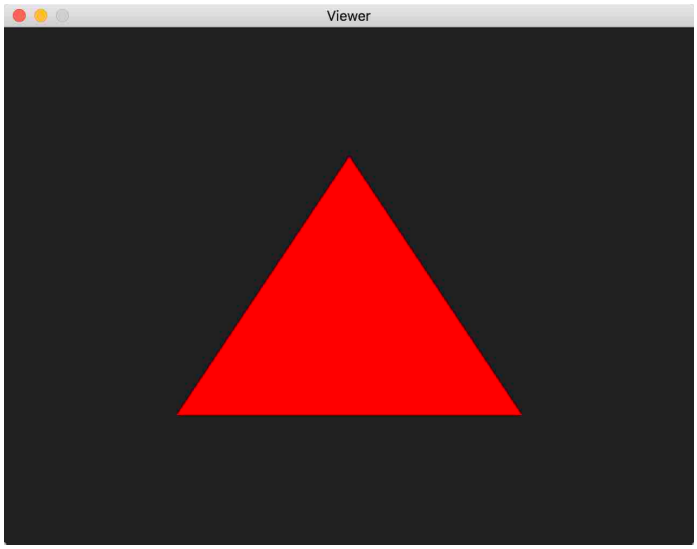
# Practical 1 - First steps

The main objectives of this practical are:

- making first contact with the OpenGL API, the GLSL shader language and the rendering pipeline
- basics of the OpenGL coordinate systems
- analyze a simple OpenGL code example and rendering loop
- learning to pass data from the main Python application to the GPU code and basic usage in the shader

We will jump-start with a bare-bones PyOpenGL (http://pyopengl.sourceforge.net) viewer application. Run it with the shell command **python3 viewer.py**.

**`Download viewer.py`** (_downloads/79adbb6b97f48006d5cf61728cd586f1/viewer.py)




(_images/triangle.jpg)

If all goes well, you should be getting this window.

# Examining the Python code

A graphics application usually has the following basic structure:

1. Create a window and OpenGL context (active set of rendering states)
2. Initialize OpenGL render state
3. Setup our render scene and objects, upload their resources to GPU
4. Run an infinite render loop which draws the scene and processes events, with the following steps:
    a. Clear the screen
    b. Update scene state and draw our scene objects
    c. Swap the draw and the viewed buffers for seamless transitions (more below)
    d. Process events (keyboard, mouse…) for user interaction
5. Cleanup on exit

The rendering loop 4 is thus at the heart of the application and everything else before is there to prepare for it.

Flatly following the structure above in a program is OK for small scenes, but it would be cumbersome as soon as we have several objects in a scene. Thus scenes are usually broken down in objects with their own state, initialization and draw code. This is what we did here for the **`SimpleTriangle`** class of objects.

We also abstract the application window with its OpenGL state initialization and rendering loop as the **`Viewer`** class. Scene objects can be added to its list of render objects using its **`add()`** method, as seen in the **`main()`** entry point:

```
def main():
    viewer = Viewer()
    viewer.add(SimpleTriangle())
    viewer.run()
```

Let us describe how the 5 main steps introduced above materialize in the code:

## 1. Create window and context

Creating the **`Viewer()`** object invokes the Viewer initializer **`__init__()`**. It uses GLFW (http://www.glfw.org) to create a system window and an OpenGL context associated to that window, which is basically a set of internal OpenGL draw states used for drawing in that window. It then makes that context active so subsequent OpenGL commands modify that particular set of states:

```
glfw.window_hint(glfw.CONTEXT_VERSION_MAJOR, 3)
glfw.window_hint(glfw.CONTEXT_VERSION_MINOR, 3)
glfw.window_hint(glfw.OPENGL_FORWARD_COMPAT, GL.GL_TRUE)
glfw.window_hint(glfw.OPENGL_PROFILE, glfw.OPENGL_CORE_PROFILE)
glfw.window_hint(glfw.RESIZABLE, False)
self.win = glfw.create_window(width, height, 'Viewer', None, None)
glfw.make_context_current(self.win)
```

Hints tell GLFW to initialize the window and context with certain characteristics, such as using OpenGL 3.3 or more for our context.

## 2. Initialize OpenGL render state

The **`Viewer.__init__()`** initializer also contains code for one-time OpenGL application state settings, such as initializing the OpenGL clear color, and initializing shaders, which is the code to be executed on GPU:

```
GL.glClearColor(0.1, 0.1, 0.1, 0.1)
self.color_shader = Shader(COLOR_VERT, COLOR_FRAG)
```

Shader code needs to be compiled, linked, checked and uploaded only once to GPU for later use throughout the application. For this we provide a helper class **`Shader`** . Its initializer gets passed a Python string for a vertex shader, the code that the GPU will execute at every vertex primitive passed, and a string for the fragment shader, the code the GPU will execute at every fragment (= pixel candidate).

## 3. Setup our scene objects

After the call to the initializer, objects can be added to the scene, with their initializer setting up its specific OpenGL state. As in the **`SimpleTriangle`** example provided, this typically consists in loading an OpenGL Vertex Array to the GPU, basically an array of user defined vertex attributes that will be needed to transform and draw the object. Here we use only one attribute in the Vertex array, the vertex **`position`** containing the three 3D coordinates of our triangle vertices:

```
# Numpy array of our three 3D coordinates
position = np.array(((0, .5, 0), (.5, -.5, 0), (-.5, -.5, 0)), np.float32)

self.glid = GL.glGenVertexArrays(1)            # create a vertex array OpenGL identifier
GL.glBindVertexArray(self.glid)                # make it active for receiving state below

self.buffers = [GL.glGenBuffers(1)]            # create one OpenGL buffer for our position
GL.glEnableVertexAttribArray(0)                # assign state below to shader attribute lay
GL.glBindBuffer(GL.GL_ARRAY_BUFFER, self.buffers[0])              # our created position b
GL.glBufferData(GL.GL_ARRAY_BUFFER, position, GL.GL_STATIC_DRAW)  # upload our vertex data
GL.glVertexAttribPointer(0, 3, GL.GL_FLOAT, False, 0, None)       # describe array unit as
```

## 4. Rendering loop

Once all this setup work is done, the render loop can be executed using the call to **`Viewer.run()`** , with exactly the four steps a, b, c, d we introduced above:

```
while not glfw.window_should_close(self.win):                    # while no close request
      GL.glClear(GL.GL_COLOR_BUFFER_BIT)                          # a. clear the screen
      for drawable in self.drawables:                             # b. draw scene objects
          drawable.draw(...)
      glfw.swap_buffers(self.win)                                 # c. double buffering sw
      glfw.poll_events()                                          # d. process system even
```

a. First we need to clear the screen with the previously defined clear color to start with a fresh frame (else we would get pixels from the previous frame)

b. The only assumption we make about drawables is that they have a parameter-compatible **`draw()`** method. For now we are just drawing our triangle object in the **`SimpleTriangle.draw()`** method. For this we need to tell OpenGL what shader to use, which vertex array to use, how the vertices in the array will be assembled to actual primitives (here a `GL_TRIANGLE` tag means we're flatly describing an array of triangles, one triangle per group of three vertices in the array), and how many vertex primitives are in our original array (3 vertices, thus describing one triangle):

```
GL.glUseProgram(color_shader.glid)
GL.glBindVertexArray(self.glid)
GL.glDrawArrays(GL.GL_TRIANGLES, 0, 3)
GL.glBindVertexArray(0)
```

This code therefore results in calls to the code of the **`color_shader`** shader program, which we will discuss in more detail below with the GPU-side code section.

Note that setting all bind states to zero once finished is good practice to avoid accidentally updating a bound state later in the code. The Vertex Array bind here would otherwise stay active until the next **`glBindVertexArray()`** call.

c. The classic double buffering (http://nasutechtips.blogspot.fr/2011/02/double-buffering-in-computer-graphics.html) strategy in computer graphics is as follows: to avoid displaying partially drawn frames which would result in flickering and visual artifacts, we always render to a *back* buffer while a finished *front* buffer is displayed, and swap the back and front buffer once drawing the back buffer is complete. GLFW transparently creates the two buffers when intializing the window.

d. We can process our own events in event handlers, as shown with **`Viewer.on_key()`** to process user keystroke events, as long as the handler is registered to our GLFW window in the initializer. The handler gets notified during the main loop's **`glfw.poll_events()`** call.

## 5. Cleanup

OpenGL requires explicit cleanup calls to release previously allocated objects using their id. We take advantage of Python classes and their destructors so that such cleanup is automatically executed when the Python object is destroyed / unscoped, for the Shader or the **`SimpleTriangle`** class of objects, as shown below:

```
def __del__(self):
    GL.glDeleteVertexArrays(1, [self.glid])
    GL.glDeleteBuffers(1, self.buffers)
```

Keep in mind that the Python version of these calls takes an iterable (here we stored them as a list) of index objects, which is why we used **`[self.glid]`** to put the single Vertex Array id in a list here.

**Note**

The OpenGL context must exist when these destructors are called since they contain OpenGL calls. If you try to make calls to OpenGL code before or after the life of your OpenGL context, you will get exceptions.

This is why we put the general GLFW initialization and termination at the topmost, global scope of the script, such that any objects added in the **`main()`** function or subcalls are sure to be destroyed before the **`glfw.terminate()`** call, which destroys our OpenGL context:

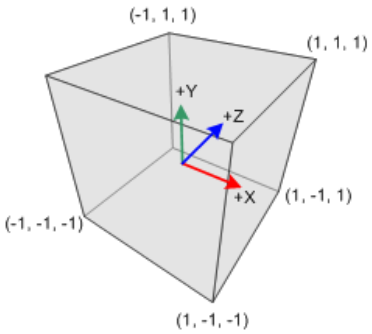
```
if __name__ == '__main__':
    glfw.init()                # initialize window system glfw
    main()                     # main function keeps variables locally scoped
    glfw.terminate()           # destroy all glfw windows and GL contexts
```

# GPU-side code

GLSL (https://www.khronos.org/opengl/wiki/OpenGL_Shading_Language) code is given for the two main stages, the vertex shader, and fragment shader stages. Additional stages exist but are optional, in fact we will not use them in these practicals. Version 330 shaders and beyond all receive a pre-processor `#version` directive declaring the compability information of the shader code.

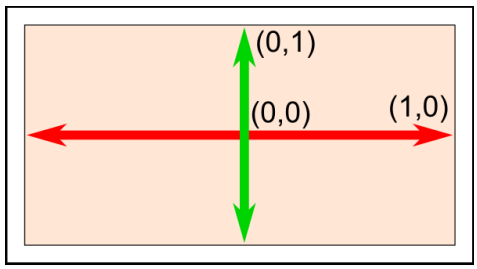
## Vertex shader

The vertex shader describes how each vertex is transformed to the homogeneous 4-vector clipping coordinates of the camera (aka normalized device coordinates), between -1 and 1 in every first 3 dimensions, and performs any per-vertex computation that may be useful for drawing.




(_images/clip_space.png)

Clip volume in normalized device coordinates




(_images/screenCoordinates.png)

Normalized screen coordinates

The clip coordinates of the vertex are to be stored in a GLSL built-in variable **`gl_Position`** . For now our shader assumes we already give it clipping coordinates and store it as the result directly:

```
#version 330 core
layout(location = 0) in vec3 position;
void main() {
    gl_Position = vec4(position, 1);
}
```

The vertex shader receives the per-vertex attributes that were passed when the above vertex array was created for intended use with this shader. Vertex attributes received from CPU arrays are tagged with the *in* qualifier. Here only one attribute is passed, **`position`** . **`vec3`** indicates that its type is a 3x 32-bit float vector. The `layout (location=0)` qualifier indicates that the attribute is assigned a layout index 0, such that it is passed whichever CPU array attribute that was enabled with index 0 with the **`glEnableVertexAttribArray(0)`** function call. The location also refers to the first parameter of **`glVertexAttribPointer(0,...)`** that specifies which array to define.

Notice that since we pass **`position`** $\in \mathbb{R}^3$, we need to extend it as **`vec4`** with a unit scale factor, since **`gl_Position`** expects a $\mathbb{R}^4$ homogeneous 3D vector.

## Fragment shader

The fragment shader describes how a fragment is to be drawn. A fragment is a pixel candidate, meaning it outputs a value for a pixel, which may still be overwritten. A given pixel in a drawn frame may have had several fragment calls.

The given fragment shader first declares what variable will be used to store the output color to be used for drawing the fragment (here **`outColor`** ). It must be a 4 dimensional vector of floats $\in [0, 1]$, the first 3 being the RGB color and the fourth an alpha transparency value we will use later on and keep to one for now. The given shader just uniformly draws pixels in red:

```
#version 330 core
out vec4 outColor;
void main() {
    outColor = vec4(1, 0, 0, 1);
}
```

# Exercises

## 1. Playing with the shader

- The red color is currently hardcoded in the fragment shader. Change the triangle color to green, blue.
- Try adding constant offsets on x, y and z, to the output clip coordinates in the vertex shader. What happens when your triangle goes beyond the clipping coordinate limits?

## 2. Color as shader uniform

Let's pass the triangle color as a program parameter.

OpenGL allows to pass user defined shader global parameters, called **uniform variables**. Global means they are to be specified only once per shader for all vertices and fragments, per primitive, object or even once per frame, depending on intended use. Syntaxically, in the vertex or fragment shader, you declare them in the prefix section of the shader with other variables, but with the *uniform* qualifier, as follows. For now, we will focus on passing just a color as vector of 3 floats to the fragment shader:

```
#version 330 core
uniform vec3 color;
out vec4 outColor;
void main() {
    ...
}
```

On the CPU side, to pass program values to this variable, you first need to get its shader program *location* using **`glGetUniformLocation()`** , basically an OpenGL id to address this variable. Location queries use the program id returned by a **`glCreateProgram()`** call, which is provided here by the member **`glid`** of our **`Shader`** class in our framework, and the string name of the variable to locate. Once the location is obtained, you can proceed to send a Python triplet to the shader:

```
my_color_location = GL.glGetUniformLocation(color_shader.glid, 'color')
GL.glUniform3fv(my_color_location, 1, (0.6, 0.6, 0.9))
```

The suffix **3fv** specifies that we're passing a vector type (**v**) of three floats (**3f**). (The second parameter of the **`glUniform3fv()`** call specifies how many vector values you wish to pass: useful for arrays, we don't use this other than 1 for now).

- Place the above Python code in the **`draw()`** method of your **`SimpleTriangle`** class
- Use the value obtained in the shader as the ouput color of your fragment shader. Beware that you need to extend it to vec4 with 1 as last value to obtain a valid output color.
- The above example is still a static color, even though passed from the CPU. Let's make it more interesting: add a color parameter to the **`SimpleTriangle.draw()`** method and modify your **`Viewer`** code to initialize a color member in **`__init__()`** , pass it to your triangle in **`run()`** , and let the user modify it interactively by associating it to key events in the **`on_key()`** callback method.

## 3. Varying the color with position

Currently the vertex and fragment shaders are not communicating. The vertex shader can output arbitrary values or vectors to the fragment shader, which will receive an interpolated version of them. For this, the variable needs to be declared with the `out` qualifier in the vertex shader, and `in` qualifier in the fragment shader, with the same variable name.

- Try passing down the clipping coordinates to the fragment shader, then use them to generate smoothly varying fragment colors. Try first replacing the output value with this new interpolated value, then try adding it to the uniform from the previous question to see the effect of both. What happens when generated colors get outside of their intended range $[0, 1]$? You can try applying offsets or functions to your color vectors to keep them smoothly varying in that range.

## 4. Colors as vertex attributes

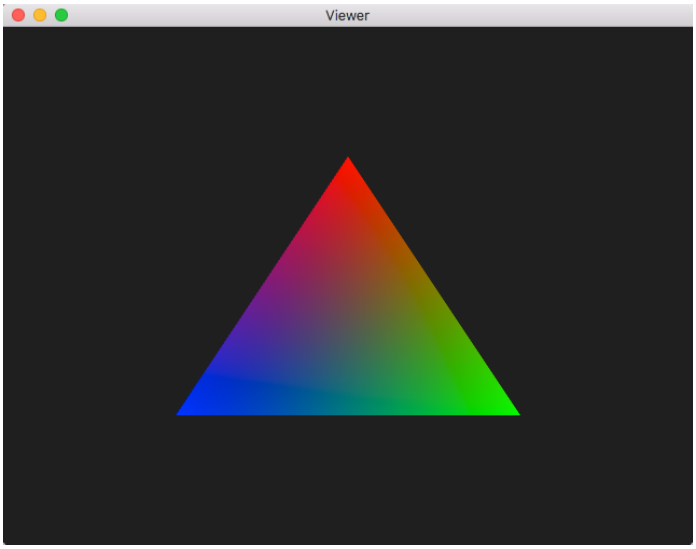
Directly inferring the color from clipping coordinates is quite constrained and mostly for demonstration purposes. Let's try passing per-vertex colors as user-defined attributes. For this you will need to reproduce all the steps that exist in the code for the **`position`** attribute, for a new attribute **`color`** :

- Modify the initializer of the **`SimpleTriangle`** class to add a second vertex buffer to our vertex array. Pass it a numpy array of 3x 3-vectors for user-defined vertex colors, for example red, green and blue, and assign it to the layout index 1.

  **Warning**

  The layout index appears as the first parameter of both the **`glEnableVertexAttribArray()`** and **`glVertexAttribPointer()`** functions. Also, **`glGenBuffers()`** returns a scalar index value when used with argument one ` ( `glGenBuffers(1)` ) but returns a list of indices when used with argument > 1

- Modify the shader program to receive the new attribute and also pass an interpolated version of it from vertex to fragment shader (replacing your previous interpolated variable).
- Don't forget to make sure the newly created vertex buffer is in the list of buffers to be destroyed in the object finalizer!




(_images/triangleColorAttrib.png)

What you should get when assigning red, blue and green as vertex attributes

## 5. Object Transforms

We made great progress on shaders but our scene is quite static still and up to now only expressed in clip space $[-1, 1]^3$. We need the ability to reposition objects and express them in any metric. Recall that 3D points are expressed in homogeneous coordinates with 4-vectors $\in \mathbb{R}^4$. So all rigid or affine 3D transforms $\mathbb{R}^4 \rightarrow \mathbb{R}^4$, are expressed as $4 \times 4$ matrices.

For convenience we provide a small Numpy-based transform module to experiment with, to be placed in the same directory as `viewer.py` :

**`Download transform.py`** (_downloads/8779a270ec6c50ad0ccff91e33cd0cf0/transform.py)

You can take a look at the matrix functions as they are pretty straightforward. Let us only focus on basic transforms for now, by including this at the beginning of the `viewer.py` file:

```
from transform import translate, rotate, scale, vec
```

Let's apply these transforms to the rendered object *in the shader*. Let us first consider rotating the object around the origin of the clip space.

- First, similarly to 2. Color as shader uniform, you want to modify your Python **`SimpleTriangle.draw()`** method to pass a $4 \times 4$ rotation matrix, here a 45 degree rotation around y axis for example:

  ```
  matrix_location = GL.glGetUniformLocation(color_shader.glid, 'matrix')
  GL.glUniformMatrix4fv(matrix_location, 1, True, rotate(vec(0, 1, 0), 45))
  ```

  Sidenote: the third boolean parameter **`True`** indicates that the matrix is passed in row major order, which is how Numpy stores bi-dimensional matrix arrays.

- Second, modify your *vertex shader*, to receive this matrix uniform, and use it to transform the position of each vertex. Position being a `vec3` , it needs to be extended to a vec4 homogeneous vector of scale 1:

```
uniform mat4 matrix;
layout(location = 0) in vec3 position;
...
void main() {
    gl_Position = matrix * vec4(position, 1);
    ...
}
```

- On the Python side, try to pass different rotations, try applying **`scale()`**, and then try composing both a scale and a rotation. You can compose transforms in Python using the `a @ b` matrix multiplication operator over Numpy arrays.

  **Warning**

  `a * b` on Numpy arrays is the coefficient-wise product, **not** the matrix product

- Now use **`translate()`** to pass a translations to the shader. What happens if you translate the object along z only? You can try composing it with a rotation and scale as well.

## 6. Projection Transform

The reason for what's happening in the last question is: there is no foreshortening in our model yet. Once in normalized device (or clipping) coordinates, OpenGL just retains the x and y components for rendering, which amounts to a 1:1 orthographic projection. Let's add perspective projections to our program to have renderings that mimic real cameras:

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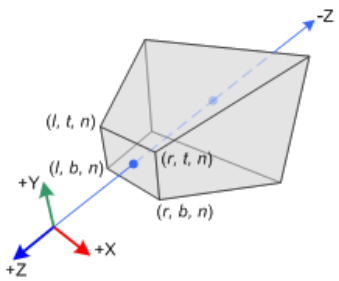
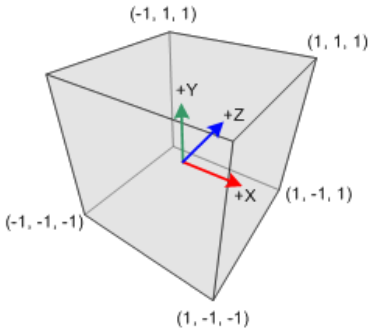



(_images/frustum.png)

Frustum clipping volume in camera coordinates before projection




(_images/clip_space.png)

Clipping volume in normalized device coordinates

For this, we have the **`perspective()`** function from the **`transform.py`** (_downloads/8779a270ec6c50ad0ccff91e33cd0cf0/transform.py) module, parameterizing the frustum using its vertical field of view in degrees and the camera aspect ratio (width / height in pixels), and both a **near** and **far** parameter indicating the distance from the front and back clipping planes of the frustum.

- first import it from the transform module:

```
from transform import perspective
```

- experiment with the function. For this you need to compose the projection matrix with a view matrix ( = camera placement matrix) translating the triangle such that it is inside the clipping planes of the frustum.

  **Question:** what is the right matrix multiplication order to apply to the projection and view matrices here?

- There are two ways to obtain the product of the projection and view matrices in your shader:

  1. Either pass both the projection and view matrices to your shader as uniforms and perform a matrix

multiplication at each vertex with the GLSL * matrix product operator

2. Or, as in the previous question, compute the product on the CPU-side with the dedicated Numpy matrix product operator `a @ b` and pass the result in one uniform matrix.

# Remarks, optional improvements

We gained understanding of how to pass variables, attributes and transforms, and use them in the shader. Regarding transforms, as seen in the course, actually three types of transforms are used in practice: projection, view, and model, for which we gave parameters placeholders in the **`draw()`** method call. We'll come back to those in more detail in Practical 3 - Hierarchical modeling (practical3.html).

- To observe your objects, you will strongly benefit from implementing some form of viewpoint control, for example, keyboard arrows controlling the object self-rotation capability you have just implemented.
- If you want more interactive viewing flexibility for the next practicals, you may consider adding the Virtual Trackball (recipes.html#trackball) code snippet to your program.

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