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Computer Graphics Assignment about the Shader Pipeline

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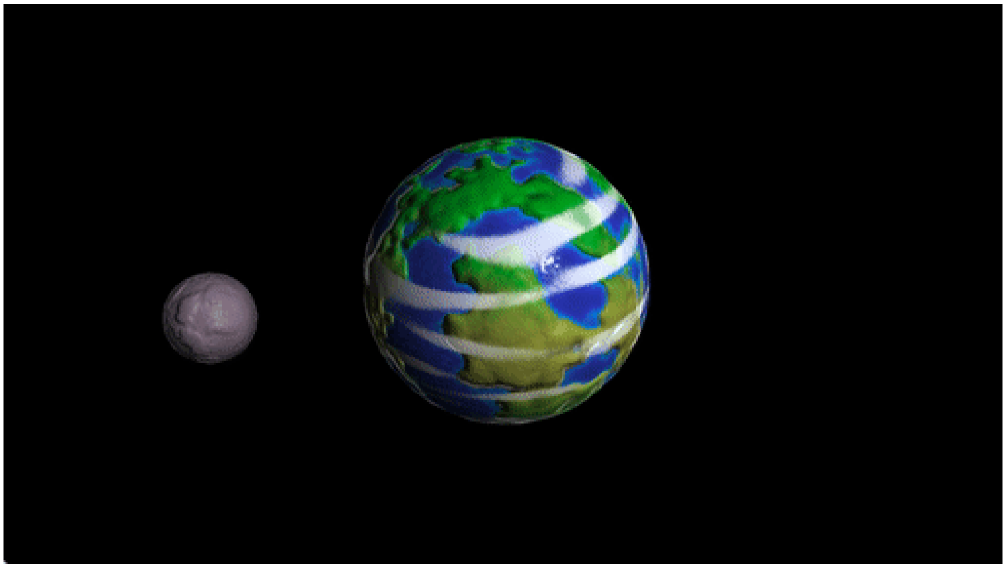
Computer Graphics – Shader Pipeline

> **To get started:** Clone this repository and all its submodule dependencies using:
>
> ```
> git clone --recursive https://github.com/alecjacobson/computer-graphics-shader-pipeline.git
> ```

Do not fork: Clicking "Fork" will create a *public* repository. If you'd like to use GitHub while you work on your assignment, then mirror this repo as a new *private* repository: https://stackoverflow.com/questions/10065526/github-how-to-make-a-fork-of-public-repository-private

> **Note for Windows users:** Windows Subsystem for Linux (WSL) is not supported for this assignment. At the time of writing, it does not support OpenGL 4.x, which is required for this assignment to run tessellation shaders.



Background

> **Review chapters 6, 7 and sections 8.1-8.2 of *Fundamentals of Computer Graphics (4th Edition)*.**

Read Sections 11.4-11.5 and Chapter 17 of *Fundamentals of Computer Graphics (4th Edition)*.

In this assignment, we will use the "real-time rendering" shader pipeline and procedural rendering to create interesting pictures.

GLSL

Your work will be implemented using the OpenGL shading language (glsl). In many ways, glsl code looks like C++ code. However, there are many builtin linear algebra types (e.g., `vec3` is a 3D-vector type) and geometric functions (e.g., `dot(a,b)` computes the dot product between vectors `a` and `b` . Since vectors are often used to represent spatial coordinates *or* colors. We can index the coordinates of a vector (`vec3 a`) using `a.r` , `a.g` , `a.b` or `a.x` , `a.y` , `a.z` . When working with perspective projection it's often useful to employ 4D homogeneous coordinates vectors: `vec4` in glsl. Glsl has many builtin ways to work with differently sized vectors and matrices. For example, if we have `vec4 h` then we can write `vec3 p = h.xyz;` to grab the first three coordinates. Similarly, we could write: `vec4 h = vec4(p,1.0)` to convert a 3D Cartesian point to a 4D homogeneous point.

Fortunately, there are many online resources and googling a glsl-related question often returns helpful answers.

On the CPU side

The shaders you write in this assignment will run on the GPU. Let's breifly describe what's happening on the CPU side.

A pseudo-code version of `main.cpp` might look like:

```
main()
  initialize window
  copy mesh vertex positions V and face indices F to GPU
  while window is open
    if shaders have not been compiled or files have changed
      compile shaders and send to GPU
    send "uniform" data to GPU
    set all pixels to background color
    tell GPU to draw mesh
    sleep a few milliseconds
```

Window

Creating a window is clearly something that will depend on the operating system (e.g., Mac OS X, Linux, Windows). This assignment, like many small scale graphics programs or games, uses an open source windowing toolkit called glfw. It works on all major operating systems. Once the window is open we have access to its contents as an RGB image. The job of our programs are to fill in all the pixels of this image with colors. The windowing toolkit also handles interactions with the mouse and keyboard as well as window resizing.

Shader compilation

Unlike your C++ code, shaders are compiled *at runtime*. This has a nice advantage that you can change your shaders without restarting the main program. So long as the change is noticed and the shaders are recompiled, the rendering will be immediately updated.

Compilation errors (usually syntax errors) will be output from the main program and the window will turn black (background color). For example, if your *fragment shader* contained:

```
#version 410 core
in vec3 pos_fs_in;
out vec3 color;
void main()
{
  color = pos_fs_in.x;
}
```

You would see an error printed to the screen:

```
ERROR: failed to compile fragment shader
ERROR: 0:6: Incompatible types (vec3 and float) in assignment (and no
available implicit conversion)

ERROR: One or more attached shaders not successfully compiled

ERROR: Failed to link shader program
```

If you change this file, the main program should immediately notice the change before drawing the next frame. If successful there will be no error message and the screen may now draw something interesting.

Data on the GPU

From the perspective of the shader pipeline, data on the GPU is separated into different types. For example, when we send the mesh vertex positions to the GPU we're associating one 3D position *per vertex*. This data is considered an "attribute" of each vertex. Each vertex invokes a single execution of the vertex shader and its corresponding position is given as the `in vec3 pos_vs_in;` variable. The output of the vertex shader will be "varying" depending on the input and computation conducted. Your program is responsible for setting this output value in `out vec3 pos_cs_in` . This variable is named ending with `_cs_in` because it will in turn be used as input to the next shader in the pipeline *tessellation control shader*.

Small amounts of data that is constant and independent of the particular vertex/tessellation patch/fragment being processed is labeled as "uniform" data. The prototypical example of this is the perspective projection matrix: `uniform mat4 proj` . Uniform data is usually changed once per draw frame (e.g., `uniform float time_since_start` is updated with the number of seconds since the start of the program) or once per "object" (e.g., `uniform bool is_moon;` is set based on whether we're drawing the first or second object in our scene).

Large amounts of data that may be randomly accessed by shaders is stored in "texture" memory (e.g., color texture images). This data must be accessed by sampling specific pixel values based on a given 2D locations (e.g., the U.V. mapping of a fragment).

Tessellation Control Shader

The tessellation control shader determines how to subdivide each input "patch" (i.e., triangle). Unlike the subdivision we saw with subdivision surfaces, the subdivision is determined independently for each triangle and *not* called recursively. The exact pattern of the resulting triangulation is left largely to implementation. As the shader programmer, you have control over:

- the number of new edges each input each should split into (`gl_TessLevelOuter[1] = 5` means the edge across from vertex `1` (i.e., the edge between vertices `0` and `2`) should be split into 5 edges); and
- the number of edges to place toward the center of the patch (`gl_TessLevelInner[0] = 5` would be a good choice if `gl_TessLevelOuter[...] = 5` and a regular tessellation was desired).

Unlike the vertex or fragment shader, the tessellation control shader has access to attribute information at *all* of the vertices of a triangle. The main responsibility of this shader is setting the `gl_TessLevelOuter` and `gl_TessLevelInner` variables.

> **Question:** If the amount of subdivision along each edge is determined independently for each triangle, how can we make sure neighboring triangles subdivide their shared edge the same amount?
>
> **Hint:** ✌️

Tessellation Evaluation Shader

The tessellation *evaluation* shader takes the result of the tessellation that the tessellation *control* shader has specified. This shader is called once for every vertex output during tessellation (including original corners). It has access to the attribute information of the original corners (e.g., in our code `in vec3 pos_es_in[]`) and a special variable `gl_TessCoord` containing the barycentric coordinates of the current vertex. Using this information, it is possible to interpolate information stored at the original corners onto the current vertex: for example, the 3D position. Like the vertex and tessellation control shader, this shader can change the 3D position of a vertex. This is the *last opportunity* to do that, since the fragment shader cannot.

How come I can't use `#include` ?

Our glsl shader programs are not compiled from files. Instead the CPU-side program must read the file contents into memory as strings and provide the raw strings to the shader compiler. Unfortunately, this means there is no `#include` preprocessor directive and sharing code across different shaders is a burden.

In this assignment, we will use a `.json` file to collect the different files whose contents are ***concatenated*** to form the input string to be compiled for each shader. For example, in `data/test-01.json` you'll see:

```
{
  "vertex": [ "../src/version410.glsl","../src/pass-through.vs"],
  "tess_control": [ "../src/version410.glsl","../src/pass-through.tcs"],
  "tess_evaluation": [ "../src/version410.glsl","../src/pass-through.tes"],
```

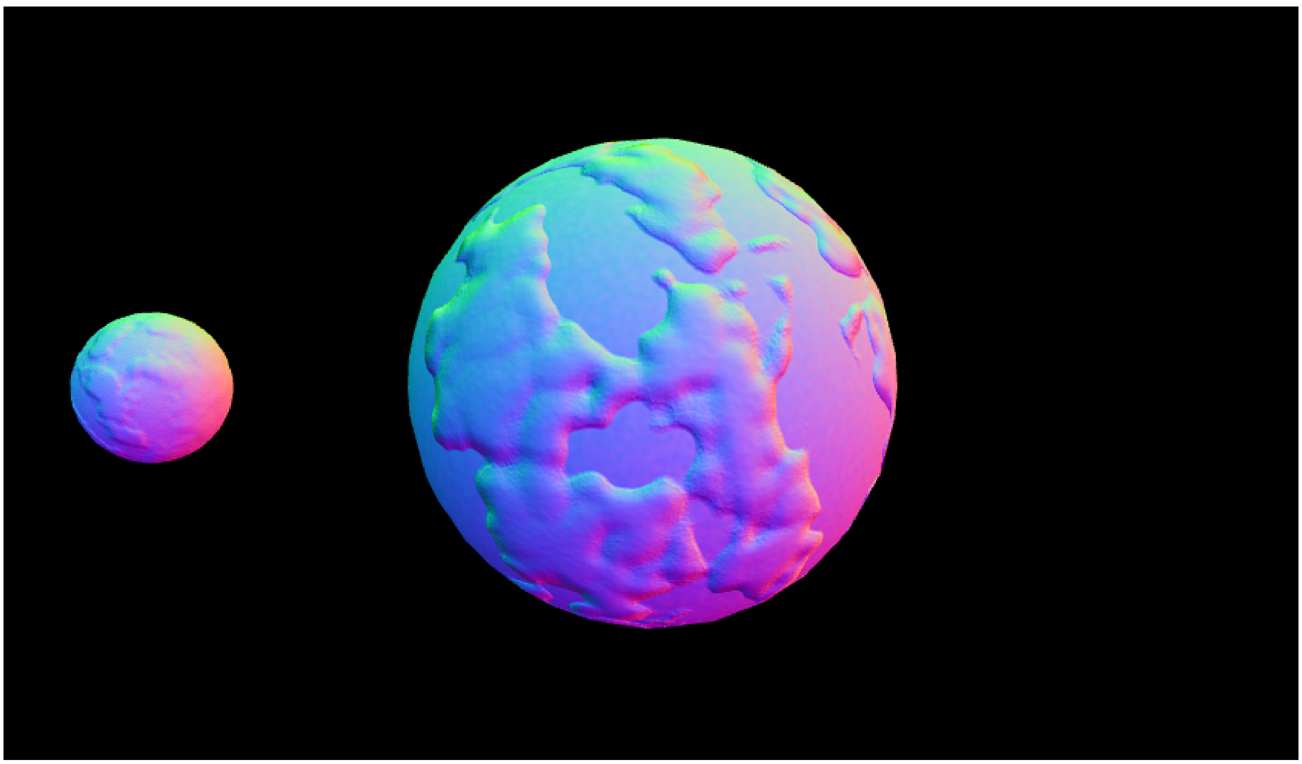
```
    "fragment": [ "../src/version410.glsl","../src/pass-through.fs"]
  }
```

This indicates that the string for the vertex shader is the concatenation of two (2) files `../src/version410.glsl` and then `"../src/pass-through.vs"` . Similarly, for each of the other shaders.

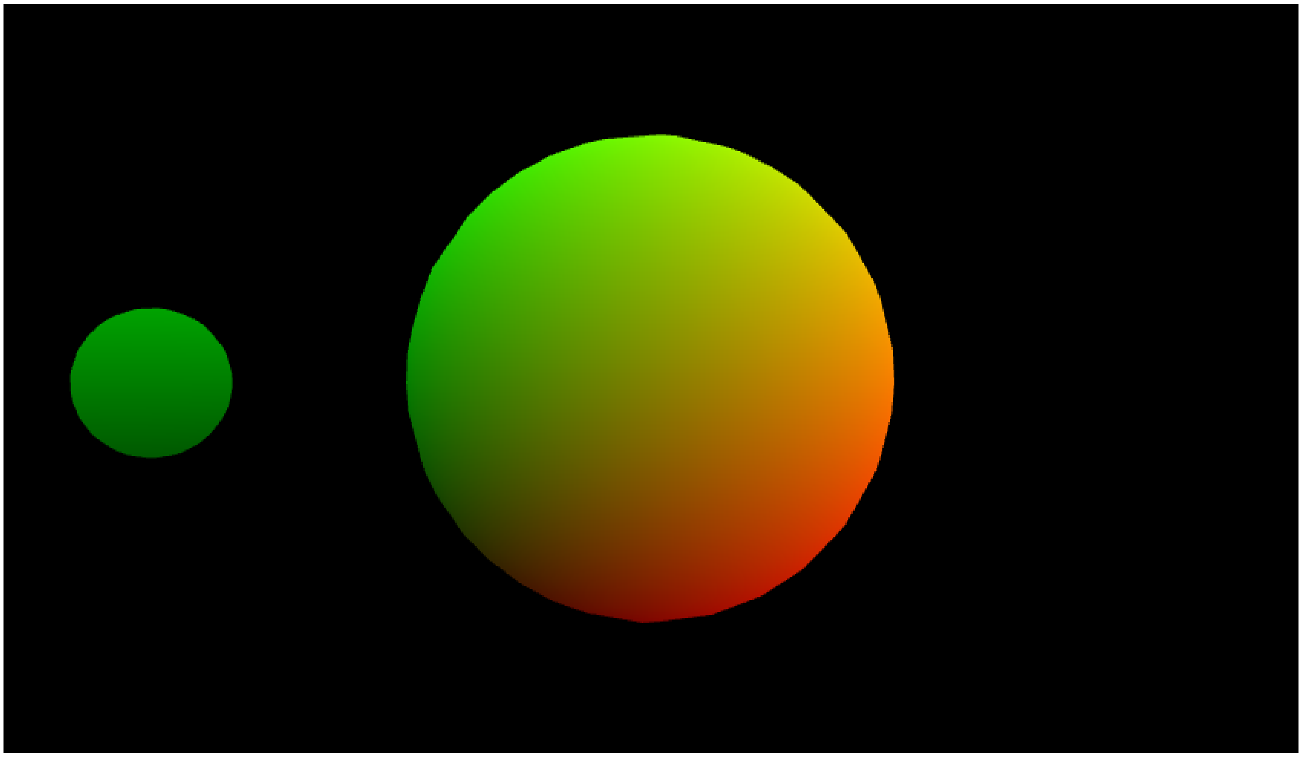
Shader debugging

Debugging shader programs must be done visually. Since we only see the result of *all* computation, we can use the shader pipeline's ability to set screen colors to debug *all* computation simultaneously. For example, when debugging the fragment shader we can check all values at once by setting the pixel color to a value we expect (or don't expect) depending on the computation. A few useful commands come in handy:

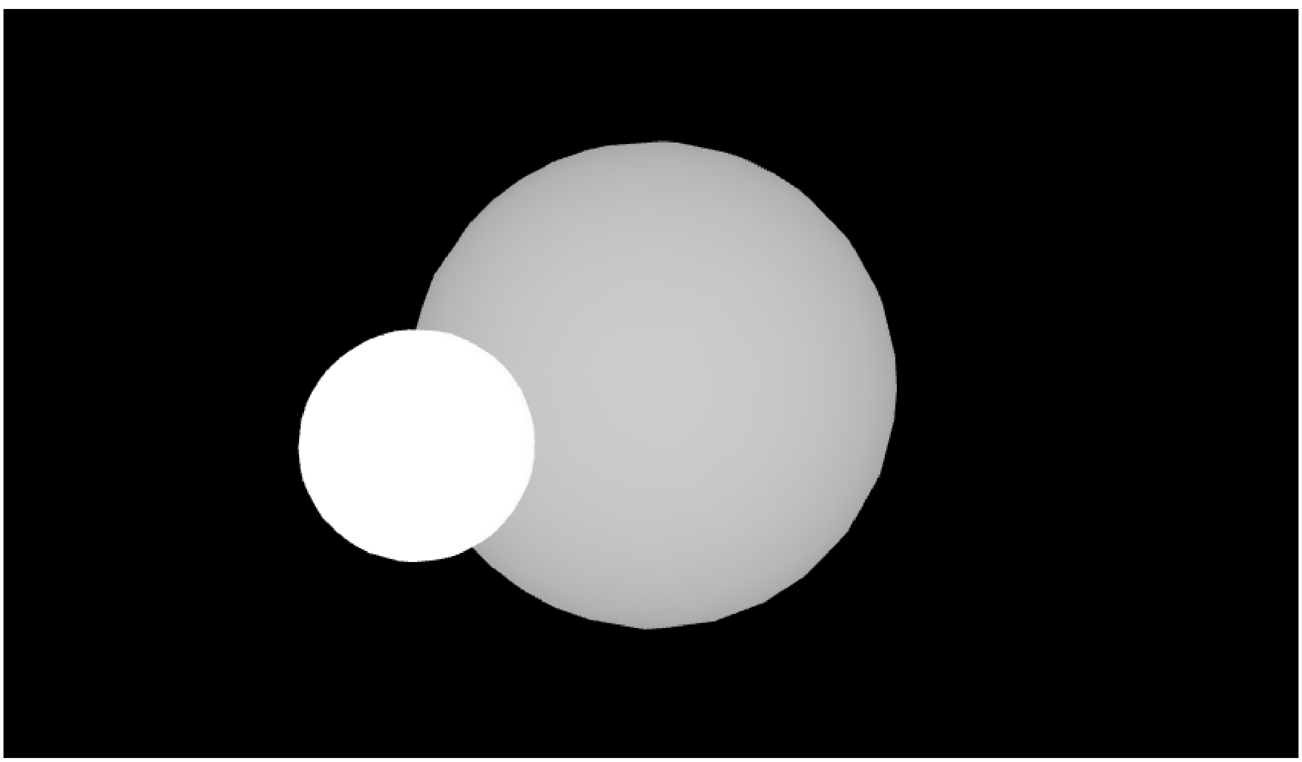
`color = 0.5+0.5*n;` will set the color based on the normal.



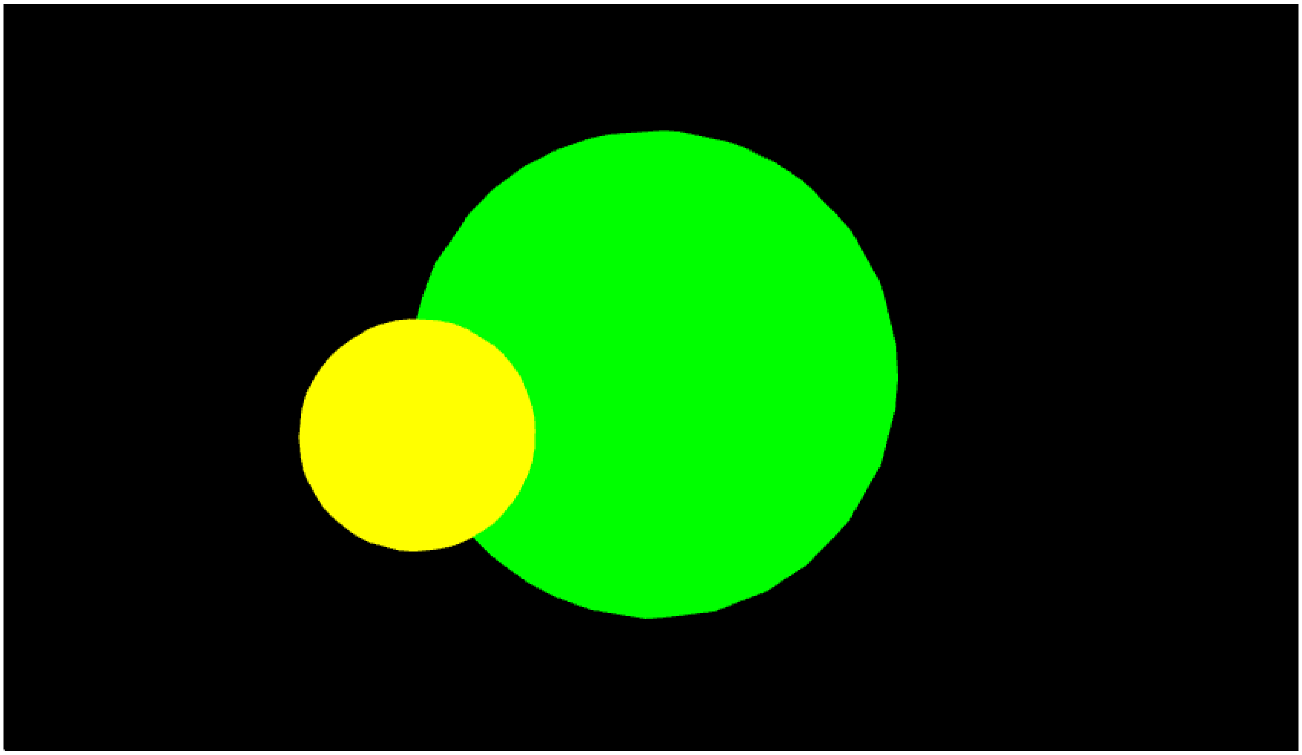
`color = vec3(0.5,0.5,0)+vec3(0.5,0.5,0)*view_pos_fs_in.xyz` will set the color based on the 2D position.



`color = (1+(view_pos_fs_in.z - -3)/5)*vec3(1,1,1);` will set the color based on the distance to the camera in the z-direction.



`color = vec3(float(is_moon),1,0);` will set the color to yellow or green based on a boolean value (in this case `is_moon`).



Bump and normal maps

A **bump map** is a mapping from a surface point to a displacement along the normal direction. A **normal map** is a mapping from a surface point to a unit normal vector. In a mathematical sense, a normal map is non-sense. A point on a surface has a specific normal completely determined by its local geometry. The normal is the direction that goes in the *most outward* direction from the surface. That is, the normal is perpendicular to the surface. Since a surface is two dimensional, the directions that *stay on* the surface are spanned by a two dimensional *tangent plane*.

Normal mapping is useful in computer graphics because we can drape the appearance of a complex surface on top a low resolution and simple one. To create a consistent and believable looking normal map, we can first generate a plausible bump map. Each point $\mathbf{p} \in \mathbb{R}^3$ on the surface is moved to a new position $\tilde{\mathbf{p}} \in \mathbb{R}^3$:

$$\tilde{\mathbf{p}}(\mathbf{p}) := \mathbf{p} + h(\mathbf{p})\ \hat{\mathbf{n}}(\mathbf{p}),$$

where $h : \mathbb{R}^3 \rightarrow \mathbb{R}$ is the bump height amount function (could be negative) and $\hat{\mathbf{n}}(\mathbf{p}) : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ is the *mathematically* correct normal at $\mathbf{p}$.

If our bump height h is a smooth function over the surface, we can compute the *perceived* normal vector $\tilde{\mathbf{n}}$ by taking a small finite difference of the 3D position:

$$\tilde{\mathbf{n}} = \frac{\partial\ \mathbf{p}}{\partial\ \mathbf{T}} \times \frac{\partial\ \mathbf{p}}{\partial\ \mathbf{B}} \approx \left(\frac{\tilde{\mathbf{p}}(\mathbf{p} + \epsilon\mathbf{T}) - \tilde{\mathbf{p}}(\mathbf{p})}{\epsilon}\right) \times \left(\frac{\tilde{\mathbf{p}}(\mathbf{p} + \epsilon\mathbf{B}) - \tilde{\mathbf{p}}(\mathbf{p})}{\epsilon}\right)$$

where $\mathbf{T}, \mathbf{B} \in \mathbb{R}^3$ are orthogonal tangent and bi-tangent vectors in the tangent plane at $\mathbf{p}$ and ϵ is a small number (e.g., `0.0001`). By abuse of notation, we'll make sure that this approximate perceived normal is unit length by dividing by its length:

$$\tilde{\mathbf{n}} \leftarrow \frac{\tilde{\mathbf{n}}}{\|\tilde{\mathbf{n}}\|}.$$

> **Question:** Can we always recover *some* orthogonal tangent vectors $\mathbf{T}$ and $\mathbf{B}$ from the unit normal $\mathbf{n}$?
>
> **Hint:** ☝️

Tasks

There are no header files. Accordingly, this assignment is organized a bit differently. The `src/` directory contains glsl files whose contents should be completed or replaced. Some of the functions have an element of creative freedom (e.g., `src/bump_position.glsl`), while others are have a well-defined specification (e.g., `src/identity.glsl`).

Since glsl does not support `#include` , the comments may hint that a previously defined function can/should/must be used by writing `// expects: ...` .

You may check the corresponding `.json` example file to see specifically which glsl files are loaded (and in which order) for each test program.

Unless otherwise noted, ***do not declare new functions***.

White list

- `mix`
- `normalize`
- `length`
- `clamp`
- `sin`
- `cos`
- `abs`
- `pow`

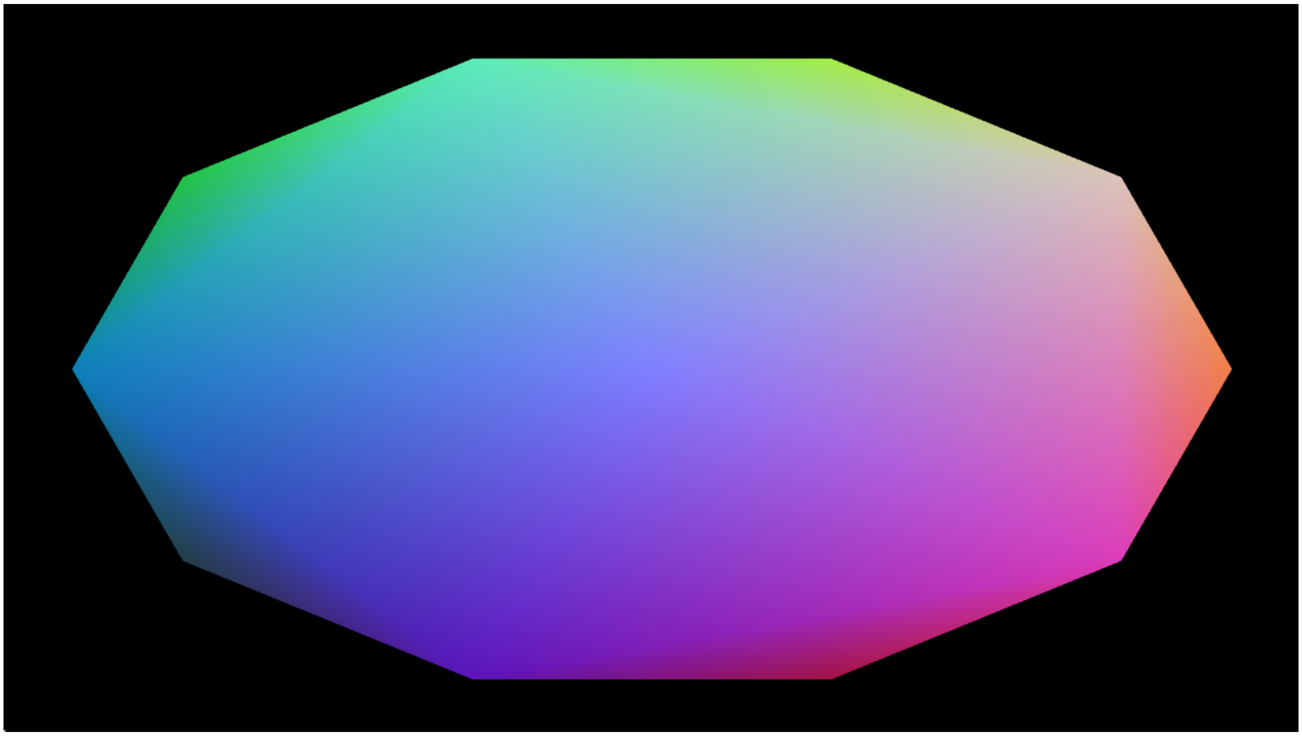
Black list

- `noise1`
- `noise2`

- `noise3`
- `noise4`

This assignment works best if you implement the following tasks *in order*.

Before editing anything be sure that your opengl and shader setup is correct. If you run `./shaderpipeline ../data/test-01.json` you should see this image:



`src/identity.glsl`

`src/uniform_scale.glsl`

`src/translate.glsl`

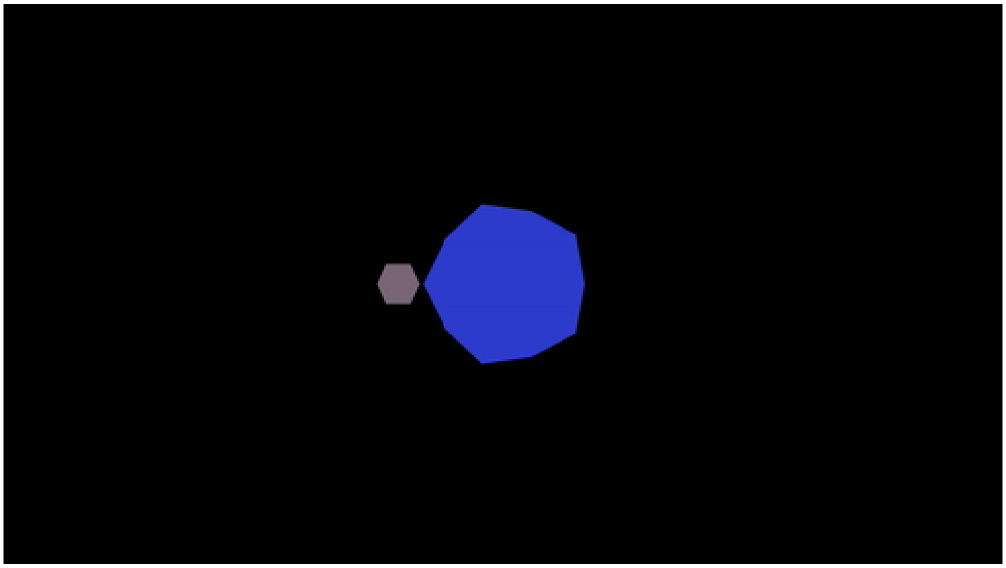
`src/rotate_about_y.glsl`

`src/model.glsl`

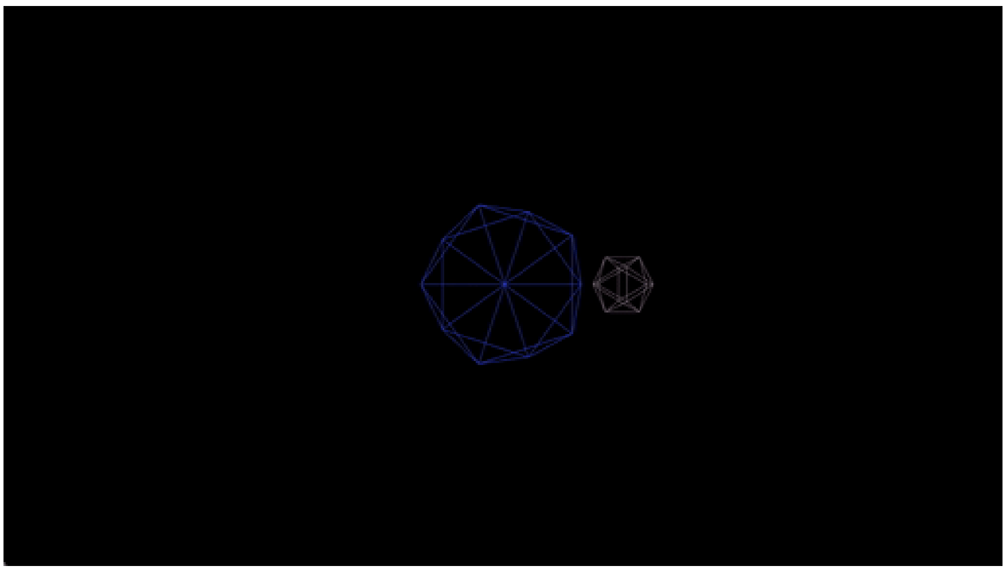
`src/model_view_projection.vs`

`src/blue_and_gray.fs`

With these implemented you should now be able to run `./shaderpipeline ../data/test-02.json` and see an animation of a gray moon orbiting around a blue planet:

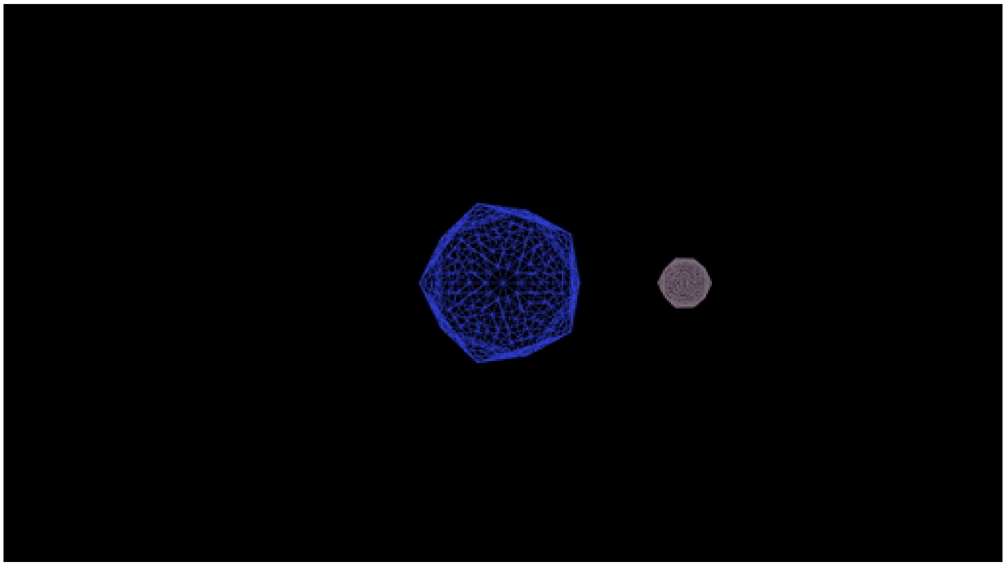


If you press `L` this should switch to a wireframe rendering:



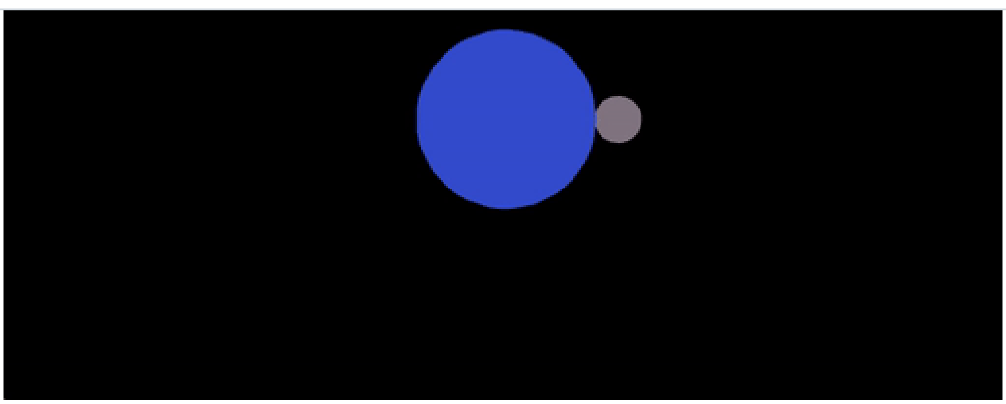
`src/5.tcs`

Running `./shaderpipeline ../data/test-03.json` and pressing `L` should produce an animation of a gray moon orbiting around a blue planet in wireframe with more triangles:



`snap_to_sphere.tes`

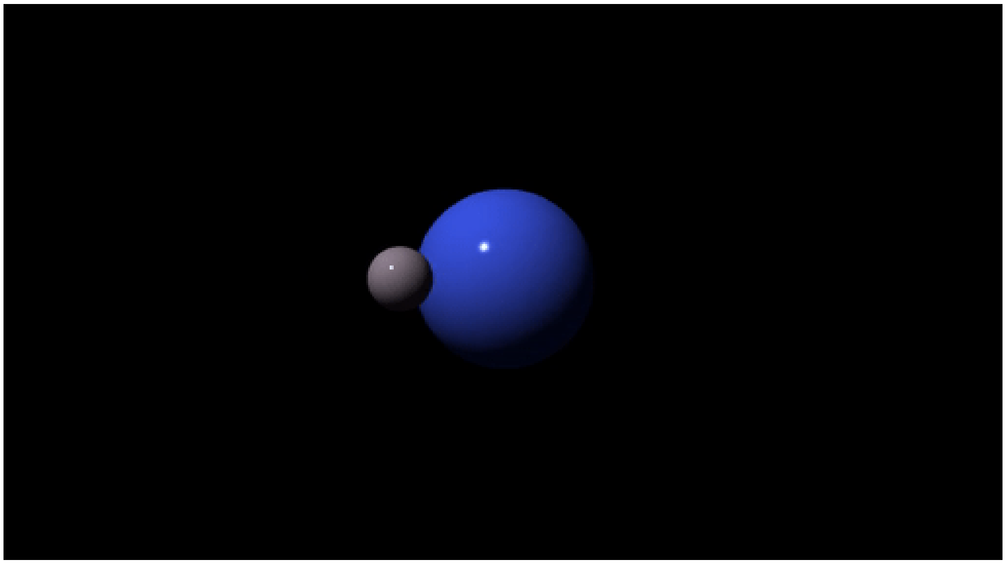
Move your model-view-projection operations from the vertex shader (e.g., `model_view_projection.vs`) to the tessellation evaluation shader. In addition, snap the vertices of each shape to the unit sphere before applying these transformations. This gives your shapes a round appearance if you run `./shaderpipeline ../data/test-04.json` :



`blinn_phong.glsl`

`lit.fs`

Running `./shaderpipeline ../data/test-05.json` adds light to the scene and we see a smooth appearance with specular highlights:



`random_direction.glsl`

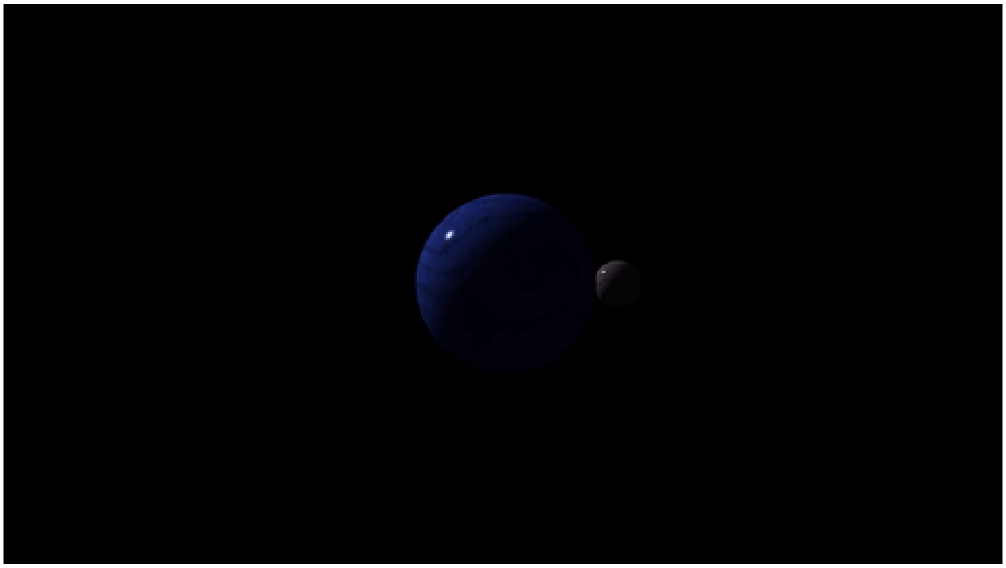
`smooth_step.glsl`

`perlin_noise.glsl`

`procedural_color.glsl`

Be creative! Your procedural colored shape does not need to look like marble specifically and does not need to match the example. Mix and match different noise frequencies and use function composition to create an interesting, complex pattern.

Running `./shaderpipeline ../data/test-06.json` adds a procedural *color* to the objects. The color should ***not*** change based on the view or model transformation. For example, this animation attempts to recreate a marble texture:



`improved_smooth_step.glsl`

`improved_perlin_noise.glsl`

`bump_height.glsl`

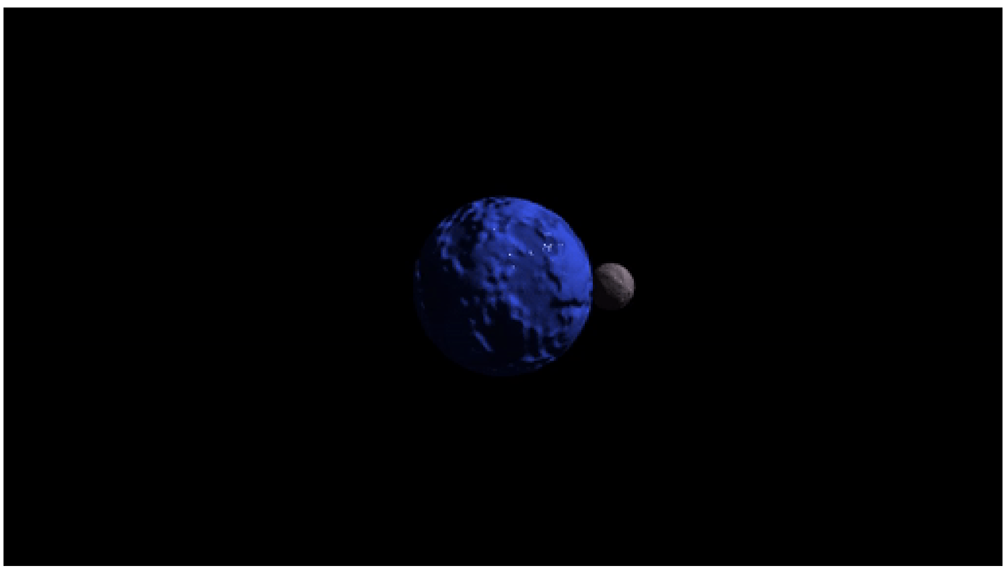
`bump_position.glsl`

`tangent.glsl`

`bump.fs`

Be creative! Your bumpy shape does not need to match the example.

Running `./shaderpipeline ../data/test-07.json` adds a normal map determined by differentiating a procedural bump map. The color should ***not*** change based on the view or model transformation. For example, this animation attempts to recreate the (very) bumpy appearance of planets and moons:



For this file, you ***may*** declare new functions: declare them directly at the top of `bump.fs` ; do not modify the .json files.

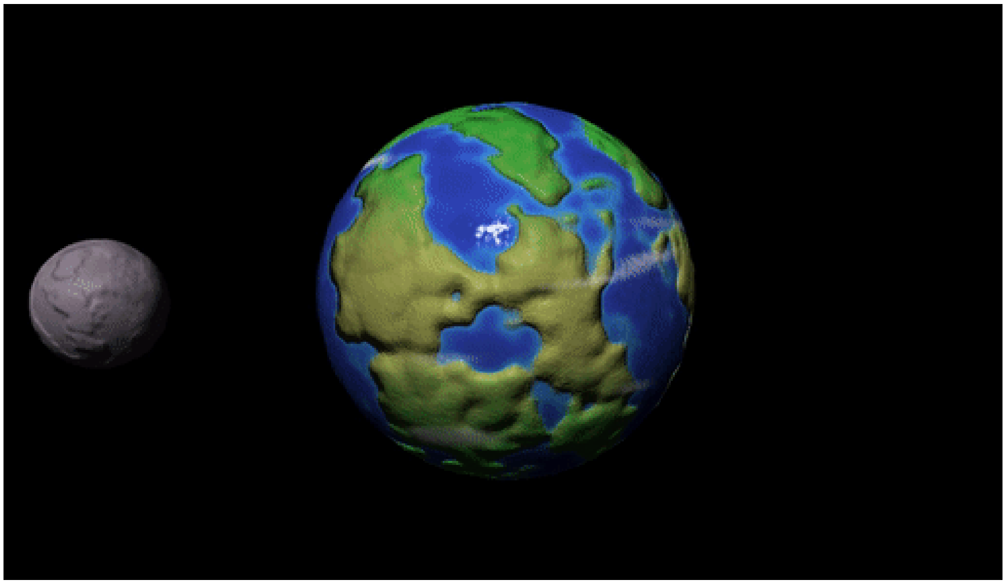
`planet.fs`

For this file, you ***may*** declare new functions: declare them directly at the top of `planet.fs` ; do not modify the .json files.

Be creative! Your planets do not need to look like the earth/moon and do not need to look like the example planets.

> **Hint:** Sprinkle noise on *everything*: diffuse color, specular color, normals, specular exponents, color over time.

Running `./shaderpipeline ../data/test-08.json` should display a creative planet scene. For example:



Releases

No releases published

Packages

No packages published

Languages

- **C++** 73.8%
- **C** 22.6%
- **CSS** 2.0%
- **GLSL** 1.4%
- **CMake** 0.2%