2017/2018, 4th quarter

INFOGR: Graphics

Practical 1: OpenTK Tutorial

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Based on the (now ancient) 2015 XNA tutorial.

The assignment:

The purpose of this assignment is to do a tutorial that takes you through the basics of 3D programming. We expect you to work through this tutorial and familiarize yourself with all the concepts and implementations provided here. The idea is to get to know 3D computer graphics from a programmer's perspective, i.e., to see how a modern 3D API works, and to familiarize yourself with the anatomy of an interactive 3D graphics application. You will need to use what you learn here for the second and third practical assignments, which will be more challenging than this one.

When doing the tutorial, you will create two programs that perform basic rendering. Opposed to last year, you do not have to hand in anything; the first assignment does not contribute to your grade and merely prepares you for things to come…

Figure 1: first result on Google for "ominous".

Setting up OpenTK for C# in Microsoft Visual Studio

For this assignment, we will be using Microsoft Visual Studio 2017 to develop in C#. OpenTK is used to interface with OpenGL.

In more detail:

- Microsoft Visual Studio can be obtained free of charge for academic purposes via the following link:
  https://www.visualstudio.com/en-us/products/visual-studio-community-vs.aspx
  You need a Microsoft account to be able to sign in and download the software. Please follow the instructions on the website. The most recent version is the 2017 Community edition; this will do just fine.
- For this course, we will assume you develop using C#. Since we focus on OpenGL, it is also possible to develop in C++. This tutorial does however not cover this. The use of other programming languages (especially Java) is not recommended for this course.
- C# does not simply let you work with OpenGL. For this we use OpenTK, which is a simple 'wrapper' for OpenGL. This means that it exposes the functionality of OpenGL from C#, while the underlying OpenGL functionality remains clearly visible. That means that anything you learn using C#/OpenTK will still be useful if you later want to work with OpenGL directly.
- OpenGL is a low level interface to the graphics hardware in your machine. It is a well-established standard for this, and, unlike DirectX, it is not tied to a specific vendor. OpenGL and DirectX bear strong similarities. That means that anything you learn using OpenGL will still be useful if you later want to work with DirectX (or any other graphics API).

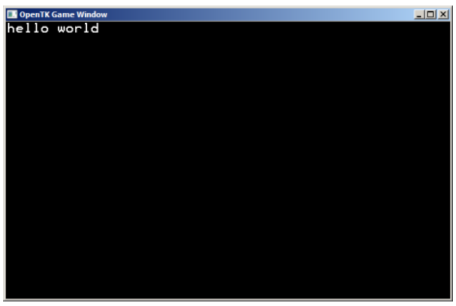
We will be using a small C# template application that provides you with some minimal graphics functionality.

In the first part of this tutorial, we will use this template to explore some basic concepts.

In the second part of this tutorial, we will expand the template so we can use OpenGL graphics via OpenTK.

Preparations:

1. Download the INFOGR template code from the website.
2. Extract the zip file to a folder on your harddisk.
3. Open the .sln file and compile the code.
4. Run the program. You should see the following output:



If this all works, proceed to PART 1.

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INFOGR: Graphics

Part 1: Basic 2D Operations using the template

Architecture

The template consists of three source files:

- `template.cs`
- `surface.cs`
- `game.cs`

The file `game.cs` is where we will be building our application. Class Game has two methods: `void Tick()`, which will be executed once per frame, and `void Init()`, which will be executed precisely once, when the application starts. There is also a single member variable `screen`, which represents the pixels in the window, as well as basic functionality to operate on these pixels.

This functionality represents the typical game application flow: after initializing the game (loading levels and sounds, setting up the state of the world, etc.) we need to produce a steady flow of frames. Each *tick* we will want to update the state of the world, and visualize this state. For this course, we will obviously focus on the visualization aspect.

The code that calls the `Tick` function can be found in template.cs, but we will ignore this for now. Two things are worth mentioning however: the first is that the frame rate is locked at 30 frames per second (fps); the second is that the template constantly monitors your ESC key; hitting it terminates the application.

Class Surface

The only member variable of the Game class is of type Surface. The implementation of this class can be found in surface.cs. Instances of Surface own a 1D array of integers, representing the pixels of the surface. Despite the 1D array, a surface typically is 2-dimensional; it has a width and a height. To read a single pixel using an x,y-coordinate, we must thus calculate the correct location in this array:

```
int location = x + y * width;
```

Reading a pixel can now be done using

```
int pixel = screen.pixels[location];
```

and writing to the pixel is done as follows:

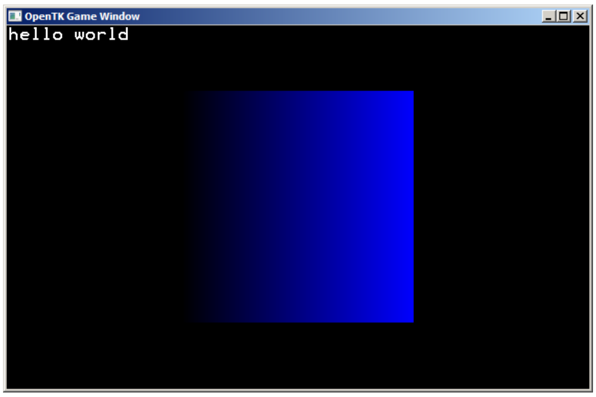
```
screen.pixels[location] = 255;
```

A single integer thus represents a color. To understand how this works, it is important to see that an integer actually consists of four bytes: it is a 32-bit value. For colors, we store red, green and blue each in a byte. This leaves us 1 byte (8 bits), which we will not use.

The first byte in the integer can store values of 0…255. These will show up as blue colors.

Exercise 1: write some code in the Tick function that draws a square of pixels in the middle of the window. Make the square 256 pixels wide, and use a unique value between 0 and 255 for each column of the square.

Depending on your interpretation of the exercise, the output could look something like this:



To get to the other bytes in the integer value, we need to use values that exceed 255. Value 256 for example yields a green rectangle (but: a very dark one). To get all shades of green, we use values 0...255, but we multiply them by 256, effectively shifting them 8 bits up. To get all shades of red, we again use values 0...255, but we multiply them by 256 * 256, shifting them up by 16 bits.

A convenient way to create a red color value would be:

```
int CalculateRedColor( int shade ) { return shade * 256 * 256; }
```

Now if we also had a green color value, we could blend the two to obtain yellow:

```
int yellow = CalculateRedColor( 255 ) + CalculateGreenColor( 255 );
```

There is an easier (and potentially faster) way to get our red shade: using bitshifting. Looking at a color as a binary value, a multiplication by 256 can be achieved by shifting values 8 bits to the left. This lets us define a fast and convenient method for constructing colors:

```
int CreateColor( int red, int green, int blue )
{
   return (red << 16) + (green << 8) + blue;
}
```

Here, red, green and blue are values between 0 and 255.

Exercise 2: modify the code from the first exercise so that it draws a gradient. Translate x to red, and y to green.

Coordinate Systems

The coordinate system of our window is simple: the template defaults to a 640x400 window, and therefore x ranges from 0...639, and y from 0...399. There are several problems with this:

1. designing an application for a single resolution is limiting;
2. the coordinate system is not centered;
3. the y-axis is inverted.

For many applications it is important to decouple window resolution from the coordinate system used for the simulation.

Suppose we want to draw a spinning square in the center of the window. Drawing the square is straightforward:

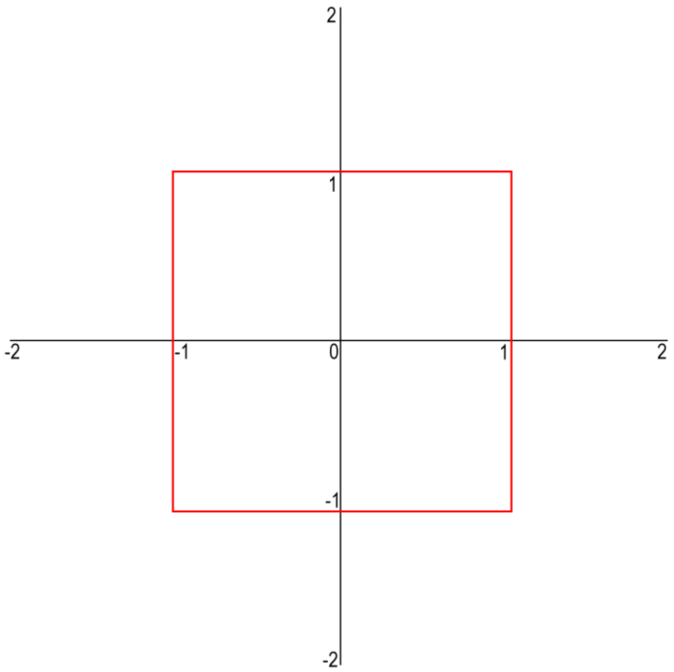
```
screen.Line( 220, 100, 420, 100, 0xffffff );
screen.Line( 220, 100, 220, 300, 0xffffff );
screen.Line( 420, 100, 420, 300, 0xffffff );
screen.Line( 220, 300, 420, 300, 0xffffff );
```

Note how the color is represented here. A 32-bit hexadecimal number (indicated by the 0x prefix) consists of 8 digits in the range 0..F (for 0...15). Each digit thus represents 4 bits, and two digits represent 1 byte. Therefore 0xff0000 is bright red, and 0x00ff00 is green.

To spin the square, we use some trigonometry. Rotating a 2x2 square around the origin requires transforming the four corners:

```
// top-left corner
float x1 = -1, y1 = 1.0f;
float rx1 = (float)(x1 * Math.Cos( a ) - y1 * Math.Sin( a ));
float ry1 = (float)(x1 * Math.Sin( a ) + y1 * Math.Cos( a ));
```

Repeating this for four corners and connecting them with lines yields the desired spinning square. But, the coordinate system looks like this:



To convert this to window coordinates, we need to make the following adjustments:

1. Invert the y-axis;
2. Shift x so that -2..2 becomes 0..4;
3. Scale x so that 0..4 becomes 0..640;
4. Shift and scale y, taking into account the window aspect ratio.

Exercise 3: create two functions TX and TY, which accept a float parameter and return an integer coordinate for drawing to the window. Use these functions to draw the spinning square.

Exercise 4: make the functions TX and TY generic, so that:

- they work for any window resolution and any range over x and y for the coordinate system of the simulation;
- the window can center on any location of the coordinate system of the simulation (not just the origin).

We will refer to the simulation coordinate system as ‘world coordinates’, and to the window coordinate system as ‘screen coordinates’ from now on.

Exercise 5 (BONUS): use functions TX and TY to implement a function plotter. Start with a 2x2 world system and use ‘Z’ and ‘X’ to zoom in and out. Use the cursor keys to translate the world system. Use the Print method of the Surface class to draw relevant labels.

END OF PART 1.

Complete this section by backing up the current state of your project.

Part 2: OpenGL using the template

Under the hood

The template uses OpenGL (via OpenTK) to rapidly draw pixels to the window. It works like this:

- an OpenGL texture is created for the screen surface (method `GenTexture` in the Surface class);
- after invoking the `game.Tick` function, the `OnRenderFrame` method of the `OpenTKApp` class copies the pixels of the surface to the texture;
- two triangles are drawn using the texture.

A bit more background information:

The OpenGL API is a *state machine*. The state affects a number of aspects of rendering, e.g.:

- the world coordinate system
- z-buffer behavior
- active textures
- draw color

Commands to OpenGL are affected by this state. When we draw a triangle, we just provide vertex coordinates; the active coordinate system determines how these map to screen coordinates. The color of the triangle is affected by the draw color, which we can modulate by using a texture.

With this in mind, let's examine how the template uses OpenGL. Open `template.cs` and look for the `OnRenderFrame` method.

To use the screen surface texture we need to bind it (line 60):

```
GL.BindTexture( TextureTarget.Texture2D, screenID );
```

Here, `screenID` is an integer which we received from OpenGL when we created the texture (line 27). It serves as a unique identifier for that texture.

Next thing we want to do is to clear the window (line 67):

```
GL.Clear( ClearBufferMask.ColorBufferBit );
```

Note that this is not strictly necessary; we will be drawing two screen-filling triangles, overwriting anything that is on the screen. Also note that we need to tell OpenGL what we are clearing: in this case, just the color values. When we later draw 3D objects, we will also want to clear the z-buffer, using

```
GL.Clear( ClearBufferMask.ColorBufferBit +
          ClearBufferMask.DepthBufferBit );
```

For now, we do not actually use the z-buffer, so we can just as well disable it:

```
GL.Disable( EnableCap.DepthTest );
```

Note that a good place to do that is in the `OnLoad` method of the `OpenTKApp` class; the state will remain like that until we change it (see line 21).

There is one part of the state that still needs to be set: the coordinate system. We will just use the identity matrix for projecting our vertices (line 69-70):

```
GL.MatrixMode( MatrixMode.Modelview );
GL.LoadIdentity();
```

Now that the state is set, we can draw the triangles. Note that OpenGL allows us to directly draw a 'quad'; the driver will translate this to two triangles for us.

```
GL.Begin( PrimitiveType.Quads );
GL.TexCoord2( 0.0f, 1.0f ); GL.Vertex2( -1.0f, -1.0f );
GL.TexCoord2( 1.0f, 1.0f ); GL.Vertex2(  1.0f, -1.0f );
GL.TexCoord2( 1.0f, 0.0f ); GL.Vertex2(  1.0f,  1.0f );
GL.TexCoord2( 0.0f, 0.0f ); GL.Vertex2( -1.0f,  1.0f );
GL.End();
```

And finally, we tell OpenTK to display the rendered image (line 81):

```
SwapBuffers();
```

> *Note: OpenTK uses double buffering, which means that one image is visible, while we work on a second image. `SwapBuffers` swaps these images. This way we prevent a partially rendered image from being visible.*

Taking control

Until now we have 'abused' OpenTK/OpenGL to quickly render pixels in C#. However, we are free to run our own OpenGL code, on top of, or instead of the code in the template. Since the template provides a convenient way to draw some text and lines, we will leave that code in. A good place to do some additional rendering is after rendering the quad, and before swapping the buffers.

Let's add a method to the Game class:

```
public void RenderGL()
{
}
```

We will call this function from the OpenTKApp method `OnRenderFrame`, right before the swap:

```
game.RenderGL();
```

There is a few things we need to take into account:

- The template code relies on a certain OpenGL state. We should either leave it that way, or restore it.
- We may want to clear the z-buffer: whatever we draw may well be behind the two triangles.

To solve the first issue, it's probably best to set the state each frame. In other words, the state modifiers in OnLoad should go to OnRenderFrame:

```
GL.ClearColor( Color.Black );
GL.Enable( EnableCap.Texture2D );
GL.Disable( EnableCap.DepthTest );
GL.Color3( 1.0f, 1.0f, 1.0f );
```

That last line wasn't there in OnLoad, but it solves a subtle problem: triangles drawn using a texture can still have a color. The colors from the texture are modulated using this color. So, if we set the color to (1, 1, 0), blue will be filtered out, and our texture looks as if we view it through yellow sunglasses.

> *This brings up another point: OpenGL colors are specified as floats, not integers. A bright red color in OpenGL is (1,0,0); the same color in integer format is (255 << 16) or 0xff0000.*

Before we go into RenderGL we probably want a slightly different state, and we will want to clear the z-buffer:

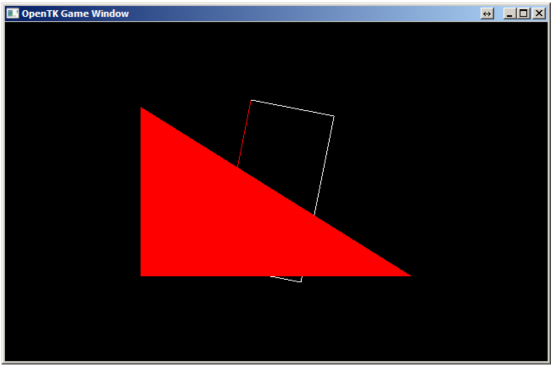
```
// prepare for generic OpenGL rendering
GL.Enable( EnableCap.DepthTest );
GL.Disable( EnableCap.Texture2D );
GL.Clear( ClearBufferMask.DepthBufferBit );
```

That completes our preparations for custom OpenGL rendering, which is what we will do next.

OpenGL

Let's render a triangle in our RenderGL function:

```
GL.Color3( 1.0f, 0.0f, 0.0f );
GL.Begin( PrimitiveType.Triangles );
GL.Vertex3( -0.5f, -0.5f, 0 );
GL.Vertex3(  0.5f, -0.5f, 0 );
GL.Vertex3( -0.5f,  0.5f, 0 );
GL.End();
```



To make this work, we will need to import `OpenTK.Graphics.OpenGL`.

The output of this code is shown on the right, along with my (still spinning) custom rectangle.

It's time to make it spin in 3D. Let's modify the matrix we use to draw the triangle using some magic instructions:

```
var M = Matrix4.CreatePerspectiveFieldOfView( 1.6f, 1.3f, .1f, 1000 );
GL.LoadMatrix( ref M );
GL.Translate( 0, 0, -1 );
GL.Rotate( 110, 1, 0, 0 );
GL.Rotate( a * 180 / PI, 0, 0, 1 );
```

Let's render something slightly more interesting: a landscape. On the INFOGR you will find a greyscale image of an island. First, we create a member variable to store the image, and an array to store the heights we find in the image:

```
Surface map;
float[,] h;
```

Now we can load the bitmap in the `Init` function (not in the `Tick` function, that would slow down our application to a crawl!):

```
map = new Surface( "../../assets/heightmap.png" );
h = new float[128,128];
for( int y = 0; y < 128; y++ ) for( int x = 0; x < 128; x++ )
      h[x,y] = ((float)(map.pixels[x + y * 128] & 255)) / 256;
```

Let's briefly discuss what happens here:

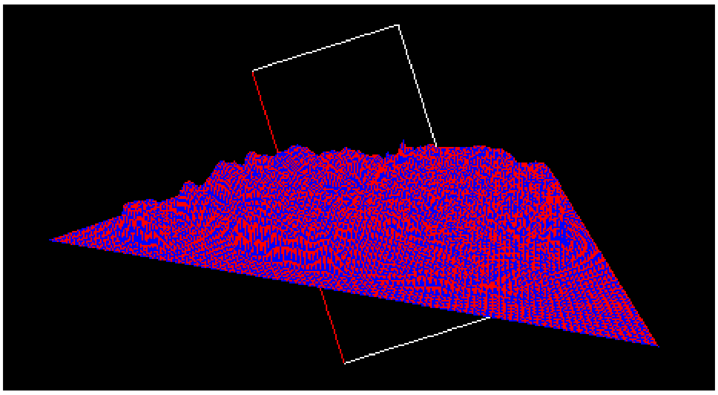
First, the image is loaded using the Surface constructor. The path is relative to the executable of our program, so we need to go two directories up before we enter the assets folder.

The bitmap is exactly 128x128 pixels, so we allocate an array for 128x128 height values.

The colors are greyscale, which means that red, green and blue are always the same. Looking at blue (or red, or green) thus gives us the intensity for a pixel in the image. We extract 'blue' using a bitmask; in this case a 32-bit value with only the lowest 8 bits set to 1. Since the other bits are set to 0, this removes red and green. The result is a value between 0 and 255.

This value is cast to a float and divided by 256, to get a value in the range 0..1. This is a convenient format to use when rendering triangles.

Exercise 6: create a loop that renders a grid of 127x127 quads (127x127x2 triangles). Use the heights stored in h to set the z-coordinate of each vertex. Use a proper scale to ensure the landscape fits in the window.



If you managed to complete assignment 6 you now have a landscape spinning on your screen, in glorious 3D. Some issues remain:

1. It is slow. If your computer manages to keep up, try a 512x512 landscape.
2. The shading is somewhat disappointing.

We will address these issues in the next section.

Modern OpenGL

The method of rendering individual triangles explained in the previous section has a name: we have been rendering in *immediate mode*. There is a better way, and that is using *vertex buffer objects*, or VBOs.

Instead of feeding OpenGL our triangle vertices one by one, we are going to prepare a buffer that we can send using a single command. This buffer simply contains the vertex coordinates; we have 127x127x2 triangles, and therefore 127x127x2x3 vertices. Each vertex has an x, y and z coordinate; the buffer thus needs to store 127x127x2x3x3 floating point values.

First, we create a member variable to store all those floats:

```
float[] vertexData;
```

Then we allocate the array, in the `Init` function of course:

```
vertexData = new float[127 * 127 * 2 * 3 * 3];
```

Finally, we fill the array. We do this with a loop very similar to the one we just used to draw in immediate mode, but this time, the values we passed to `GL.Vertex3` go to the array.

Exercise 7: fill the array.

We need a bit more code to send the array to OpenGL. First of all, we need to create a VBO. OpenGL will give us an ID for this object, like it did for textures.

```
VBO = GL.GenBuffer();
```

Don't forget to create an integer member variable named VBO. Next, we need to bind the VBO to be able to work with it, again just like we did with the texture:

```
GL.BindBuffer( BufferTarget.ArrayBuffer, VBO );
```

Next, we inform OpenGL about our float array:

```
GL.BufferData<float>(
      BufferTarget.ArrayBuffer,
      (IntPtr)(vertexData.Length * 4),
      vertexData,
      BufferUsageHint.StaticDraw
);
```

This is a complex line. The first argument tells OpenGL we are providing data for the VBO we just bound. The second argument is the size of our array in bytes. Inconveniently, we need to pass this as an integer pointer. Next argument is our array. The last argument tells OpenGL what the intended purpose of the array is. The driver can use this to optimize certain things under the hood.

Next, we need to tell OpenGL what is in the array. For now, it only contains vertex coordinates, consisting of 3 floats, with a total size of 12 bytes per vertex, and an offset in the array of 0.

```
GL.EnableClientState( ArrayCap.VertexArray );
GL.VertexPointer( 3, VertexPointerType.Float, 12, 0 );
```

That's all we need in terms of initialization. In the `RenderGL` function we can now draw using the VBO:

```
GL.BindBuffer( BufferTarget.ArrayBuffer, VBO );
GL.DrawArrays( PrimitiveType.Triangles, 0, 127 * 127 * 2 * 3 );
```

The `GL.DrawArrays` call replaces our nested loop and renders all triangles in one go. Best of all, the `StaticDraw` buffer hint pretty much ensures our data is already on the GPU; communication between CPU and GPU is therefore significantly reduced, and as a result, performance is much better.

Exercise 8: modify your program so that it renders using the GL.DrawArrays command.

Shaders

Modern GPUs use a programmable graphics pipeline. Based on a stream of vertices, they draw triangles to the screen. This stream is processed in several fixed stages, which we can program.

The first stage is the vertex shader. In this stage, 3D coordinates are transformed using a 4x4 matrix to obtain screen coordinates.

Once three vertices have been processed, the resulting screen coordinates are passed to the rasterizer. This part of the GPU interpolates and produces a stream of fragments, i.e. the pixels covered by the triangle.

The stream of fragments is then processed by a fragment shader. The fragment shader program receives a single screen position, plus any other interpolated values. It emits a single value: the fragment color. This is the color that will show up on the screen.

Here is a minimalistic vertex shader:

```
#version 330
in vec3 vPosition;
in  vec3 vColor;
out vec4 color;
uniform mat4 M;
void main()
{
    gl_Position = M * vec4( vPosition, 1.0 );
    color = vec4( vColor, 1.0);
}
```

This vertex shader is written in GLSL. It takes two parameters:

1. `vPosition`: the 3D vertex position;
2. `vColor`: a RGB color.

There is a third parameter, but it is different: unlike the positions and color, which we specify per vertex, the matrix `M` will be applied to all vertices in the stream. It is therefore sent only once. In the shader, such a variable is labelled 'uniform'.

The shader has two outputs. The first is `color`. This shader simply passes the color it receives from the input stream. The second output is mandatory: it is the transformed position of the vertex. This is stored in `gl_Position`.

As said, we also need a fragment shader. Here is a minimalistic one:

```
#version 330
in vec4 color;
out vec4 outputColor;
void main()
{
    outputColor = color;
}
```

This shader does very little: it receives an (interpolated!) color from the rasterizer and simply emits this color.

Shaders grant us detailed control over vertex processing and fragment shading. Example: if we pass the vertex shader a stream of vertex normals and texture coordinates, these too will be interpolated over the triangle. The fragment shader could then implement a detailed shading model, taking into account several textures, a normal map, and the interpolated surface normal.

Adding Shaders

To add the shaders to our program, we first need to add two text files to the project, one for the vertex shader, and one for the fragment shader.

We load the shader code using a small utility function:

```
void LoadShader( String name, ShaderType type, int program, out int ID )
{
    ID = GL.CreateShader( type );
    using (StreamReader sr = new StreamReader( name ))
        GL.ShaderSource( ID, sr.ReadToEnd() );
    GL.CompileShader( ID );
    GL.AttachShader( program, ID );
    Console.WriteLine( GL.GetShaderInfoLog( ID ) );
}
```

The first line creates the shader. As before, we receive an integer value to identify the shader later on. Next, we load the actual source text, and compile it. We then attach the shader to a program, which will consist of a vertex and a fragment shader.

Using the utility function, we create the program:

```
programID = GL.CreateProgram();
LoadShader( "../../shaders/vs.glsl",
            ShaderType.VertexShader, programID, out vsID );
LoadShader( "../../shaders/fs.glsl",
            ShaderType.FragmentShader, programID, out fsID );
GL.LinkProgram( programID );
```

Next, we need to get access to the input variables used in the vertex shader. We get another set of identifiers for these:

```
attribute_vpos = GL.GetAttribLocation( programID, "vPosition" );
attribute_vcol = GL.GetAttribLocation( programID, "vColor" );
uniform_mview = GL.GetUniformLocation( programID, "M" );
```

The input for the vertex shader consists of two streams and a matrix. We already have our position data. To link it to the shader, we use the following code:

```
vbo_pos = GL.GenBuffer();
GL.BindBuffer( BufferTarget.ArrayBuffer, vbo_pos );
GL.BufferData<float>( BufferTarget.ArrayBuffer,
                      (IntPtr)(vertexData.Length * 4),
                      vertexData, BufferUsageHint.StaticDraw
                    );
GL.VertexAttribPointer( attribute_vpos, 3,
                        VertexAttribPointerType.Float,
                        false, 0, 0
                      );
```

Likewise, we need to pass a stream of colors. The layout of this stream (let's call it vbo_color) is exactly the same (three floats per vertex), so we create it in the same way. The only difference is that this data is linked to `attribute_vcol` instead of `attribute_vpos`.

Setup is done now; time to adjust the Tick function.

First change is the use of matrices. So far, we relied on OpenGL to rotate and project our vertices. We can easily do that ourselves, by sending the correct matrix to the vertex shader.

Creating the matrix:

```
Matrix4 M = Matrix4.CreateFromAxisAngle( new Vector3( 0, 0, 1 ), a );
M *= Matrix4.CreateFromAxisAngle( new Vector3( 1, 0, 0 ), 1.9f );
M *= Matrix4.CreateTranslation( 0, 0, -1 );
M *= Matrix4.CreatePerspectiveFieldOfView( 1.6f, 1.3f, .1f, 1000 );
```

Passing it to the GPU:

```
GL.UseProgram( programID );
GL.UniformMatrix4( uniform_mview, false, ref M );
```

We are ready to render.

```
GL.EnableVertexAttribArray( attribute_vpos );
GL.EnableVertexAttribArray( attribute_vcol );
GL.DrawArrays( PrimitiveType.Triangles, 0, 127 * 127 * 2 * 3 );
```

And there you have it; the landscape in all its rasterized glory, processed by a vertex shader and a fragment shader under our own control.

From here, the sky is the limit.

Exercise 9: modify the program to use the shaders described in this section.

Exercise 10: pass a stream of vertex normals to the vertex shader, and from the vertex shader to the fragment shader. Use this data to calculate basic diffuse illumination on the landscape.

END OF PART 2.

Complete this section by backing up the current state of your project.