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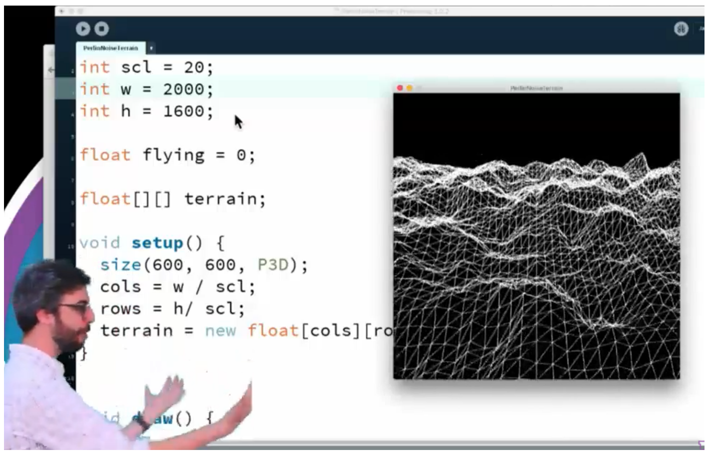
CS 450 Final Project Proposal: Procedurally Generated Infinite-Scrolling 3D Terrain Simulation

For my final project, I would like to create a procedurally generated infinite-scrolling 3D terrain simulation, inspired by this video demonstration from *The Coding Train*:



https://www.youtube.com/watch?v=IKB1hWWedMk

In the video, Daniel Shiffman (of *The Coding Train*) demonstrates how Perlin noise (a noise algorithm invented by Ken Perlin in 1983) can be used to generate a 2D height map which, applied to the vertices of a triangle grid, results in a 3D terrain-like mesh. Because Perlin noise is deterministic, the height map values can be recalculated and "shifted" across the terrain mesh over time using an offset value, resulting in a scrolling effect.

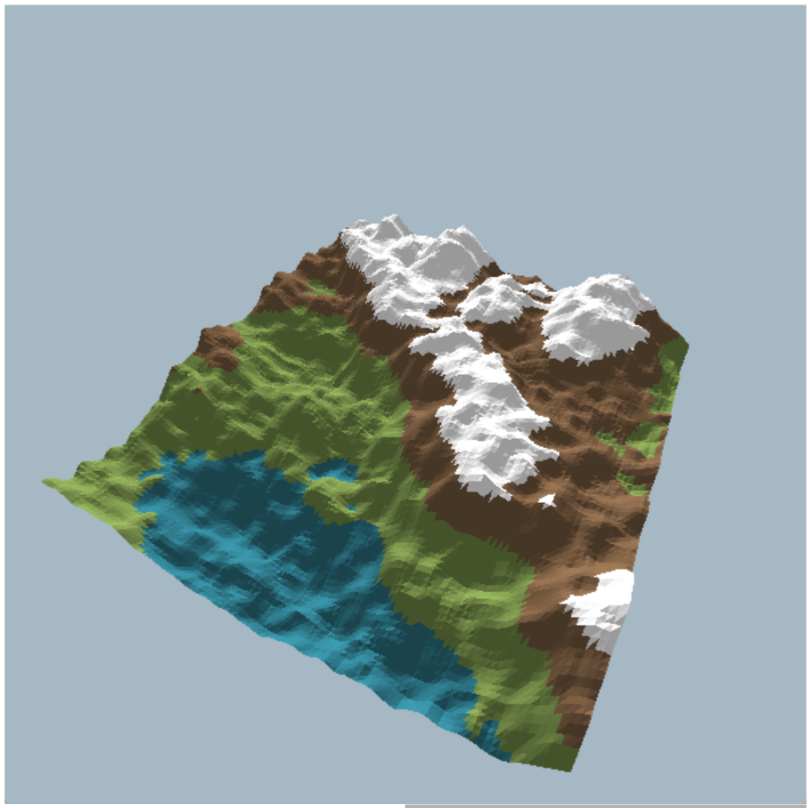
Implementation considerations

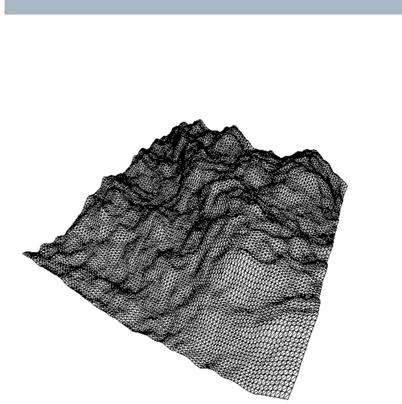
The demo in the video is created in a program called Processing that abstracts away many of the implementation details. Some challenges/goals I am anticipating for an OpenGL implementation:

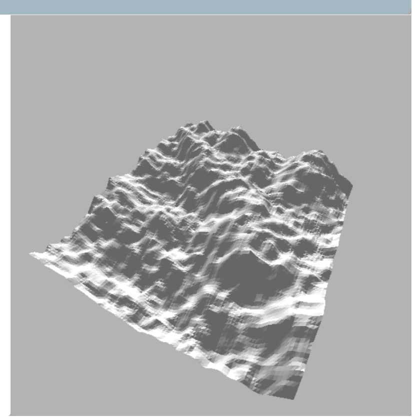
- Geometry/transformations: I plan to take a standard OpenGL ("fixed-function") implementation approach in the research phase, but I would like to transition to a vertex buffer/shader implementation (after I've had more exposure/practice with in project 6) for calculating heights and transforming vertices.
- Perlin noise algorithm: I will likely use an open-source C++ library or header file such as https://github.com/Reputeless/PerlinNoise to generate the height map data at least in the research phase, but it would be a fun stretch goal to implement my own simplified Perlin noise algorithm.
- Lighting: The inspiration project is done using a transparent mesh, meaning there is no surface lighting. I would like to achieve a flat-shading/low-poly lighting style, which will require recalculating the surface normals each time the height map changes.
- Movement: The inspiration project scrolls infinitely in a single direction; as a stretch goal, I would like to implement a movement system that allows the user to "fly over" (scroll) the terrain in any direction using the keyboard.

CS 450 Final Project Report: Procedurally Generated Infinite-Scrolling 3D Terrain Simulation

This report details the design and development of my final project, a procedurally generated infinite-scrolling 3D terrain simulation.







Video

See a video demo: https://media.oregonstate.edu/media/1_ezhu1ccz

What I did, and how (and why) it differs from my proposal

I was able to deliver all of the functionality that I had originally proposed, with some additional features as well. The scene consists of a single triangle grid. The application turns the grid into a 3D terrain mesh by transforming each vertex's y-height according to a deterministic 2D Perlin noise algorithm. The noise algorithm produces a height map in real time that can be shifted across the mesh, producing an infinite-scrolling "terrain flyover" effect. I was also able to add several rendering/color themes to alter the final appearance of the mesh.

This section details how I addressed each implementation concern from the proposal, and how my actual approach differed from my expected approach.

Transformations (vertex buffer object/vertex shader)

In my proposal, I wrote that I planned to take a fixed-function OpenGL approach for calculating vertex transformations, and potentially transition to a vertex buffer object and shader-based implementation after I was more comfortable with shaders after Project 6.

Ultimately, I skipped the fixed-function implementation altogether and went straight for the vertex buffer object (VBO) and shader approach. Because the topology of the mesh structure itself never actually changes, it made more sense to store a single set of vertices using a VBO and perform the height transformations for each vertex independently, in parallel, rather than doing all 10,000-1,000,000 calculations (depending on grid size) on the CPU and sending new coordinates to the GPU every single frame.

```
// InitGraphics()

// Init shader program
Terrain.Init();

// Compile, generate error messages, download executable to GPU
Terrain.Create("terrain.vert", "terrain.geom", "terrain.frag");

// ...

// Generate VBO handle
glGenBuffers(1, &VertexBuffer);

// Send vertex VBO send data
glBindBuffer(GL_ARRAY_BUFFER, VertexBuffer);
glBufferData(GL_ARRAY_BUFFER, sizeof(VertexArray), VertexArray, GL_STATIC_DRAW);
Terrain.EnableVertexAttribArray("aVertex");
```

```
// Display()

// Set vertex coordinate attribute pointer
glBindBuffer(GL_ARRAY_BUFFER, VertexBuffer);
Terrain.SetAttributePointer3fv("aVertex", 3, (GLfloat*)0);

// Draw
Terrain.Use();
glDrawArrays(GL_TRIANGLES, 0, 6 * GRID_RES_LOW * GRID_RES_LOW);
Terrain.UnUse();
```

Noise algorithm (vertex shader)

The other component to the vertex transformations is the noise algorithm itself, used to determine the y-height of each vertex given its x- and z-coordinates. In my proposal, I had planned to import an existing noise function from an external C++ library/header file, but when I decided to move my vertex transformations to the GPU, this changed as well.

Instead, I decided to write the Perlin noise functions directly in my vertex shader so the calculation could be performed in parallel for each grid point. I used ChatGPT to help write the algorithm using the prompt: "Provide a deterministic GLSL Perlin noise algorithm that takes vec2 coordinate and returns a height value between 0 and 1."

Originally, the ChatGPT gave me an implementation that it attributed to graphics programmer and researcher Inigo Quilez that included a permutation table-based hashing algorithm; I was, however, unable to substantiate the veracity of this attribution.

After some re-prompting for my particular application, I landed on this function-based hashing algorithm which uses a well-known GLSL hash function (commonly shared in online forums like Stack Overflow) in place of the permutation table.

```
// terrain.vert

float hash(vec2 p)
{
    // Generate pseudo-random value between 0 and 1
    return fract(sin(dot(p, vec2(127.1, 311.7))) * 43758.5453);
}

vec2 randomGradient(vec2 gridPoint)
{
    // Convert hash value to angle (in radians) along the unit circle
    float angle = hash(gridPoint) * 6.28318530718;

    // Return the x and y components of the resultant angle
    return vec2(cos(angle), sin(angle));
}

float perlin(vec2 point)
{
    // Integer part of the coordinates (the "cell" that contains this point)
    // Fractional part of the coordinates (how far into the cell the coordinates
are)
    vec2 gridPoint = floor(point);
    vec2 offset = point - gridPoint;

    // Get gradients (2D vector) for each corner of the "cell"
    vec2 g00 = randomGradient(gridPoint + vec2(0.0, 0.0));
```

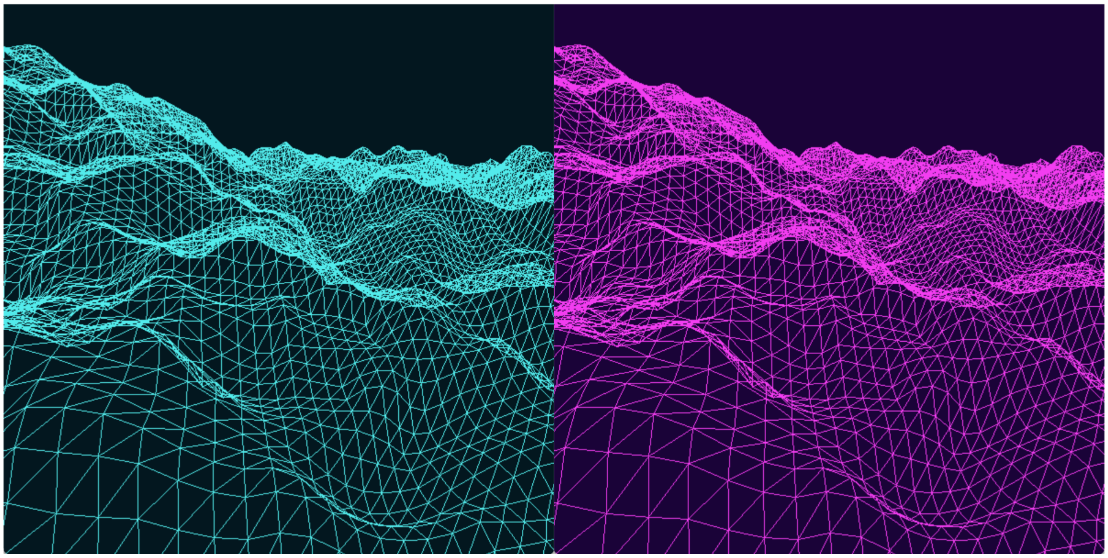
```
    vec2 g10 = randomGradient(gridPoint + vec2(1.0, 0.0));
    vec2 g01 = randomGradient(gridPoint + vec2(0.0, 1.0));
    vec2 g11 = randomGradient(gridPoint + vec2(1.0, 1.0));

    // Calculate dot product for coordinate and each corner (distance to each
gradient)
    float d00 = dot(g00, offset - vec2(0.0, 0.0));
    float d10 = dot(g10, offset - vec2(1.0, 0.0));
    float d01 = dot(g01, offset - vec2(0.0, 1.0));
    float d11 = dot(g11, offset - vec2(1.0, 1.0));

    // Interpolate between the values (linear interpolation)
    float u = offset.x;  // X interpolation factor
    float v = offset.y;  // Y interpolation factor

    float nx0 = mix(d00, d10, u);
    float nx1 = mix(d01, d11, u);

    // Returns a value between -1 and +1
    return mix(nx0, nx1, v);  // Final interpolation between the two results
}
```

The algorithm above did produce results, however I was not happy with the low level of variation between points on the grid. The terrain features were too smooth, with small levels of variation between grid points. It also produced noticeable visual creases along the "cell" lines (due to the definite integer/fractional-part nature of Perlin noise), resulting in a grid-like pattern at the scale I was working with.

I provided this feedback to ChatGPT, and it provided me with one more piece to the puzzle; multi-octave noise in which several "octaves" (or "layers") of noise are applied, one on top of the other, at a constant-decreasing "level of influence" as more noise is applied. Essentially, the base level of noise creates the larger, general shape of the terrain while additional octaves zoom in on the terrain and apply smaller, textural variations across those surfaces.

```
float perlinMultiOctave(vec2 point, int octaves, float persistence)
{
    float total = 0.0;
    float frequency = 1.0;  // Base frequency (larger values for more zoomed-in
noise)
    float amplitude = 1.0;  // Base amplitude (larger values for more influence)

    for (int i = 0; i < octaves; i++) {
        total += perlin(point * frequency) * amplitude;  // Apply Perlin noise with
frequency and amplitude
        frequency *= 2;  // Double the frequency for next octave (zoom in)
        amplitude *= persistence;  // Decrease the amplitude (less influence as
octaves increase)
    }
```

```
    return total;
}
```



Lighting (geometry shader)

The biggest challenge I faced was determining how to achieve a flat lighting style on a solid-fill mesh. In my proposal, I noted how the inspiration video for this project is done with a transparent, line-only mesh with no surface lighting at all. I specifically wanted a flat-shading, low-poly visual style, which means recalculating surface normals for each triangle as a whole every time the program transforms the vertices.

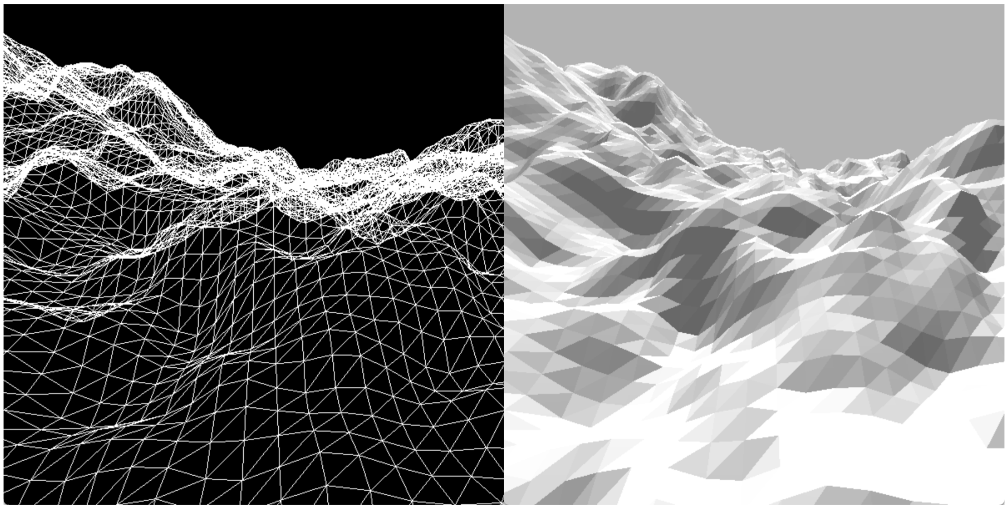
A triangle's surface normal is the cross product of two of its edges. In order to perform this calculation, you must have the coordinates of all three of the triangle's vertices, and the resultant surface normal must be applied to each vertex. Because I went with the vertex shader approach (where the noise calculation and height transformation is done on each vertex discretely), I was not going to be able to access the coordinates for each vertex's neighbor post-transformation, and therefore had no way to calculate the correct surface normal.

After several attempts with different vertex shader-based techniques (passing neighbor coordinates via VBO, using texture coordinates instead of absolute grid coordinates to calculate each neighboring transformation, etc.), my research eventually led me to using a geometry shader. The geometry shader allowed me to perform calculations per-polygon (with all three component vertices), after the individual vertex transformations had been applied.

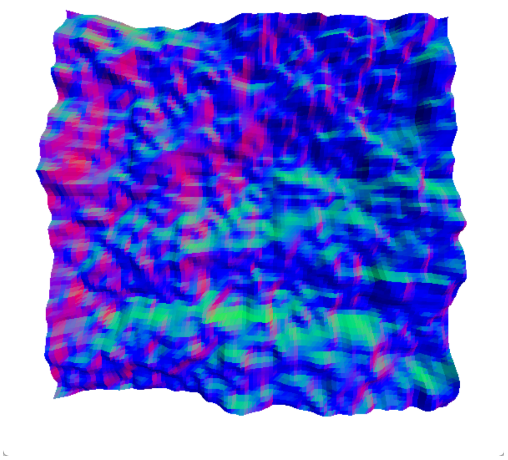
```
// terrain.geom

vec3 p0 = vPosition[0];
vec3 p1 = vPosition[1];
vec3 p2 = vPosition[2];

// Define two edge vectors
vec3 U = p1 - p0;
vec3 V = p2 - p0;
```

```
// Set normalized cross product as surface normal (applies to all vertices)
gNormalVector = normalize(cross(U, V));
```

This ensured I was able to set the exact same surface normal vector for all three vertices, achieving the flat-shading, low-poly visual style I was going for.



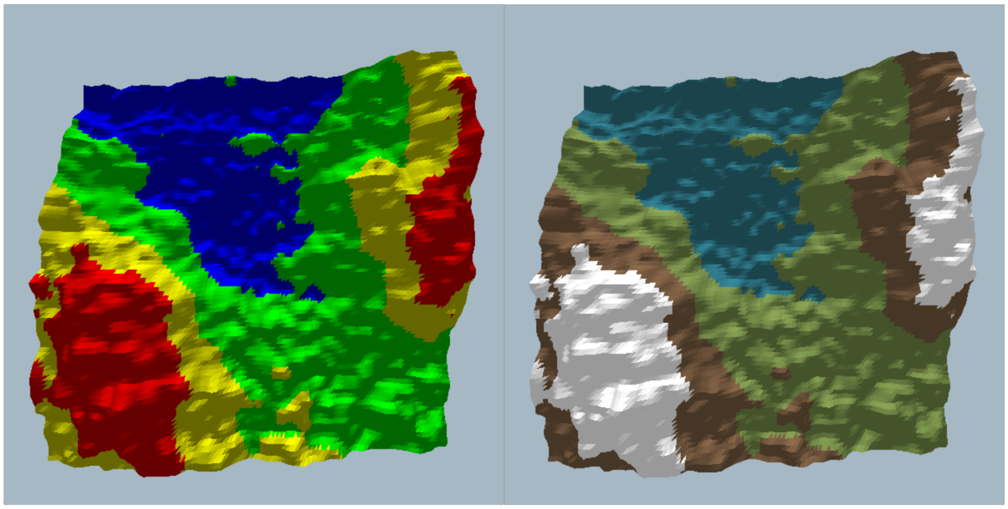
One thing that was helpful for visual debugging was using the surface normal as my `gl_FragColor` vector (in the fragment shader) to help visualize the direction of each triangle's surface normal and detect any inconsistencies between vertices on each face. The XYZ coordinates of the normal vector map directly to RGB intensities, resulting in a unique "iridescent" effect where the colors shift as mesh and surface normals change orientation.



Color (fragment shader)

Applying different rendering/color themes was not something I'd originally put in my proposal, but the implementation was fairly straightforward, so I made a few basic color schemes. Some of them render the triangles as just lines (like in the inspiration video), and others render them as solid polygons.

The Normal Map (mentioned above in the Lighting section) applies the XYZ surface normal vector in place of an RGB color vector. The multi-colored themes (Earth and Heat Map) apply a fragment color based on the average model coordinate height of all three vertices in each triangle.



Movement

The final implementation consideration I outlined in my proposal was a movement system that allows the user to scroll the terrain in any direction indefinitely, taking advantage of the infinite terrain generation.

I achieved this with a simple `KeyDown` event listener function that checks if a directional key (WASD) is held down and if so, increments/decrements the offset accordingly. For auto-scrolling, the Z offset is decremented automatically each frame. The offset values are sent to the vertex shader as a `uniform` variable.

```
if (CurrentScrollMode == MANUAL)
{
    if (wKeyDown) OffsetZ -= 1;
    if (aKeyDown) OffsetX -= 1;
    if (sKeyDown) OffsetZ += 1;
    if (dKeyDown) OffsetX += 1;
}
if (CurrentScrollMode == AUTO) {
    OffsetZ -= 1;
}
```

What I learned

The key concepts I learned from this project are:

- **Vertex buffer objects and how they are used to assemble and send vertex position and attribute data to the GPU.** Since there was no prior assignment that required using VBOs, it took some time re-reading and understanding the lecture notes, but eventually I was able to implement it. Although the final version of the project only uses vertex position data, I had several different attribute buffers throughout various iterations of the project that included things like neighbor vertex data, initial surface normal vector, and vertex color. Technically, the current implementation is also sending texture coordinates for each vertex that could be used to texture the grid or apply an actual texture image-based height map.

- **Noise algorithms and their application in creating pseudo-random patterns.** The 2D Perlin noise implementation I am using is a common classic noise algorithm often used for terrain generation applications. I learned how basic noise works in two dimensions, how to apply it, and I am interested in exploring other types of 2D noise, either for terrain or other natural-world applications like water and waves.
- **Geometry shaders.** While I wasn't planning on using a geometry shader at first, my research revealed it to be the simplest way to solve my surface normal recalculation problem. The ability to work on all three vertices of a triangle in sequence opens up a lot of possibilities for transformations, adding/removing vertices, and manipulating the geometry per-face, rather than just per-vertex. I intend to continue researching ways of approaching lighting problems without the geometry shader, as I would like to experiment with porting my application to WebGL as well (which supports only vertex and fragment shaders).
- **Modern OpenGL matrix and lighting techniques.** This project presented a bit of a bonus learning opportunity in that it forced me to become much more familiar/comfortable with the modern OpenGL model-view transformation and lighting pipeline. Although these are concepts we covered in the first few weeks of class, I needed to be much more mindful about how/when I was transforming vertices, and which version of the vertices I was using for various calculations and comparisons (e.g., before/after model-to-world or world-to-eye transformations). For example, the multi-color rendering themes required me to store and compare *model* coordinates, meaning I had to set those as an `out` variable before applying the model or view matrices, which came before calculating the lighting vectors are based on view coordinates. I used this project as an opportunity to experiment more with managing the transformation matrices using more of a modern OpenGL approach.