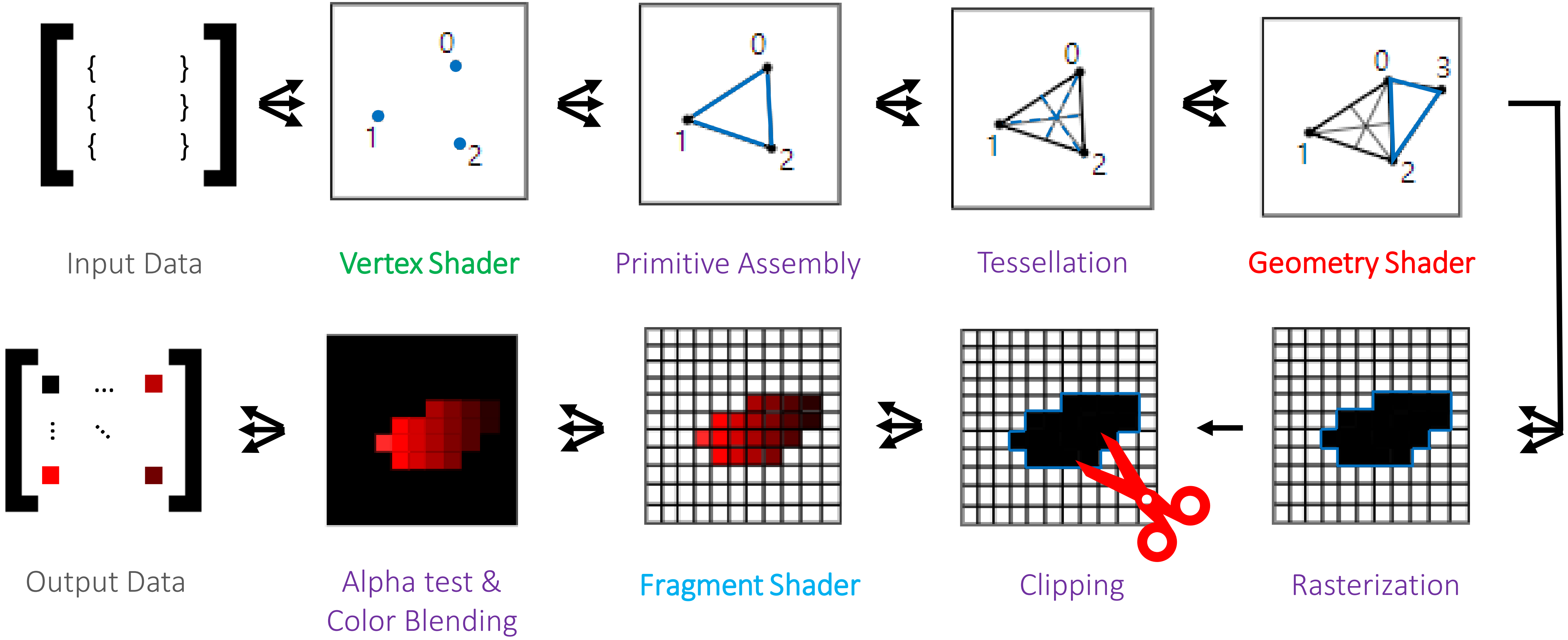
Output Data



Return a Framebuffer

The information in this buffer are the values of the color components (RGB) for each pixel

Overall view



Textures

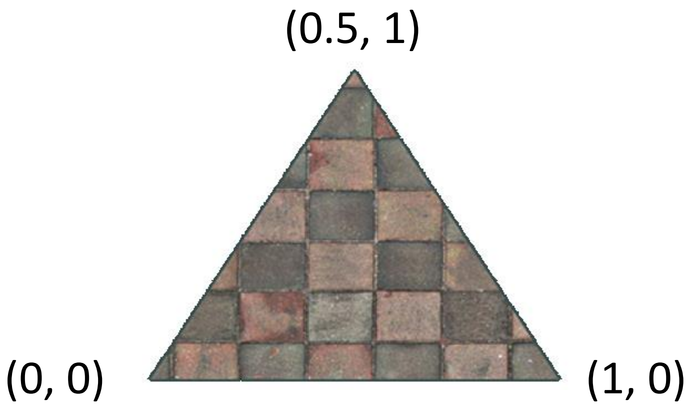
Allows to give the illusion the object is detailed without having to specify vertices

Associate each vertex to a texture coordinate

A fragment interpolation is then done for the other fragments

Sample code:

```
float texCoords[] = {
    0.0f, 0.0f,  // lower-left corner
    1.0f, 0.0f,  // lower-right corner
    0.5f, 1.0f   // top-center corner
};
```



Transformations

Make an object dynamic using matrix objects
& by combining the matrices

Some library can be used like the GLM (OpenGL
Mathematics) library

Useful matrices

Scaling Matrix

$$\begin{bmatrix} S_1 & 0 & 0 & 0 \\ 0 & S_2 & 0 & 0 \\ 0 & 0 & S_3 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} = \begin{pmatrix} S_1 \cdot x \\ S_2 \cdot y \\ S_3 \cdot z \\ 1 \end{pmatrix}$$

Translation Matrix

$$\begin{bmatrix} 1 & 0 & 0 & T_x \\ 0 & 1 & 0 & T_y \\ 0 & 0 & 1 & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} = \begin{pmatrix} x + T_x \\ y + T_y \\ z + T_z \\ 1 \end{pmatrix}$$

Rotation Matrix

Around X-axis

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta & 0 \\ 0 & \sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} = \begin{pmatrix} x \\ \cos\theta \cdot y - \sin\theta \cdot z \\ \sin\theta \cdot y + \cos\theta \cdot z \\ 1 \end{pmatrix}$$

Around Y-axis

$$\begin{bmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} = \begin{pmatrix} \cos\theta \cdot x + \sin\theta \cdot z \\ y \\ -\sin\theta \cdot x + \cos\theta \cdot z \\ 1 \end{pmatrix}$$

Around Z-axis

$$\begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} = \begin{pmatrix} \cos\theta \cdot x - \sin\theta \cdot y \\ \sin\theta \cdot x + \cos\theta \cdot y \\ z \\ 1 \end{pmatrix}$$

Sample code

Translating a vector of (1,0,0) by (1,1,0)

The matrix to transform (identity Matrix4)

The translation vector to apply to the matrix

```
trans = glm::translate(trans, glm::vec3(1.0f, 1.0f, 0.0f));
vec = trans * vec;
```

Multiply vec by the translation matrix

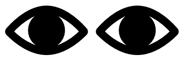
A translate function

Coordinates system

Transforming coordinates to NDC is done by a process regrouping several intermediate coordinate systems

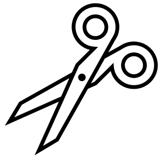
Local Space

World Space

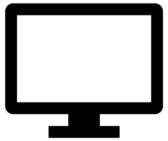


View Space

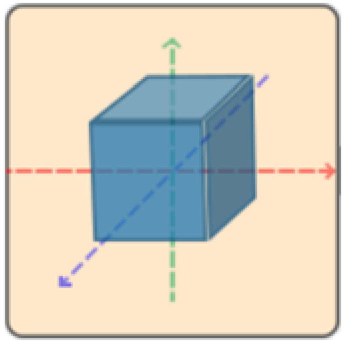
Clip Space



Screen Space



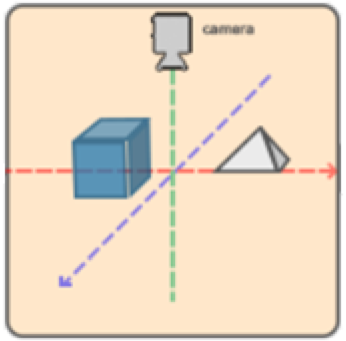
Local Space



Coordinates of the object relative to its local origin

In general, all new objects have (0, 0, 0) as initial position

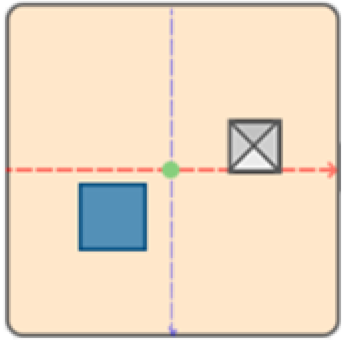
World Space



Coordinates of all the objects are relative to some global origin of the world

We use a model matrix which translates, scales and/or rotates the object to place it in the world

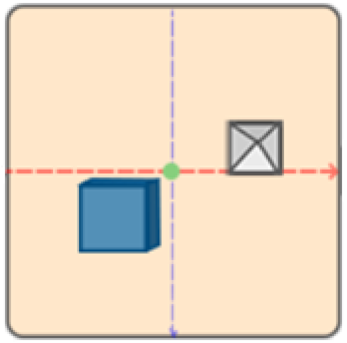
View Space



Each coordinates is seen from the camera's point of view

This is done by a combination of translations & rotations of the scene which is stored in a view matrix

Clip Space



Each coordinates is seen from the camera's point of view

For this step, we use a <u>projection matrix</u> which transform the coordinates into NDC

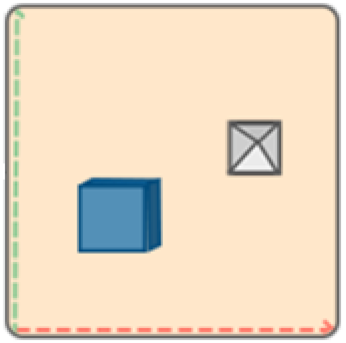
Example:

Specified range [-1000, 1000] for each dimension

(1250, 500, 750) → Not visible

(900, 500, 750) → Visible

Screen Space

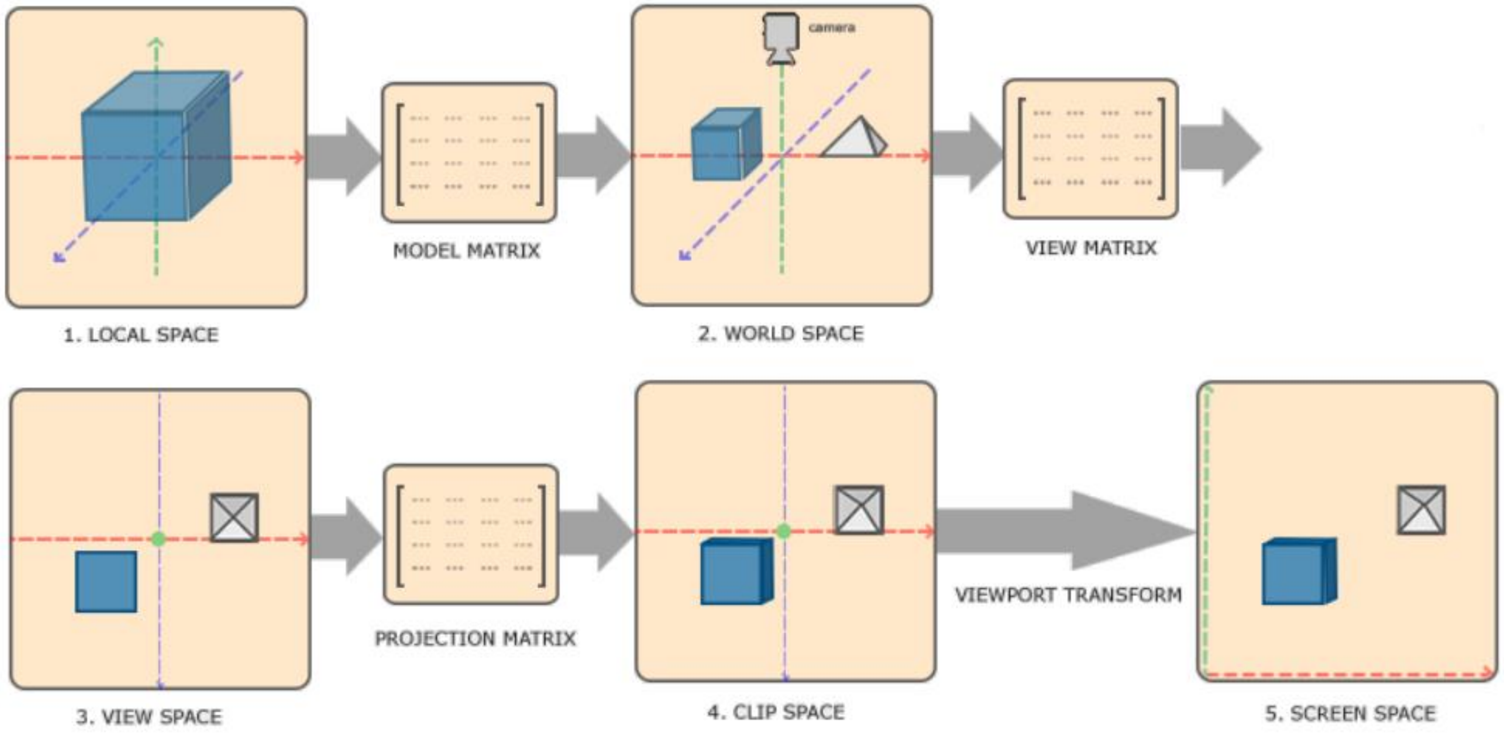


Transforms the NDC coordinates to the window coordinates with the *glViewport()* function

Resulting coordinates are then sent to the rasterizer

Overall view

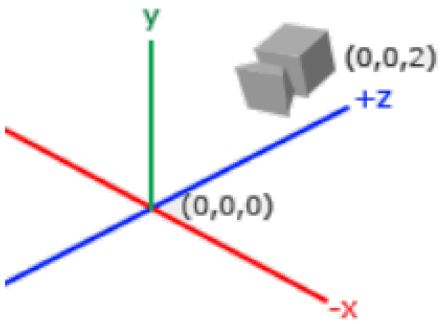
A vertex coordinate is transformed to clip coordinates as follow: $V_{clip} = \underline{M_{projection} \cdot M_{view} \cdot M_{model}} \cdot V_{local}$



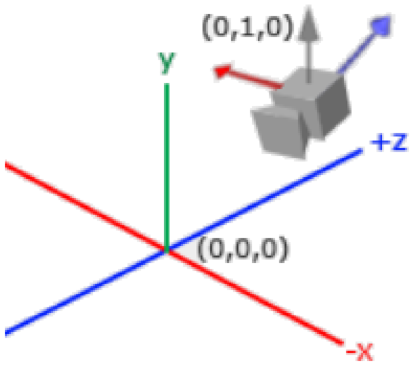
Source: https://learnopengl.com/Getting-started/Coordinate-Systems

Camera

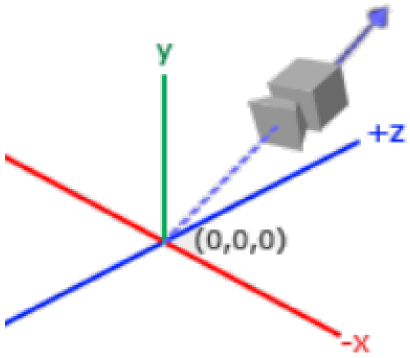
To define a camera we need 4 pieces of information



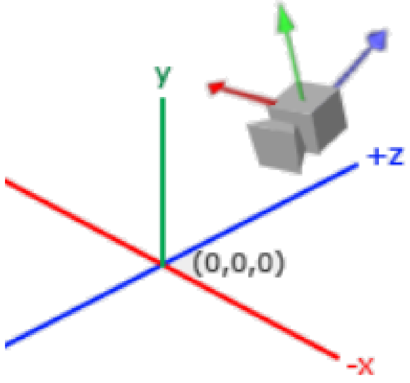
1. Its position in the world space



3. A vector pointing to the right

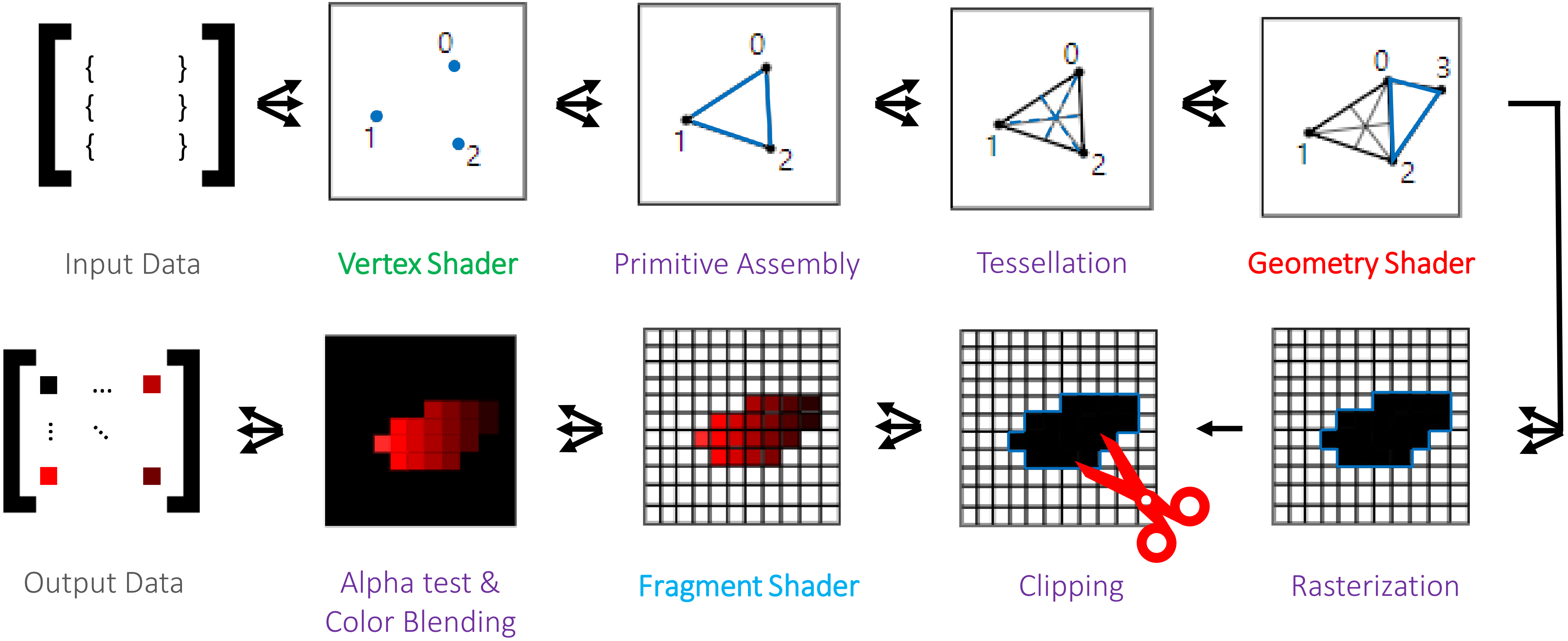


2. Its direction



4. A vector pointing upwards

Recall : Graphics pipeline



Pipeline abstraction

We can see the pipeline as a function composition which can give us:

$$output\_data = (\mathrm{cb} \circ \mathrm{at} \circ \mathrm{fs} \circ \mathrm{c} \circ \mathrm{r} \circ \mathrm{t} \circ \mathrm{pa} \circ \mathrm{vs})\ (input\_data)$$

Fragment Shader function

Vertex Shader function

Recall: Input data

A VBO is built containing the attributes of all vertices which give us a huge vector of data

To work with that, we have to use offsets, strides, etc.

Idea of the abstraction

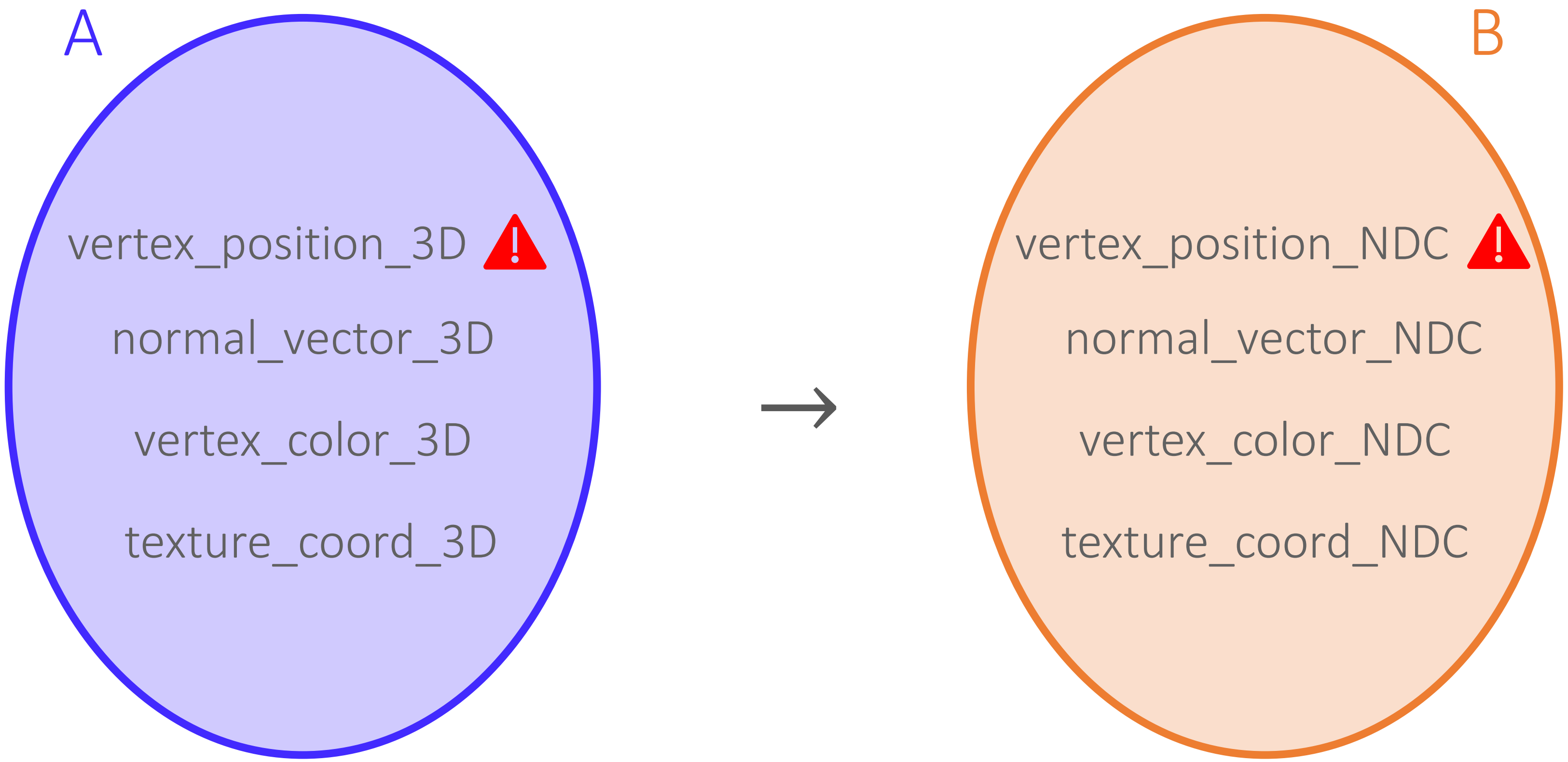
No longer working with containers of type

Ex: vec3, ~~vec4, ivec4~~, mat4, …

But with abstract type objects

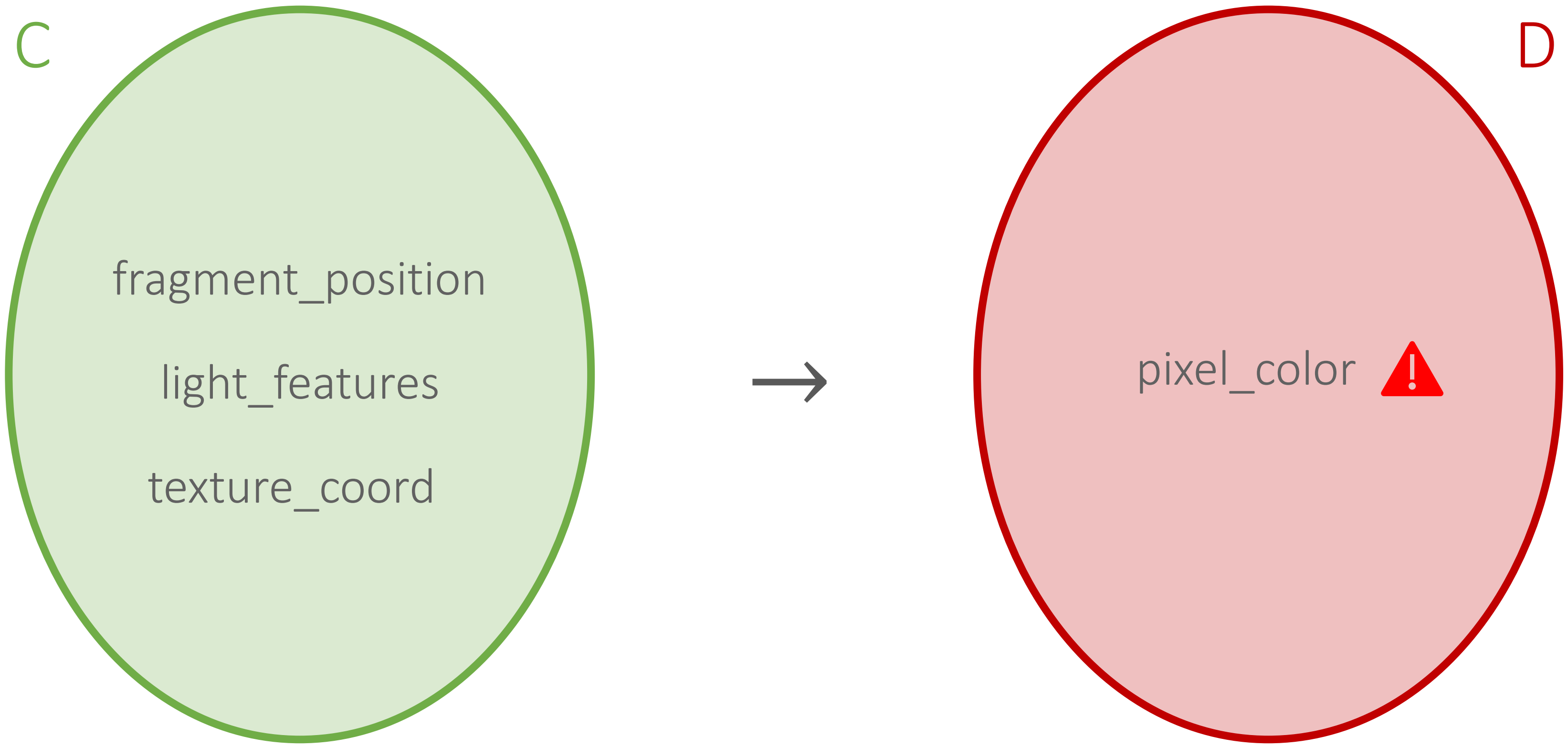
Ex: color, position, textures, …

Vertex Shader function $\quad$ vs : A → B



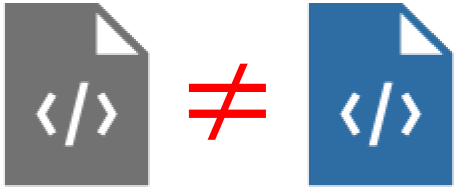
vs(position: normal: color: texture:)

Fragment Shader function   fs : C → D



fs(fragment: light: texture:)

Several signatures



Depending on why a shader is created, the signature will be different

vs(position: normal?: color?: texture?:)

fs(fragment?: light?: texture?:)

Uniforms

Uniform variables must be considered
in the signature

vs(position: normal?: color?: texture?: [+uniforms]?:)

fs(fragment?: light?: texture?: [+uniforms]?:)

Constraints

Names and types variables shared between the vertex & the fragment shader must be identical which implies

subset(B) ⊂ C

Example:

```
#version 330 core
layout (location = 0) in vec3 aPos;

out vec4 vertexColor;

void main()
{
    gl_Position = vec4(aPos, 1.0);
    vertexColor = vec4(0.5, 0.0, 0.0, 1.0);
}
```

Vertex shader

```
#version 330 core
out vec4 FragColor;

in vec4 vertexColor;

void main()
{
    FragColor = vertexColor;
}
```

Fragment shader

Recall : Different languages

DirectX High-Level Shader Language

(Unreal Engine)

Cg Shader Language

(Unity)

OpenGL Shading Language

Similar structures

A sample Cg vertex shader:

Types definition

Calculate output coordinates & colors

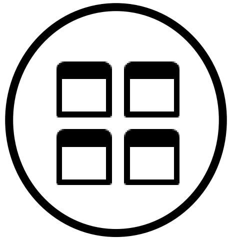
Uniform keyword

Output

```
// input vertex
struct VertIn {
    float4 pos   : POSITION;
    float4 color : COLOR0;
};

// output vertex
struct VertOut {
    float4 pos   : POSITION;
    float4 color : COLOR0;
};

// vertex shader main entry
VertOut main(VertIn IN, uniform float4x4 modelViewProj) {
    VertOut OUT;
    OUT.pos     = mul(modelViewProj, IN.pos);
    OUT.color   = IN.color;
    return OUT;
}
```

Same abstraction

The different shader languages are very similar



We could therefore use the same abstraction for any language

Domain-Specific Language (DSL)

A DSL is a programming language whose specifications allow to overcome some constraints in a specific domain

The specific domain will be for us the shaders and especially vertex & fragment shaders

Advantages & disadvantages

✓

A DSL will allow us to gain in productivity

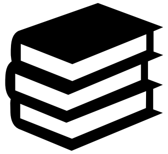
DSL can be reused for other purposes

✗

These new languages can be redundant & not standard

Work incoming

Begin to work with Rendery



To document more about other shader languages

Learn more about DSL & SIMD language

References

https://learnopengl.com

https://fr.wikipedia.org/wiki/Shader

https://fr.wikipedia.org/wiki/OpenGL

https://fr.wikipedia.org/wiki/DirectX

https://developer.apple.com/metal

https://github.com/RenderyEngine/Rendery

https://www.khronos.org/opengl/wiki

https://en.wikipedia.org/wiki/Domain-specific_language

Working with shaders

Patrick SARDINHA