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1 Introduction

The images above were made in different ways. The first one was made by Van Gogh's hand applying layer over layer of paint. It took him hours. The second was produced in seconds by the combination of four matrices of pixels: one for cyan, one for magenta, one for yellow and one for black. The key difference is that the second image is produced in a non-serial way (that means not step-by-step, but all at the same time).

This book is about the revolutionary computational technique, *fragment shaders*, that is taking digitally generated images to the next level. You can think of it as the equivalent of Gutenberg's press for graphics.

Fragment shaders give you total control over the pixels rendered on the screen at a super fast speed. This is why they're used in all sort of cases, from video filters on cellphones to incredible 3D video games.

In the following chapters you will discover how incredibly fast and powerful this technique is and how to apply it to your professional and personal work.

1.1 Who is this book for?

This book is written for creative coders, game developers and engineers who have coding experience, a basic knowledge of linear algebra and trigonometry, and who want to take their work to an exciting new level of graphical quality. (If you want to learn how to code, I highly recommend you start with [Processing](#) and come back later when you are comfortable with it.)

This book will teach you how to use and integrate shaders into your projects, improving their performance and graphical quality. Because GLSL (OpenGL Shading Language) shaders compile and run on a variety of platforms, you will be able to apply what you learn here to any environment that uses OpenGL, OpenGL ES or WebGL. In other words, you will be able to apply and use your knowledge with [Processing](#) sketches, [openFrameworks](#) applications, [Cinder](#) interactive installations, [Three.js](#) websites or iOS/Android games.

1.2 What does this book cover?

This book will focus on the use of GLSL pixel shaders. First we'll define what shaders are; then we'll learn how to make procedural shapes, patterns, textures and animations

1 Introduction

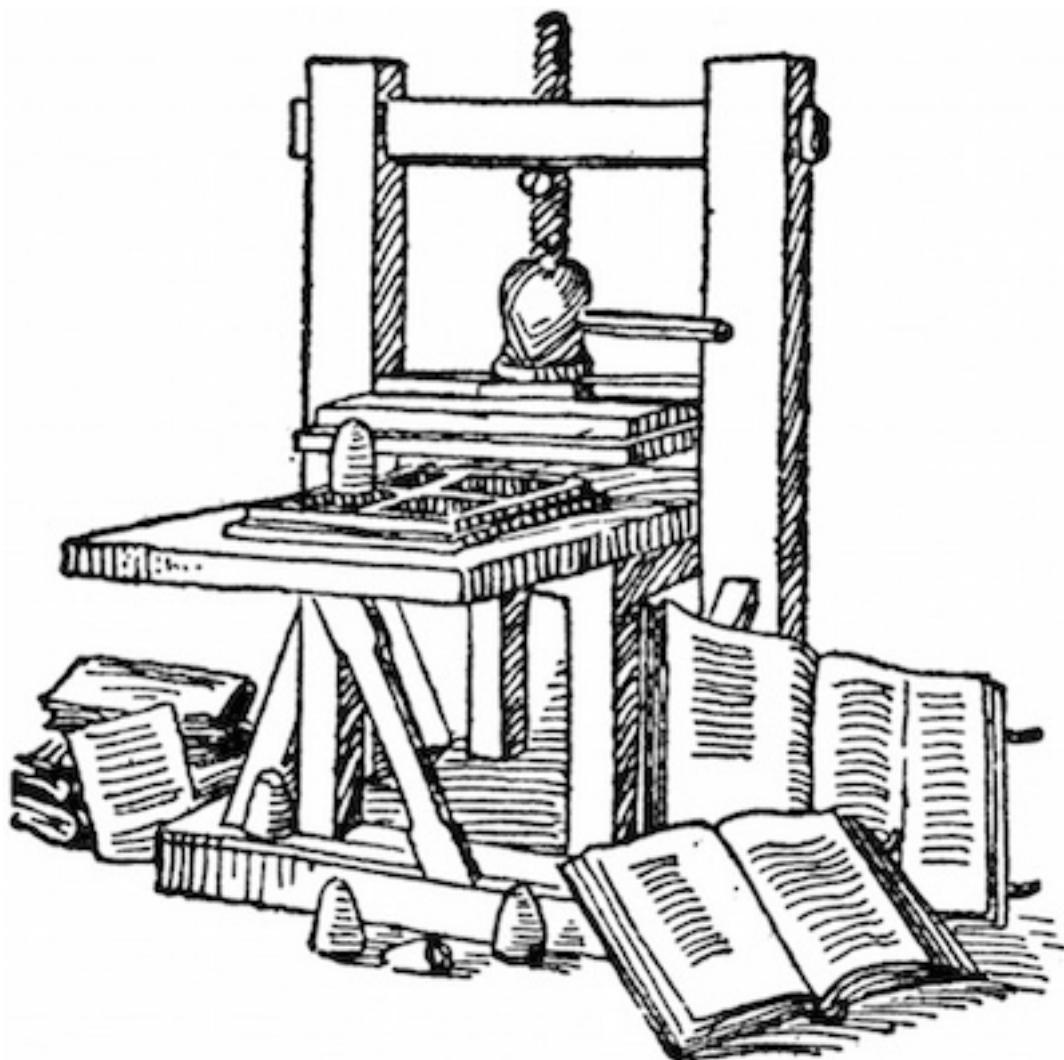


Figure 1.1: Gutenberg's press

1.2 What does this book cover?



Figure 1.2: Journey by That Game Company

1 Introduction

with them. You'll learn the foundations of shading language and apply it to more useful scenarios such as: image processing (image operations, matrix convolutions, blurs, color filters, lookup tables and other effects) and simulations (Conway's game of life, Gray-Scott's reaction-diffusion, water ripples, watercolor effects, Voronoi cells, etc.). Towards the end of the book we'll see a set of advanced techniques based on Ray Marching.

There are interactive examples for you to play with in every chapter. When you change the code, you will see the changes immediately. The concepts can be abstract and confusing, so the interactive examples are essential to helping you learn the material. The faster you put the concepts into motion the easier the learning process will be.

What this book doesn't cover:

- This *is not* an openGL or webGL book. OpenGL/webGL is a bigger subject than GLSL or fragment shaders. To learn more about OpenGL/webGL I recommend taking a look at: [OpenGL Introduction, the 8th edition of the OpenGL Programming Guide](#) (also known as the red book) or [WebGL: Up and Running](#)
- This *is not* a math book. Although we will cover a number of algorithms and techniques that rely on an understanding of algebra and trigonometry, we will not explain them in detail. For questions regarding the math I recommend keeping one of the following books nearby: [3rd Edition of Mathematics for 3D Game Programming and computer Graphics](#) or [2nd Edition of Essential Mathematics for Games and Interactive Applications](#).

1.3 What do you need to start?

Not much! If you have a modern browser that can do WebGL (like Chrome, Firefox or Safari) and a internet connection, click the “Next” Chapter button at the end of this page to get started.

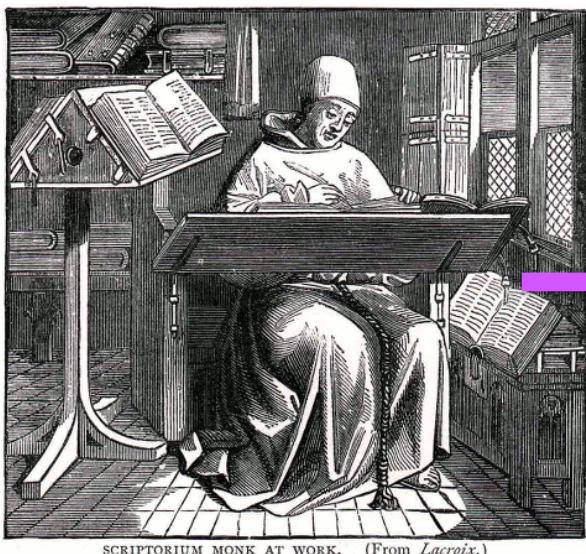
Alternatively, based on what you have or what you need from this book you can:

- [Make an off-line version of this book](#)
- [Run the examples on a RaspberryPi without a browser](#)
- [Make a PDF of the book to print](#)
- Use the [on-line repository](#) to help resolve issues and share code.

2 Getting started

2.1 What is a fragment shader?

In the previous chapter we described shaders as the equivalent of the Gutenberg press for graphics. Why? And more importantly: what's a shader?



SCRIPTORIUM MONK AT WORK. (From *Lacreix*.)



Figure 2.1: From Leter-by-Leter, Right: William Blades (1891). To Page-by-page, Left: Rolt-Wheeler (1920).

If you already have experience making drawings with computers, you know that in that process you draw a circle, then a rectangle, a line, some triangles until you compose the image you want. That process is very similar to writing a letter or a book by hand - it is a set of instructions that do one task after another.

Shaders are also a set of instructions, but the instructions are executed all at once for every single pixel on the screen. That means the code you write has to behave differently depending on the position of the pixel on the screen. Like a type press, your program will work as a function that receives a position and returns a color, and when it's compiled it will run extraordinarily fast.



Figure 2.2: Chinese movable type

2.2 Why are shaders fast?

To answer this, I present the wonders of *parallel processing*.

Imagine the CPU of your computer as a big industrial pipe, and every task as something that passes through it - like a factory line. Some tasks are bigger than others, which means they require more time and energy to deal with. We say they require more processing power. Because of the architecture of computers the jobs are forced to run in a series; each job has to be finished one at a time. Modern computers usually have groups of four processors that work like these pipes, completing tasks one after another to keep things running smoothly. Each pipe is also known as *thread*.

Video games and other graphic applications require a lot more processing power than other programs. Because of their graphic content they have to do huge numbers of pixel-by-pixel operations. Every single pixel on the screen needs to be computed, and in 3D games geometries and perspectives need to be calculated as well.

Let's go back to our metaphor of the pipes and tasks. Each pixel on the screen represents a simple small task. Individually each pixel task isn't an issue for the CPU, but (and here is the problem) the tiny task has to be done to each pixel on the screen! That means in an old 800x600 screen, 480,000 pixels have to be processed per frame which means 14,400,000 calculations per second! Yes! That's a problem big enough to overload a microprocessor. In a modern 2880x1800 retina display running at 60 frames per second that calculation

2.2 Why are shaders fast?

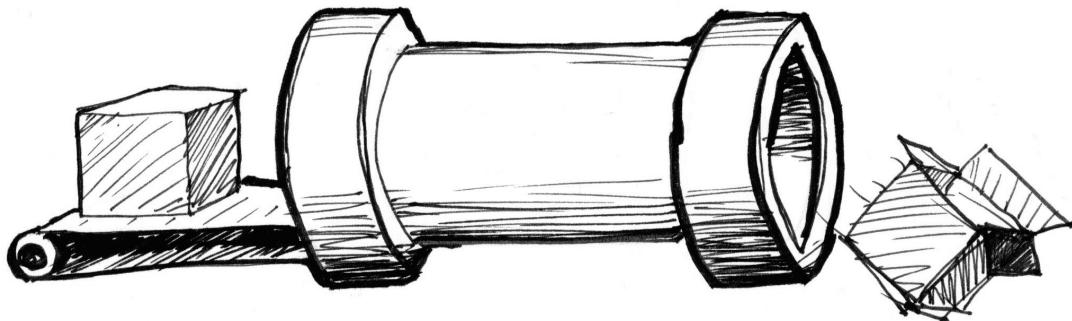


Figure 2.3: CPU

adds up to 311,040,000 calculations per second. How do graphics engineers solve this problem?

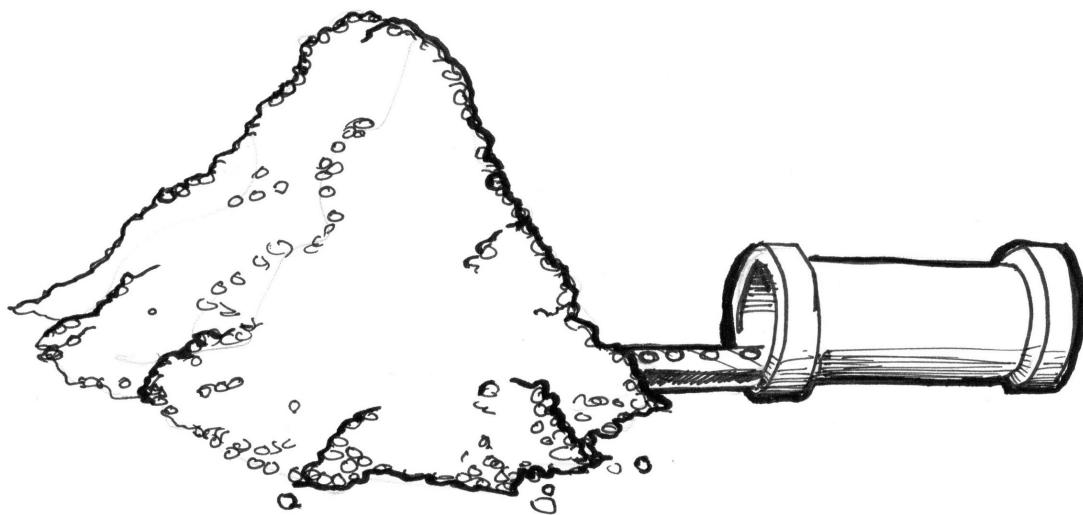


Figure 2.4:

This is when parallel processing becomes a good solution. Instead of having a couple of big and powerful microprocessors, or *pipes*, it is smarter to have lots of tiny microprocessors running in parallel at the same time. That's what a Graphic Processor Unit (GPU) is.

Picture the tiny microprocessors as a table of pipes, and the data of each pixel as a ping pong ball. 14,400,000 ping pong balls a second can obstruct almost any pipe. But a table of 800x600 tiny pipes receiving 30 waves of 480,000 pixels a second can be handled smoothly. This works the same at higher resolutions - the more parallel hardware you

2 Getting started

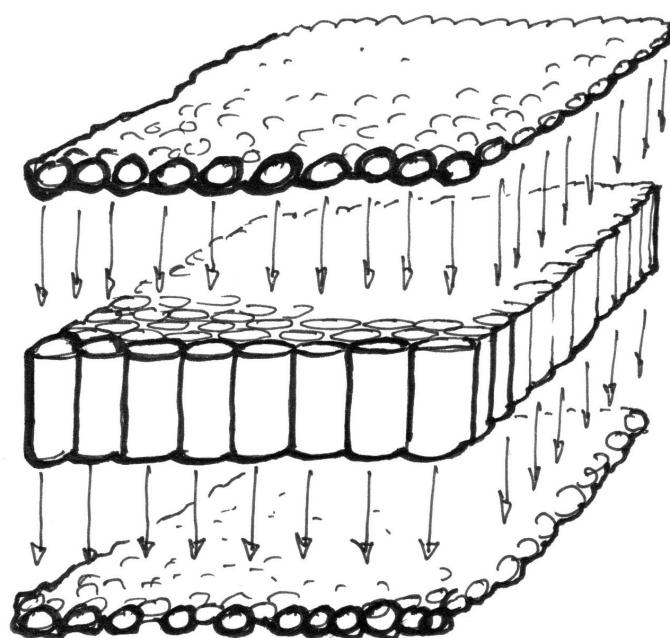


Figure 2.5: GPU

have, the bigger the stream it can manage.

Another “super power” of the GPU is special math functions accelerated via hardware, so complicated math operations are resolved directly by the microchips instead of by software. That means extra fast trigonometrical and matrix operations - as fast as electricity can go.

2.3 What is GLSL?

GLSL stands for openGL Shading Language, which is the specific standard of shader programs you’ll see in the following chapters. There are other types of shaders depending on hardware and Operating Systems. Here we will work with the openGL specs regulated by [Khronos Group](#). Understanding the history of OpenGL can be helpful for understanding most of its weird conventions, for that I recommend taking a look at: openglbook.com/chapter-0-preface-what-is-opengl.html

2.4 Why are Shaders famously painful?

As Uncle Ben said “with great power comes great responsibility,” and parallel computation follows this rule; the powerful architectural design of the GPU comes with its own constraints and restrictions.

In order to run in parallel every pipe, or thread, has to be independent from every other thread. We say the threads are *blind* to what the rest of the threads are doing. This restriction implies that all data must flow in the same direction. So it’s impossible to check the result of another thread, modify the input data, or pass the outcome of a thread into another thread. Allowing thread-to-thread communications puts the integrity of the data at risk.

Also the GPU keeps the parallel micro-processor (the pipes) constantly busy; as soon as they get free they receive new information to process. It’s impossible for a thread to know what it was doing in the previous moment. It could be drawing a button from the UI of the operating system, then rendering a portion of sky in a game, then displaying the text of an email. Each thread is not just **blind** but also **memoryless**. Besides the abstraction required to code a general function that changes the result pixel by pixel depending on its position, the blind and memoryless constraints make shaders not very popular among beginning programmers.

Don’t worry! In the following chapters, we will learn step-by-step how to go from simple to advanced shading computations. If you are reading this with a modern browser, you will appreciate playing with the interactive examples. So let’s not delay the fun any longer and press *Next >>* to jump into the code!

2.5 Hello World

Usually the “Hello world!” example is the first step to learning a new language. It’s a simple one-line program that outputs an enthusiastic welcoming message and declares opportunities ahead.

In GPU-land rendering text is an overcomplicated task for a first step, instead we’ll choose a bright welcoming color to shout our enthusiasm!

```
#ifdef GL_ES
precision mediump float;
#endif

void main() {
    gl_FragColor = vec4(1.0,0.0,1.0,1.0);
}
```

If you are reading this book in a browser the previous block of code is interactive. That means you can click and change any part of the code you want to explore. Changes will be updated immediately thanks to the GPU architecture that compiles and replaces shaders *on the fly*. Give it a try by changing the values on line 6.

Although these simple lines of code don’t look like a lot, we can infer substantial knowledge from them:

1. Shader Language has a single `main` function that returns a color at the end. This is similar to C.
2. The final pixel color is assigned to the reserved global variable `gl_FragColor`.
3. This C-flavored language has built in *variables* (like `gl_FragColor`), *functions* and *types*. In this case we’ve just been introduced to `vec4` that stands for a four dimensional vector of floating point precision. Later we will see more types like `vec3` and `vec2` together with the popular: `float`, `int` and `bool`.
4. If we look closely to the `vec4` type we can infer that the four arguments respond to the RED, GREEN, BLUE and ALPHA channels. Also we can see that these values are *normalized*, which means they go from 0.0 to 1.0. Later, we will learn how normalizing values makes it easier to *map* values between variables.
5. Another important *C feature* we can see in this example is the presence of pre-processor macros. Macros are part of a pre-compilation step. With them it is possible to `#define` global variables and do some basic conditional operation (with `#ifdef` and `#endif`). All the macro commands begin with a hashtag (#). Pre-compilation happens right before compiling and copies all the calls to `#defines` and check `#ifdef` (is defined) and `#ifndef` (is not defined) conditionals. In our “hello world!” example above, we only insert the line 2 if `GL_ES` is defined, which mostly happens when the code is compiled on mobile devices and browsers.

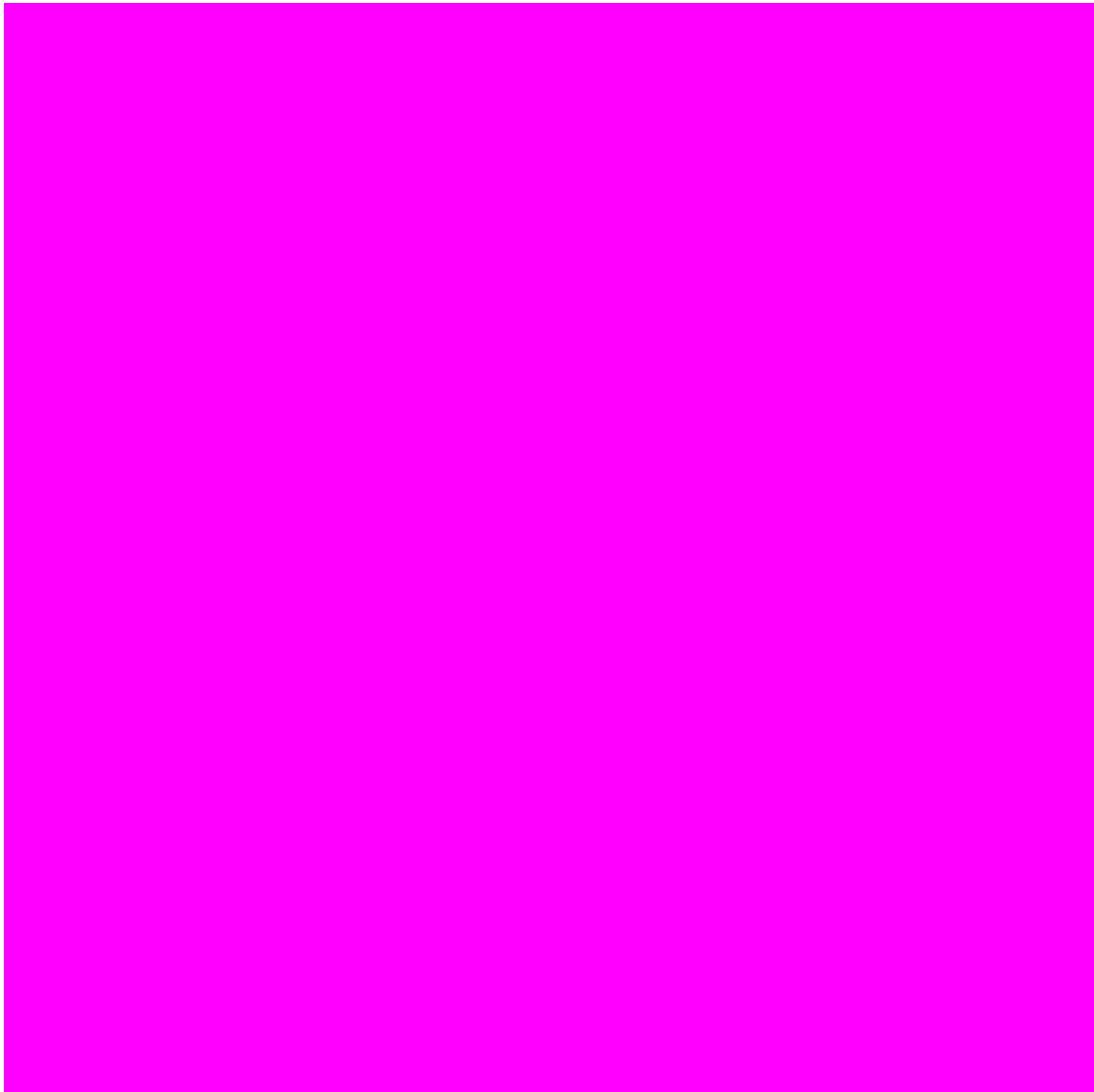


Figure 2.6:

2 Getting started

6. Float types are vital in shaders, so the level of *precision* is crucial. Lower precision means faster rendering, but at the cost of quality. You can be picky and specify the precision of each variable that uses floating point. In the first line (`precision mediump float;`) we are setting all floats to medium precision. But we can choose to set them to low (`precision lowp float;`) or high (`precision highp float;`).
7. The last, and maybe most important, detail is that GLSL specs don't guarantee that variables will be automatically casted. What does that mean? Manufacturers have different approaches to accelerate graphic card processes but they are forced to guarantee minimum specs. Automatic casting is not one of them. In our "hello world!" example `vec4` has floating point precision and for that it expects to be assigned with `floats`. If you want to make good consistent code and not spend hours debugging white screens, get used to putting the point (.) in your floats. This kind of code will not always work:

```
void main() {  
    gl_FragColor = vec4(1,0,0,1);           // ERROR  
}
```

Now that we've described the most relevant elements of our "hello world!" program, it's time to click on the code block and start challenging all that we've learned. You will note that on errors, the program will fail to compile, showing a white screen. There are some interesting things to try, for example:

- Try replacing the floats with integers, your graphic card may or may not tolerate this behavior.
- Try commenting out line 6 and not assigning any pixel value to the function.
- Try making a separate function that returns a specific color and use it inside `main()`. As a hint, here is the code for a function that returns a red color:

```
vec4 red(){  
    return vec4(1.0,0.0,0.0,1.0);  
}
```

- There are multiple ways of constructing `vec4` types, try to discover other ways. The following is one of them:

```
vec4 color = vec4(vec3(1.0,0.0,1.0),1.0);
```

Although this example isn't very exciting, it is the most basic example - we are changing all the pixels inside the canvas to the same exact color. In the following chapter we will see how to change the pixel colors by using two types of input: space (the place of the pixel on the screen) and time (the number of seconds since the page was loaded).

2.6 Uniforms

So far we have seen how the GPU manages large numbers of parallel threads, each one responsible for assigning the color to a fraction of the total image. Although each parallel thread is blind to the others, we need to be able to send some inputs from the CPU to all the threads. Because of the architecture of the graphic card those inputs are going to be equal (*uniform*) to all the threads and necessarily set as *read only*. In other words, each thread receives the same data which it can read but cannot change.

These inputs are called **uniform** and come in most of the supported types: **float**, **vec2**, **vec3**, **vec4**, **mat2**, **mat3**, **mat4**, **sampler2D** and **samplerCube**. Uniforms are defined with the corresponding type at the top of the shader right after assigning the default floating point precision.

```
#ifdef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution; // Canvas size (width,height)
uniform vec2 u_mouse;      // mouse position in screen pixels
uniform float u_time;      // Time in seconds since load
```

You can picture the uniforms like little bridges between the CPU and the GPU. The names will vary from implementation to implementation but in this series of examples I'm always passing: **u_time** (time in seconds since the shader started), **u_resolution** (billboard size where the shader is being drawn) and **u_mouse** (mouse position inside the billboard in pixels). I'm following the convention of putting **u_** before the uniform name to be explicit about the nature of this variable but you will find all kinds of names for uniforms. For example [ShaderToy.com](#) uses the same uniforms but with the following names:

```
uniform vec3 iResolution;    // viewport resolution (in pixels)
uniform vec4 iMouse;         // mouse pixel coords. xy: current, zw: click
uniform float iGlobalTime;   // shader playback time (in seconds)
```

Enough talking, let's see the uniforms in action. In the following code we use **u_time** - the number of seconds since the shader started running - together with a sine function to animate the transition of the amount of red in the billboard.

```
#ifdef GL_ES
precision mediump float;
#endif

uniform float u_time;

void main() {
```

2 Getting started

```
gl_FragColor = vec4(abs(sin(u_time)),0.0,0.0,1.0);  
}
```

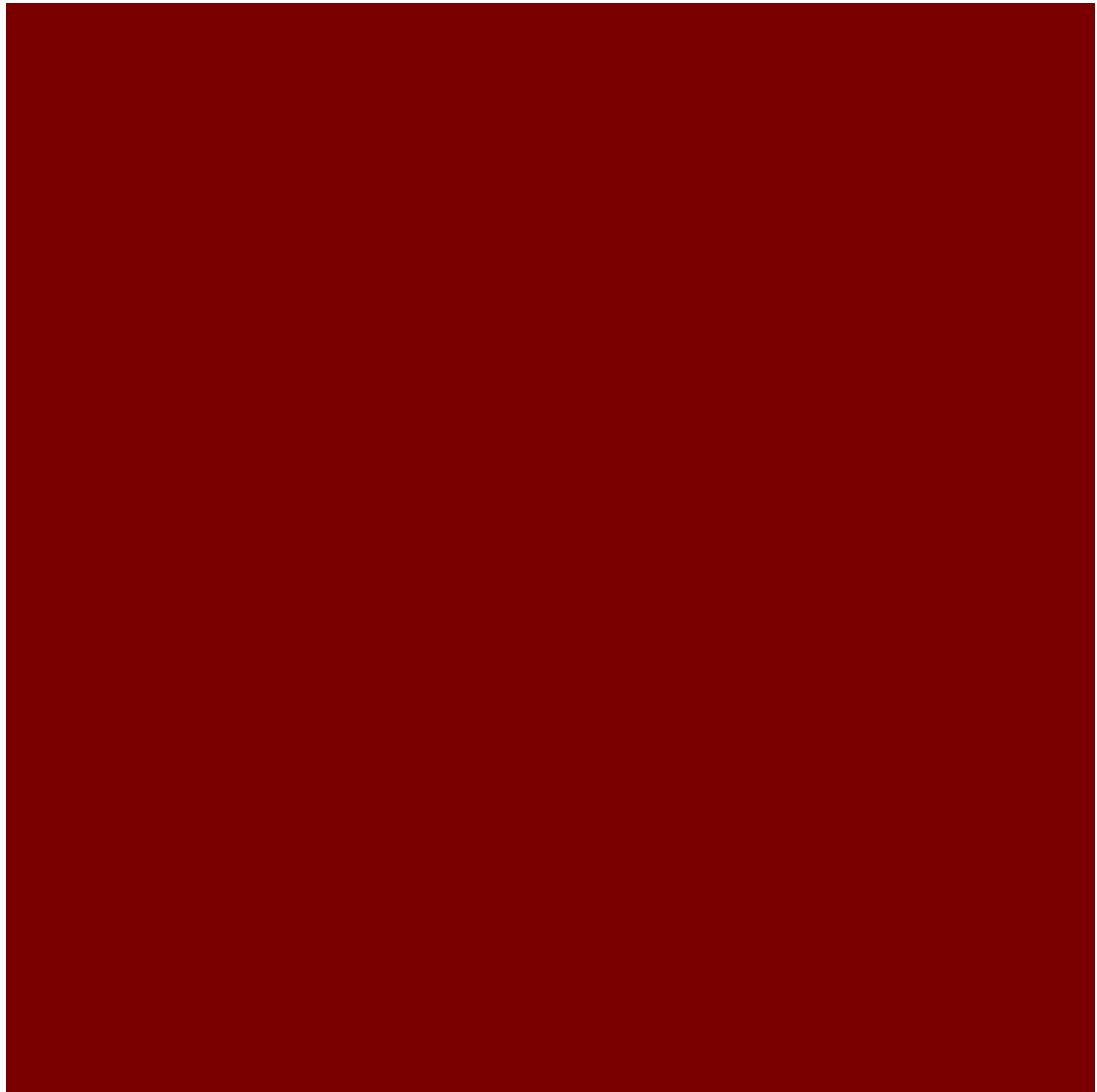


Figure 2.7:

As you can see GLSL has more surprises. The GPU has hardware accelerated angle, trigonometric and exponential functions. Some of those functions are: `sin()`, `cos()`, `tan()`, `asin()`, `acos()`, `atan()`, `pow()`, `exp()`, `log()`, `sqrt()`, `abs()`, `sign()`, `floor()`, `ceil()`, `fract()`, `mod()`, `min()`, `max()` and `clamp()`.

Now it is time again to play with the above code.

- Slow down the frequency until the color change becomes almost imperceptible.

- Speed it up until you see a single color without flickering.
- Play with the three channels (RGB) in different frequencies to get interesting patterns and behaviors.

2.7 ***gl_FragCoord***

In the same way GLSL gives us a default output, `vec4 gl_FragColor`, it also gives us a default input, `vec4 gl_FragCoord`, which holds the screen coordinates of the *pixel* or *screen fragment* that the active thread is working on. With `vec4 gl_FragCoord`, we know where a thread is working inside the billboard. In this case we don't call it `uniform` because it will be different from thread to thread, instead `gl_FragCoord` is called a *varying*.

```
#ifdef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

void main() {
    vec2 st = gl_FragCoord.xy/u_resolution;
    gl_FragColor = vec4(st.x,st.y,0.0,1.0);
}
```

In the above code we *normalize* the coordinate of the fragment by dividing it by the total resolution of the billboard. By doing this the values will go between 0.0 and 1.0, which makes it easy to map the X and Y values to the RED and GREEN channel.

In shader-land we don't have too many resources for debugging besides assigning strong colors to variables and trying to make sense of them. You will discover that sometimes coding in GLSL is very similar to putting ships inside bottles. Is equally hard, beautiful and gratifying.

Now it is time to try and challenge our understanding of this code.

- Can you tell where the coordinate (0.0,0.0) is in our canvas?
- What about (1.0,0.0), (0.0,1.0), (0.5,0.5) and (1.0,1.0)?
- Can you figure out how to use `u_mouse` knowing that the values are in pixels and NOT normalized values? Can you use it to move colors around?
- Can you imagine an interesting way of changing this color pattern using `u_time` and `u_mouse` coordinates?

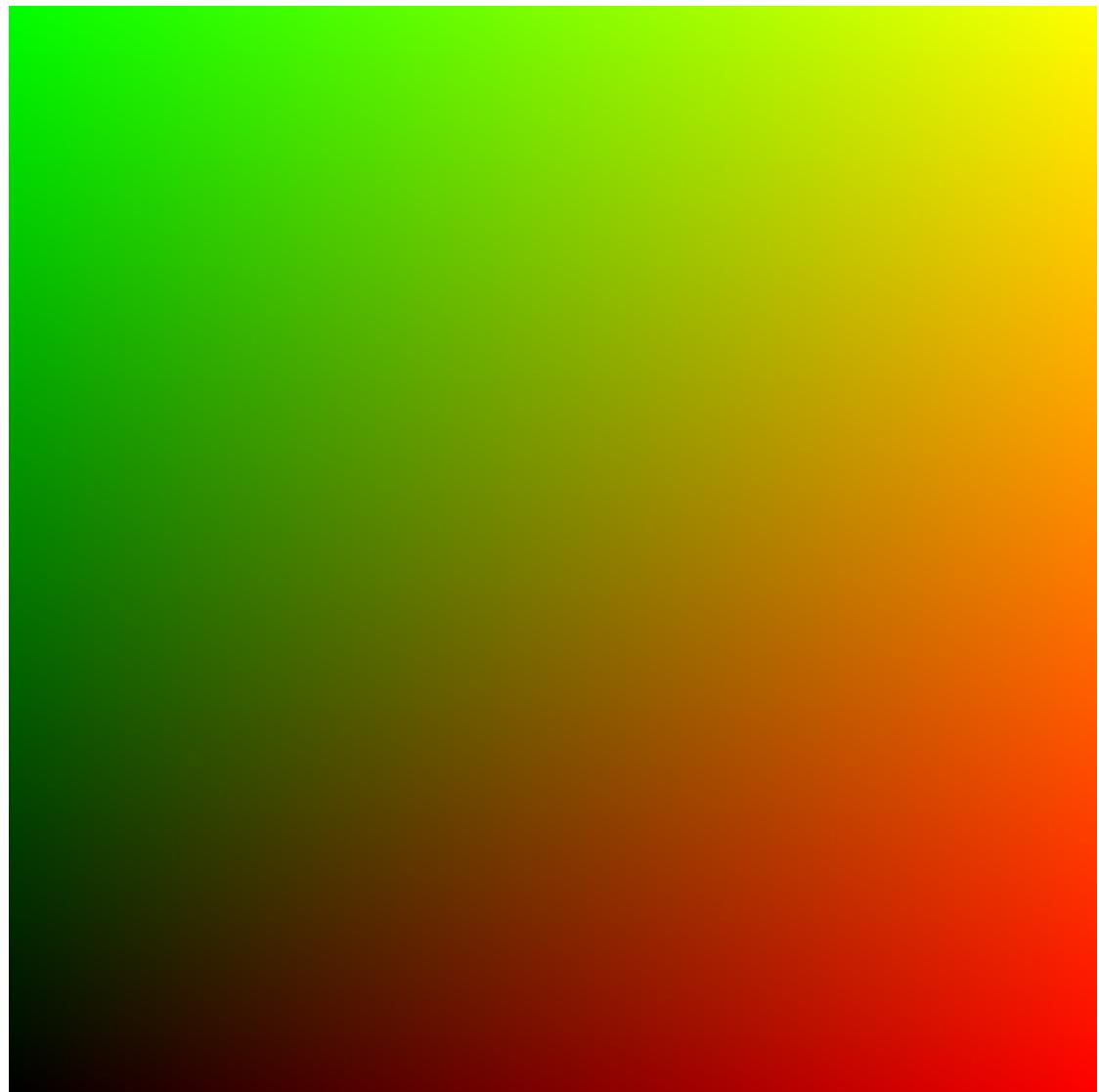


Figure 2.8:

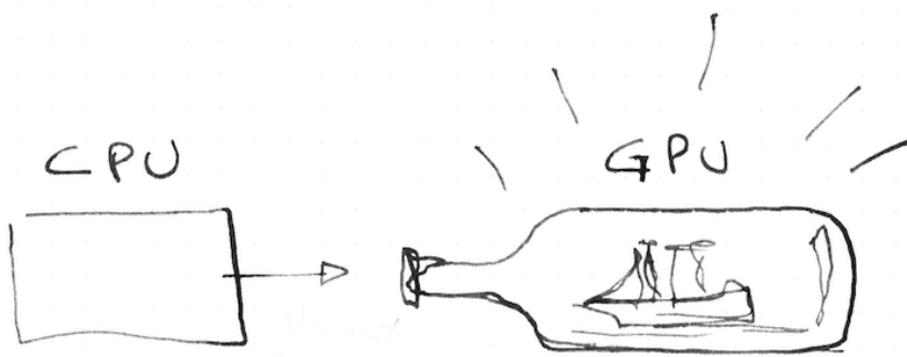


Figure 2.9:

After doing these exercises you might wonder where else you can try your new shader-powers. In the following chapter we will see how to make your own shader tools in three.js, Processing, and openFrameworks.

2.8 Running your shader

At this point you're probably excited to try shaders on platforms you feel comfortable with. The following are examples of how to set shaders in some popular frameworks with the same uniforms that we are going to use throughout this book. (In the [GitHub repository for this chapter](#), you'll find the full source code for these three frameworks.)

Note: In case you don't want to try shaders on the following frameworks, but you want to work outside a browser, you can download and compile [glslViewer](#). This MacOS and RaspberryPi program runs directly from terminal and is especially designed to execute the examples in this book.

2.8.1 In Three.js

The brilliant and very humble Ricardo Cabello (aka [MrDoob](#)) has been developing along with other [contributors](#) probably one of the most famous frameworks for WebGL, called [Three.js](#). You will find a lot of examples, tutorials and books that teach you how to use this JavaScript library to make cool 3D graphics.

Below is an example of the HTML and JS you need to get started with shaders in three.js. Pay attention to the `id="fragmentShader"` script, here is where you can copy the shaders you find in this book.

2 Getting started

```
<body>
  <div id="container"></div>
  <script src="js/three.min.js"></script>
  <script id="vertexShader" type="x-shader/x-vertex">
    void main() {
      gl_Position = vec4( position, 1.0 );
    }
  </script>
  <script id="fragmentShader" type="x-shader/x-fragment">
    uniform vec2 u_resolution;
    uniform float u_time;

    void main() {
      vec2 st = gl_FragCoord.xy/u_resolution.xy;
      gl_FragColor=vec4(st.x,st.y,0.0,1.0);
    }
  </script>
  <script>
    if ( ! Detector.webgl ) Detector.addGetWebGLMessage();

    var container;
    var camera, scene, renderer;
    var uniforms;

    init();
    animate();

    function init() {
      container = document.getElementById( 'container' );

      camera = new THREE.Camera();
      camera.position.z = 1;

      scene = new THREE.Scene();

      var geometry = new THREE.PlaneBufferGeometry( 2, 2 );

      uniforms = {
        u_time: { type: "f", value: 1.0 },
        u_resolution: { type: "v2", value: new THREE.Vector2() }
      };

      var material = new THREE.ShaderMaterial( {
        uniforms: uniforms,
```

```

        vertexShader: document.getElementById( 'vertexShader' ).textContent,
        fragmentShader: document.getElementById( 'fragmentShader' ).textContent
    } );

var mesh = new THREE.Mesh( geometry, material );
scene.add( mesh );

renderer = new THREE.WebGLRenderer();
renderer.setPixelRatio( window.devicePixelRatio );

container.appendChild( renderer.domElement );

onWindowResize();
window.addEventListener( 'resize', onWindowResize, false );
}

function onWindowResize( event ) {
    renderer.setSize( window.innerWidth, window.innerHeight );
    uniforms.u_resolution.value.x = renderer.domElement.width;
    uniforms.u_resolution.value.y = renderer.domElement.height;
}

function animate() {
    requestAnimationFrame( animate );
    render();
}

function render() {
    uniforms.u_time.value += 0.05;
    renderer.render( scene, camera );
}
</script>
</body>

```

2.8.2 In Processing

Started by [Ben Fry](#) and [Casey Reas](#) in 2001, [Processing](#) is an extraordinarily simple and powerful environment in which to take your first steps in code (it was for me at least). [Andres Colubri](#) has made important updates to the openGL and video in Processing, making it easier than ever to use and play with GLSL shaders in this friendly environment. Processing will search for the shader named "`shader.frag`" in the `data` folder of the sketch. Be sure to copy the examples you find here into that folder and rename the file.

2 Getting started

```
PShader shader;

void setup() {
    size(640, 360, P2D);
    noStroke();

    shader = loadShader("shader.frag");
}

void draw() {
    shader.set("u_resolution", float(width), float(height));
    shader.set("u_mouse", float(mouseX), float(mouseY));
    shader.set("u_time", millis() / 1000.0);
    shader(shader);
    rect(0,0,width,height);
}
```

In order for the shader to work on versions previous to 2.1, you need to add the following line at the beginning of your shader: `#define PROCESSING_COLOR_SHADER`. So that it looks like this:

```
#ifdef GL_ES
precision mediump float;
#endif

#define PROCESSING_COLOR_SHADER

uniform vec2 u_resolution;
uniform vec3 u_mouse;
uniform float u_time;

void main() {
    vec2 st = gl_FragCoord.st/u_resolution;
    gl_FragColor = vec4(st.x,st.y,0.0,1.0);
}
```

For more information about shaders in Processing check out this [tutorial](#).

2.8.3 In openFrameworks

Everybody has a place where they feel comfortable, in my case, that's still the [openFrameworks community](#). This C++ framework wraps around OpenGL and other open source C++ libraries. In many ways it's very similar to Processing, but with the obvious complications of dealing with C++ compilers. In the same way as Processing,

2.8 Running your shader

openFrameworks will search for your shader files in the data folder, so don't forget to copy the `.frag` files you want to use and change the name when you load them.

```
void ofApp::draw(){
    ofShader shader;
    shader.load("", "shader.frag");

    shader.begin();
    shader.setUniform1f("u_time", ofGetElapsedTimef());
    shader.setUniform2f("u_resolution", ofGetWidth(), ofGetHeight());
    ofRect(0,0,ofGetWidth(), ofGetHeight());
    shader.end();
}
```

For more information about shaders in openFrameworks go to this [excellent tutorial](#) made by [Joshua Noble](#).

3 Algorithmic drawing

3.1 Shaping functions

This chapter could be named “Mr. Miyagi’s fence lesson.” Previously, we mapped the normalized position of x and y to the *red* and *green* channels. Essentially we made a function that takes a two dimensional vector (x and y) and returns a four dimensional vector (r , g , b and a). But before we go further transforming data between dimensions we need to start simpler... much simpler. That means understanding how to make one dimensional functions. The more energy and time you spend learning and mastering this, the stronger your shader karate will be.



Figure 3.1: The Karate Kid (1984)

The following code structure is going to be our fence. In it, we visualize the normalized value of the x coordinate (`st.x`) in two ways: one with brightness (observe the nice gradient from black to white) and the other by plotting a green line on top (in that case the x value is assigned directly to y). Don’t focus too much on the plot function, we will go through it in more detail in a moment.

```
#ifdef GL_ES  
precision mediump float;
```

3 Algorithmic drawing

```
#endif

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

// Plot a line on Y using a value between 0.0-1.0
float plot(vec2 st, float pct){
    return smoothstep( pct-0.02, pct, st.y) -
        smoothstep( pct, pct+0.02, st.y);
}

void main() {
    vec2 st = gl_FragCoord.xy/u_resolution;

    float y = st.x;

    vec3 color = vec3(y);

    // Plot a line
    float pct = plot(st,y);
    color = (1.0-pct)*color+pct*vec3(0.0,1.0,0.0);

    gl_FragColor = vec4(color,1.0);
}
```

Quick Note: The `vec3` type constructor “understands” that you want to assign the three color channels with the same value, while `vec4` understands that you want to construct a four dimensional vector with a three dimensional one plus a fourth value (in this case the value that controls the alpha or opacity). See for example lines 20 and 26 above.

This code is your fence; it’s important to observe and understand it. You will come back over and over to this space between *0.0* and *1.0*. You will master the art of blending and shaping this line.

This one-to-one relationship between *x* and *y* (or the brightness) is known as *linear interpolation*. From here we can use some mathematical functions to *shape* the line. For example we can raise *x* to the power of 5 to make a *curved* line.

```
#ifdef GL_ES
precision mediump float;
#endif

#define PI 3.14159265359
```

3.1 Shaping functions

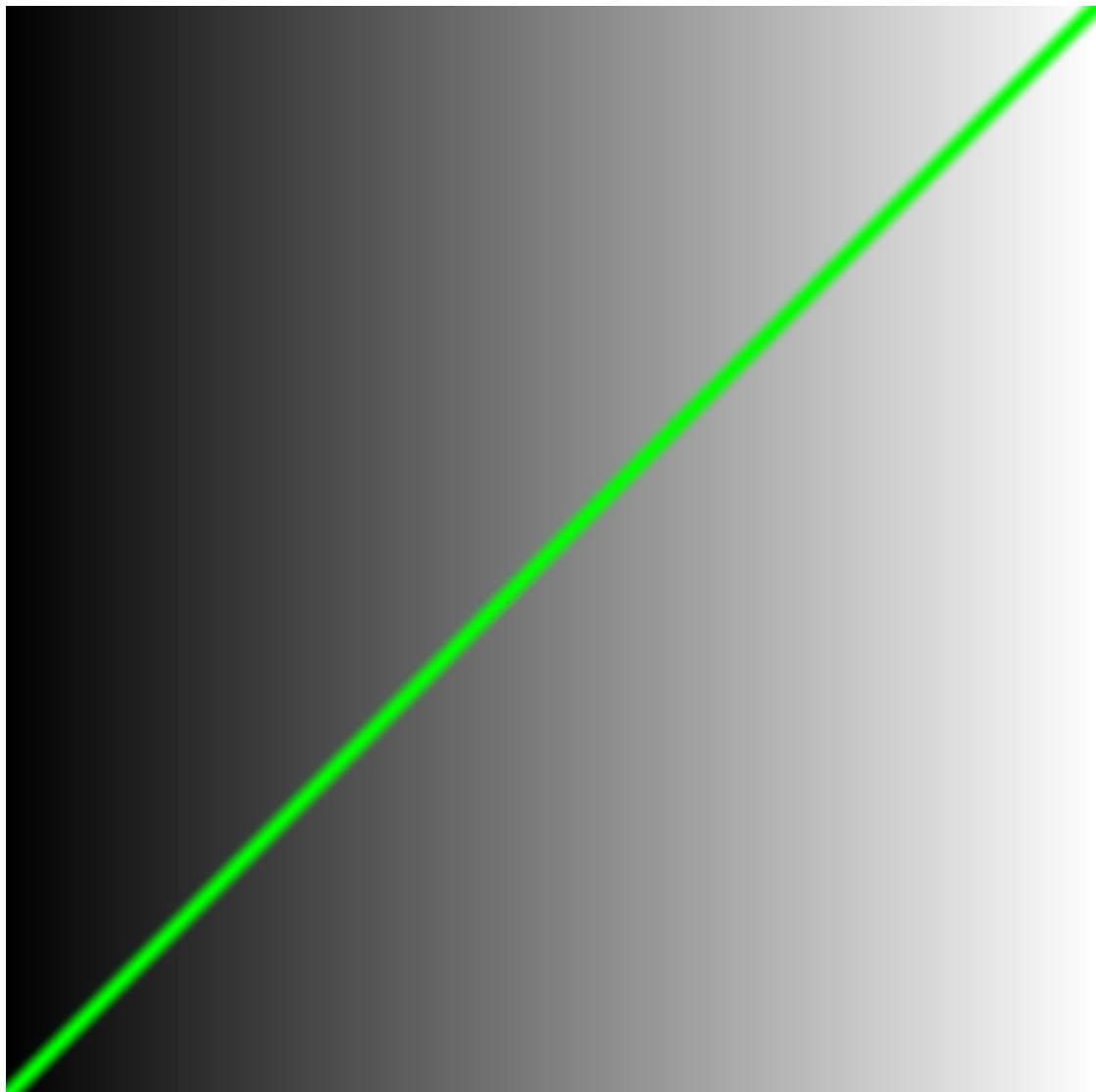


Figure 3.2:

3 Algorithmic drawing

```
uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

float plot(vec2 st, float pct){
    return smoothstep( pct-0.02, pct, st.y) -
           smoothstep( pct, pct+0.02, st.y);
}

void main() {
    vec2 st = gl_FragCoord.xy/u_resolution;

    float y = pow(st.x,5.0);

    vec3 color = vec3(y);

    float pct = plot(st,y);
    color = (1.0-pct)*color+pct*vec3(0.0,1.0,0.0);

    gl_FragColor = vec4(color,1.0);
}
```

Interesting, right? On line 19 try different exponents: 20.0, 2.0, 1.0, 0.0, 0.2 and 0.02 for example. Understanding this relationship between the value and the exponent will be very helpful. Using these types of mathematical functions here and there will give you expressive control over your code, a sort of data acupuncture that let you control the flow of values.

`pow()` is a native function in GLSL and there are many others. Most of them are accelerated at the level of the hardware, which means if they are used in the right way and with discretion they will make your code faster.

Replace the power function on line 19. Try other ones like: `exp()`, `log()` and `sqrt()`. Some of these functions are more interesting when you play with them using PI. You can see on line 5 that I have defined a macro that will replace any call to PI with the value 3.14159265359.

3.1.1 Step and Smoothstep

GLSL also has some unique native interpolation functions that are hardware accelerated. The `step()` interpolation receives two parameters. The first one is the limit or threshold, while the second one is the value we want to check or pass. Any value under the limit will return 0.0 while everything above the limit will return 1.0.

Try changing this threshold value on line 20 of the following code.

3.1 Shaping functions

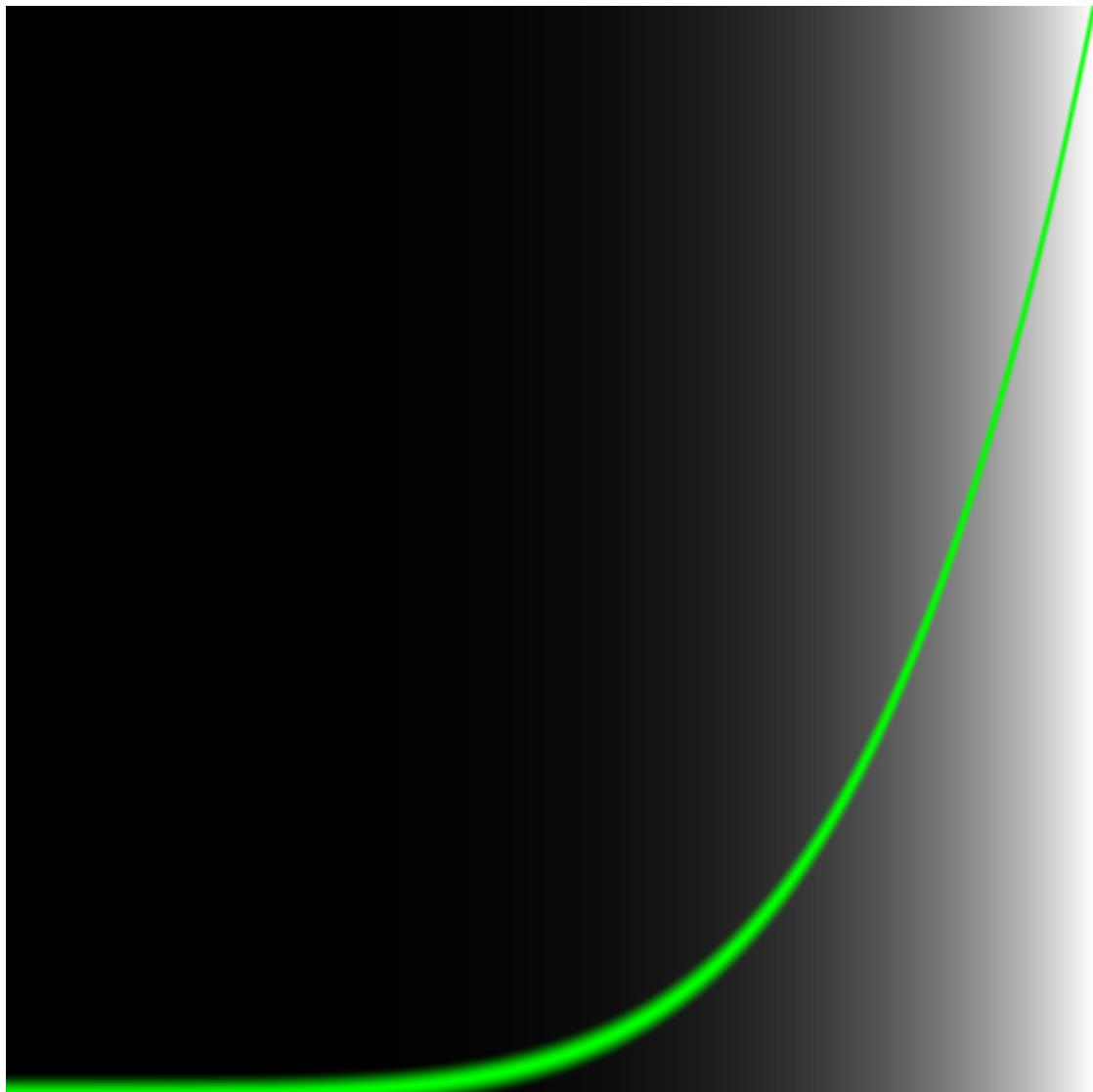


Figure 3.3:

3 Algorithmic drawing

```
#ifdef GL_ES
precision mediump float;
#endif

#define PI 3.14159265359

uniform vec2 u_resolution;
uniform float u_time;

float plot(vec2 st, float pct){
    return smoothstep( pct-0.02, pct, st.y) -
           smoothstep( pct, pct+0.02, st.y);
}

void main() {
    vec2 st = gl_FragCoord.xy/u_resolution;

    // Step will return 0.0 unless the value is over 0.5,
    // in that case it will return 1.0
    float y = step(0.5,st.x);

    vec3 color = vec3(y);

    float pct = plot(st,y);
    color = (1.0-pct)*color+pct*vec3(0.0,1.0,0.0);

    gl_FragColor = vec4(color,1.0);
}
```

The other unique function is known as `smoothstep()`. Given a range of two numbers and a value, this function will interpolate the value between the defined range. The two first parameters are for the beginning and end of the transition, while the third is for the value to interpolate.

```
#ifdef GL_ES
precision mediump float;
#endif

#define PI 3.14159265359

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;
```

3.1 Shaping functions



Figure 3.4:

3 Algorithmic drawing

```
float plot(vec2 st, float pct){
    return smoothstep( pct-0.02, pct, st.y) -
           smoothstep( pct, pct+0.02, st.y);
}

void main() {
    vec2 st = gl_FragCoord.xy/u_resolution;

    // Smooth interpolation between 0.1 and 0.9
    float y = smoothstep(0.1,0.9,st.x);

    vec3 color = vec3(y);

    float pct = plot(st,y);
    color = (1.0-pct)*color+pct*vec3(0.0,1.0,0.0);

    gl_FragColor = vec4(color,1.0);
}
```

In the previous example, on line 12, notice that we've been using `smoothstep` to draw the green line on the `plot()` function. For each position along the x axis this function makes a *bump* at a particular value of y . How? By connecting two `smoothstep()` together. Take a look at the following function, replace it for line 20 above and think of it as a vertical cut. The background does look like a line, right?

```
float y = smoothstep(0.2,0.5,st.x) - smoothstep(0.5,0.8,st.x);
```

3.1.2 Sine and Cosine

When you want to use some math to animate, shape or blend values, there is nothing better than being friends with sine and cosine.

These two basic trigonometric functions work together to construct circles that are as handy as MacGyver's Swiss army knife. It's important to know how they behave and in what ways they can be combined. In a nutshell, given an angle (in radians) they will return the correct position of x (`cosine`) and y (`sine`) of a point on the edge of a circle with a radius equal to 1. But, the fact that they return normalized values (values between -1 and 1) in such a smooth way makes them an incredible tool.

While it's difficult to describe all the relationships between trigonometric functions and circles, the above animation does a beautiful job of visually summarizing these relationships.

Take a careful look at this sine wave. Note how the y values flow smoothly between +1 and -1. As we saw in the time example in the previous chapter, you can use this rhythmic behavior of `sin()` to animate properties. If you are reading this example in

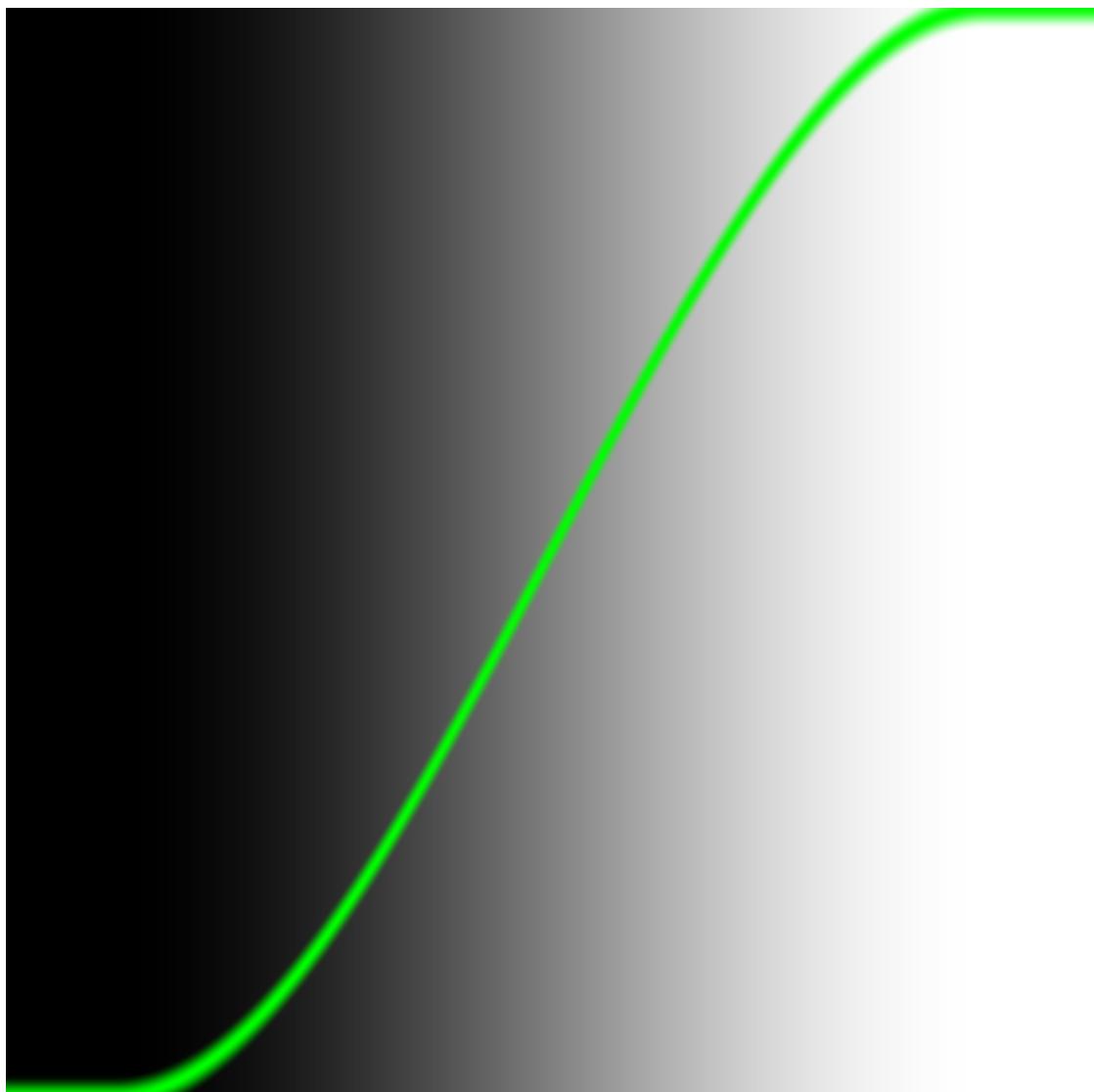


Figure 3.5:

3 Algorithmic drawing

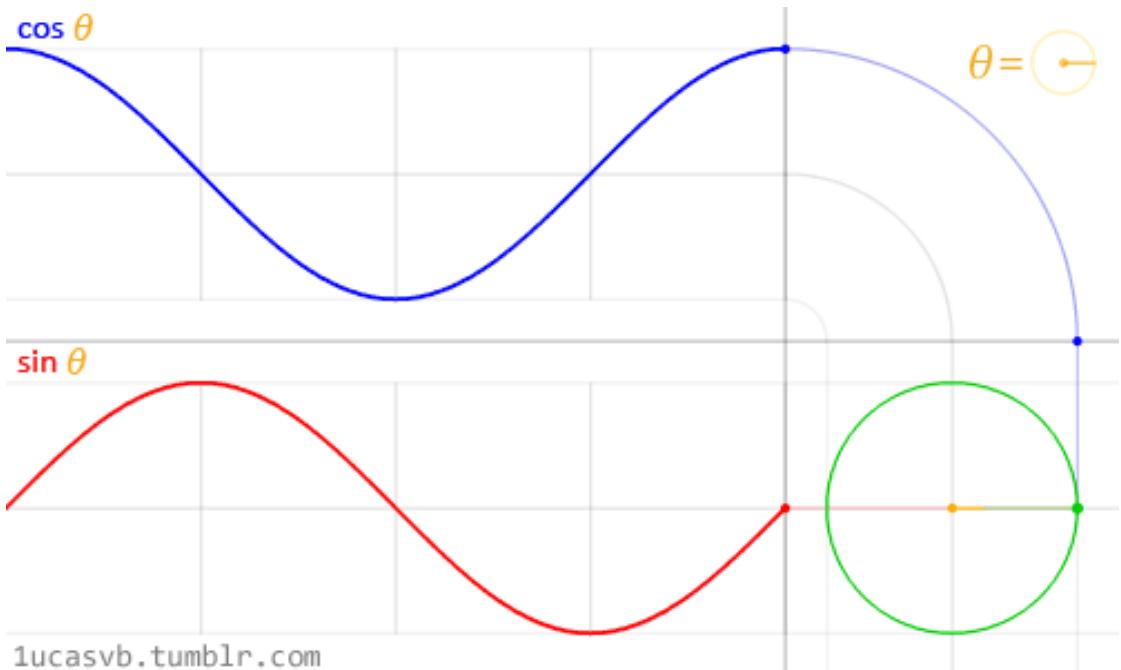


Figure 3.6:

a browser you will see that the you can change the code in the formula above to watch how the wave changes. (Note: don't forget the semicolon at the end of the lines.)

Try the following exercises and notice what happens:

- Add time (`u_time`) to x before computing the `sin`. Internalize that **motion** along x .
- Multiply x by PI before computing the `sin`. Note how the two phases **shrink** so each cycle repeats every 2 integers.
- Multiply time (`u_time`) by x before computing the `sin`. See how the **frequency** between phases becomes more and more compressed. Note that `u_time` may have already become very large, making the graph hard to read.
- Add 1.0 to `sin(x)`. See how all the wave is **displaced** up and now all values are between 0.0 and 2.0.
- Multiply `sin(x)` by 2.0. See how the **amplitude** doubles in size.
- Compute the absolute value (`abs()`) of `sin(x)`. It looks like the trace of a **bouncing ball**.
- Extract just the fraction part (`fract()`) of the resultant of `sin(x)`.
- Add the higher integer (`ceil()`) and the smaller integer (`floor()`) of the resultant of `sin(x)` to get a digital wave of 1 and -1 values.

3.1.3 Some extra useful functions

At the end of the last exercise we introduced some new functions. Now it's time to experiment with each one by uncommenting the lines below one at a time. Get to know these functions and study how they behave. I know, you are wondering... why? A quick google search on "generative art" will tell you. Keep in mind that these functions are our fence. We are mastering the movement in one dimension, up and down. Soon, it will be time for two, three and four dimensions!

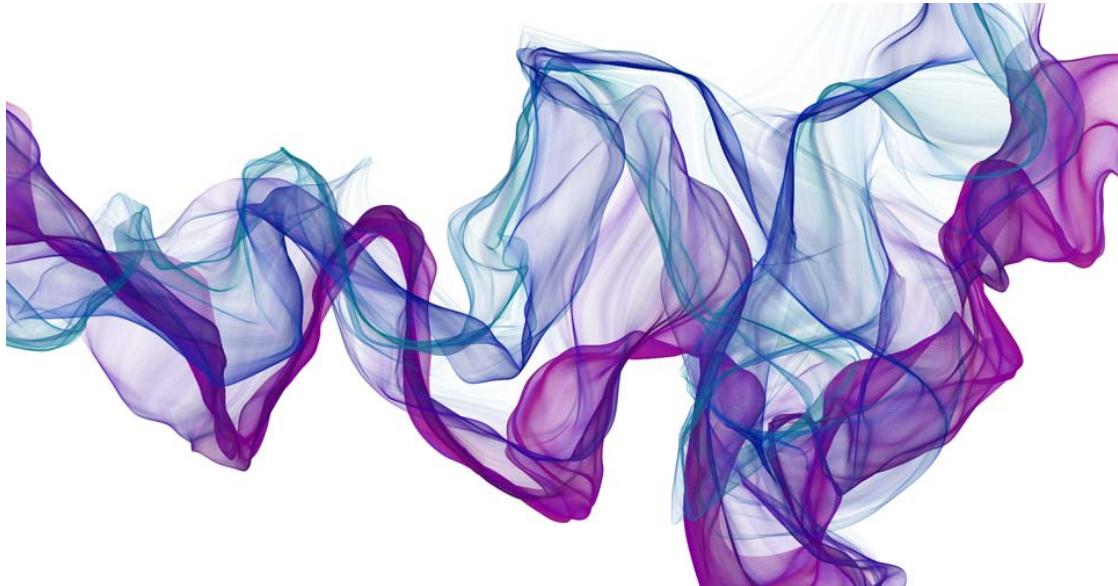


Figure 3.7: Anthony Mattox (2009)

3.1.4 Advance shaping functions

Golan Levin has great documentation of more complex shaping functions that are extraordinarily helpful. Porting them to GLSL is a really smart move, to start building your own resource of snippets of code.

- Polynomial Shaping Functions: www.flong.com/texts/code/shapers_poly
- Exponential Shaping Functions: www.flong.com/texts/code/shapers_exp
- Circular & Elliptical Shaping Functions: www.flong.com/texts/code/shapers_circ
- Bezier and Other Parametric Shaping Functions: www.flong.com/texts/code/shapers_bez

Like chefs that collect spices and exotic ingredients, digital artists and creative coders have a particular love of working on their own shaping functions.

3 Algorithmic drawing

Iñigo Quiles has a great collection of [useful functions](#). After reading [this article](#) take a look at the following translation of these functions to GLSL. Pay attention to the small changes required, like putting the “.” (dot) on floating point numbers and using the GLSL name for *C functions*; for example instead of `powf()` use `pow()`:

- [Impulse](#)
- [Cubic Pulse](#)
- [Exponential Step](#)
- [Parabola](#)
- [Power Curve](#)

To keep your motivation up, here is an elegant example (made by [Danguafer](#)) of mastering the shaping-functions karate.

```
<iframe width="800" height="450" frameborder="0" src="https://www.shadertoy.com/embed/XsX" allowfullscreen>
```

In the *Next >>* chapter we will start using our new moves. First with mixing colors and then drawing shapes.

3.1.4.1 Exercise

Take a look at the following table of equations made by [Kynd](#). See how he is combining functions and their properties to control the values between 0.0 and 1.0. Now it's time for you to practice by replicating these functions. Remember the more you practice the better your karate will be.

3.1.4.2 For your toolbox

Here are some tools that will make it easier for you to visualize these types of functions.

- Grapher: if you have a MacOS computer, type `grapher` in your spotlight and you'll be able to use this super handy tool.
- [GraphToy](#): once again Iñigo Quilez made a tool to visualize GLSL functions in WebGL.
- [Shadershop](#): this amazing tool created by Toby Schachman will teach you how to construct complex functions in an incredible visual and intuitive way.

3.2 Colors

We haven't much of a chance to talk about GLSL vector types. Before going further it's important to learn more about these variables and the subject of colors is a great way to find out more about them.

3.2 Colors

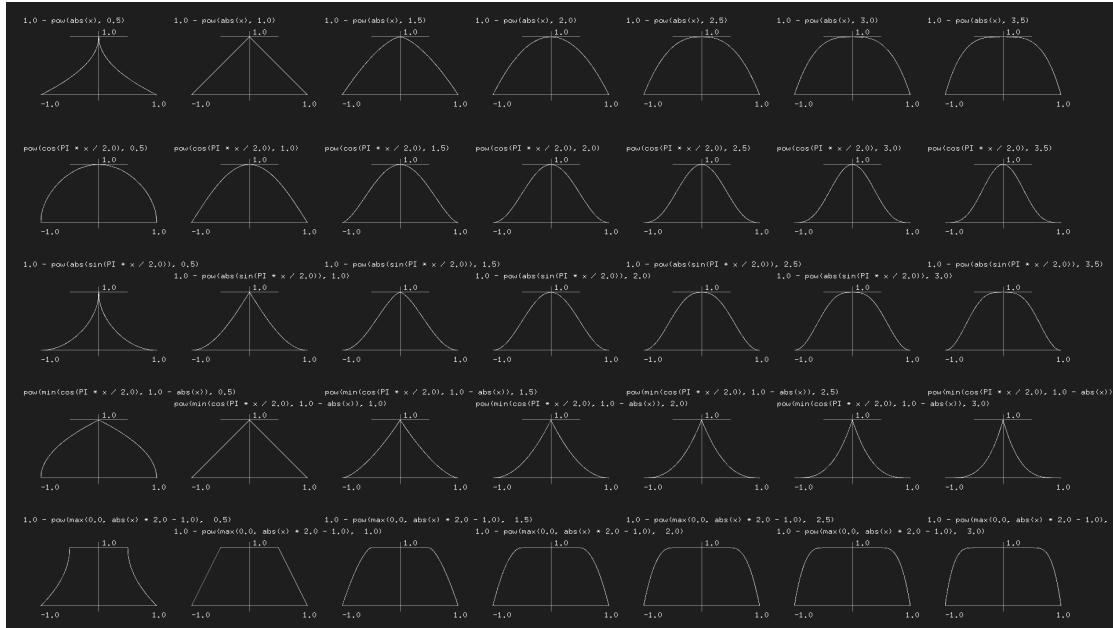


Figure 3.8: Kynd - www.flickr.com/photos/kynd/9546075099/ (2013)

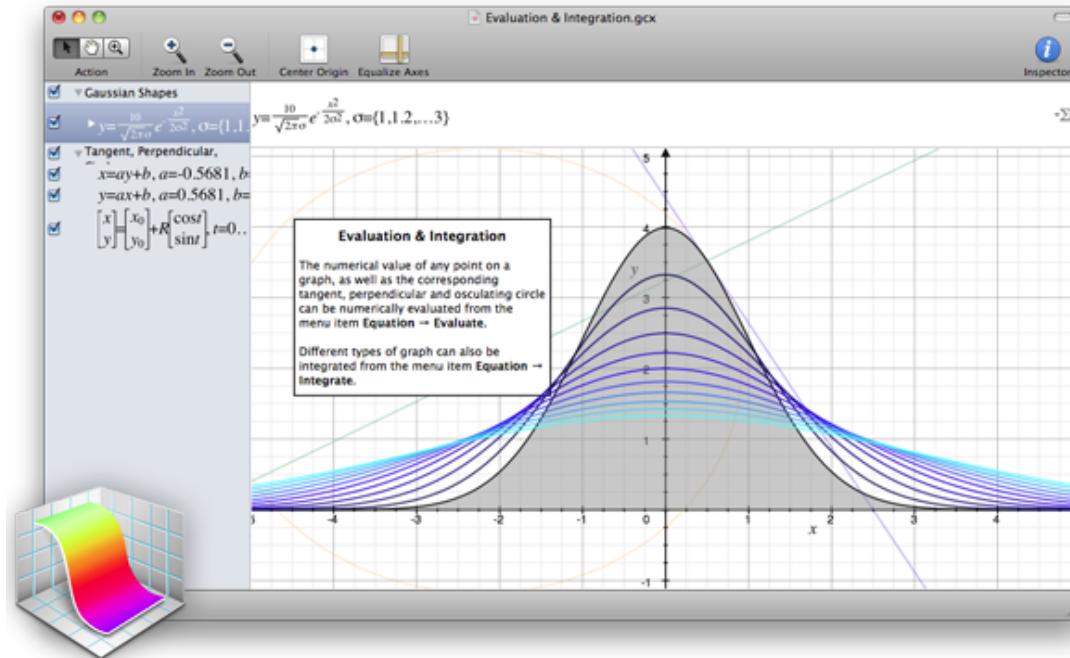


Figure 3.9: OS X Grapher (2004)

3 Algorithmic drawing

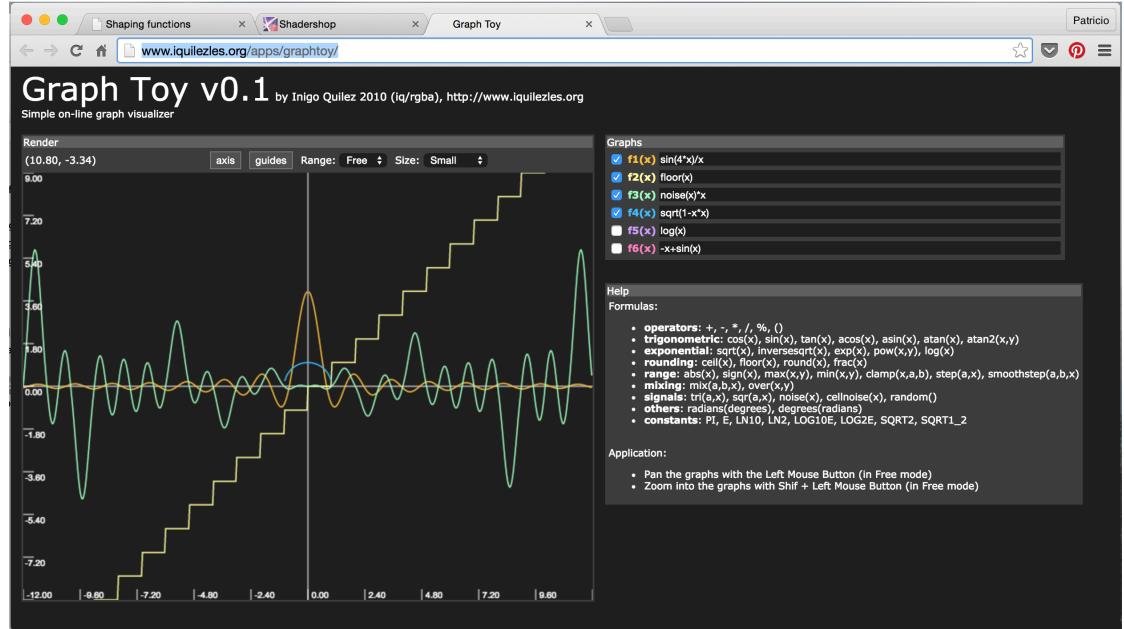


Figure 3.10: Iñigo Quilez - GraphToy (2010)

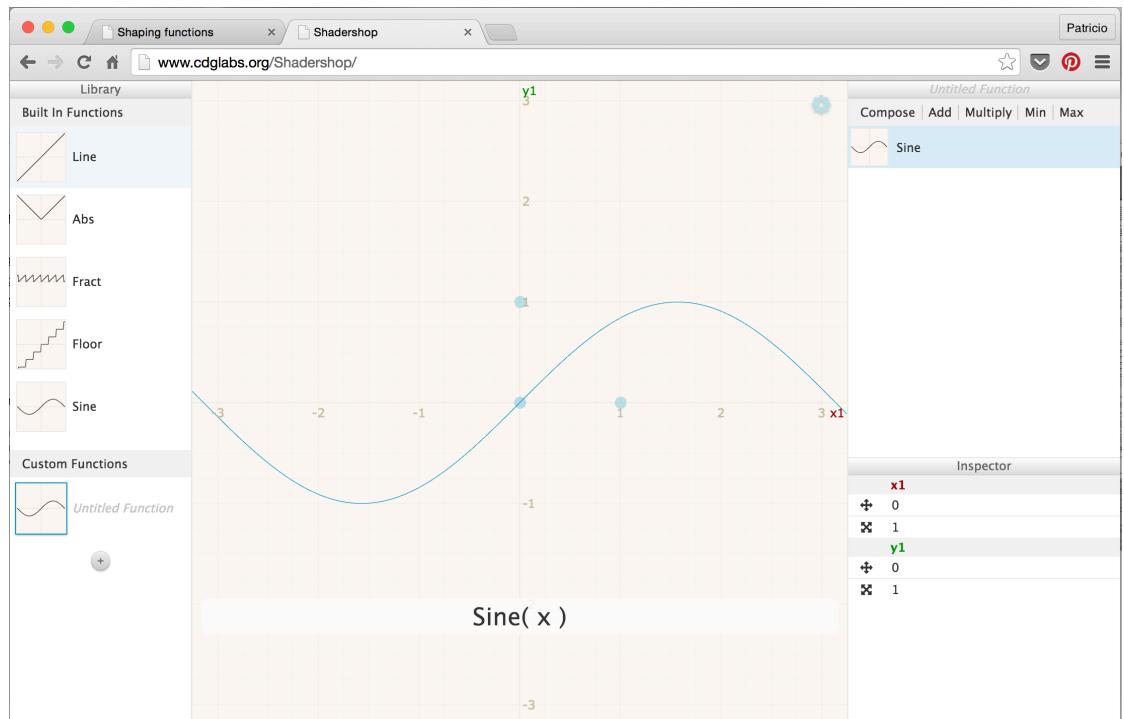


Figure 3.11: Toby Schachman - Shadershop (2014)



Figure 3.12: Paul Klee - Color Chart (1931)

3 Algorithmic drawing

If you are familiar with object oriented programming paradigms you've probably noticed that we have been accessing the data inside the vectors like any regular C-like `struct`.

```
vec3 red = vec3(1.0,0.0,0.0);
red.x = 1.0;
red.y = 0.0;
red.z = 0.0;
```

Defining color using an *x*, *y* and *z* notation can be confusing and misleading, right? That's why there are other ways to access this same information, but with different names. The values of `.x`, `.y` and `.z` can also be called `.r`, `.g` and `.b`, and `.s`, `.t` and `.p`. (`.s`, `.t` and `.p` are usually used for spatial coordinates of a texture, which we'll see in a later chapter.) You can also access the data in a vector by using the index position, `[0]`, `[1]` and `[2]`.

The following lines show all the ways to access the same data:

```
vec4 vector;
vector[0] = vector.r = vector.x = vector.s;
vector[1] = vector.g = vector.y = vector.t;
vector[2] = vector.b = vector.z = vector.p;
vector[3] = vector.a = vector.w = vector.q;
```

These different ways of pointing to the variables inside a vector are just nomenclatures designed to help you write clear code. This flexibility embedded in shading language is a door for you to start thinking interchangably about color and space coordinates.

Another great feature of vector types in GLSL is that the properties can be combined in any order you want, which makes it easy to cast and mix values. This ability is call *swizzle*.

```
vec3 yellow, magenta, green;

// Making Yellow
yellow.rg = vec2(1.0); // Assigning 1. to red and green channels
yellow[2] = 0.0;         // Assigning 0. to blue channel

// Making Magenta
magenta = yellow.rgb;   // Assign the channels with green and blue swapped

// Making Green
green.rgb = yellow.bgb; // Assign the blue channel of Yellow (0) to red and blue ch
```

3.2.0.3 For your toolbox

You might not be used to picking colors with numbers - it can be very counterintuitive. Lucky for you, there are a lot of smart programs that make this job easy. Find one that

fits your needs and then train it to deliver colors in `vec3` or `vec4` format. For example, here are the templates I use on [Spectrum](#):

```
vec3({{rn}},{{gn}},{{bn}})
vec4({{rn}},{{gn}},{{bn}},1.0)
```

3.2.1 Mixing color

Now that you know how colors are defined, it's time to integrate this with our previous knowledge. In GLSL there is a very useful function, `mix()`, that lets you mix two values in percentages. Can you guess what the percentage range is? Yes, values between 0.0 and 1.0! Which is perfect for you, after those long hours practicing your karate moves with the fence - it is time to use them!

Check the following code at line 18 and see how we are using the absolute values of a sin wave over time to mix `colorA` and `colorB`.

```
#ifdef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform float u_time;

vec3 colorA = vec3(0.149,0.141,0.912);
vec3 colorB = vec3(1.000,0.833,0.224);

void main() {
    vec3 color = vec3(0.0);

    float pct = abs(sin(u_time));

    // Mix uses pct (a value from 0-1) to
    // mix the two colors
    color = mix(colorA, colorB, pct);

    gl_FragColor = vec4(color,1.0);
}
```

Show off your skills by:

- Make an expressive transition between colors. Think of a particular emotion. What color seems most representative of it? How does it appear? How does it fade away? Think of another emotion and the matching color for it. Change the beginning and ending color of the above code to match those emotions. Then animate the

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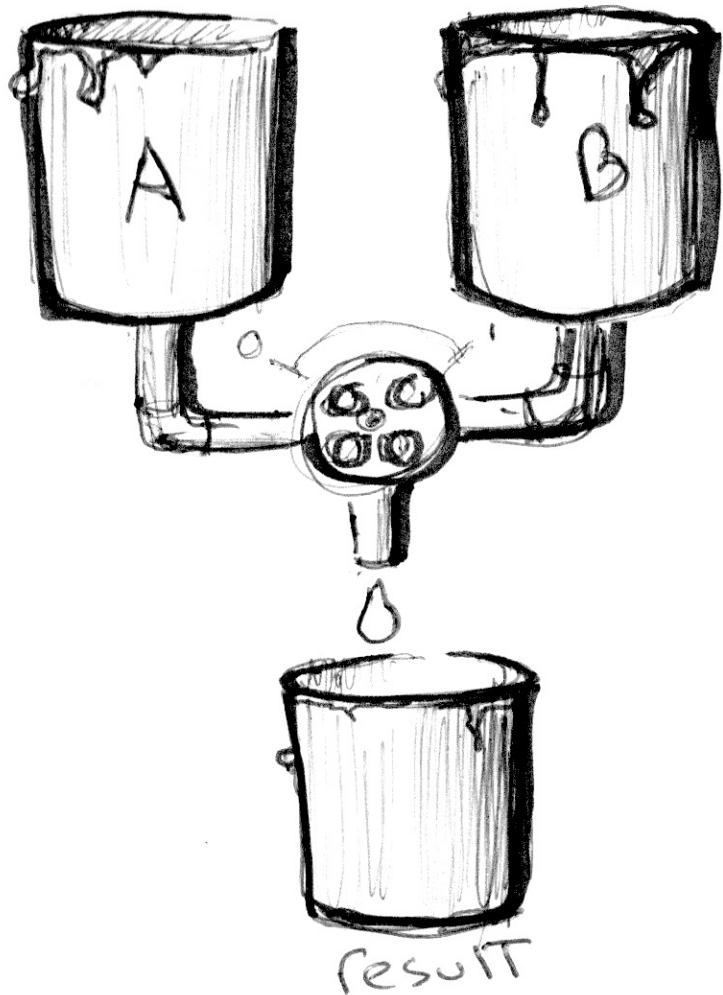


Figure 3.13:

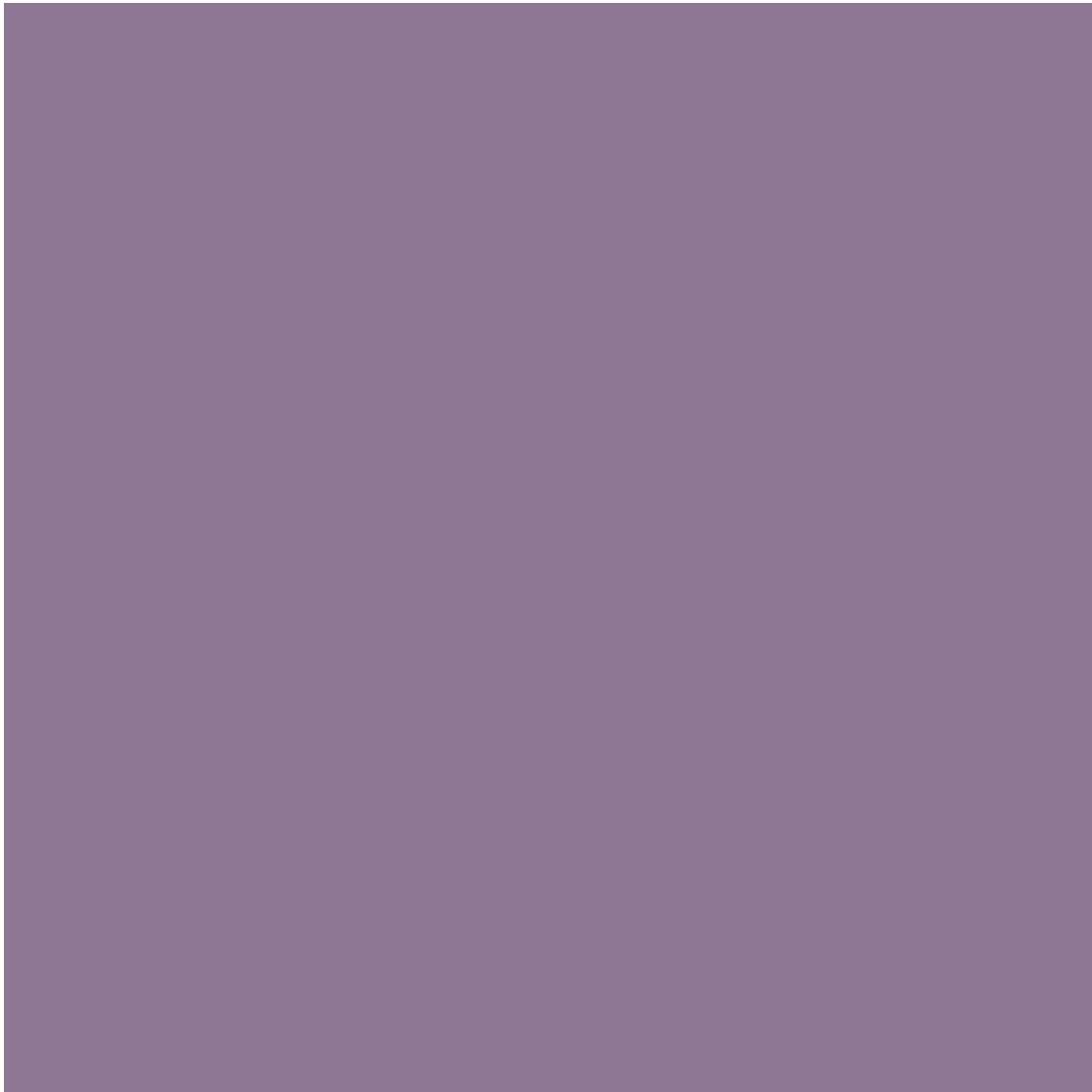


Figure 3.14:

3 Algorithmic drawing

transition using shaping functions. Robert Penner developed a series of popular shaping functions for computer animation known as [easing functions](#), you can use [this example](#) as research and inspiration but the best result will come from making your own transitions.

3.2.2 Playing with gradients

The `mix()` function has more to offer. Instead of a single `float`, we can pass a variable type that matches the two first arguments, in our case a `vec3`. By doing that we gain control over the mixing percentages of each individual color channel, `r`, `g` and `b`.

Take a look at the following example. Like the examples in the previous chapter, we are hooking the transition to the normalized x coordinate and visualizing it with a line. Right now all the channels go along the same line.

Now, uncomment line number 25 and watch what happens. Then try uncommenting lines 26 and 27. Remember that the lines visualize the amount of `colorA` and `colorB` to mix per channel.

```
#ifdef GL_ES
precision mediump float;
#endif

#define PI 3.14159265359

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

vec3 colorA = vec3(0.149,0.141,0.912);
vec3 colorB = vec3(1.000,0.833,0.224);

float plot (vec2 st, float pct){
    return smoothstep( pct-0.01, pct, st.y) -
           smoothstep( pct, pct+0.01, st.y);
}

void main() {
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    vec3 color = vec3(0.0);

    vec3 pct = vec3(st.x);

    // pct.r = smoothstep(0.0,1.0, st.x);
    // pct.g = sin(st.x*PI);
```

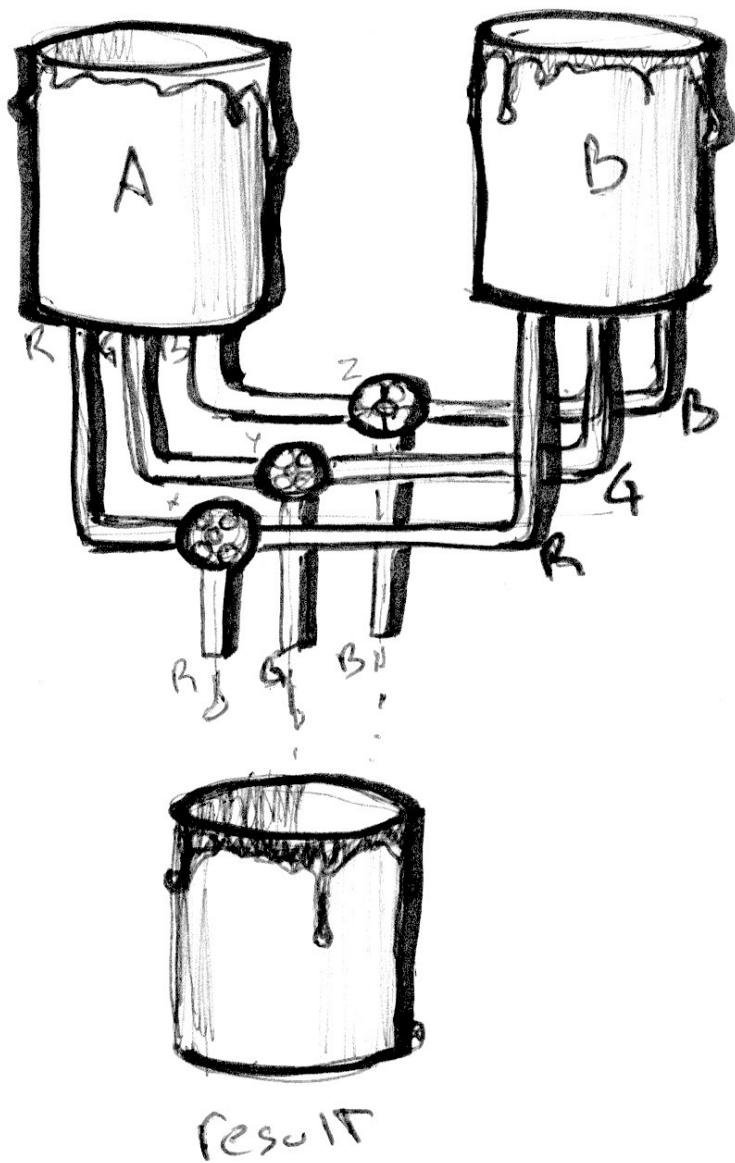


Figure 3.15:

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```
// pct.b = pow(st.x,0.5);

color = mix(colorA, colorB, pct);

// Plot transition lines for each channel
color = mix(color,vec3(1.0,0.0,0.0),plot(st,pct.r));
color = mix(color,vec3(0.0,1.0,0.0),plot(st,pct.g));
color = mix(color,vec3(0.0,0.0,1.0),plot(st,pct.b));

gl_FragColor = vec4(color,1.0);
}
```

You probably recognize the three shaping functions we are using on lines 25 to 27. Play with them! It's time for you to explore and show off your skills from the previous chapter and make interesting gradients. Try the following exercises:

- Compose a gradient that resembles a William Turner sunset
- Animate a transition between a sunrise and sunset using `u_time`.
- Can you make a rainbow using what we have learned so far?
- Use the `step()` function to create a colorful flag.

3.2.3 HSB

We can't talk about color without speaking about color space. As you probably know there are different ways to organize color besides by red, green and blue channels.

`HSB` stands for Hue, Saturation and Brightness (or Value) and is a more intuitive and useful organization of colors. Take a moment to read the `rgb2hsv()` and `hsv2rgb()` functions in the following code.

By mapping the position on the x axis to the Hue and the position on the y axis to the Brightness, we obtain a nice spectrum of visible colors. This spatial distribution of color can be very handy; it's more intuitive to pick a color with HSB than with RGB.

```
#ifdef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform float u_time;

vec3 rgb2hsb( in vec3 c ){
    vec4 K = vec4(0.0, -1.0 / 3.0, 2.0 / 3.0, -1.0);
    vec4 p = mix(vec4(c.bg, K.wz),
    
```

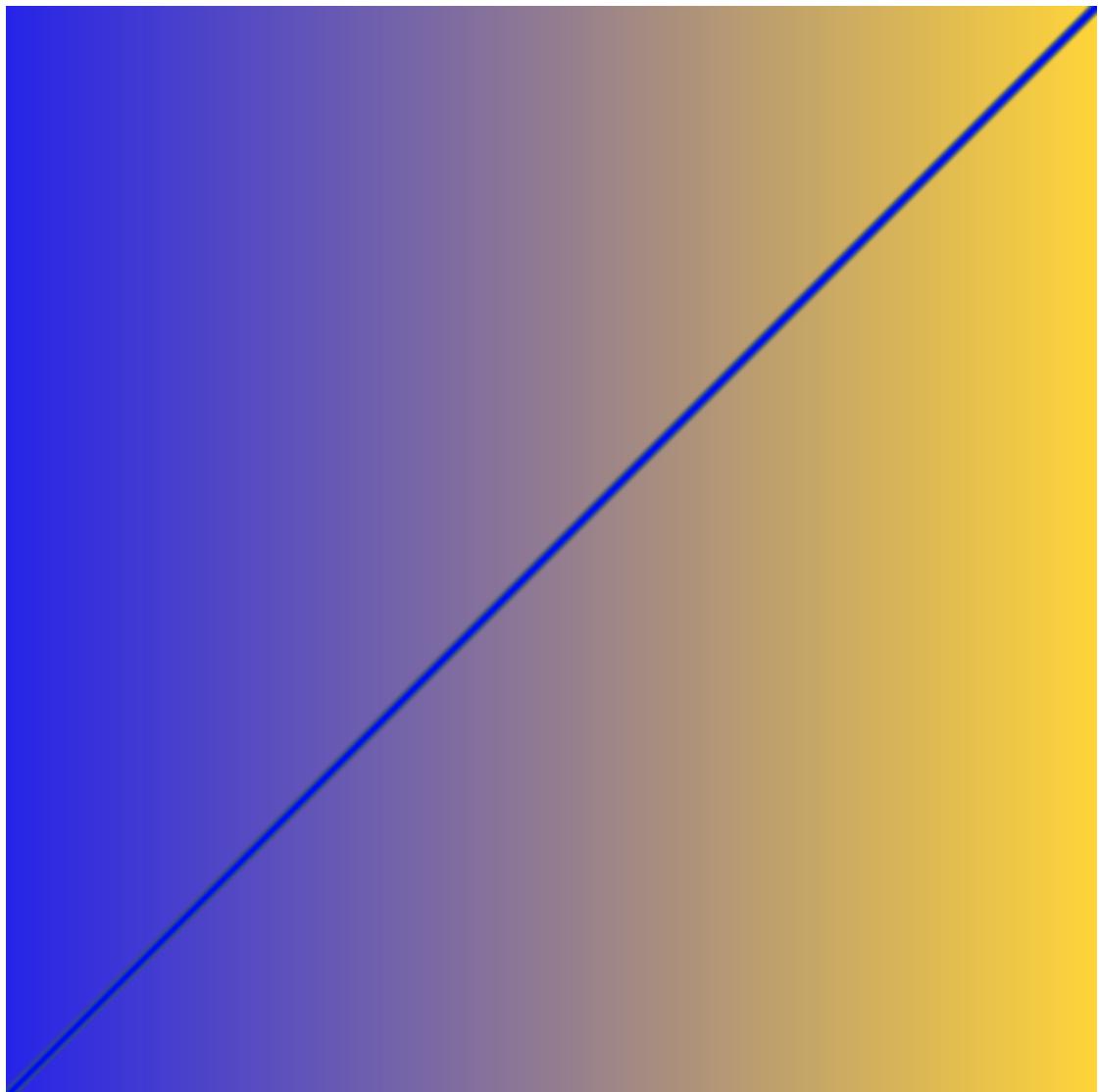


Figure 3.16:

3 Algorithmic drawing

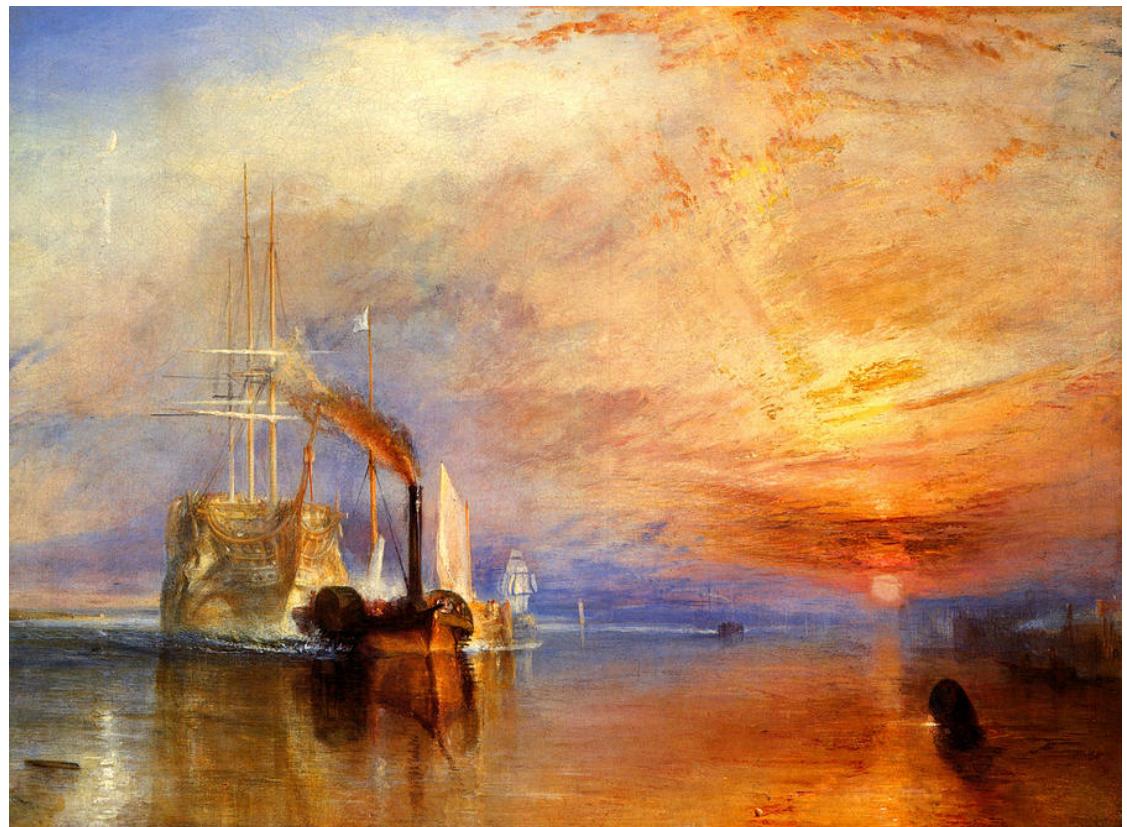


Figure 3.17: William Turner - The Fighting Temeraire (1838)

```

        vec4(c.gb, K.xy),
        step(c.b, c.g));
vec4 q = mix(vec4(p.xyw, c.r),
             vec4(c.r, p.yzx),
             step(p.x, c.r));
float d = q.x - min(q.w, q.y);
float e = 1.0e-10;
return vec3(abs(q.z + (q.w - q.y) / (6.0 * d + e)),
            d / (q.x + e),
            q.x);
}

// Function from Iñigo Quiles
// https://www.shadertoy.com/view/MsS3Wc
vec3 hsb2rgb( in vec3 c ){
    vec3 rgb = clamp(abs(mod(c.x*6.0+vec3(0.0,4.0,2.0),
                             6.0)-3.0)-1.0,
                      0.0,
                      1.0 );
    rgb = rgb*rgb*(3.0-2.0*rgb);
    return c.z * mix(vec3(1.0), rgb, c.y);
}

void main(){
    vec2 st = gl_FragCoord.xy/u_resolution;
    vec3 color = vec3(0.0);

    // We map x (0.0 - 1.0) to the hue (0.0 - 1.0)
    // And the y (0.0 - 1.0) to the brightness
    color = hsb2rgb(vec3(st.x,1.0,st.y));

    gl_FragColor = vec4(color,1.0);
}

```

3.2.4 HSB in polar coordinates

HSB was originally designed to be represented in polar coordinates (based on the angle and radius) instead of cartesian coordinates (based on x and y). To map our HSB function to polar coordinates we need to obtain the angle and distance from the center of the billboard to the pixel coordinate. For that we will use the `length()` function and `atan(y,x)` (which is the GLSL version of the commonly used `atan2(y,x)`).

When using vector and trigonometric functions, `vec2`, `vec3` and `vec4` are treated as vectors even when they represent colors. We will start treating colors and vectors similarly,

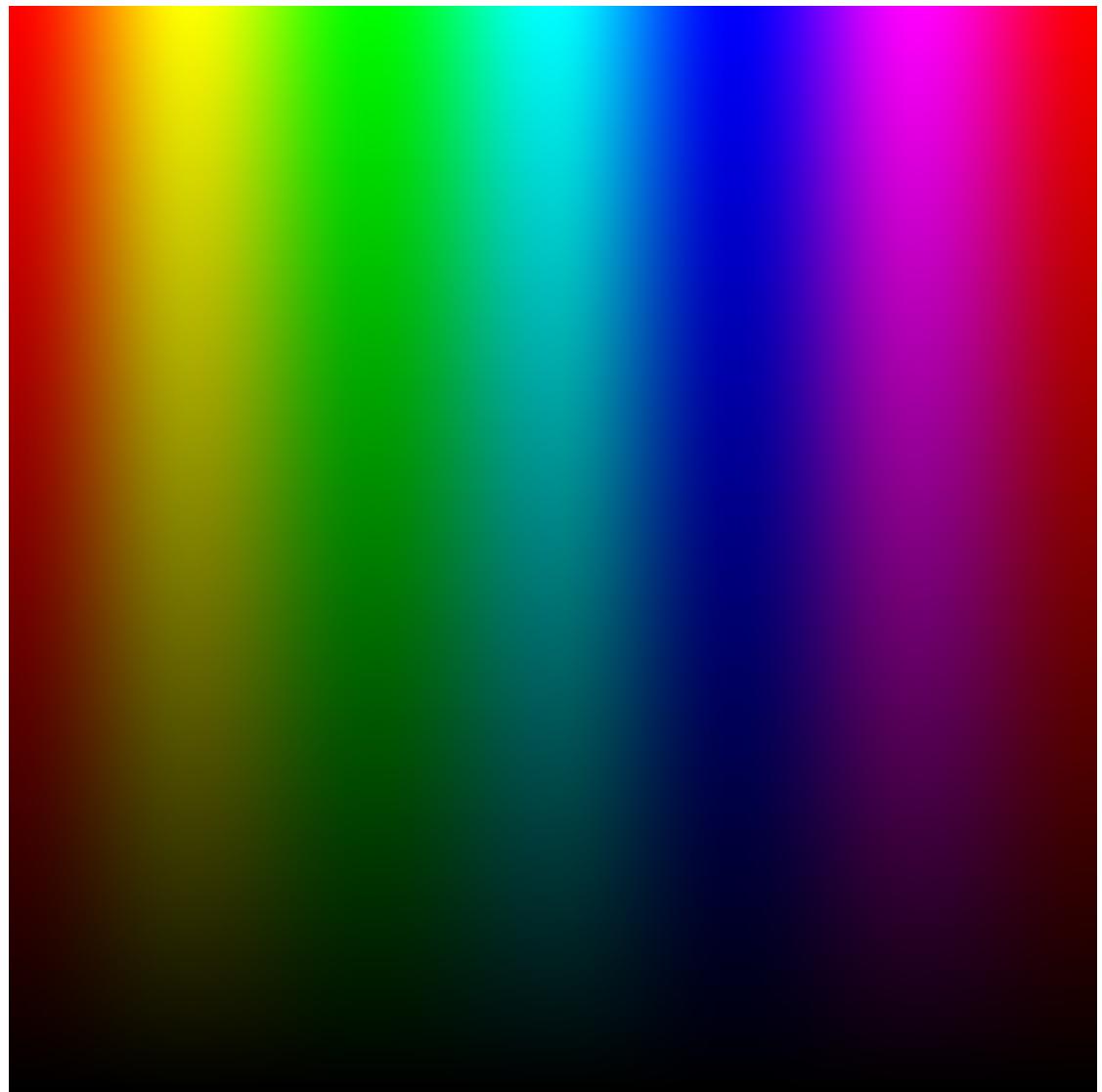


Figure 3.18:

in fact you will come to find this conceptual flexibility very empowering.

Note: If you were wondering, there are more geometric functions besides `length` like: `distance()`, `dot()`, `cross`, `normalize()`, `faceforward()`, `reflect()` and `refract()`. Also GLSL has special vector relational functions such as: `lessThan()`, `lessThanEqual()`, `greaterThan()`, `greaterThanEqual()`, `equal()` and `notEqual()`.

Once we obtain the angle and length we need to “normalize” their values to the range between 0.0 to 1.0. On line 27, `atan(y,x)` will return an angle in radians between -PI and PI (-3.14 to 3.14), so we need to divide this number by `TWO_PI` (defined at the top of the code) to get values between -0.5 to 0.5, which by simple addition we change to the desired range of 0.0 to 1.0. The radius will return a maximum of 0.5 (because we are calculating the distance from the center of the viewport) so we need to double this range (by multiplying by two) to get a maximum of 1.0.

As you can see, our game here is all about transforming and mapping ranges to the 0.0 to 1.0 that we like.

```
#ifdef GL_ES
precision mediump float;
#endif

#define TWO_PI 6.28318530718

uniform vec2 u_resolution;
uniform float u_time;

// Function from Iñigo Quiles
// https://www.shadertoy.com/view/MsS3Wc
vec3 hsb2rgb( in vec3 c ){
    vec3 rgb = clamp(abs(mod(c.x*6.0+vec3(0.0,4.0,2.0),
        6.0)-3.0)-1.0,
        0.0,
        1.0 );
    rgb = rgb*rgb*(3.0-2.0*rgb);
    return c.z * mix( vec3(1.0), rgb, c.y );
}

void main(){
    vec2 st = gl_FragCoord.xy/u_resolution;
    vec3 color = vec3(0.0);

    // Use polar coordinates instead of cartesian
    vec2 toCenter = vec2(0.5)-st;
    float angle = atan(toCenter.y,toCenter.x);
    float radius = length(toCenter)*2.0;
```

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```
// Map the angle (-PI to PI) to the Hue (from 0 to 1)
// and the Saturation to the radius
color = hsb2rgb(vec3((angle/TWO_PI)+0.5, radius, 1.0));

gl_FragColor = vec4(color, 1.0);
}
```

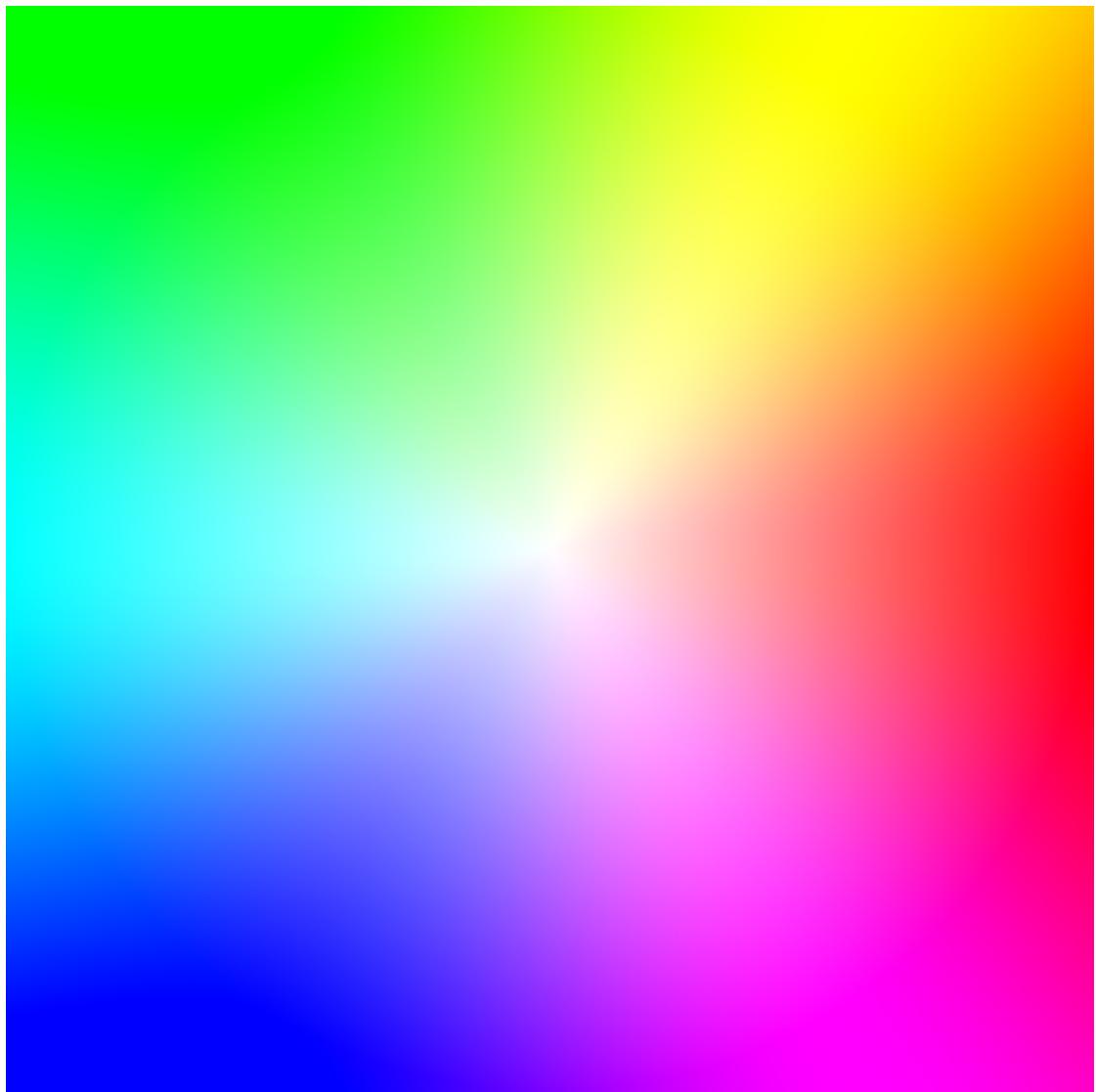


Figure 3.19:

Try the following exercises:

- Modify the polar example to get a spinning color wheel, just like the waiting mouse

icon.

- Use a shaping function together with the conversion function from HSB to RGB to expand a particular hue value and shrink the rest.
- If you look closely at the color wheel used on color pickers (see the image below), they use a different spectrum according to RYB color space. For example, the opposite color of red should be green, but in our example it is cyan. Can you find a way to fix that in order to look exactly like the following image? [Hint: this is a great moment to use shaping functions.]

3.2.4.1 Note about functions and arguments

Before jumping to the next chapter let's stop and rewind. Go back and take look at the functions in previous examples. You will notice `in` before the type of the arguments. This is a *qualifier* and in this case it specifies that the variable is read only. In future examples we will see that it is also possible to define arguments as `out` or `inout`. This last one, `inout`, is conceptually similar to passing an argument by reference which will give us the possibility to modify a passed variable.

```
int newFunction(in vec4 aVec4,    // read-only
               out vec3 aVec3,    // write-only
               inout int aInt); // read-write
```

You may not believe it but now we have all the elements to make cool drawings. In the next chapter we will learn how to combine all our tricks to make geometric forms by *blending* the space. Yep... *blending* the space.

3.3 Shapes

Finally! We have been building skills for this moment! You have learned most of the GLSL foundations, types and functions. You have practiced your shaping equations over and over. Now is the time to put it all together. You are up for this challenge! In this chapter you'll learn how to draw simple shapes in a parallel procedural way.

3.3.1 Rectangle

Imagine we have grid paper like we used in math classes and our homework is to draw a square. The paper size is 10x10 and the square is supposed to be 8x8. What will you do?

You'd paint everything except the first and last rows and the first and last column, right?

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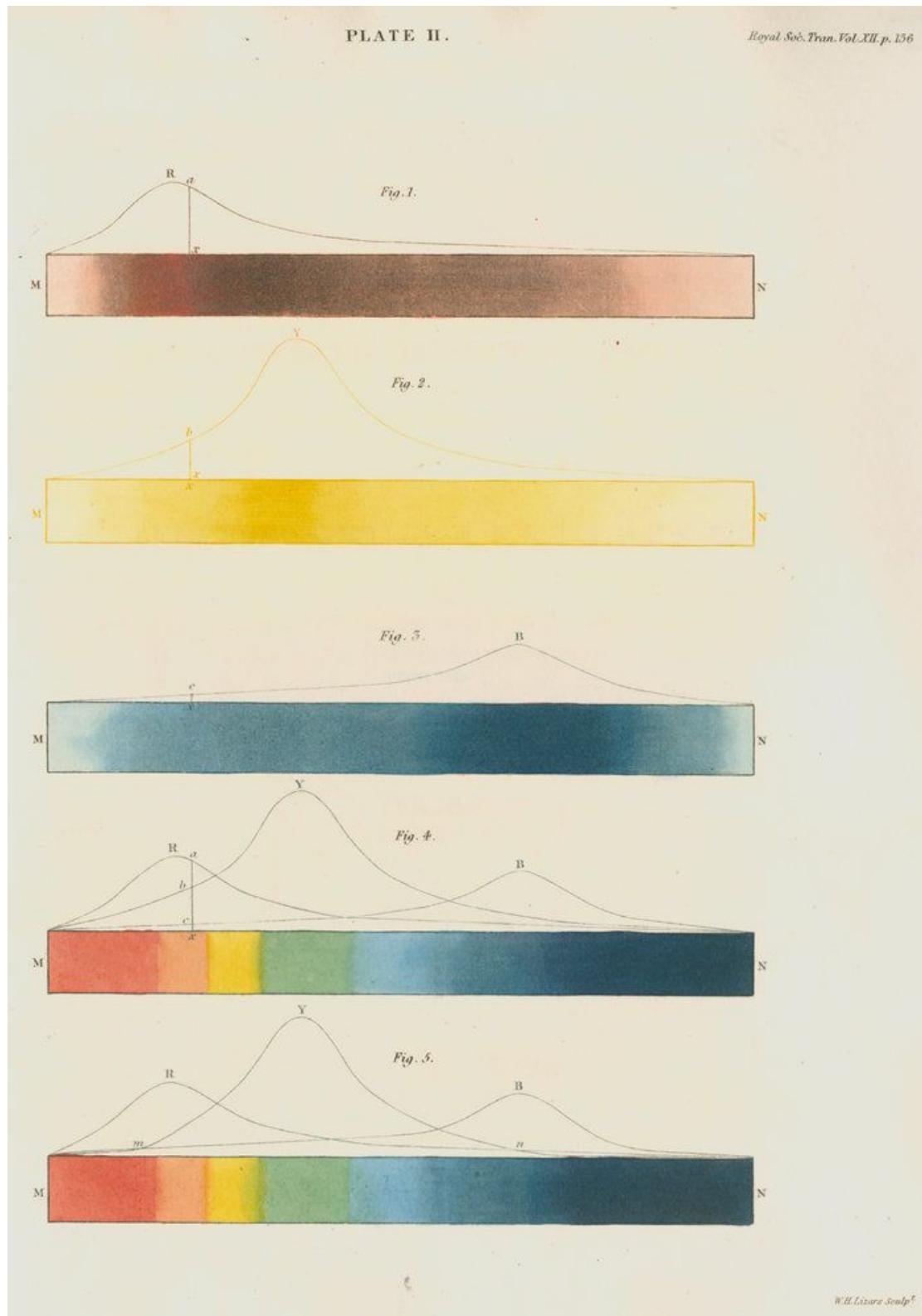


Figure 3.20: William Home Lizars - Red, blue and yellow spectra, with the solar spectrum (1834)



Figure 3.21:

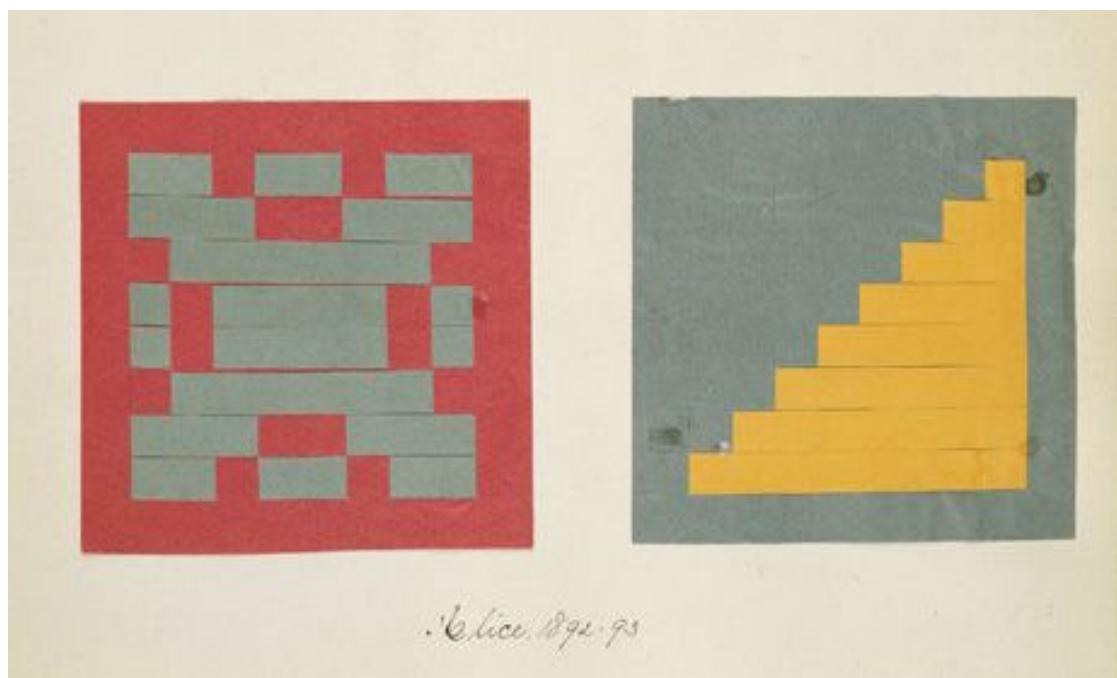


Figure 3.22: Alice Hubbard, Providence, United States, ca. 1892. Photo: Zindman/Freemont.

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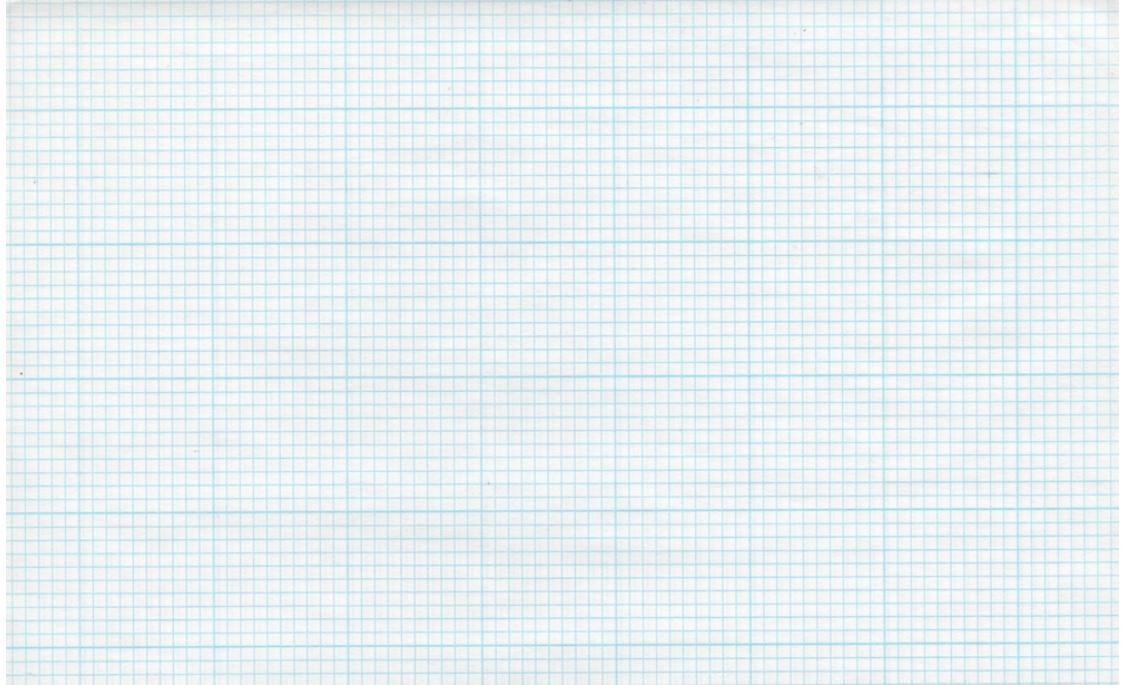


Figure 3.23:

How does this relate to shaders? Each little square of our grid paper is a thread (a pixel). Each little square knows its position, like the coordinates of a chess board. In previous chapters we mapped x and y to the *red* and *green* color channels, and we learned how to use the narrow two dimensional territory between 0.0 and 1.0. How can we use this to draw a centered square in the middle of our billboard?

Let's start by sketching pseudocode that uses `if` statements over the spatial field. The principles to do this are remarkably similar to how we think of the grid paper scenario.

```
if ( (X GREATER THAN 1) AND (Y GREATER THAN 1) )
    paint white
else
    paint black
```

Now that we have a better idea of how this will work, let's replace the `if` statement with `step()`, and instead of using 10x10 let's use normalized values between 0.0 and 1.0:

```
uniform vec2 u_resolution;

void main(){
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    vec3 color = vec3(0.0);
```

```

// Each result will return 1.0 (white) or 0.0 (black).
float left = step(0.1,st.x); // Similar to ( X greater than 0.1 )
float bottom = step(0.1,st.y); // Similar to ( Y greater than 0.1 )

// The multiplication of left*bottom will be similar to the logical AND.
color = vec3( left * bottom );

gl_FragColor = vec4(color,1.0);
}

```

The `step()` function will turn every pixel below 0.1 to black (`vec3(0.0)`) and the rest to white (`vec3(1.0)`). The multiplication between `left` and `bottom` works as a logical AND operation, where both must be 1.0 to return 1.0. This draws two black lines, one on the bottom and the other on the left side of the canvas.

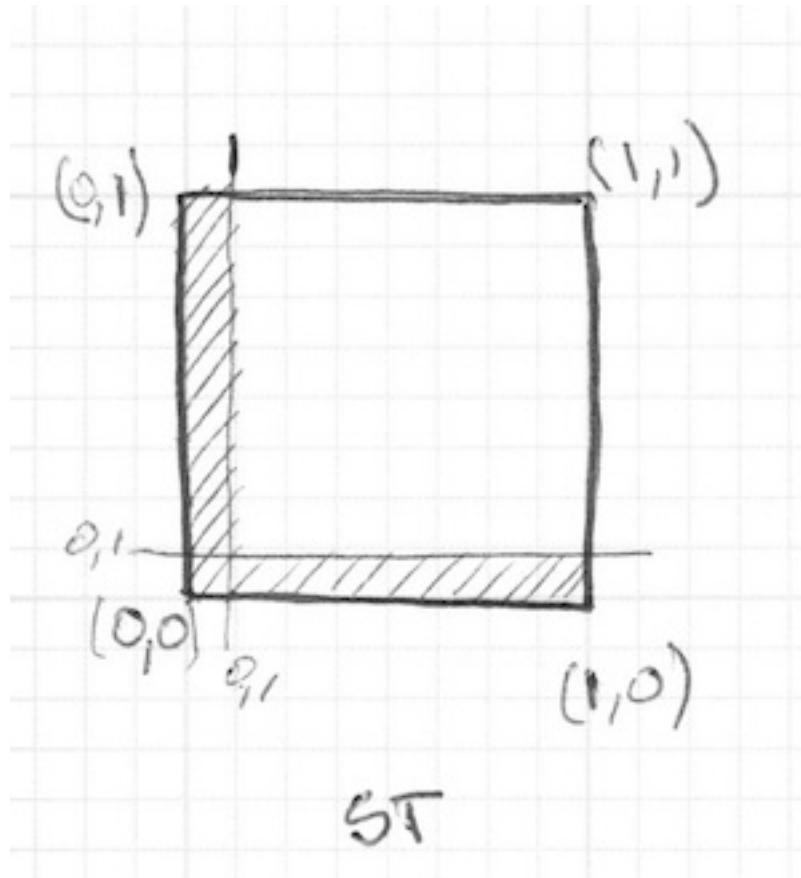


Figure 3.24:

In the previous code we repeat the structure for each axis (left and bottom). We can save some lines of code by passing two values directly to `step()` instead of one. That

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looks like this:

```
vec2 borders = step(vec2(0.1),st);
float pct = borders.x * borders.y;
```

So far, we've only drawn two borders (bottom-left) of our rectangle. Let's do the other two (top-right). Check out the following code:

```
// Author @patriciogv - 2015
// http://patriciogonzalezvivo.com

#ifndef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

void main(){
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    vec3 color = vec3(0.0);

    // bottom-left
    vec2 bl = step(vec2(0.1),st);
    float pct = bl.x * bl.y;

    // top-right
    // vec2 tr = step(vec2(0.1),1.0-st);
    // pct *= tr.x * tr.y;

    color = vec3(pct);

    gl_FragColor = vec4(color,1.0);
}
```

Uncomment *lines 21-22* and see how we invert the **st** coordinates and repeat the same **step()** function. That way the **vec2(0.0,0.0)** will be in the top right corner. This is the digital equivalent of flipping the page and repeating the previous procedure.

Take note that in *lines 18 and 22* all of the sides are being multiplied together. This is equivalent to writing:

```
vec2 bl = step(vec2(0.1),st);      // bottom-left
vec2 tr = step(vec2(0.1),1.0-st);  // top-right
color = vec3(bl.x * bl.y * tr.x * tr.y);
```



Figure 3.25:

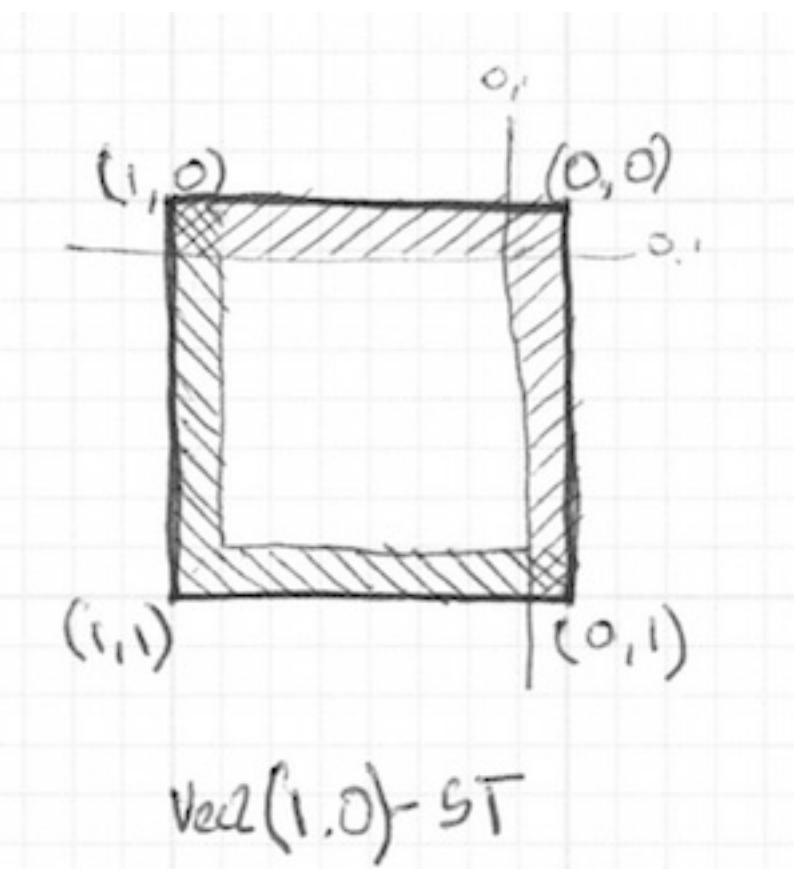


Figure 3.26:

Interesting right? This technique is all about using `step()` and multiplication for logical operations and flipping the coordinates.

Before going forward, try the following exercises:

- Change the size and proportions of the rectangle.
- Experiment with the same code but using `smoothstep()` instead of `step()`. Note that by changing values, you can go from blurred edges to elegant smooth borders.
- Do another implementation that uses `floor()`.
- Choose the implementation you like the most and make a function of it that you can reuse in the future. Make your function flexible and efficient.
- Make another function that just draws the outline of a rectangle.
- How do you think you can move and place different rectangles in the same billboard? If you figure out how, show off your skills by making a composition of rectangles and colors that resembles a [Piet Mondrian](#) painting.

3.3.2 Circles

It's easy to draw squares on grid paper and rectangles on cartesian coordinates, but circles require another approach, especially since we need a "per-pixel" algorithm. One solution is to *re-map* the spatial coordinates so that we can use a `step()` function to draw a circle.

How? Let's start by going back to math class and the grid paper, where we opened a compass to the radius of a circle, pressed one of the compass points at the center of the circle and then traced the edge of the circle with a simple spin.

Translating this to a shader where each square on the grid paper is a pixel implies *asking* each pixel (or thread) if it is inside the area of the circle. We do this by computing the distance from the pixel to the center of the circle.

There are several ways to calculate that distance. The easiest one uses the `distance()` function, which internally computes the `length()` of the difference between two points (in our case the pixel coordinate and the center of the canvas). The `length()` function is nothing but a shortcut of the [hypotenuse equation](#) that uses square root (`sqrt()`) internally.

You can use `distance()`, `length()` or `sqrt()` to calculate the distance to the center of the billboard. The following code contains these three functions and the non-surprising fact that each one returns exactly same result.

- Comment and uncomment lines to try the different ways to get the same result.

```
// Author @patriciogv - 2015
// http://patriciogonzalezvivo.com
```

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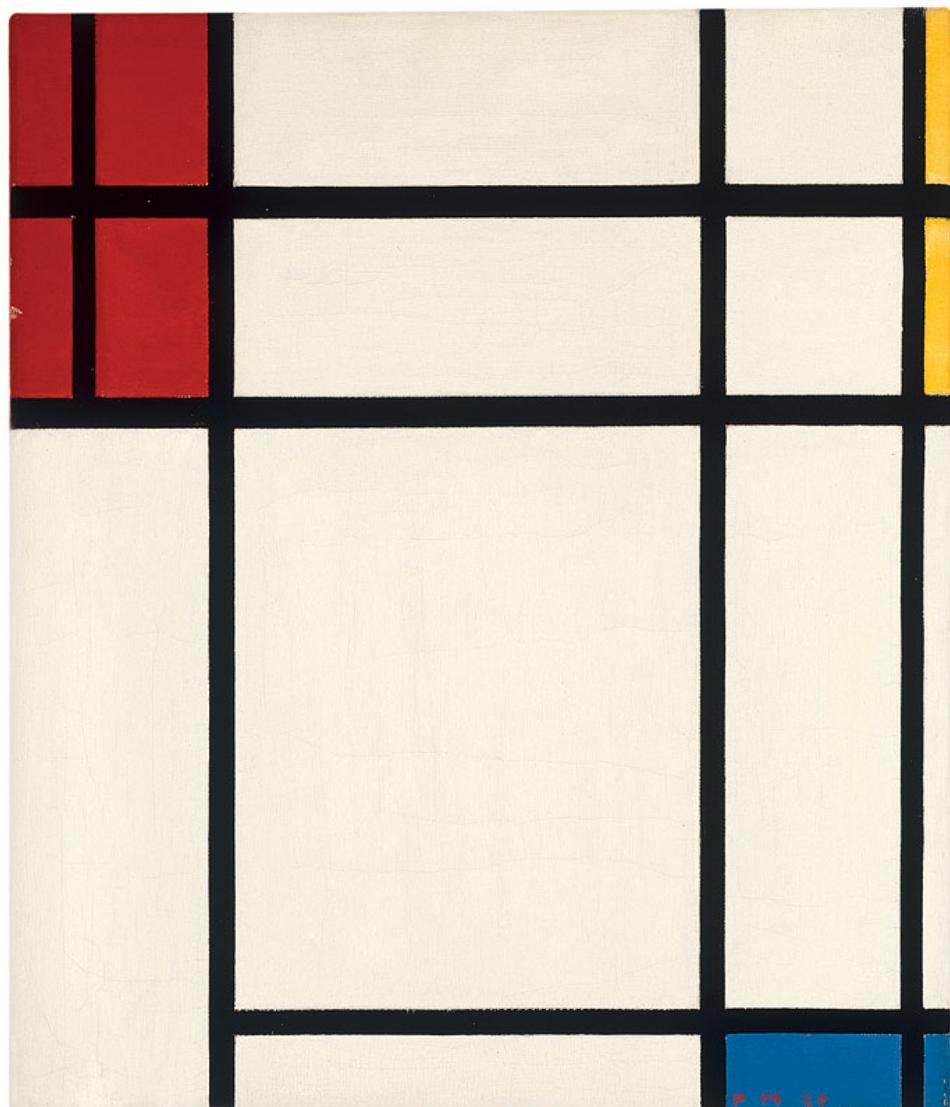


Figure 3.27: Piet Mondria - Tableau (1921)

3.3 Shapes

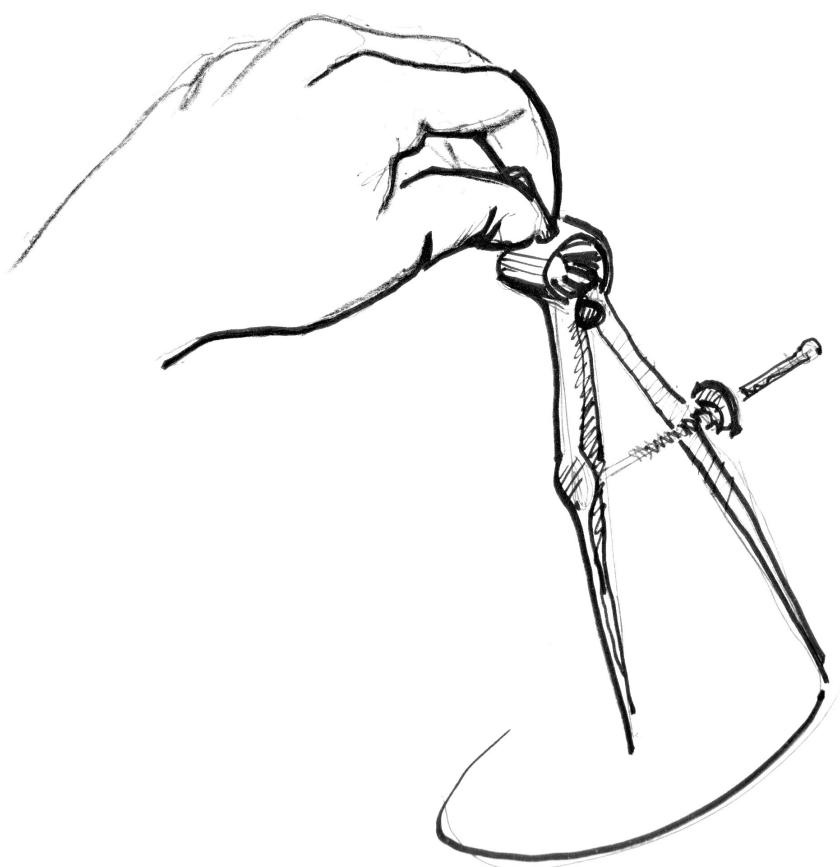


Figure 3.28:

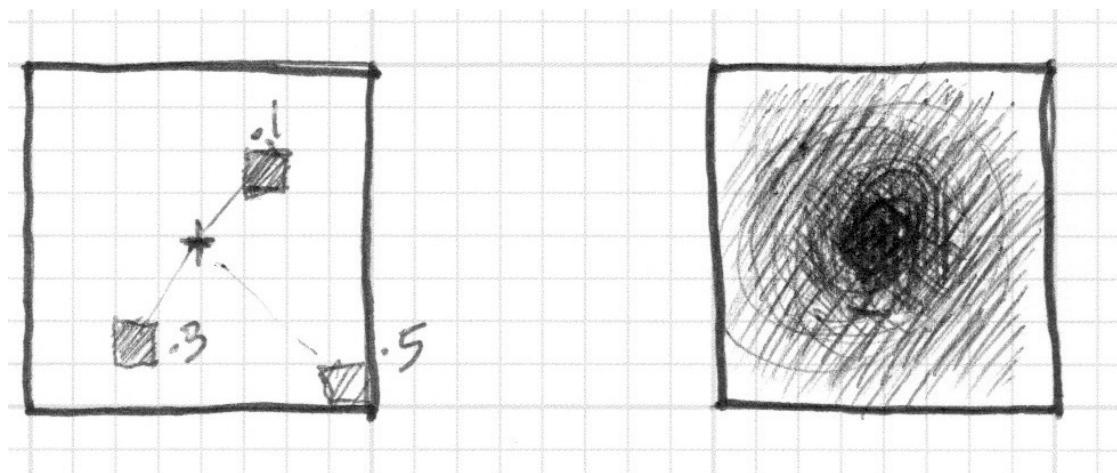


Figure 3.29:

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$$c = \sqrt{a^2 + b^2}.$$

Figure 3.30:

```
#ifdef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

void main(){
    vec2 st = gl_FragCoord.xy/u_resolution;
    float pct = 0.0;

    // a. The DISTANCE from the pixel to the center
    pct = distance(st,vec2(0.5));

    // b. The LENGTH of the vector
    //     from the pixel to the center
    // vec2 toCenter = vec2(0.5)-st;
    // pct = length(toCenter);

    // c. The SQUARE ROOT of the vector
    //     from the pixel to the center
    // vec2 tC = vec2(0.5)-st;
    // pct = sqrt(tC.x*tC.x+tC.y*tC.y);

    vec3 color = vec3(pct);

    gl_FragColor = vec4( color, 1.0 );
}
```

In the previous example we map the distance to the center of the billboard to the color brightness of the pixel. The closer a pixel is to the center, the lower (darker) value it has. Notice that the values don't get too high because from the center (`vec2(0.5, 0.5)`) the maximum distance barely goes over 0.5. Contemplate this map and think:

- What you can infer from it?
- How we can use this to draw a circle?
- Modify the above code in order to contain the entire circular gradient inside the

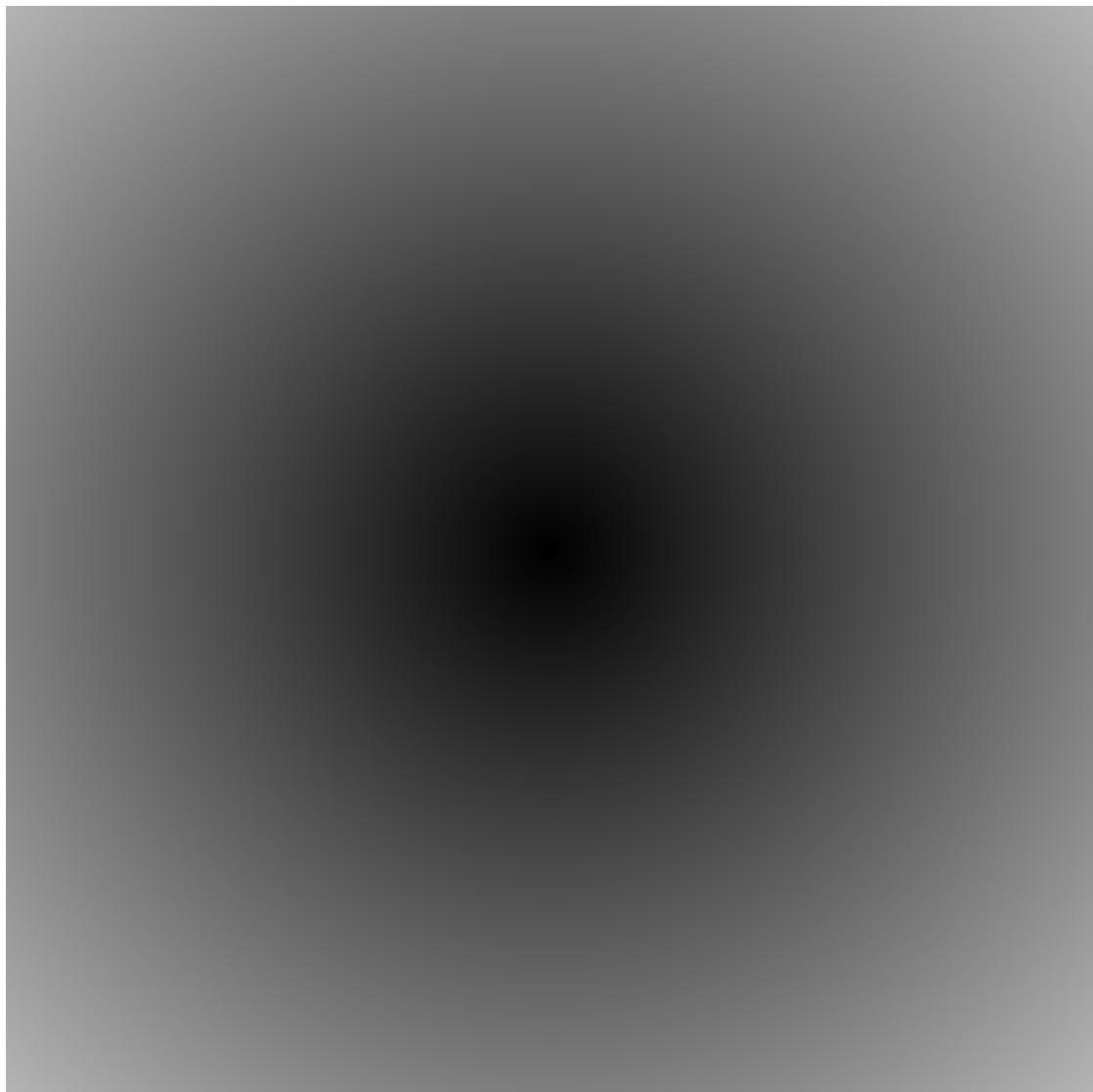


Figure 3.31:

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canvas.

3.3.3 Distance field

We can also think of the above example as an altitude map, where darker implies taller. The gradient shows us something similar to the pattern made by a cone. Imagine yourself on the top of that cone. The horizontal distance to the edge of the cone is 0.5. This will be constant in all directions. By choosing where to “cut” the cone you will get a bigger or smaller circular surface.

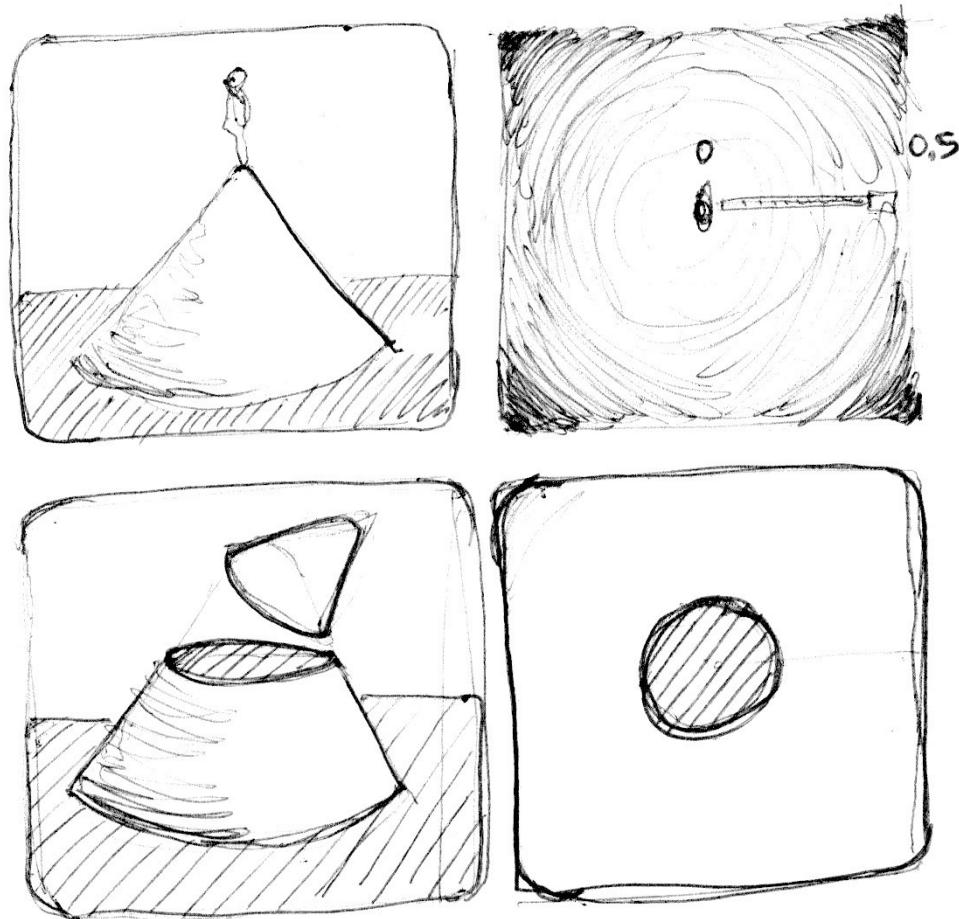


Figure 3.32:

Basically we are using a re-interpretation of the space (based on the distance to the center) to make shapes. This technique is known as a “distance field” and is used in different ways from font outlines to 3D graphics.

Try the following exercises:

- Use `step()` to turn everything above 0.5 to white and everything below to 0.0.
- Inverse the colors of the background and foreground.
- Using `smoothstep()`, experiment with different values to get nice smooth borders on your circle.
- Once you are happy with an implementation, make a function of it that you can reuse in the future.
- Add color to the circle.
- Can you animate your circle to grow and shrink, simulating a beating heart? (You can get some inspiration from the animation in the previous chapter.)
- What about moving this circle? Can you move it and place different circles in a single billboard?
- What happens if you combine distances fields together using different functions and operations?

```
pct = distance(st,vec2(0.4)) + distance(st,vec2(0.6));
pct = distance(st,vec2(0.4)) * distance(st,vec2(0.6));
pct = min(distance(st,vec2(0.4)),distance(st,vec2(0.6)));
pct = max(distance(st,vec2(0.4)),distance(st,vec2(0.6)));
pct = pow(distance(st,vec2(0.4)),distance(st,vec2(0.6)));
```

- Make three compositions using this technique. If they are animated, even better!

3.3.3.1 For your tool box

In terms of computational power the `sqrt()` function - and all the functions that depend on it - can be expensive. Here is another way to create a circular distance field by using `dot()` product.

```
// Author @patriciogv - 2015
// http://patriciogonzalezvivo.com

#ifndef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

float circle(in vec2 _st, in float _radius){
    vec2 l = _st-vec2(0.5);
```

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```
        return 1.-smoothstep(_radius-(_radius*0.01),
                            _radius+(_radius*0.01),
                            dot(l,l)*4.0);
    }

void main(){
    vec2 st = gl_FragCoord.xy/u_resolution.xy;

    vec3 color = vec3(circle(st,0.9));

    gl_FragColor = vec4( color, 1.0 );
}
```

3.3.4 Useful properties of a Distance Field

Distance fields can be used to draw almost everything. Obviously the more complex a shape is, the more complicated its equation will be, but once you have the formula to make distance fields of a particular shape it is very easy to combine and/or apply effects to it, like smooth edges and multiple outlines. Because of this, distance fields are popular in font rendering, like [Mapbox GL Labels](#), [Matt DesLauriers Material Design Fonts](#) and as is describe on Chapter 7 of [iPhone 3D Programming](#), O'Reilly.

Take a look at the following code.

```
#ifdef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

void main(){
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    st.x *= u_resolution.x/u_resolution.y;
    vec3 color = vec3(0.0);
    float d = 0.0;

    // Remap the space to -1. to 1.
    st = st *2.-1.;

    // Make the distance field
    d = length( abs(st)-.3 );
    // d = length( min(abs(st)-.3,0.) );
```

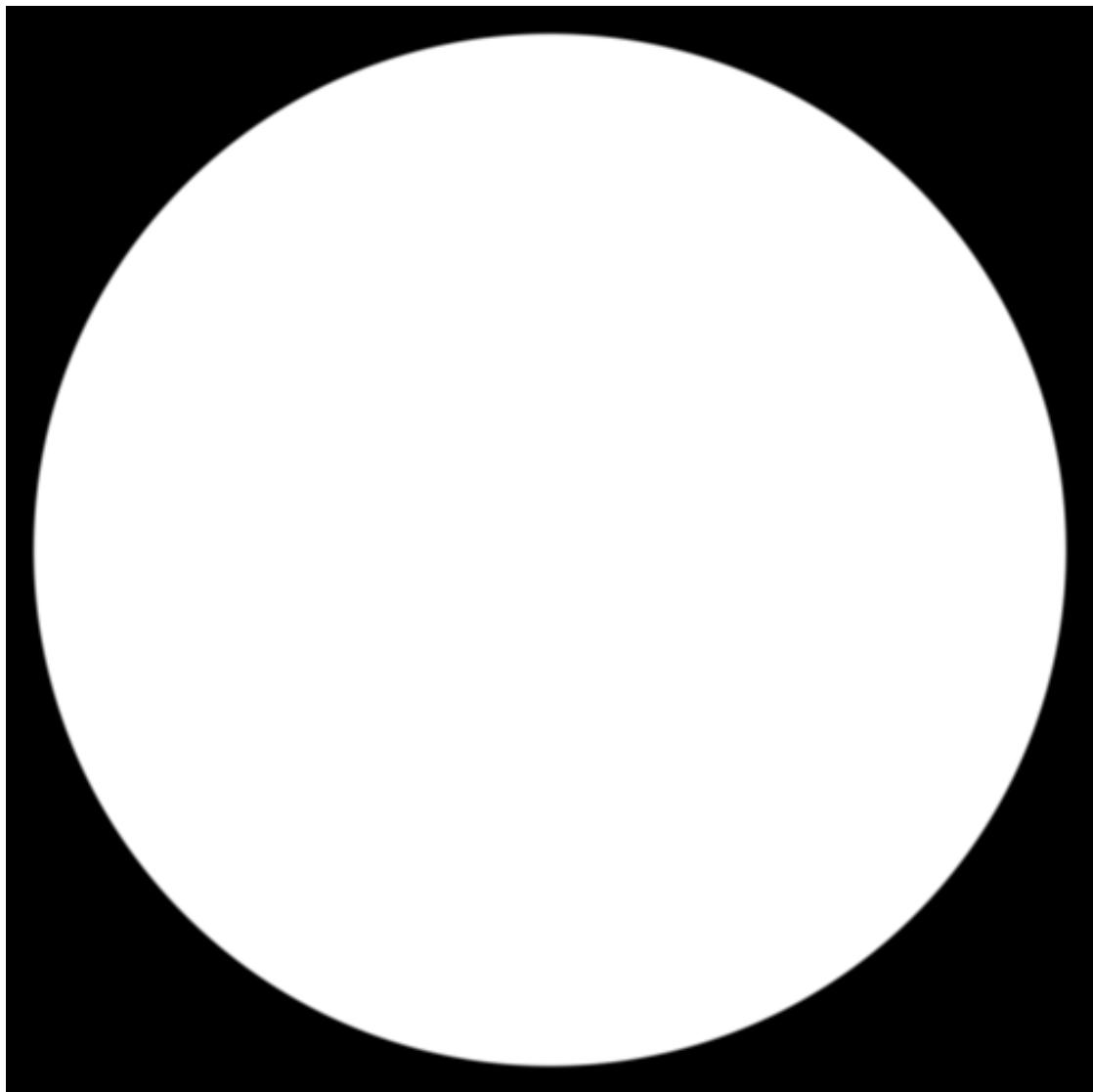


Figure 3.33:

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Figure 3.34: Zen garden

```
// d = length( max(abs(st)-.3,0.) );

// Visualize the distance field
gl_FragColor = vec4(vec3(fract(d*10.0)),1.0);

// Drawing with the distance field
// gl_FragColor = vec4(vec3( step(.3,d) ),1.0);
// gl_FragColor = vec4(vec3( step(.3,d) * step(d,.4)),1.0);
// gl_FragColor = vec4(vec3( smoothstep(.3,.4,d)* smoothstep(.6,.5,d)) ,1.0);
}
```

We start by moving the coordinate system to the center and shrinking it in half in order to remap the position values between -1 and 1. Also on *line 24* we are visualizing the distance field values using a `fract()` function making it easy to see the pattern they create. The distance field pattern repeats over and over like rings in a Zen garden.

Let's take a look at the distance field formula on *line 19*. There we are calculating the distance to the position on $(.3, .3)$ or `vec3(.3)` in all four quadrants (that's what `abs()` is doing there).

If you uncomment *line 20*, you will note that we are combining the distances to these four points using the `min()` to zero. The result produces an interesting new pattern.

Now try uncommenting *line 21*; we are doing the same but using the `max()` function. The result is a rectangle with rounded corners. Note how the rings of the distance field get smoother the further away they get from the center.

Finish uncommenting *lines 27 to 29* one by one to understand the different uses of a

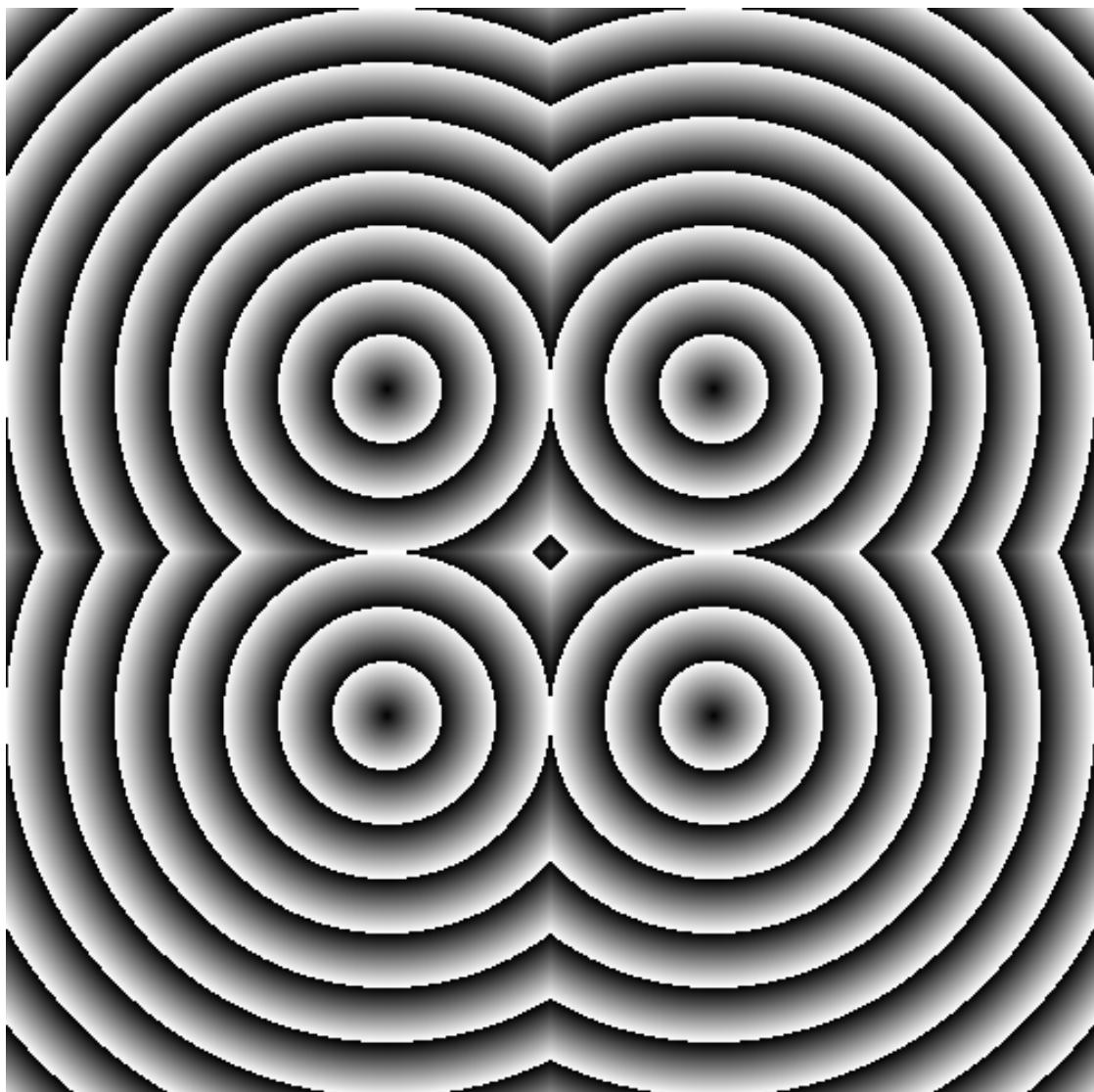


Figure 3.35:

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distance field pattern.

3.3.5 Polar shapes

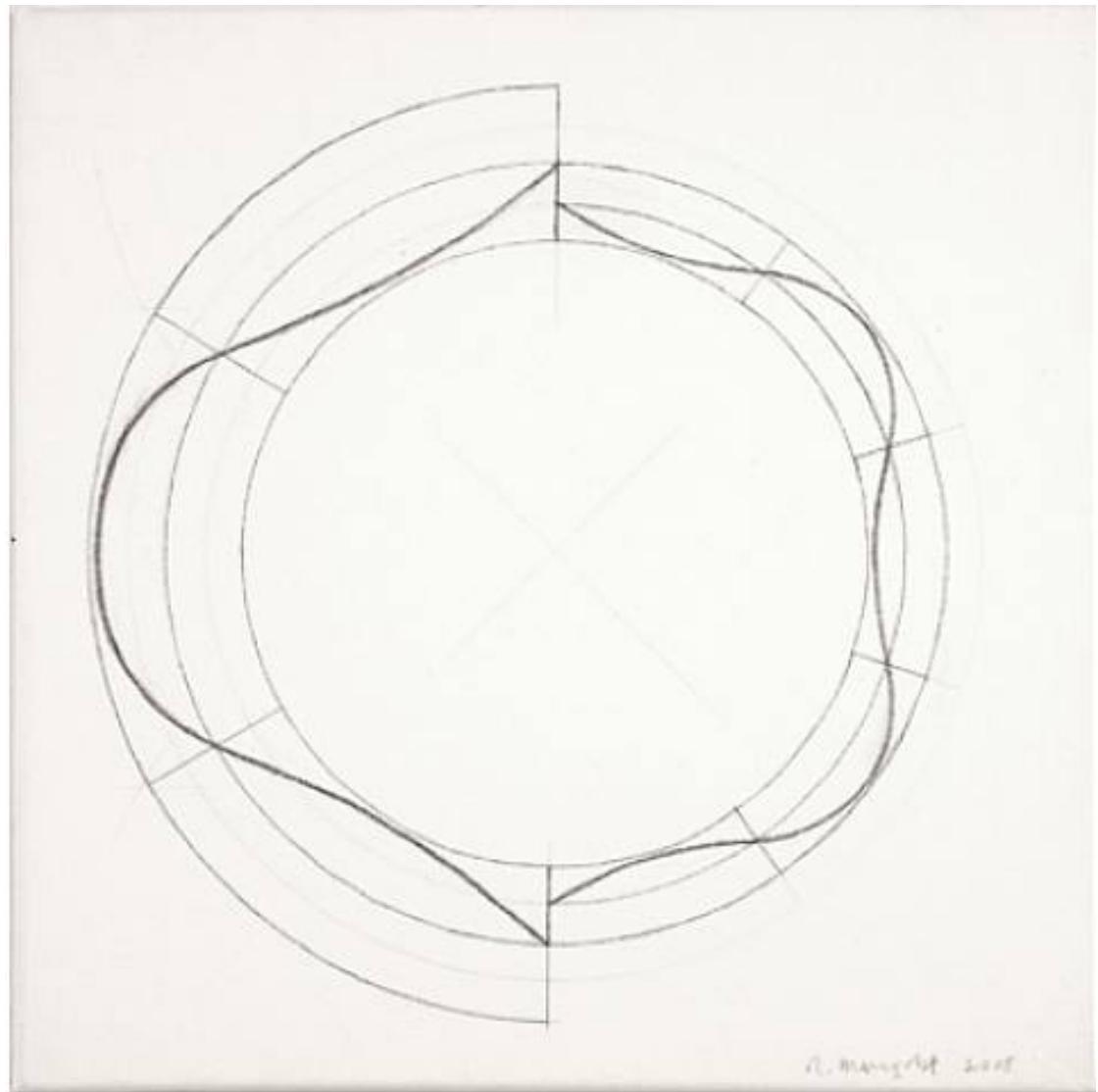


Figure 3.36: Robert Mangold - Untitled (2008)

In the chapter about color we map the cartesian coordinates to polar coordinates by calculating the *radius* and *angles* of each pixel with the following formula:

```
vec2 pos = vec2(0.5)-st;  
float r = length(pos)*2.0;  
float a = atan(pos.y, pos.x);
```

We use part of this formula at the beginning of the chapter to draw a circle. We calculated the distance to the center using `length()`. Now that we know about distance fields we can learn another way of drawing shapes using polar coordinates.

This technique is a little restrictive but very simple. It consists of changing the radius of a circle depending on the angle to achieve different shapes. How does the modulation work? Yes, using shaping functions!

Below you will find the same functions in the cartesian graph and in a polar coordinates shader example (between *lines 21 and 25*). Uncomment the functions one-by-one, paying attention the relationship between one coordinate system and the other.

```
// Author @patriciogv - 2015
// http://patriciogonzalezvivo.com

#ifndef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

void main(){
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    vec3 color = vec3(0.0);

    vec2 pos = vec2(0.5)-st;

    float r = length(pos)*2.0;
    float a = atan(pos.y,pos.x);

    float f = cos(a*3.);
    // f = abs(cos(a*3.));
    // f = abs(cos(a*2.5))*.5+.3;
    // f = abs(cos(a*12.)*sin(a*3.))*.8+.1;
    // f = smoothstep(-.5,1., cos(a*10.))*0.2+0.5;

    color = vec3( 1.-smoothstep(f,f+0.02,r) );
    gl_FragColor = vec4(color, 1.0);
}
```

Try to:

- Animate these shapes.

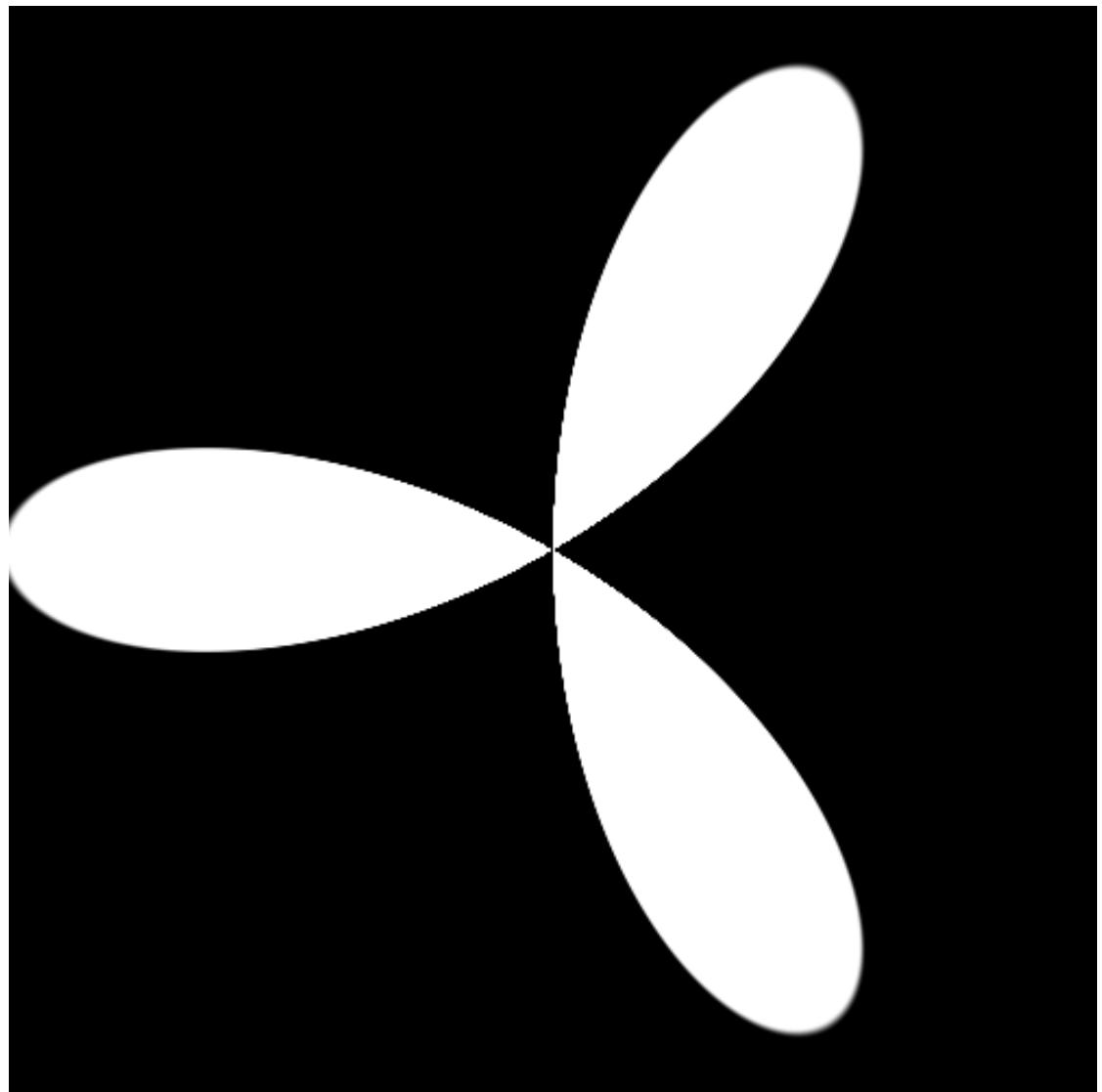


Figure 3.37:

- Combine different shaping functions to *cut holes* in the shape to make flowers, snowflakes and gears.
- Use the `plot()` function we were using in the *Shaping Functions Chapter* to draw just the contour.

3.3.6 Combining powers

Now that we've learned how to modulate the radius of a circle according to the angle using the `atan()` to draw different shapes, we can learn how use `atan()` with distance fields and apply all the tricks and effects possible with distance fields.

The trick will use the number of edges of a polygon to construct the distance field using polar coordinates. Check out [the following code from Andrew Baldwin](#).

```
#ifdef GL_ES
precision mediump float;
#endif

#define PI 3.14159265359
#define TWO_PI 6.28318530718

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

// Reference to
// http://thndl.com/square-shaped-shaders.html

void main(){
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    st.x *= u_resolution.x/u_resolution.y;
    vec3 color = vec3(0.0);
    float d = 0.0;

    // Remap the space to -1. to 1.
    st = st *2.-1.;

    // Number of sides of your shape
    int N = 3;

    // Angle and radius from the current pixel
    float a = atan(st.x,st.y)+PI;
    float r = TWO_PI/float(N);
```

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```
// Shaping function that modulate the distance  
d = cos(floor(.5+a/r)*r-a)*length(st);  
  
color = vec3(1.0-smoothstep(.4,.41,d));  
// color = vec3(d);  
  
gl_FragColor = vec4(color,1.0);  
}
```

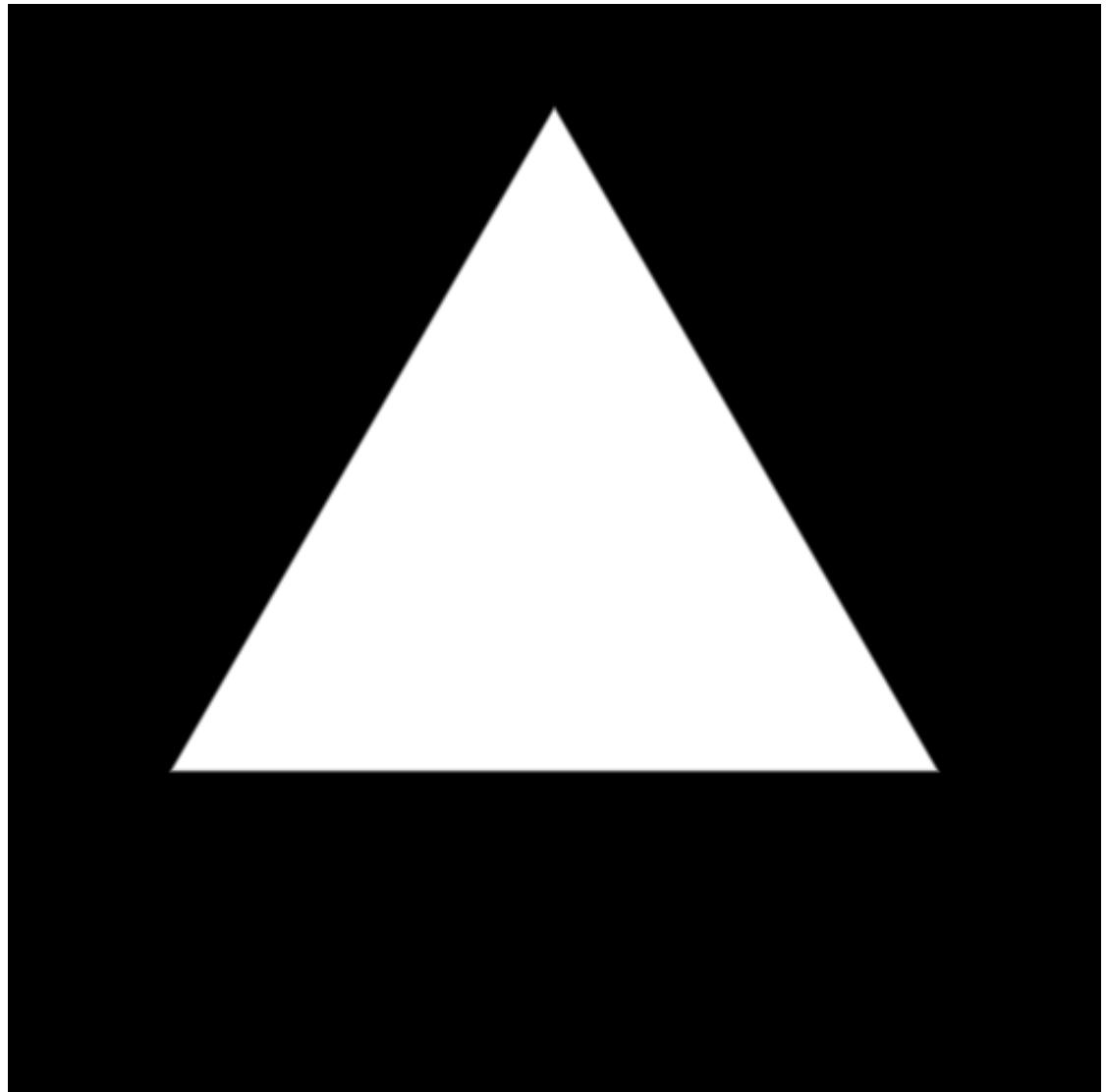


Figure 3.38:

- Using this example, make a function that inputs the position and number of corners

of a desired shape and returns a distance field value.

- Mix distance fields together using `min()` and `max()`.
- Choose a geometric logo to replicate using distance fields.

Congratulations! You have made it through the rough part! Take a break and let these concepts settle - drawing simple shapes in Processing is easy but not here. In shaderland drawing shapes is twisted, and it can be exhausting to adapt to this new paradigm of coding.

Now that you know how to draw shapes I'm sure new ideas will pop into your mind. In the following chapter you will learn how to move, rotate and scale shapes. This will allow you to make compositions!

3.4 2D Matrices

3.4.1 Translate

In the previous chapter we learned how to make some shapes - the trick to moving those shapes is to move the coordinate system itself. We can achieve that by simply adding a vector to the `st` variable that contains the location of each fragment. This causes the whole space coordinate system to move.

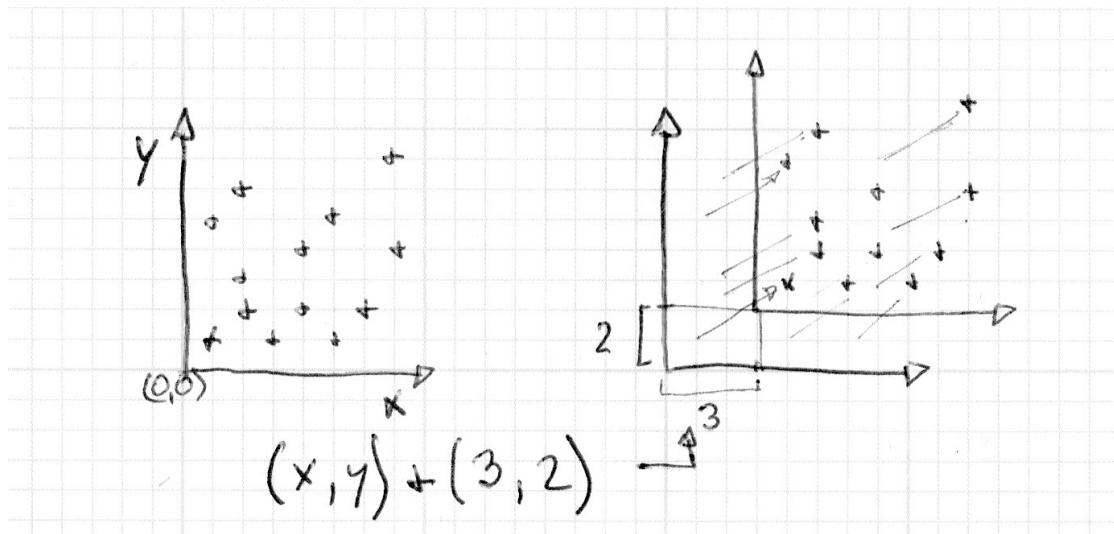


Figure 3.39:

This is easier to see than to explain, so to see for yourself:

- Uncomment line 35 of the code below to see how the space itself moves around.

3 Algorithmic drawing

```
// Author @patriciogv ( patriciogonzalezvivo.com ) - 2015

#ifndef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform float u_time;

float box(in vec2 _st, in vec2 _size){
    _size = vec2(0.5) - _size*0.5;
    vec2 uv = smoothstep(_size,
                         _size+vec2(0.001),
                         _st);
    uv *= smoothstep(_size,
                     _size+vec2(0.001),
                     vec2(1.0)-_st);
    return uv.x*uv.y;
}

float cross(in vec2 _st, float _size){
    return box(_st, vec2(_size,_size/4.)) +
           box(_st, vec2(_size/4.,_size));
}

void main(){
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    vec3 color = vec3(0.0);

    // To move the cross we move the space
    vec2 translate = vec2(cos(u_time),sin(u_time));
    st += translate*0.35;

    // Show the coordinates of the space on the background
    // color = vec3(st.x,st.y,0.0);

    // Add the shape on the foreground
    color += vec3(cross(st,0.25));

    gl_FragColor = vec4(color,1.0);
}
```

Now try the following exercise:

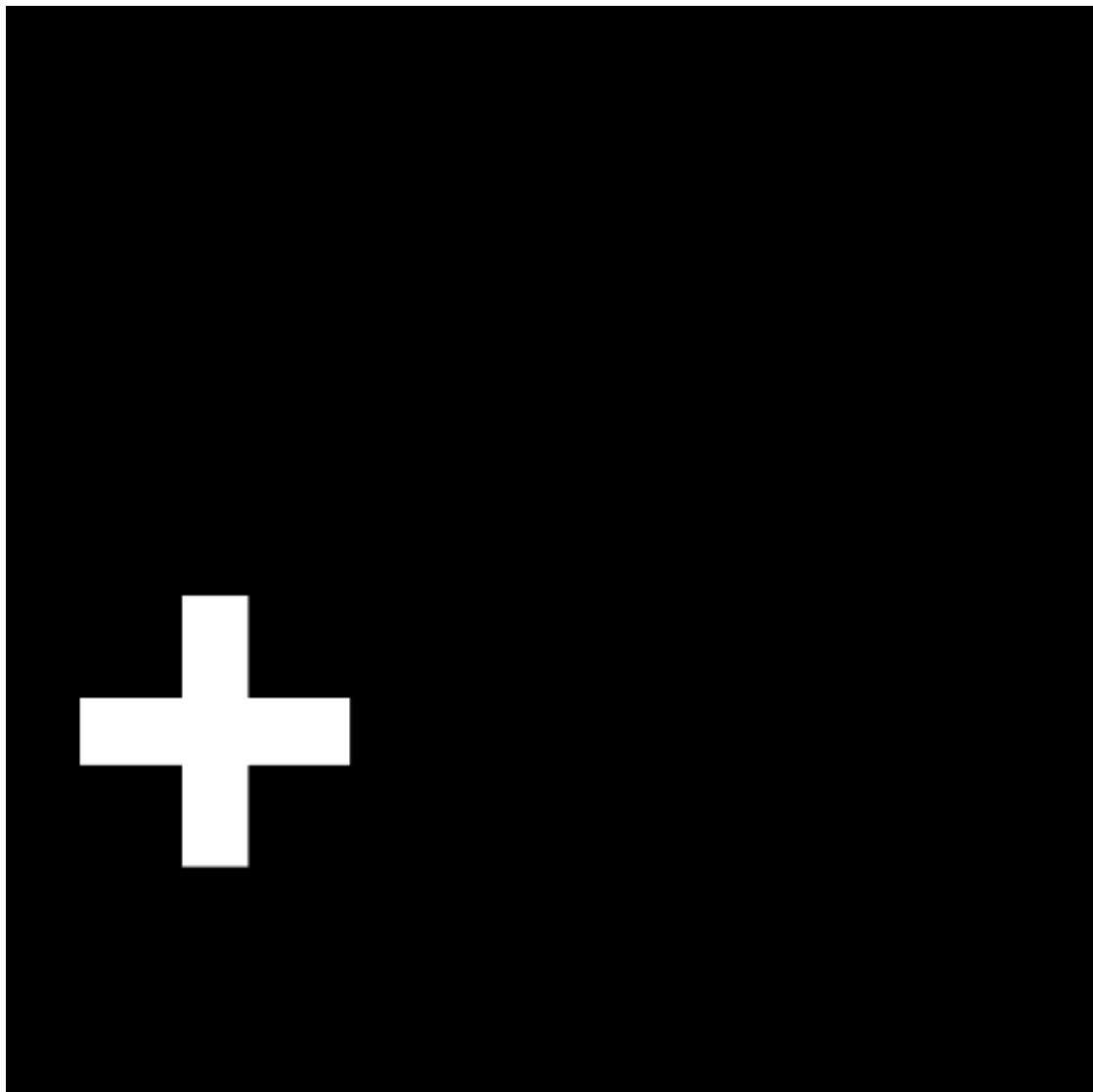


Figure 3.40:

3 Algorithmic drawing

- Using `u_time` together with the shaping functions move the small cross around in an interesting way. Search for a specific quality of motion you are interested in and try to make the cross move in the same way. Recording something from the “real world” first might be useful - it could be the coming and going of waves, a pendulum movement, a bouncing ball, a car accelerating, a bicycle stopping.

3.4.2 Rotations

To rotate objects we also need to move the entire space system. For that we are going to use a `matrix`. A matrix is an organized set of numbers in columns and rows. Vectors are multiplied by matrices following a precise set of rules in order to modify the values of the vector in a particular way.

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} \cdot \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} ax + by \\ cx + dy \end{bmatrix}$$

$$\begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} ax + by + c \\ dx + ey + f \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} ax + by + cz \\ dx + ey + fz \\ gx + hy + iz \end{bmatrix}$$

$$\begin{bmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} ax + by + cz + d \\ ex + fy + gz + h \\ ix + jy + kz + l \\ 1 \end{bmatrix}$$

GLSL has native support for two, three and four dimensional matrices: `mat2` (2x2), `mat3` (3x3) and `mat4` (4x4). GLSL also supports matrix multiplication (*) and a matrix specific function (`matrixCompMult()`).

Based on how matrices behave it's possible to construct matrices to produce specific behaviors. For example we can use a matrix to translate a vector:

More interestingly, we can use a matrix to rotate the coordinate system:

Take a look at the following code for a function that constructs a 2D rotation matrix.

$$\begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} x + t_x \\ y + t_y \\ 1 \end{bmatrix}$$

Figure 3.41:

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

Figure 3.42:

This function follows the above [formula](#) for two dimensional vectors to rotate the coordinates around the `vec2(0.0)` point.

```
mat2 rotate2d(float _angle){
    return mat2(cos(_angle), -sin(_angle),
                sin(_angle), cos(_angle));
}
```

According to the way we've been drawing shapes, this is not exactly what we want. Our cross shape is drawn in the center of the canvas which corresponds to the position `vec2(0.5)`. So, before we rotate the space we need to move shape from the `center` to the `vec2(0.0)` coordinate, rotate the space, then finally move it back to the original place.

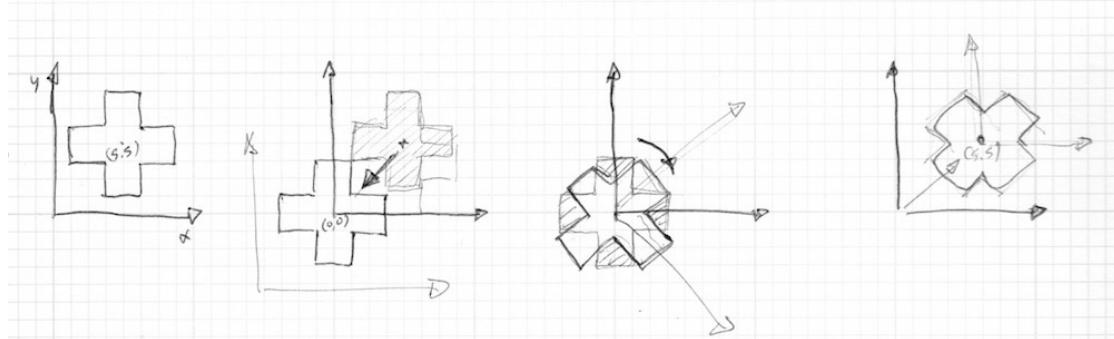


Figure 3.43:

That looks like the following code:

```
// Author @patriciogv ( patriciogonzalezvivo.com ) - 2015
```

3 Algorithmic drawing

```
#ifdef GL_ES
precision mediump float;
#endif

#define PI 3.14159265359

uniform vec2 u_resolution;
uniform float u_time;

mat2 rotate2d(float _angle){
    return mat2(cos(_angle),-sin(_angle),
                sin(_angle),cos(_angle));
}

float box(in vec2 _st, in vec2 _size){
    _size = vec2(0.5) - _size*0.5;
    vec2 uv = smoothstep(_size,
                         _size+vec2(0.001),
                         _st);
    uv *= smoothstep(_size,
                     _size+vec2(0.001),
                     vec2(1.0)-_st);
    return uv.x*uv.y;
}

float cross(in vec2 _st, float _size){
    return box(_st, vec2(_size,_size/4.)) +
           box(_st, vec2(_size/4.,_size));
}

void main(){
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    vec3 color = vec3(0.0);

    // move space from the center to the vec2(0.0)
    st -= vec2(0.5);
    // rotate the space
    st = rotate2d( sin(u_time)*PI ) * st;
    // move it back to the original place
    st += vec2(0.5);

    // Show the coordinates of the space on the background
    // color = vec3(st.x,st.y,0.0);
```

```
// Add the shape on the foreground  
color += vec3(cross(st,0.4));  
  
gl_FragColor = vec4(color,1.0);  
}
```

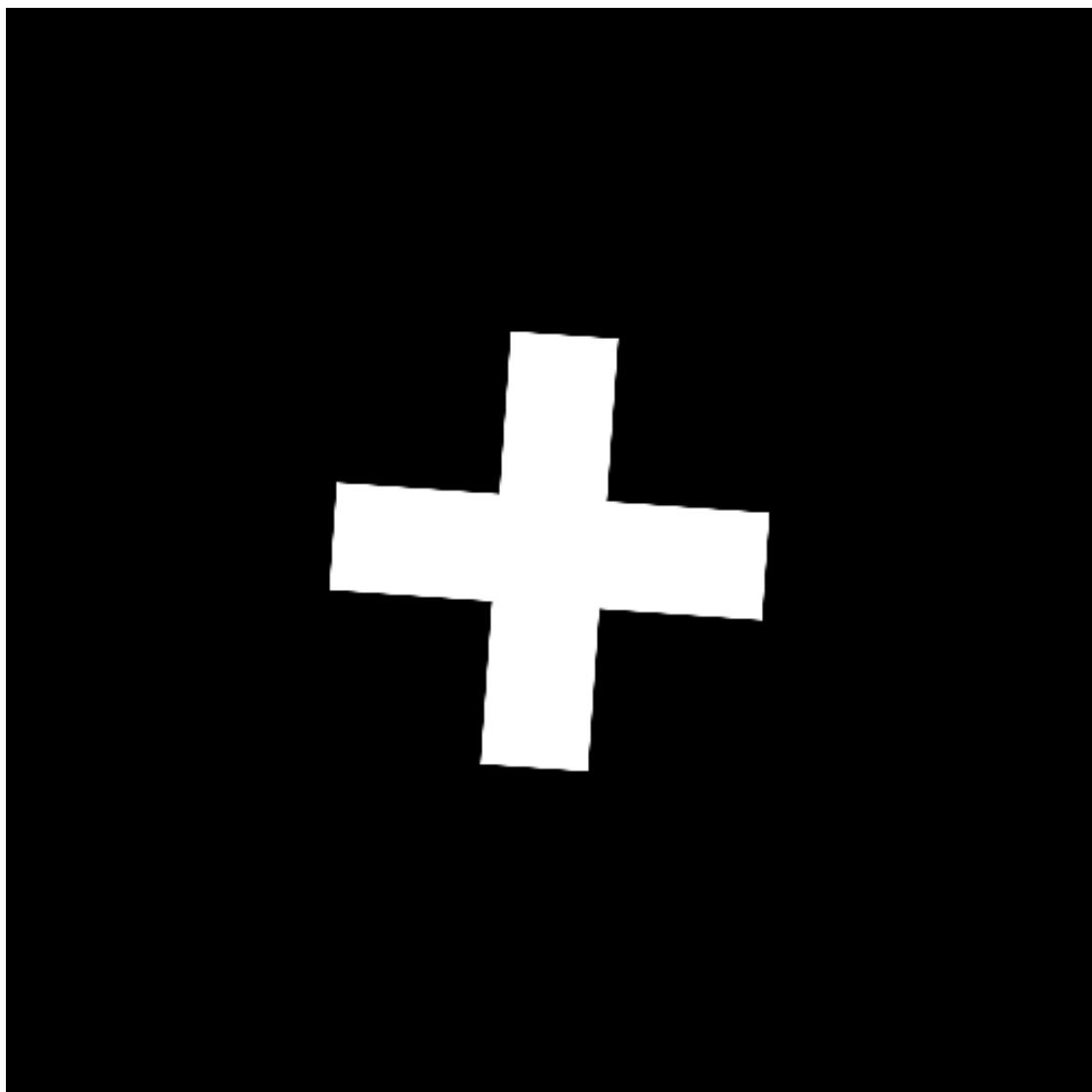


Figure 3.44:

Try the following exercises:

- Uncomment line 45 of above code and pay attention to what happens.
- Comment the translations before and after the rotation, on lines 37 and 39, and

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observe the consequences.

- Use rotations to improve the animation you simulated in the translation exercise.

3.4.3 Scale

We've seen how matrices are used to translate and rotate objects in space. (Or more precisely to transform the coordinate system to rotate and move the objects.) If you've used 3D modeling software or the push and pop matrix functions in Processing, you will know that matrices can also be used to scale the size of an object.

$$\begin{bmatrix} S_x & 0 & 0 \\ 0 & S_y & 0 \\ 0 & 0 & S_z \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} S_x \cdot x \\ S_y \cdot y \\ S_z \cdot z \end{bmatrix}$$

Figure 3.45:

Following the previous formula, we can figure out how to make a 2D scaling matrix:

```
mat2 scale(vec2 _scale){
    return mat2(_scale.x,0.0,
                0.0,_scale.y);
}

// Author @patriciogv ( patriciogonzalezvivo.com ) - 2015

#ifndef GL_ES
precision mediump float;
#endif

#define PI 3.14159265359

uniform vec2 u_resolution;
uniform float u_time;

mat2 scale(vec2 _scale){
    return mat2(_scale.x,0.0,
                0.0,_scale.y);
}

float box(in vec2 _st, in vec2 _size){
    _size = vec2(0.5) - _size*0.5;
    vec2 uv = smoothstep(_size,
                        _size+vec2(0.001),
```

```

        _st);
uv *= smoothstep(_size,
                 _size+vec2(0.001),
                 vec2(1.0)-_st);
return uv.x*uv.y;
}

float cross(in vec2 _st, float _size){
    return box(_st, vec2(_size,_size/4.)) +
           box(_st, vec2(_size/4.,_size));
}

void main(){
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    vec3 color = vec3(0.0);

    st -= vec2(0.5);
    st = scale( vec2(sin(u_time)+1.0) ) * st;
    st += vec2(0.5);

    // Show the coordinates of the space on the background
    // color = vec3(st.x,st.y,0.0);

    // Add the shape on the foreground
    color += vec3(cross(st,0.2));

    gl_FragColor = vec4(color,1.0);
}

```

Try the following exercises to understand more deeply how this works.

- Uncomment line 42 of above code to see the space coordinate being scaled.
- See what happens when you comment the translations before and after the scaling on lines 37 and 39.
- Try combining a rotation matrix together with a scale matrix. Be aware that the order matters. Multiply by the matrix first and then multiply the vectors.
- Now that you know how to draw different shapes, and move, rotate and scale them, it's time to make a nice composition. Design and construct a [fake UI or HUD \(heads up display\)](#). Use the following ShaderToy example by [Ndel](#) for inspiration and reference.

```
<iframe width="800" height="450" frameborder="0" src="https://www.shadertoy.com/embed/4s2SRt?gui=true" allowfullscreen>
```

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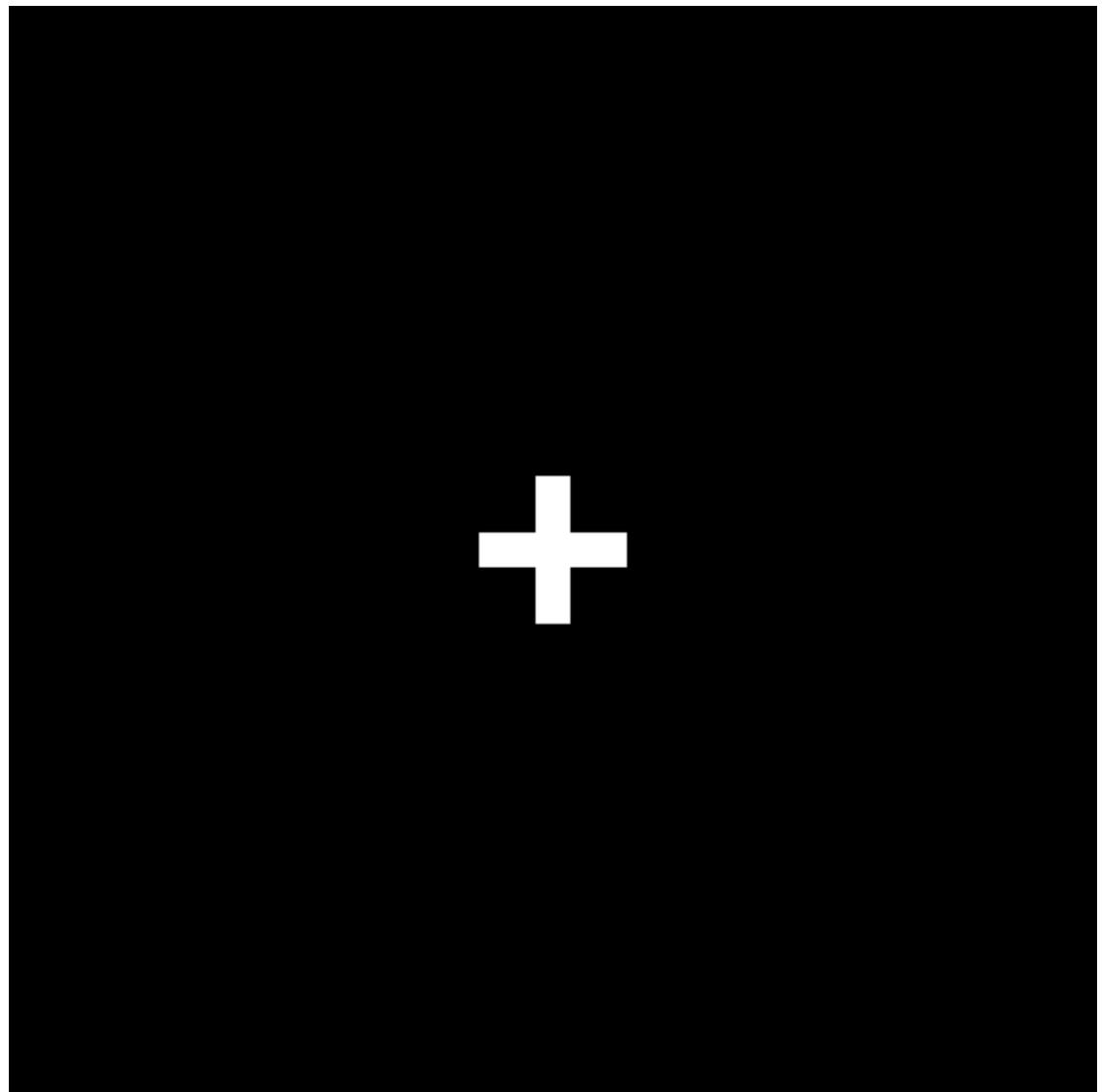


Figure 3.46:

3.4.4 Other uses for matrices: YUV color

YUV is a color space used for analog encoding of photos and videos that takes into account the range of human perception to reduce the bandwidth of chrominance components.

The following code is an interesting opportunity to use matrix operations in GLSL to transform colors from one mode to another.

```
// Author @patriciogv - 2015
// http://patriciogonzalezvivo.com
#ifndef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform float u_time;

// YUV to RGB matrix
mat3 yuv2rgb = mat3(1.0, 0.0, 1.13983,
                     1.0, -0.39465, -0.58060,
                     1.0, 2.03211, 0.0);

// RGB to YUV matrix
mat3 rgb2yuv = mat3(0.2126, 0.7152, 0.0722,
                     -0.09991, -0.33609, 0.43600,
                     0.615, -0.5586, -0.05639);

void main(){
    vec2 st = gl_FragCoord.xy/u_resolution;
    vec3 color = vec3(0.0);

    // UV values goes from -1 to 1
    // So we need to remap st (0.0 to 1.0)
    st -= 0.5; // becomes -0.5 to 0.5
    st *= 2.0; // becomes -1.0 to 1.0

    // we pass st as the y & z values of
    // a three dimentional vector to be
    // properly multiply by a 3x3 matrix
    color = yuv2rgb * vec3(0.5, st.x, st.y);

    gl_FragColor = vec4(color,1.0);
}
```

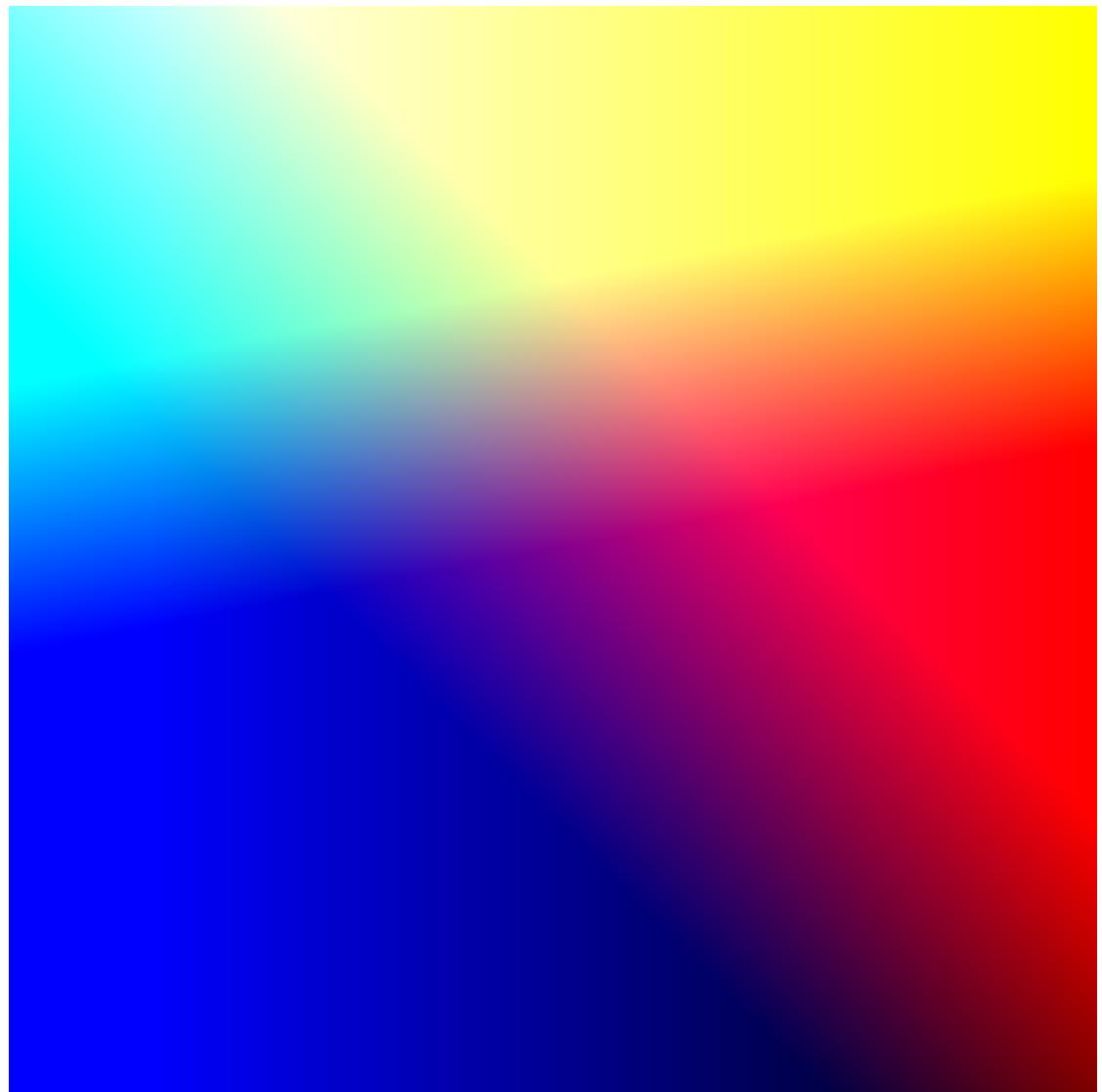


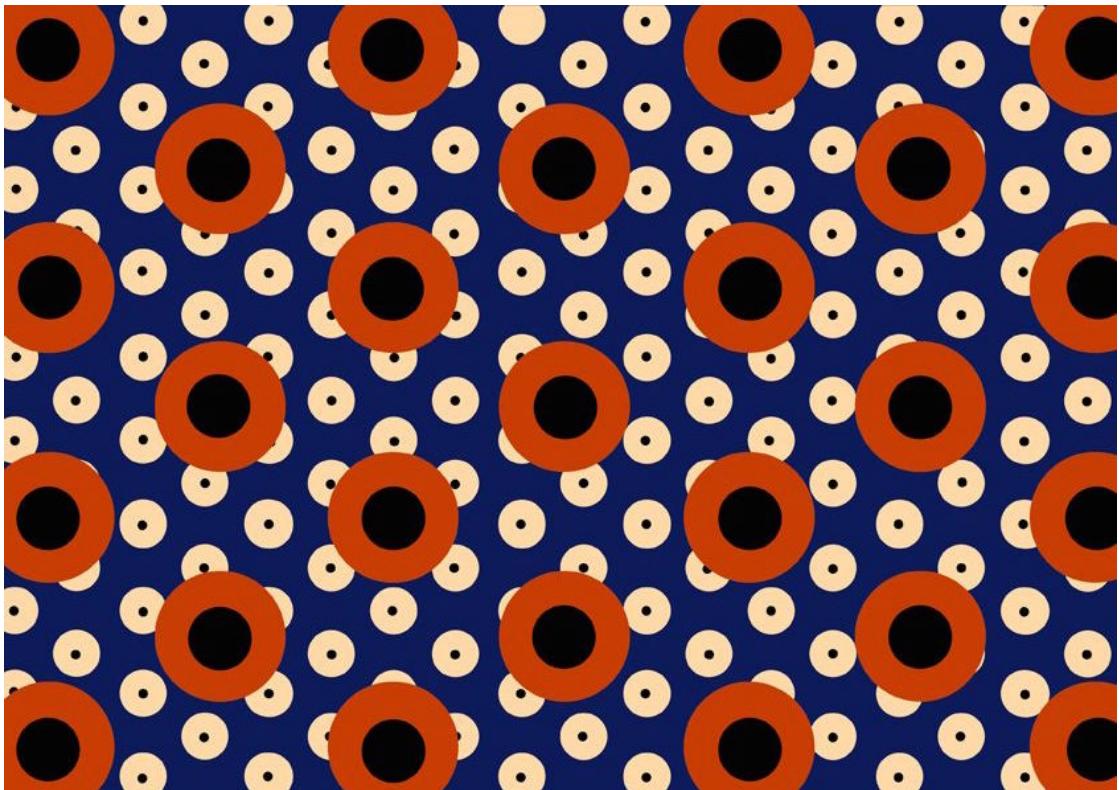
Figure 3.47:

As you can see we are treating colors as vectors by multiplying them with matrices. In that way we “move” the values around.

In this chapter we’ve learned how to use matrix transformations to move, rotate and scale vectors. These transformations will be essential for making compositions out of the shapes we learned about in the previous chapter. In the next chapter we’ll apply all we’ve learned to make beautiful procedural patterns. You will find that coding repetition and variation can be an exciting practice.

3.5 Patterns

Since shader programs are executed by pixel-by-pixel no matter how much you repeat a shape the number of calculations stays constant. This means that fragment shaders are particularly suitable for tile patterns.



In this chapter we are going to apply what we’ve learned so far and repeat it along a canvas. Like in previous chapters, our strategy will be based on multiplying the space coordinates (between 0.0 and 1.0), so that the shapes we draw between the values 0.0 and 1.0 will be repeated to make a grid.

“The grid provides a framework within which human intuition and invention can operate and that it can subvert. Within the chaos of nature patterns provide a contrast and

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promise of order. From early patterns on pottery to geometric mosaics in Roman baths, people have long used grids to enhance their lives with decoration.” 10 PRINT, Mit Press, (2013)

First let's remember the `fract()` function. It returns the fractional part of a number, making `fract()` in essence the modulo of one (`mod(x,1.0)`). In other words, `fract()` returns the number after the floating point. Our normalized coordinate system variable (`st`) already goes from 0.0 to 1.0 so it doesn't make sense to do something like:

```
void main(){
    vec2 st = gl_FragCoord.xy/u_resolution;
    vec3 color = vec3(0.0);
    st = fract(st);
    color = vec3(st,0.0);
    gl_FragColor = vec4(color,1.0);
}
```

But if we scale the normalized coordinate system up - let's say by three - we will get three sequences of linear interpolations between 0-1: the first one between 0-1, the second one for the floating points between 1-2 and the third one for the floating points between 2-3.

```
// Author @patriciogu - 2015

#ifndef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform float u_time;

float circle(in vec2 _st, in float _radius){
    vec2 l = _st-vec2(0.5);
    return 1.-smoothstep(_radius-(_radius*0.01),
                        _radius+(_radius*0.01),
                        dot(l,l)*4.0);
}

void main() {
    vec2 st = gl_FragCoord.xy/u_resolution;
    vec3 color = vec3(0.0);

    st *= 3.0;           // Scale up the space by 3
    st = fract(st); // Wrap arround 1.0

    // Now we have 3 spaces that goes from 0-1
```

```
color = vec3(st,0.0);
//color = vec3(circle(st,0.5));

gl_FragColor = vec4(color,1.0);
}
```

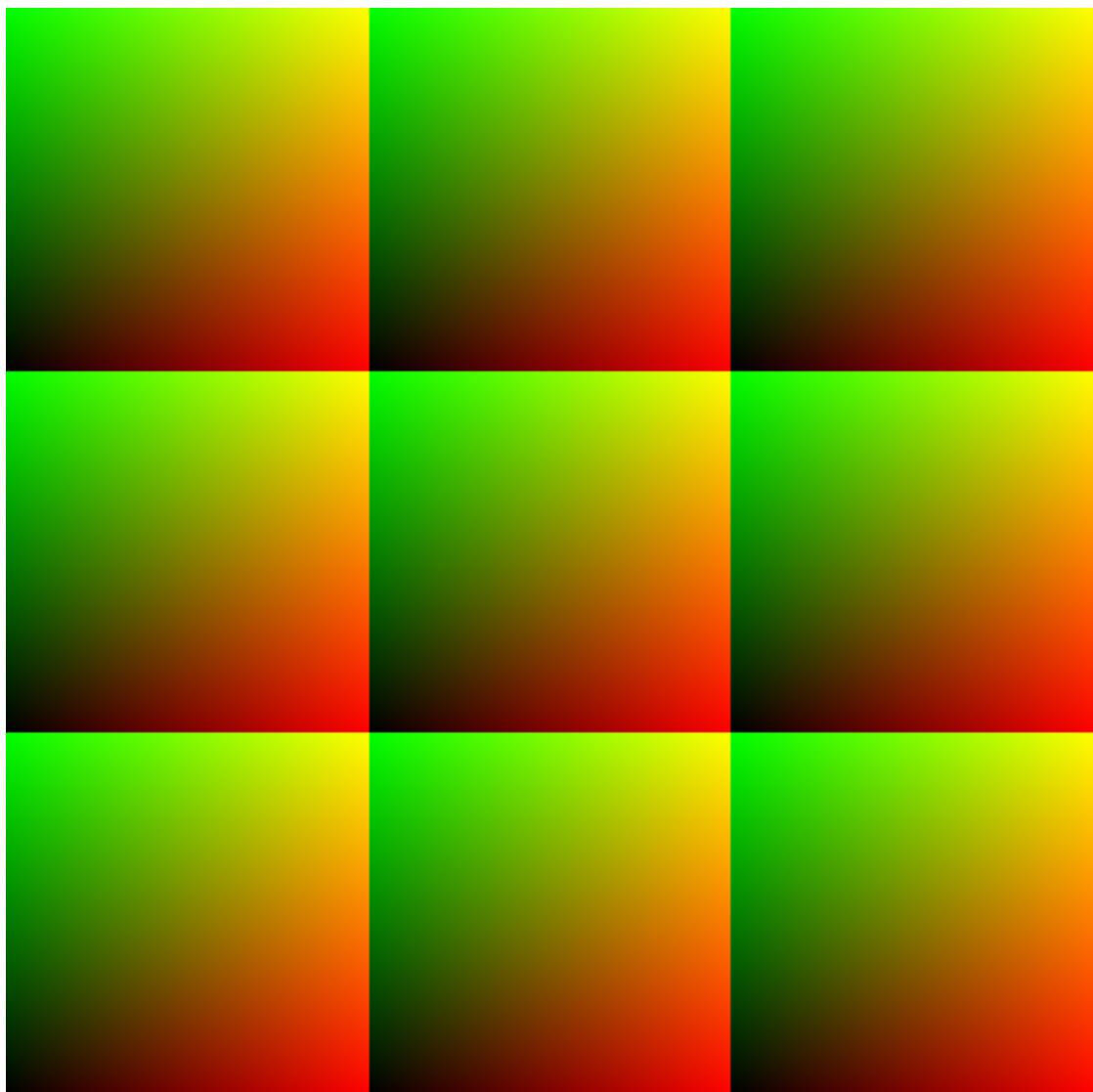


Figure 3.48:

Now it's time to draw something in each subspace, by uncommenting line 27. (Because we are multiplying equally in x and y the aspect ratio of the space doesn't change and shapes will be as expected.)

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Try some of the following exercises to get a deeper understanding:

- Multiply the space by different numbers. Try with floating point values and also with different values for x and y.
- Make a reusable function of this tiling trick.
- Divide the space into 3 rows and 3 columns. Find a way to know in which column and row the thread is and use that to change the shape that is displaying. Try to compose a tic-tac-toe match.

3.5.1 Apply matrices inside patterns

Since each subdivision or cell is a smaller version of the normalized coordinate system we have already been using, we can apply a matrix transformation to it in order to translate, rotate or scale the space inside.

```
// Author @patriciogu ( patriciogonzalezvivo.com ) - 2015

#ifndef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform float u_time;

#define PI 3.14159265358979323846

vec2 rotate2D(vec2 _st, float _angle){
    _st -= 0.5;
    _st = mat2(cos(_angle),-sin(_angle),
               sin(_angle),cos(_angle)) * _st;
    _st += 0.5;
    return _st;
}

vec2 tile(vec2 _st, float _zoom){
    _st *= _zoom;
    return fract(_st);
}

float box(vec2 _st, vec2 _size, float _smoothEdges){
    _size = vec2(0.5)-_size*0.5;
    vec2 aa = vec2(_smoothEdges*0.5);
    vec2 uv = smoothstep(_size,_size+aa,_st);
```

```

uv *= smoothstep(_size,_size+aa,vec2(1.0)-_st);
return uv.x*uv.y;
}

void main(void){
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    vec3 color = vec3(0.0);

    // Divide the space in 4
    st = tile(st,4.);

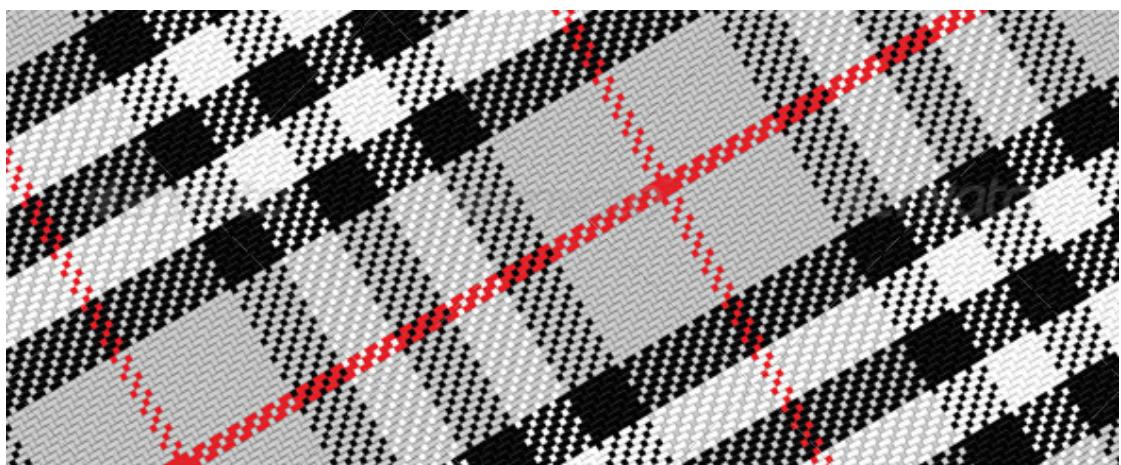
    // Use a matrix to rotate the space 45 degrees
    st = rotate2D(st,PI*0.25);

    // Draw a square
    color = vec3(box(st,vec2(0.7),0.01));
    // color = vec3(st,0.0);

    gl_FragColor = vec4(color,1.0);
}

```

- Think of interesting ways of animating this pattern. Consider animating color, shapes and motion. Make three different animations.
- Recreate more complicated patterns by composing different shapes.
- Combine different layers of patterns to compose your own [Scottish Tartan Patterns](#).



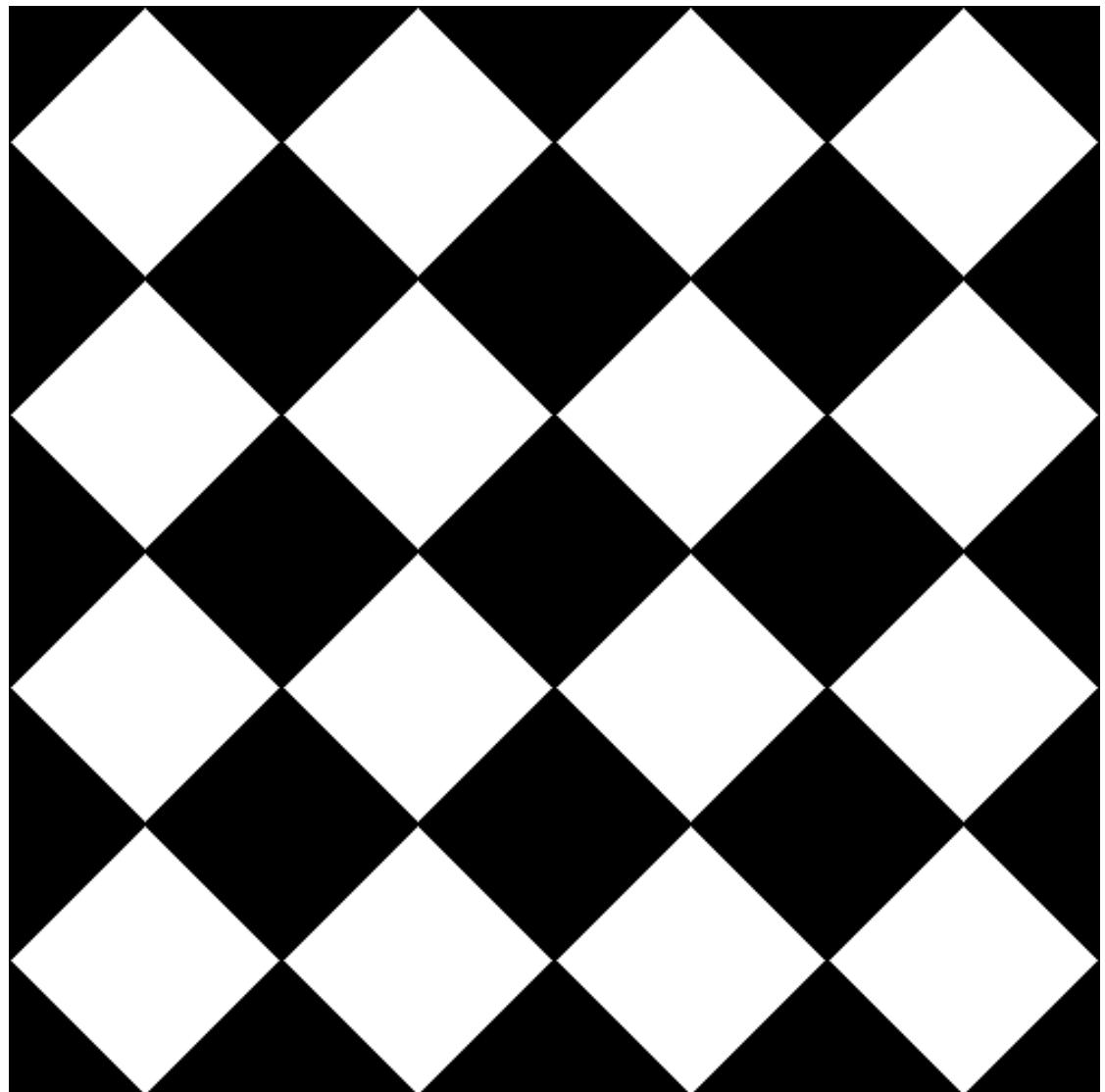


Figure 3.49:

3.5.2 Offset patterns

So let's say we want to imitate a brick wall. Looking at the wall, you can see a half brick offset on x in every other row. How we can do that?

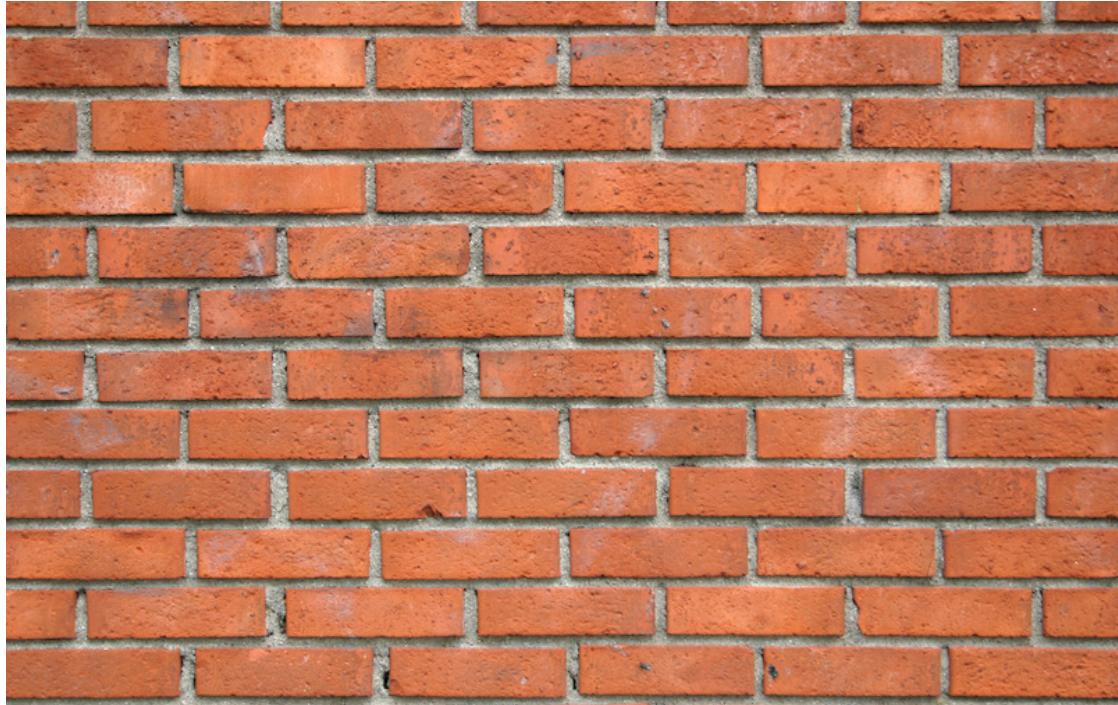


Figure 3.50:

As a first step we need to know if the row of our thread is an even or odd number, because we can use that to determine if we need to offset the x in that row.

_____we have to fix these next two paragraphs together_____

To determine if our thread is in an odd or even row, we are going to use `mod()` of 2.0 and then see if the result is under 1.0 or not. Take a look at the following formula and uncomment the two last lines.

As you can see we can use a `ternary operator` to check if the `mod()` of 2.0 is under 1.0 (second line) or similarly we can use a `step()` function which does that the same operation, but faster. Why? Although is hard to know how each graphic card optimizes and compiles the code, it is safe to assume that built-in functions are faster than non-built-in ones. Everytime you can use a built-in function, use it!

So now that we have our odd number formula we can apply an offset to the odd rows to give a *brick* effect to our tiles. Line 14 of the following code is where we are using the function to “detect” odd rows and give them a half-unit offset on `x`. Note that for even rows, the result of our function is 0.0, and multiplying 0.0 by the offset of 0.5 gives an

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offset of 0.0. But on odd rows we multiply the result of our function, 1.0, by the offset of 0.5, which moves the x axis of the coordinate system by 0.5.

Now try uncommenting line 32 - this stretches the aspect ratio of the coordinate system to mimic the aspect of a “modern brick”. By uncommenting line 40 you can see how the coordinate system looks mapped to red and green.

```
// Author @patriciogv ( patriciogonzalezvivo.com ) - 2015

#ifndef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform float u_time;

vec2 brickTile(vec2 _st, float _zoom){
    _st *= _zoom;

    // Here is where the offset is happening
    _st.x += step(1., mod(_st.y,2.0)) * 0.5;

    return fract(_st);
}

float box(vec2 _st, vec2 _size){
    _size = vec2(0.5)-_size*0.5;
    vec2 uv = smoothstep(_size,_size+vec2(1e-4),_st);
    uv *= smoothstep(_size,_size+vec2(1e-4),vec2(1.0)-_st);
    return uv.x*uv.y;
}

void main(void){
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    vec3 color = vec3(0.0);

    // Modern metric brick of 215mm x 102.5mm x 65mm
    // http://www.jaharrison.me.uk/Brickwork/Sizes.html
    // st /= vec2(2.15,0.65)/1.5;

    // Apply the brick tiling
    st = brickTile(st,5.0);

    color = vec3(box(st,vec2(0.9)));
}
```

```
// Uncomment to see the space coordinates  
// color = vec3(st,0.0);  
  
gl_FragColor = vec4(color,1.0);  
}
```

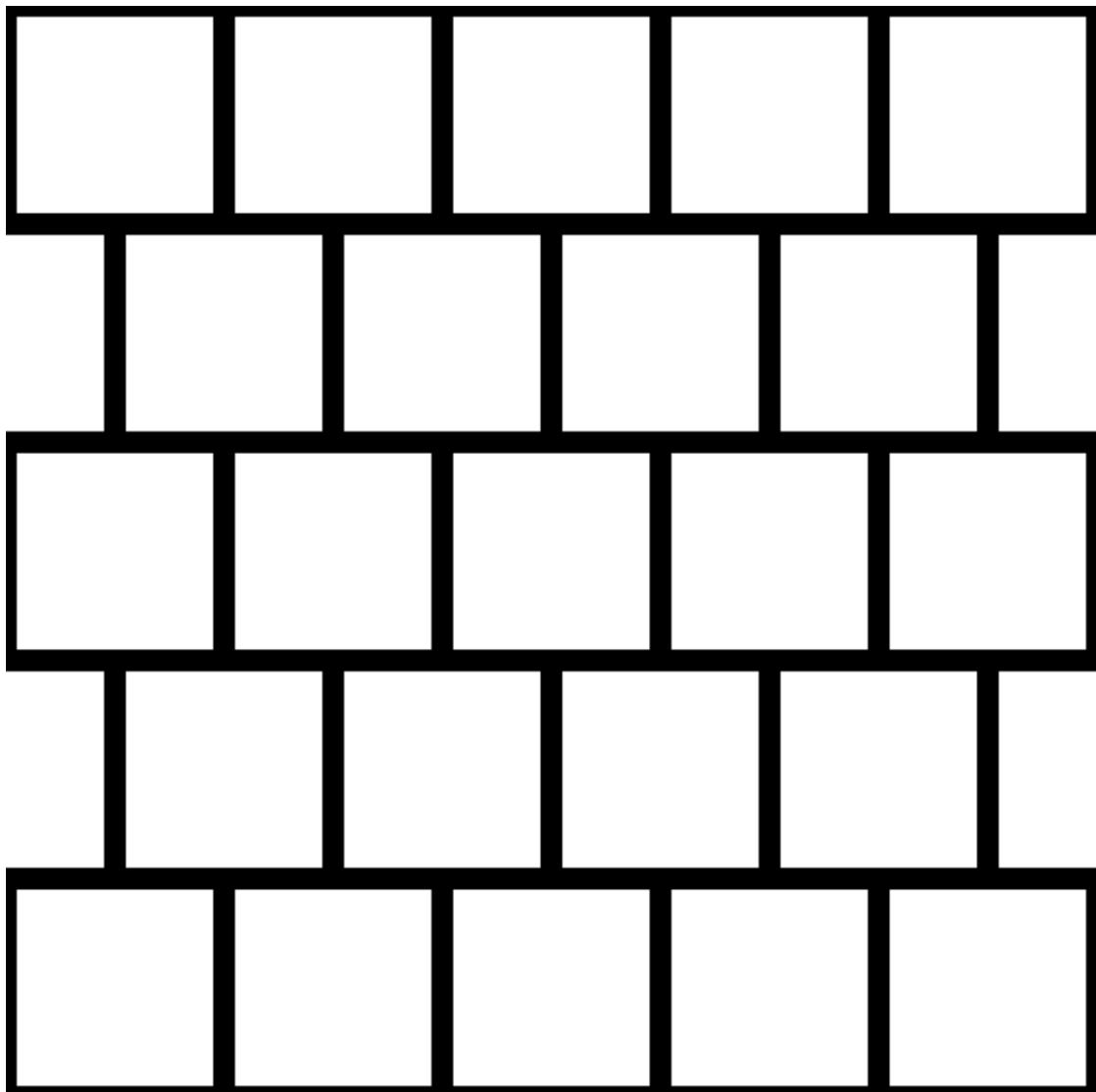


Figure 3.51:

- Try animating this by moving the offset according to time.
- Make another animation where even rows move to the left and odd rows move to the right.

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- Can you repeat this effect but with columns?
- Try combining an offset on x and y axis to get something like this:

3.6 Truchet Tiles

Now that we've learned how to tell if our cell is in an even or odd row or column, it's possible to reuse a single design element depending on its position. Consider the case of the [Truchet Tiles](#) where a single design element can be presented in four different ways:



Figure 3.52:

By changing the pattern across tiles, it's possible to construct an infinite set of complex designs.

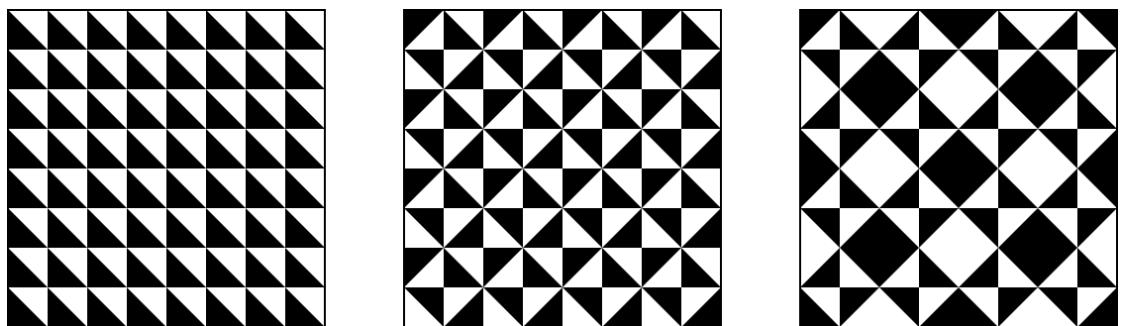


Figure 3.53:

Pay close attention to the function `rotateTilePattern()`, which subdivides the space into four cells and assigns an angle of rotation to each one.

// Author @patriciogv (patriciogonzalezvivo.com) - 2015

```
#ifdef GL_ES
precision mediump float;
#endif

#define PI 3.14159265358979323846
```

```

uniform vec2 u_resolution;
uniform float u_time;

vec2 rotate2D (vec2 _st, float _angle) {
    _st -= 0.5;
    _st = mat2(cos(_angle),-sin(_angle),
               sin(_angle),cos(_angle)) * _st;
    _st += 0.5;
    return _st;
}

vec2 tile (vec2 _st, float _zoom) {
    _st *= _zoom;
    return fract(_st);
}

vec2 rotateTilePattern(vec2 _st){

    // Scale the coordinate system by 2x2
    _st *= 2.0;

    // Give each cell an index number
    // according to its position
    float index = 0.0;
    index += step(1., mod(_st.x,2.0));
    index += step(1., mod(_st.y,2.0))*2.0;

    //      |
    // 0  |  1
    //      |
    //-----
    //      |
    // 2  |  3
    //      |

    // Make each cell between 0.0 - 1.0
    _st = fract(_st);

    // Rotate each cell according to the index
    if(index == 1.0){
        // Rotate cell 1 by 90 degrees
        _st = rotate2D(_st,PI*0.5);
    } else if(index == 2.0){

```

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```
// Rotate cell 2 by -90 degrees
_st = rotate2D(_st,PI*-0.5);
} else if(index == 3.0){
    // Rotate cell 3 by 180 degrees
    _st = rotate2D(_st,PI);
}

return _st;
}

void main (void) {
    vec2 st = gl_FragCoord.xy/u_resolution.xy;

    st = tile(st,3.0);
    st = rotateTilePattern(st);

    // Make more interesting combinations
    // st = tile(st,2.0);
    // st = rotate2D(st,-PI*u_time*0.25);
    // st = rotateTilePattern(st*2.);
    // st = rotate2D(st,PI*u_time*0.25);

    // step(st.x,st.y) just makes a b&w triangles
    // but you can use whatever design you want.
    gl_FragColor = vec4(vec3(step(st.x,st.y)),1.0);
}
```

- Comment, uncomment and duplicate lines 69 to 72 to compose new designs.
- Change the black and white triangle for another element like: half circles, rotated squares or lines.
- Code other patterns where the elements are rotated according to their position.
- Make a pattern that changes other properties according to the position of the elements.
- Think of something else that is not necessarily a pattern where you can apply the principles from this section. (Ex: I Ching hexagrams)

3.7 Making your own rules

Making procedural patterns is a mental exercise in finding minimal reusable elements. This practice is old; we as a species have been using grids and patterns to decorate textiles, floors and borders of objects for a long time: from meanders patterns in ancient

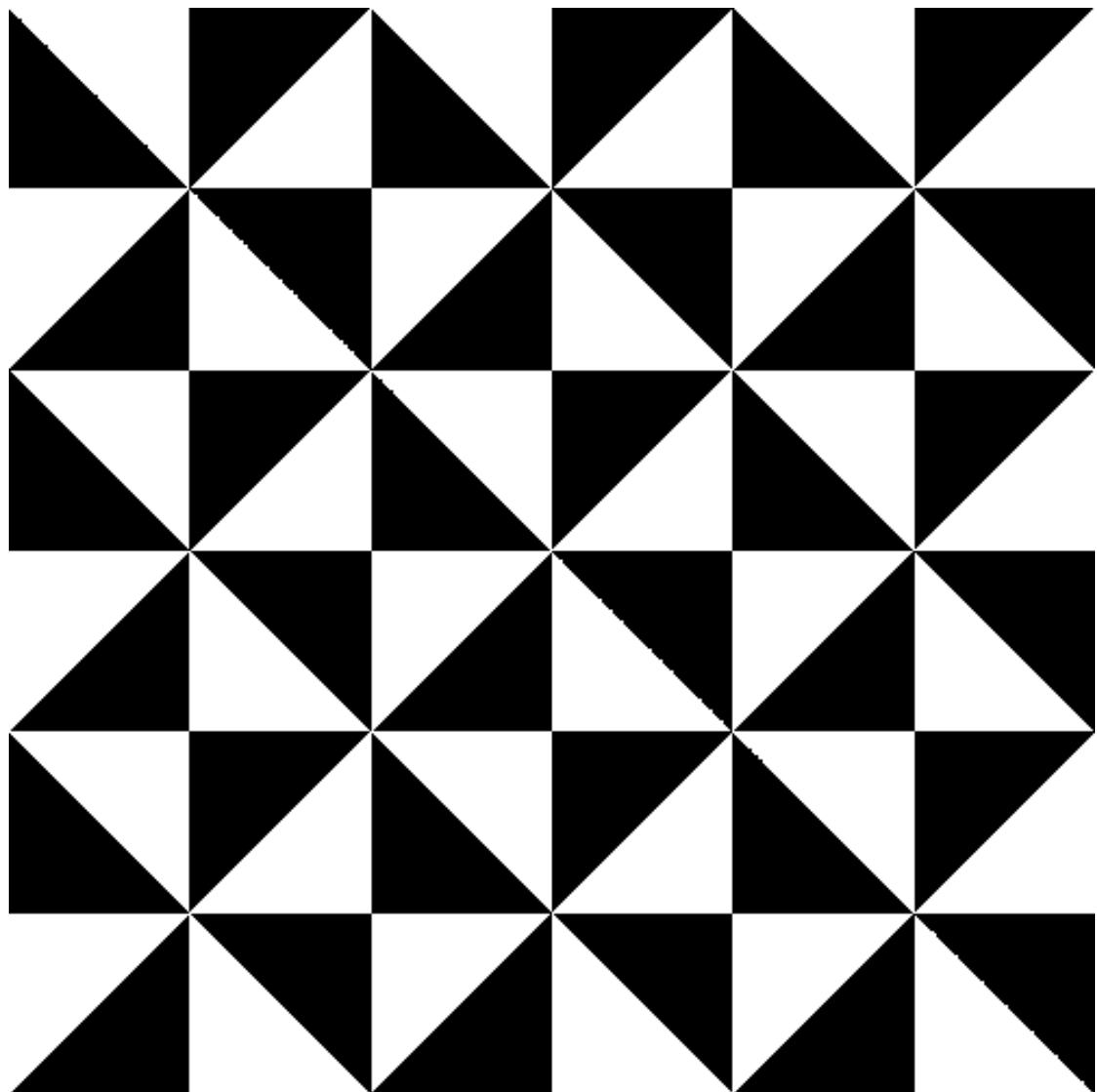


Figure 3.54:

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Greece, to Chinese lattice design, the pleasure of repetition and variation catches our imagination. Take some time to look at [decorative patterns](#) and see how artists and designers have a long history of navigating the fine edge between the predictability of order and the surprise of variation and chaos. From Arabic geometrical patterns, to gorgeous African fabric designs, there is an entire universe of patterns to learn from.

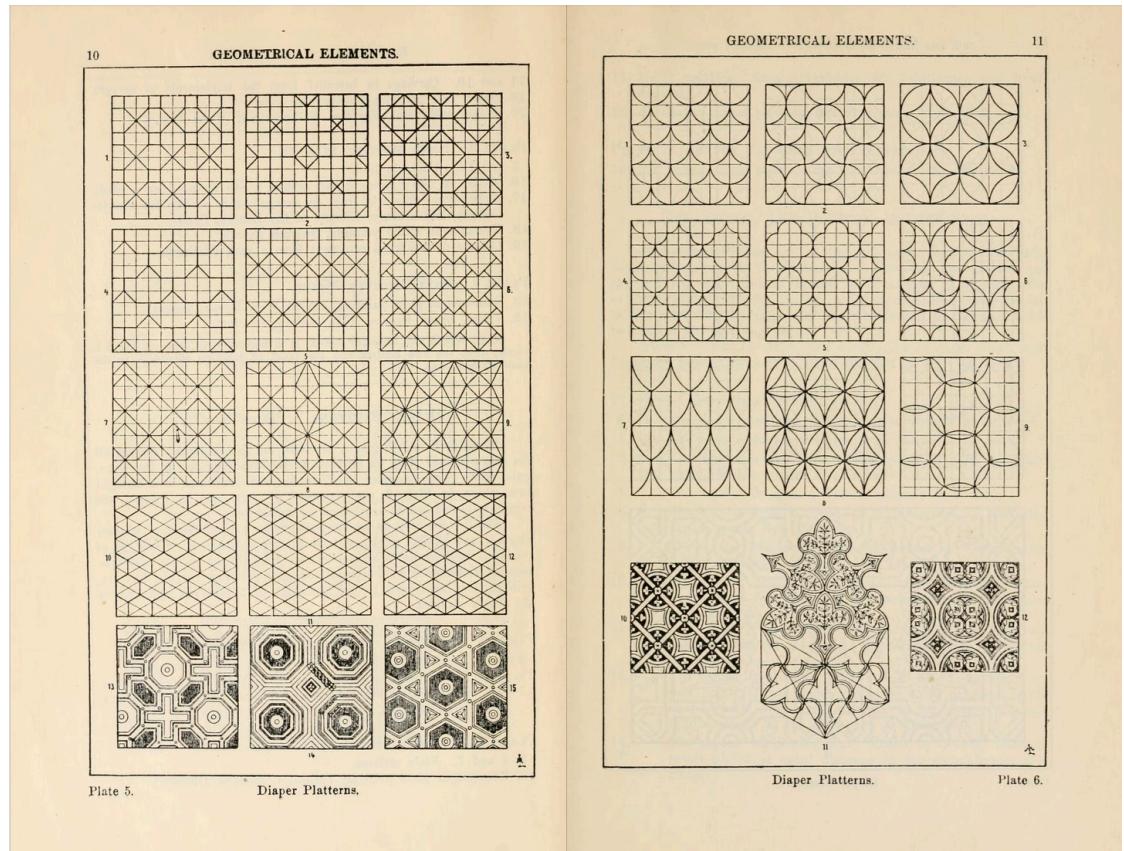


Figure 3.55: Franz Sales Meyer - A handbook of ornament (1920)

With this chapter we end the section on Algorithmic Drawing. In the following chapters we will learn how to bring some entropy to our shaders and produce generative designs.

4 Generative designs

It is not a surprise that after so much repetition and order the author is forced to bring some chaos.

4.1 Random



Randomness is a maximal expression of entropy. How can we generate randomness inside the seemingly predictable and rigid code environment?

Let's start by analyzing the following function:

Above we are extracting the fractional content of a sine wave. The `sin()` values that fluctuate between -1.0 and 1.0 have been chopped behind the floating point, returning all positive values between 0.0 and 1.0. We can use this effect to get some pseudo-random values by “breaking” this sine wave into smaller pieces. How? By multiplying the resultant of `sin(x)` by larger numbers. Go ahead and click on the function above and start adding some zeros.

By the time you get to 100000.0 (and the equation looks like this: `y = fract(sin(x)*100000.0)`) you aren't able to distinguish the sine wave any more.

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The granularity of the fractional part has corrupted the flow of the sine wave into pseudo-random chaos.

4.2 Controlling chaos

Using random can be hard; it is both too chaotic and sometimes not random enough. Take a look at the following graph. To make it, we are using a `rand()` function which is implemented exactly like we describe above.

Taking a closer look, you can see the `sin()` wave crest at `-1.5707` and `1.5707`. I bet you now understand why - it's where the maximum and minimum of the sine wave happens.

If look closely at the random distribution, you will note that there is some concentration around the middle compared to the edges.

A while ago [Pixelero](#) published an [interesting article about random distribution](#). I've added some of the functions he uses in the previous graph for you to play with and see how the distribution can be changed. Uncomment the functions and see what happens.

If you read [Pixelero's article](#), it is important to keep in mind that our `rand()` function is a deterministic random, also known as pseudo-random. Which means for example `rand(1.)` is always going to return the same value. [Pixelero](#) makes reference to the ActionScript function `Math.random()` which is non-deterministic; every call will return a different value.

4.3 2D Random

Now that we have a better understanding of randomness, it's time to apply it in two dimensions, to both the `x` and `y` axis. For that we need a way to transform a two dimensional vector into a one dimensional floating point value. There are different ways to do this, but the `dot()` function is particularly helpful in this case. It returns a single float value between `0.0` and `1.0` depending on the alignment of two vectors.

```
// Author @patriciogu - 2015
// http://patriciogonzalezvivo.com

#ifndef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;
```

```

float random (vec2 st) {
    return fract(sin(dot(st.xy,
                         vec2(12.9898,78.233)))*
        43758.5453123);
}

void main() {
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    float rnd = random( st );
    gl_FragColor = vec4(vec3(rnd),1.0);
}

```

Take a look at lines 13 to 15 and notice how we are comparing the `vec2 st` with another two dimensional vector (`vec2(12.9898,78.233)`).

- Try changing the values on lines 14 and 15. See how the random pattern changes and think about what we can learn from this.
- Hook this random function to the mouse interaction (`u_mouse`) and time (`u_time`) to understand better how it works.

4.4 Using the chaos

Random in two dimensions looks a lot like TV noise, right? It's a hard raw material to use to compose images. Let's learn how to make use of it.

Our first step is to apply a grid to it; using the `floor()` function we will generate an integer table of cells. Take a look at the following code, especially lines 22 and 23.

```

// Author @patriciogv - 2015
// http://patriciogonzalezvivo.com

#ifndef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

float random (vec2 st) {
    return fract(sin(dot(st.xy,
                         vec2(12.9898,78.233)))*

```

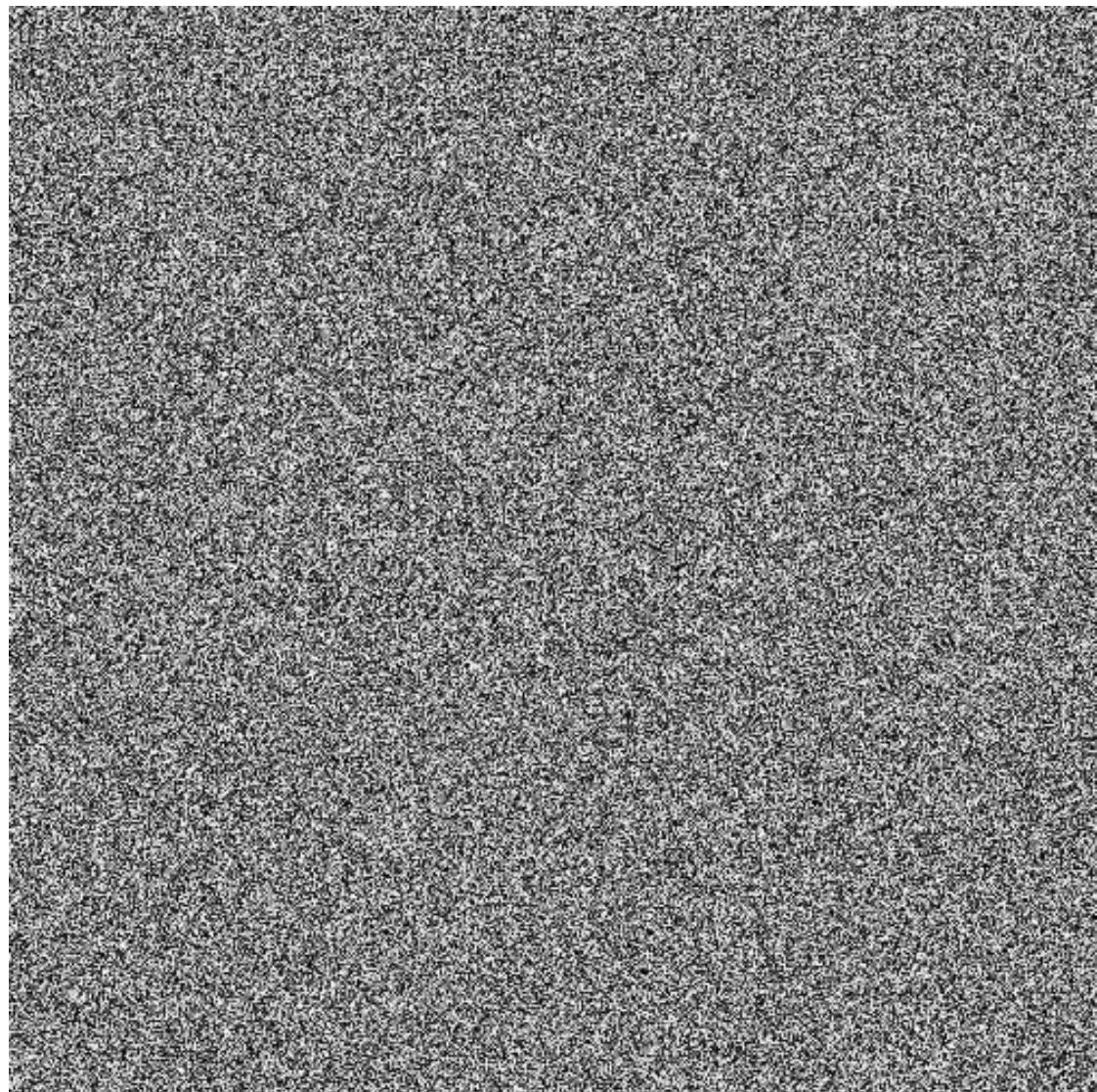


Figure 4.1:

```

    43758.5453123);
}

void main() {
    vec2 st = gl_FragCoord.xy/u_resolution.xy;

    st *= 10.0; // Scale the coordinate system by 10
    vec2 ipos = floor(st); // get the integer coords
    vec2 fpos = fract(st); // get the fractional coords

    // Assign a random value based on the integer coord
    vec3 color = vec3(random( ipos ));

    // Uncomment to see the subdivided grid
    // color = vec3(fpos,0.0);

    gl_FragColor = vec4(color,1.0);
}

```

After scaling the space by 10 (on line 21), we separate the integers of the coordinates from the fractional part. We are familiar with this last operation because we have been using it to subdivide a space into smaller cells that go from 0.0 to 1.0. By obtaining the integer of the coordinate we isolate a common value for a region of pixels, which will look like a single cell. Then we can use that common integer to obtain a random value for that area. Because our random function is deterministic, the random value returned will be constant for all the pixels in that cell.

Uncomment line 29 to see that we preserve the floating part of the coordinate, so we can still use that as a coordinate system to draw things inside each cell.

Combining these two values - the integer part and the fractional part of the coordinate - will allow you to mix variation and order.

Take a look at this GLSL port of the famous `10 PRINT CHR$(205.5+RND(1)); : GOTO 10` maze generator.

```

// Author @patriciogv - 2015
// http://patriciogonzalezvivo.com

#ifndef GL_ES
precision mediump float;
#endif

#define PI 3.14159265358979323846

uniform vec2 u_resolution;

```

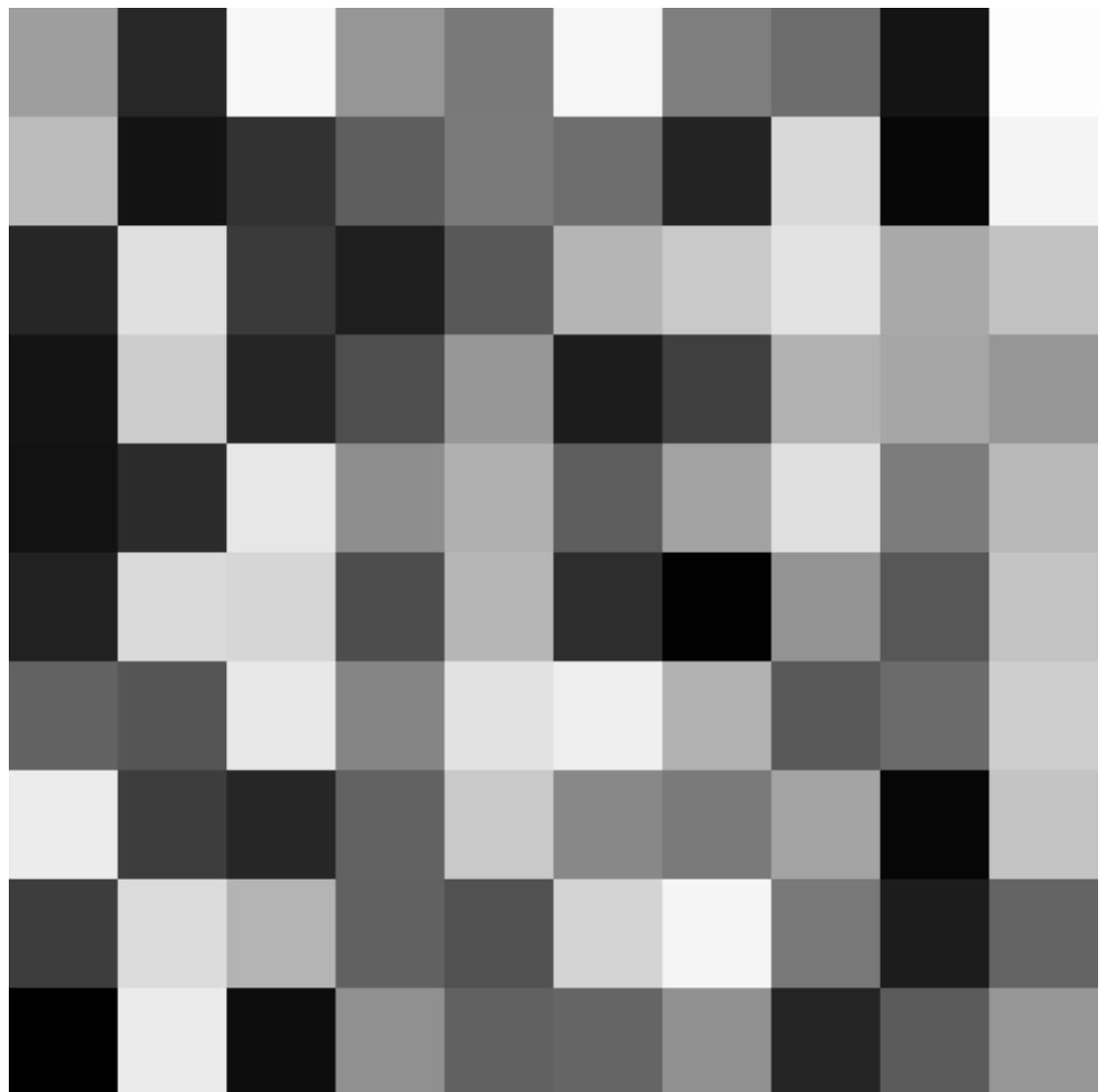


Figure 4.2:

```

uniform vec2 u_mouse;
uniform float u_time;

float random (in vec2 _st) {
    return fract(sin(dot(_st.xy,
                         vec2(12.9898,78.233)))*
        43758.5453123);
}

vec2 truchetPattern(in vec2 _st, in float _index){
    _index = fract((( _index-0.5)*2.0));
    if (_index > 0.75) {
        _st = vec2(1.0) - _st;
    } else if (_index > 0.5) {
        _st = vec2(1.0-_st.x,_st.y);
    } else if (_index > 0.25) {
        _st = 1.0-vec2(1.0-_st.x,_st.y);
    }
    return _st;
}

void main() {
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    st *= 10.0;
    // st = (st-vec2(5.0))*(abs(sin(u_time*0.2))*5.);
    // st.x += u_time*3.0;

    vec2 ipos = floor(st); // integer
    vec2 fpos = fract(st); // fraction

    vec2 tile = truchetPattern(fpos, random( ipos ));

    float color = 0.0;

    // Maze
    color = smoothstep(tile.x-0.3,tile.x,tile.y)-
        smoothstep(tile.x,tile.x+0.3,tile.y);

    // Circles
    // color = (step(length(tile),0.6) -
    //           step(length(tile),0.4) ) +
    //           (step(length(tile-vec2(1.)),0.6) -
    //           step(length(tile-vec2(1.)),0.4) );
}

```

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```
// Truchet (2 triangles)
// color = step(tile.x,tile.y);

gl_FragColor = vec4(vec3(color),1.0);
}
```



Figure 4.3:

Here I'm using the random values of the cells to draw a line in one direction or the other using the `truchetPattern()` function from the previous chapter (lines 41 to 47).

You can get another interesting pattern by uncommenting the block of lines between 50 to 53, or animate the pattern by uncommenting lines 35 and 36.

4.5 Master Random

Ryoji Ikeda, Japanese electronic composer and visual artist, has mastered the use of random; it is hard not to be touched and mesmerized by his work. His use of randomness in audio and visual mediums is forged in such a way that it is not annoying chaos but a mirror of the complexity of our technological culture.

```
<iframe src="https://player.vimeo.com/video/76813693?title=0&byline=0&portrait=0"
width="800" height="450" frameborder="0" webkitallowfullscreen mozallowfullscreen
allowfullscreen>
```

Take a look at [Ikeda](#)'s work and try the following exercises:

- Make rows of moving cells (in opposite directions) with random values. Only display the cells with brighter values. Make the velocity of the rows fluctuate over time.
- Similarly make several rows but each one with a different speed and direction. Hook the position of the mouse to the threshold of which cells to show.
- Create other interesting effects.

Using random aesthetically can be problematic, especially if you want to make natural-looking simulations. Random is simply too chaotic and very few things look `random()` in real life. If you look at a rain pattern or a stock chart, which are both quite random, they are nothing like the random pattern we made at the begining of this chapter. The reason? Well, random values have no correlation between them what so ever, but most natural patterns have some memory of the previous state.

In the next chapter we will learn about noise, the smooth and *natural looking* way of creating computational chaos.

4.6 Noise

Break time! We have been playing with all this random functions that looks like TV white noise, our head is still spinning around thinking on shaders, and our eyes are tired. Time to get out side and walk!

We feel the air in our face, the sun in our nose and chicks. The world is such a vivid and rich places. Colors, textures, sounds. While we walk we can avoid notice the surface of the roads, rocks, trees and clouds. Suddenly all seams random. But definitely not the type of random we were making. The real world is such a rich place. How we can approximate to this level of variety computationally?

We are on the same path of thoughts that Ken Perlin's walk through on 1982 when he was commissioned with the job of generating "more realistic" textures for a new disney

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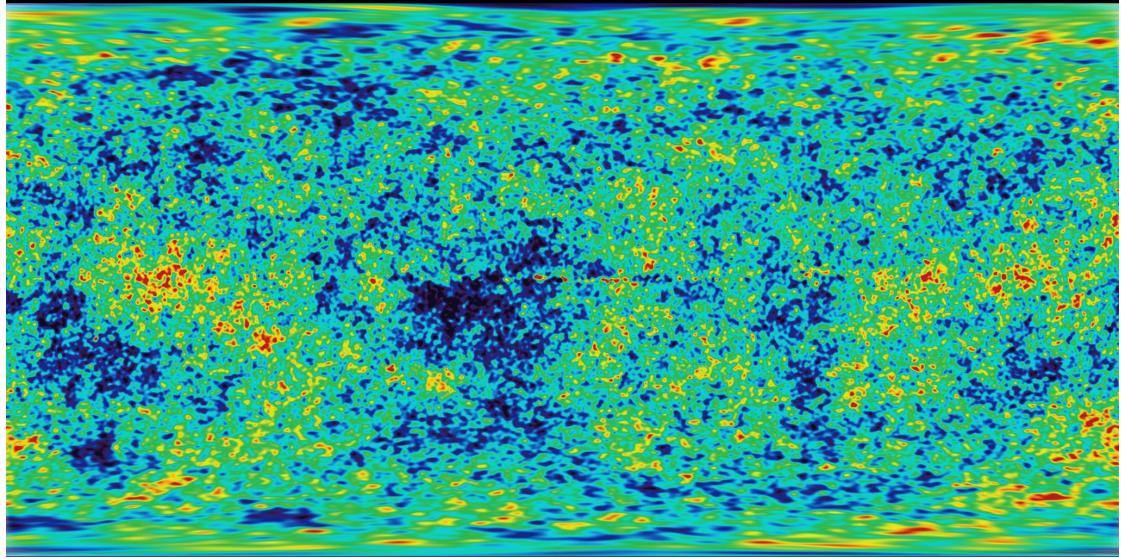


Figure 4.4: NASA / WMAP science team

movie call “Tron”. In response to that he came up with an elegant *oscar winner* noise algorithm.

The following is not the Perlin noise algorithm, but is a good starting point to start getting our head around the idea of how to generate *noise o smooth random*.

Look at the following graph, is in essence what we were doing on line 36 and 37 on the last example of the previous chapter. We are computing the `rand()` of the integers of `x` (the `i` variable).

By uncommenting the following line, you can make a linear interpolation between the random value of an integer to the next one.

```
y = mix(rand(i), rand(i + 1.0), f);
```

At this point we have learned that we can do better than a linear interpolation. Right? By uncommenting the following line, we will use the native `smoothstep()` to make a *smooth* transition between the previous random values.

```
y = mix(rand(i), rand(i + 1.0), smoothstep(0., 1., f));
```

You will find in other implementations that people use cubic curves (like the following formula) instead of using a `smoothstep()`.

```
float u = f * f * (3.0 - 2.0 * f );
y = mix(rand(i), rand(i + 1.0), u);
```

4.7 2D Noise

Now that we understand how noise is made in one dimension, is time to port it to two dimensions. Check how on the following code the interpolation (line 29) is made between the four corners of a square (lines 22-25).

```
// Author @patrickogv - 2015
// http://patrickgonzalezvivo.com

#ifndef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

float random (in vec2 st) {
    return fract(sin(dot(st.xy,
                         vec2(12.9898,78.233)))*
        43758.5453123);
}

// Based on Morgan McGuire @morgan3d
// https://www.shadertoy.com/view/4dS3Wd
float noise (in vec2 st) {
    vec2 i = floor(st);
    vec2 f = fract(st);

    // Four corners in 2D of a tile
    float a = random(i);
    float b = random(i + vec2(1.0, 0.0));
    float c = random(i + vec2(0.0, 1.0));
    float d = random(i + vec2(1.0, 1.0));

    vec2 u = f * f * (3.0 - 2.0 * f);

    return mix(a, b, u.x) +
           (c - a)* u.y * (1.0 - u.x) +
           (d - b) * u.x * u.y;
}

void main() {
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
```

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```
vec3 color = vec3(0.0);  
  
vec2 pos = vec2(st*5.0+u_time);  
  
color = vec3( noise(pos) );  
  
gl_FragColor = vec4(color,1.0);  
}
```



Figure 4.5:

At this point you can recognize what's going on at line 40. We are scaling and "moving" the space, right?

Try:

- Change the multiplier. Try to animate it.
- At what level of zoom the noise start looking like random again?
- At what zoom level the noise is imperceptible.
- Change the u_time by the normalize values of the mouse coordinates.
- Now that you achieve some control over noise & chaos, is time to mix it with previous knowledge. Making a composition of rectangles, colors and noise that resemble some of the complexity of the texture of the following painting made by [Mark Rothko](#).

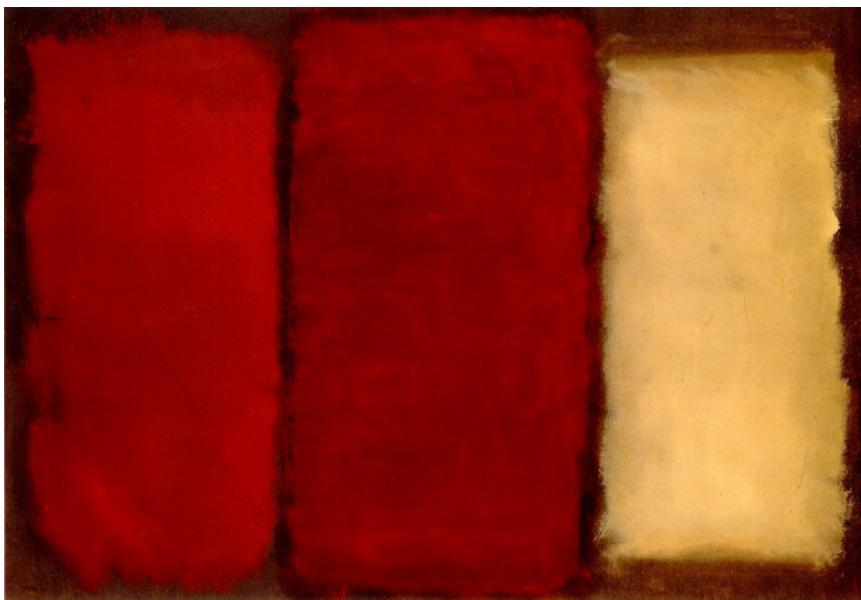


Figure 4.6: Mark Rothko - Three (1950)

4.8 Using 2D Noise

As we saw, noise was designed to give a natural *je ne sais quoi* to digital textures, and could be used to make convincing generative textures. Lets refresh some of the previous knowledge and then jump forward learning how to mix all the knowledge we have learned so far.

In the following code you will find:

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- Shaping functions to create: random (line 13), noise (line 32) and a line pattern (line 46).
- A color gradient (line 68).
- A matrix to rotate the line pattern (line 37-40 and 45)
- A 2d random function (line 12-16)
- A 2d noise function (line 20-35)

```
// Author @patriciogv - 2015
// http://patriciogonzalezvivo.com

#ifndef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

float random (in vec2 st) {
    return fract(sin(dot(st.xy,
                         vec2(12.9898,78.233)))*
        43758.5453123);
}

// Based on Morgan McGuire @morgan3d
// https://www.shadertoy.com/view/4dS3Wd
float noise (in vec2 st) {
    vec2 i = floor(st);
    vec2 f = fract(st);

    // Four corners in 2D of a tile
    float a = random(i);
    float b = random(i + vec2(1.0, 0.0));
    float c = random(i + vec2(0.0, 1.0));
    float d = random(i + vec2(1.0, 1.0));

    vec2 u = f * f * (3.0 - 2.0 * f);

    return mix(a, b, u.x) +
        (c - a)* u.y * (1.0 - u.x) +
        (d - b) * u.x * u.y;
}

mat2 rotate2d(float angle){
```

```

    return mat2(cos(angle),-sin(angle),
                sin(angle),cos(angle));
}

float lines(in vec2 pos, float angle, float b){
    float scale = 10.0;
    pos *= scale;
    pos = rotate2d( angle ) * pos;
    return smoothstep(0.0,
                      0.5+b*0.5,
                      abs((sin(pos.x*3.1415)+b*2.0))*0.5);
}

void main() {
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    vec3 color = vec3(0.0);

    vec2 pos = vec2(st*5.0);

    float pattern = pos.x;

    // Stripes
    // pattern = lines(pos*0.1, 0.0, 0.5 );

    // Add noise
    // pattern = lines(pos, noise(pos), 0.5 );

    // Strech the noise pattern
    //pattern = lines(pos, noise(pos*vec2(2.,0.5)),0.5);

    color = mix(vec3(0.275,0.145,0.059),
                vec3(0.761,0.529,0.239),
                pattern*1.7);

    gl_FragColor = vec4(color,1.0);
}

```

By uncommenting line 60 you will see the line pattern we are talking about. Revealing line 63 you can see how we can alternate this pattern in a “natural-like” way, to then finally, uncommenting line 66 we can stretch the noise pattern in y axis.

Wow! You really should be proud of your self. He have went from nothing to generating our own wood procedural texture!

Now is time for you to play with it:

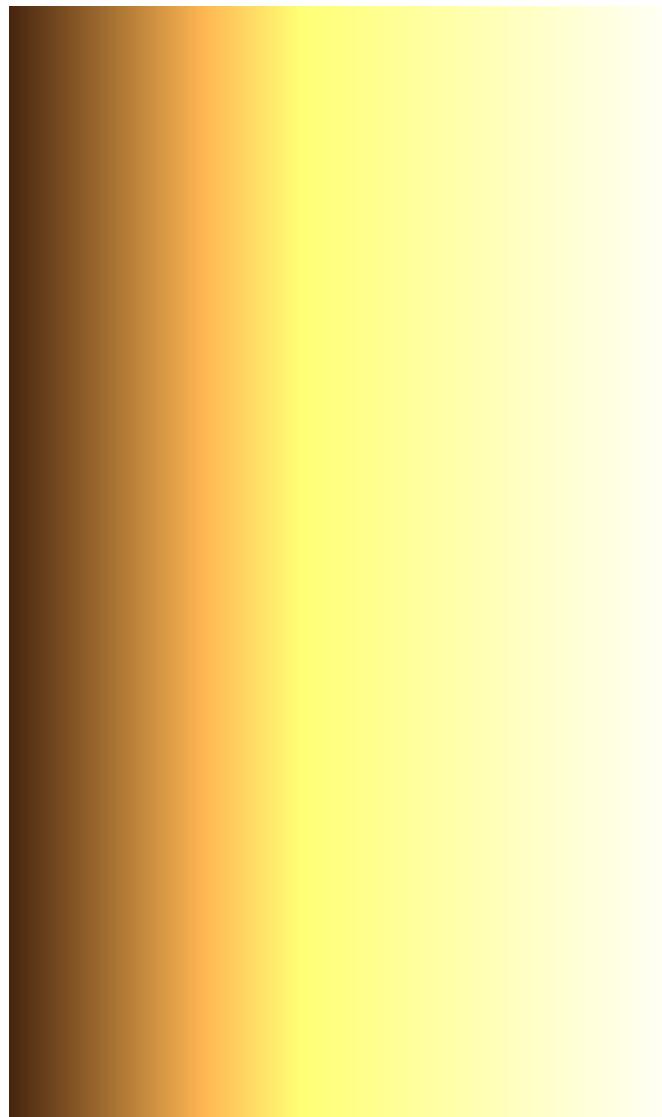


Figure 4.7:

- What do you think it will happen if the pattern looks like this:

```
pattern = sin(lines(pos, noise(pos*vec2(2.,0.5)),0.5)*3.14);
```

Or like this

```
pattern = fract(lines(pos, noise(pos*vec2(2.,0.5)),0.5)*2.0);
```

- What other generative pattern can you make? What about granite? marble? magma? water?
- What about noise apply to motion? Go back to the Matrix chapter and use the translation example that move a the “+” around to apply some *random* and *noise* movements to it.

Nothing like having some control over the chaos and chances. Right? Noise is one of those subjects that you can dig and always find new exciting formulas. In fact, noise means different things for different people. Musicians will think in audio noise, communicators into interference, and astrophysics on cosmic microwave background. On the next chapter we will use some related concepts from sign and audio behavior to our noise function to explore more uses of noise.

4.9 Fractal Brownian Motion

At the end of the previous chapter we were thinking about noise and discovering that in fact noise could be interpreted as audio signals. In fact sound can be constructed by the manipulation of the amplitude and frequency of a sine waves.

```
y = amplitud + sin( frequency );
```

An interesting property of waves in general is that they can be add up. The following graph shows what happens if you add sine waves of different frequencies and amplitudes.

Think on it as the surface of the ocean. Massive amount of water propagating waves across its surface. Waves of different heights (amplitude) and rhythms (frequencies) bouncing and interfering each other.

Musicians learn long time ago that there are sounds that play well with each other. Those sounds, carried by waves of air, vibrate in such a particular way that the resultant sound seems to be burst and enhance. Those sounds are called *harmonics*.

Back to code, we can add harmonics together and see how the resultant looks like. Try the following code on the previous graph.

```
y = 0.;
for( int i = 0; i < 5; ++i ) {
    y += sin(PI*x*float(i))/float(i);
}
y *= 0.6;
```

As you can see in the above code, on every iteration the frequency increase by the double. By augmenting the number of iterations (chaining the 5 for a 10, a 20 or 50) the wave tends to break into smaller fractions, with more details and sharper fluctuations.

4.10 Fractal Brownian Motion

So we try adding different waves together, and the result was chaotic, we add up harmonic waves and the result was a consistent fractal pattern. We can use the best of both worlds and add up harmonic noise waves to exacerbate a noise pattern.

By adding different octaves of increasing frequencies and decreasing amplitudes of noise we can obtain a bigger level of detail or granularity. This technique is call Fractal Brownian Motion and usually consist on a fractal sum of noise functions.

Take a look to the following example and progressively change the for loop to do 2,3,4,5,6,7 and 8 iterations. See what happens

If we apply this one dimensional example to a bidimensional space it will look like the following example:

```
// Author @patriciogv - 2015
// http://patriciogonzalezvivo.com

#ifndef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

float random (in vec2 st) {
    return fract(sin(dot(st.xy,
                         vec2(12.9898,78.233)))*
        43758.5453123);
}

// Based on Morgan McGuire @morgan3d
// https://www.shadertoy.com/view/4dS3Wd
float noise (in vec2 st) {
    vec2 i = floor(st);
    vec2 f = fract(st);

    // Four corners in 2D of a tile
    float a = random(i);
```

```

float b = random(i + vec2(1.0, 0.0));
float c = random(i + vec2(0.0, 1.0));
float d = random(i + vec2(1.0, 1.0));

vec2 u = f * f * (3.0 - 2.0 * f);

return mix(a, b, u.x) +
       (c - a)* u.y * (1.0 - u.x) +
       (d - b) * u.x * u.y;
}

#define NUM_OCTAVES 5

float fbm ( in vec2 st) {
    float v = 0.0;
    float a = 0.5;
    vec2 shift = vec2(100.0);
    // Rotate to reduce axial bias
    mat2 rot = mat2(cos(0.5), sin(0.5),
                    -sin(0.5), cos(0.5));
    for (int i = 0; i < NUM_OCTAVES; ++i) {
        v += a * noise(st);
        st = rot * st * 2.0 + shift;
        a *= 0.5;
    }
    return v;
}

void main() {
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    st.x *= u_resolution.x/u_resolution.y;
    vec3 color = vec3(0.0);

    float noise = noise(st*3.0);
    float fractal = fbm(st*3.0);
    color = vec3(mix(noise,fractal,abs(sin(u_time))));

    gl_FragColor = vec4(color,1.0);
}

```

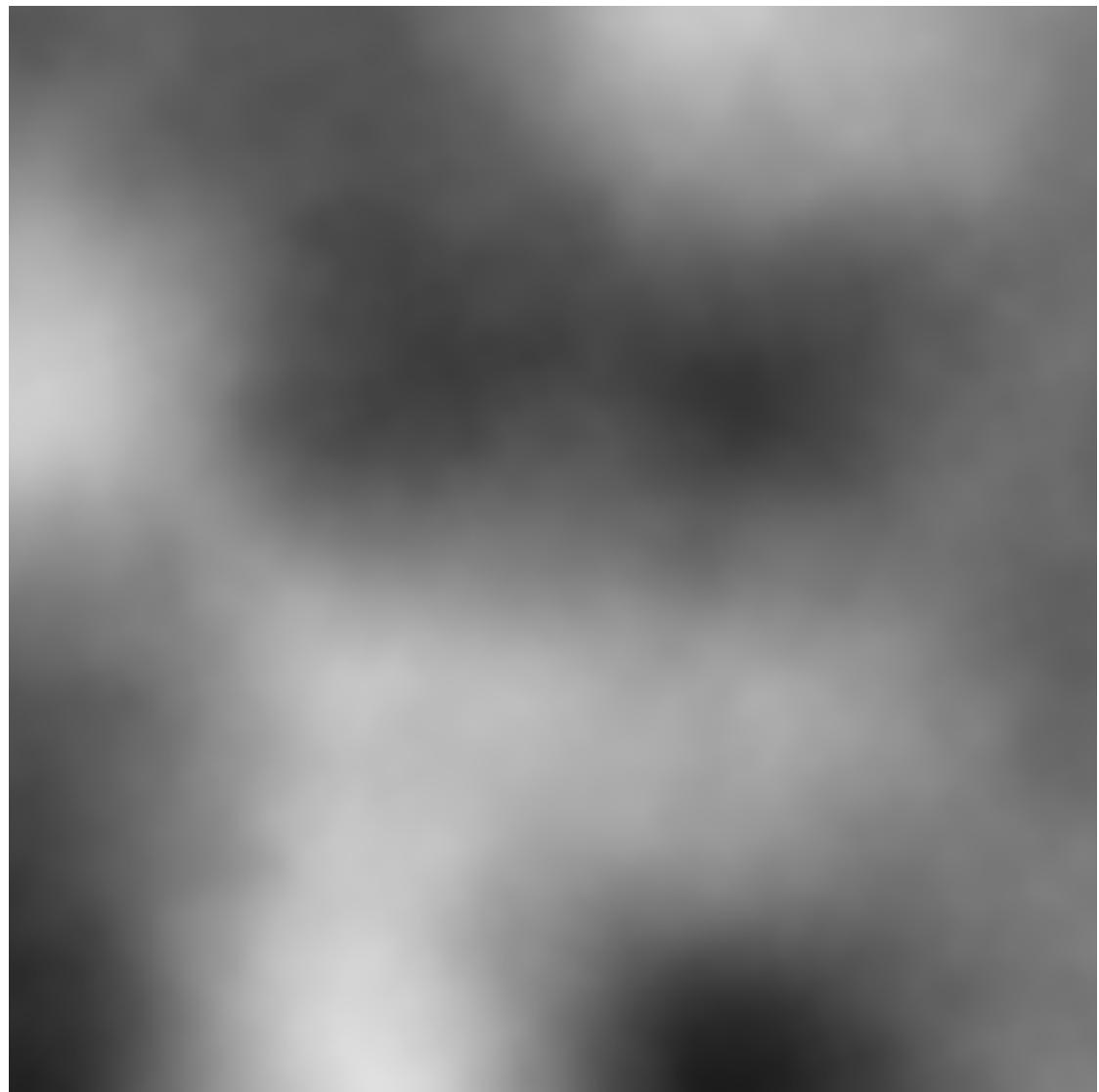


Figure 4.8:

4.11 Using Fractal Brownian Motion

In this [article](#) Iñigo Quilez describe an interesting use of fractal brownian motion constructing patterns by adding successive results of fractal brownian motions.

Take a look to the code and how it looks

```
// Author @patriciogv - 2015
// http://patriciogonzalezvivo.com

#ifndef GL_ES
precision mediump float;
#endif

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

float random (in vec2 _st) {
    return fract(sin(dot(_st.xy,
                         vec2(12.9898,78.233)))*
        43758.5453123);
}

// Based on Morgan McGuire @morgan3d
// https://www.shadertoy.com/view/4dS3Wd
float noise (in vec2 _st) {
    vec2 i = floor(_st);
    vec2 f = fract(_st);

    // Four corners in 2D of a tile
    float a = random(i);
    float b = random(i + vec2(1.0, 0.0));
    float c = random(i + vec2(0.0, 1.0));
    float d = random(i + vec2(1.0, 1.0));

    vec2 u = f * f * (3.0 - 2.0 * f);

    return mix(a, b, u.x) +
        (c - a)* u.y * (1.0 - u.x) +
        (d - b) * u.x * u.y;
}

#define NUM_OCTAVES 5
```

```

float fbm ( in vec2 _st) {
    float v = 0.0;
    float a = 0.5;
    vec2 shift = vec2(100.0);
    // Rotate to reduce axial bias
    mat2 rot = mat2(cos(0.5), sin(0.5),
                    -sin(0.5), cos(0.5));
    for (int i = 0; i < NUM_OCTAVES; ++i) {
        v += a * noise(_st);
        _st = rot * _st * 2.0 + shift;
        a *= 0.5;
    }
    return v;
}

void main() {
    vec2 st = gl_FragCoord.xy/u_resolution.xy*3.;
    // st += st * abs(sin(u_time*0.1)*3.0);
    vec3 color = vec3(0.0);

    vec2 q = vec2(0.);
    q.x = fbm( st + 0.00*u_time);
    q.y = fbm( st + vec2(1.0));

    vec2 r = vec2(0.);
    r.x = fbm( st + 1.0*q + vec2(1.7,9.2)+ 0.15*u_time );
    r.y = fbm( st + 1.0*q + vec2(8.3,2.8)+ 0.126*u_time);

    float f = fbm(st+r);

    color = mix(vec3(0.101961,0.619608,0.666667),
                vec3(0.666667,0.666667,0.498039),
                clamp((f*f)*4.0,0.0,1.0));

    color = mix(color,
                vec3(0,0,0.164706),
                clamp(length(q),0.0,1.0));

    color = mix(color,
                vec3(0.666667,1,1),
                clamp(length(r.x),0.0,1.0));

    gl_FragColor = vec4((f*f*f+.6*f*f+.5*f)*color,1.);
}

```

}



Figure 4.9:

4.12 Fractals

<https://www.shadertoy.com/view/lsX3W4>

<https://www.shadertoy.com/view/Mss3Wf>

<https://www.shadertoy.com/view/4df3Rn>

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<https://www.shadertoy.com/view/Mss3R8>
<https://www.shadertoy.com/view/4dfGRn>
<https://www.shadertoy.com/view/lss3zs>
<https://www.shadertoy.com/view/4dXGDX>
<https://www.shadertoy.com/view/XsXGz2>
<https://www.shadertoy.com/view/lls3D7>
<https://www.shadertoy.com/view/XdB3DD>
<https://www.shadertoy.com/view/XdBSWw>
<https://www.shadertoy.com/view/llfGD2>
<https://www.shadertoy.com/view/Mlf3RX>

5 Image processing

5.1 Textures

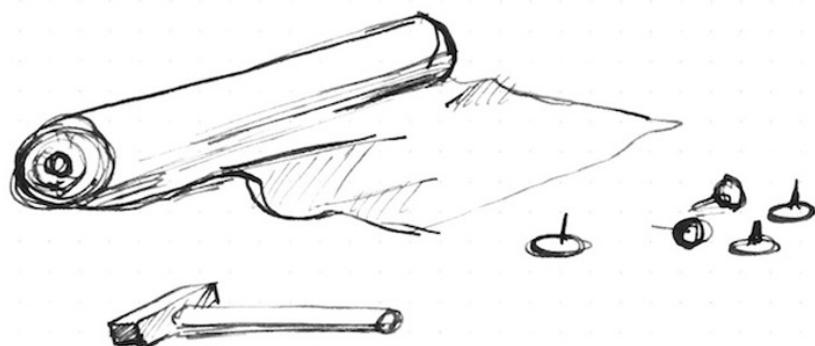


Figure 5.1:

Graphic cards (GPUs) have special memory types for images. Usually on CPUs images are stores as arrays of bites but on GPUs store images as `sampler2D` which is more like a table (or matrix) of floating point vectors. More interestingly is that the values of this *table* of vectors are continuously. That means that value between pixels are interpolated in a low level.

In order to use this feature we first need to *upload* the image from the CPU to the GPU, to then pass the `id` of the texture to the right `uniform`. All that happens outside the shader.

Once the texture is loaded and linked to a valid `uniform sampler2D` you can ask for specific color value at specific coordinates (formated on a `vec2` variable) usin the `texture2D()` function which will return a color formated on a `vec4` variable.

```
vec4 texture2D(sampler2D texture, vec2 coordinates)
```

Check the following code where we load Hokusai's Wave (1830) as `uniform sampler2D u_tex0` and we call every pixel of it inside the billboard:

```
// Author @patriciogv - 2015  
// http://patriciogonzalezvivo.com
```

5 Image processing

```
#ifdef GL_ES
precision mediump float;
#endif

uniform sampler2D u_tex0;
uniform vec2 u_tex0Resolution;

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

void main () {
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    vec4 color = vec4(st.x,st.y,0.0,1.0);

    color = texture2D(u_tex0,st);

    gl_FragColor = color;
}
```

If you pay attention you will note that the coordinates for the texture are normalized! What a surprise right? Textures coordenates are consisten with the rest of the things we had saw and their coordenates are between 0.0 and 1.0 whitch match perfectly with the normalized space coordinates we have been using.

Now that you have seen how we load correctly a texture is time to experiment to discover what we can do with it, by trying:

- Scaling the previus texture by half.
- Rotating the previus texture 90 degrees.
- Hooking the mouse position to the coordenates to move it.

Why you should be excited about textures? Well first of all forget about the sad 255 values for channel, once your image is trasformed into a `uniform sampler2D` you have all the values between 0.0 and 1.0 (depending on what you set the `precision` to). That's why shaders can make really beatiful post-processing effects.

Second, the `vec2()` means you can get values even between pixels. As we said before the textures are a continuum. This means that if you set up your texture correctly you can ask for values all arround the surface of your image and the values will smoothly vary from pixel to pixel with no jumps!

Finnally, you can setup your image to repeat in the edges, so if you give values over or lower of the normalized 0.0 and 1.0, the values will wrap around starting over.

All this features makes your images more like an infinit spandex fabric. You can streach



Figure 5.2:

5 Image processing

and shrinks your texture without noticing the grid of bites they originally where compose of or the ends of it. To experience this take a look to the following code where we distort a texture using [the noise function we already made](#).

```
// Author @patriciogv - 2015
// http://patriciogonzalezvivo.com

#ifndef GL_ES
precision mediump float;
#endif

#define PI 3.14159265359

uniform sampler2D u_tex0;
uniform vec2 u_tex0Resolution;

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

// Based on Morgan
// https://www.shadertoy.com/view/4dS3Wd
float random (in vec2 st) {
    return fract(sin(dot(st.xy,
                         vec2(12.9898,78.233)))*
        43758.5453123);
}

float noise (in vec2 st) {
    vec2 i = floor(st);
    vec2 f = fract(st);

    // Four corners in 2D of a tile
    float a = random(i);
    float b = random(i + vec2(1.0, 0.0));
    float c = random(i + vec2(0.0, 1.0));
    float d = random(i + vec2(1.0, 1.0));

    vec2 u = f * f * (3.0 - 2.0 * f);

    return mix(a, b, u.x) +
           (c - a)* u.y * (1.0 - u.x) +
           (d - b) * u.x * u.y;
}
```

```

void main () {
    vec2 st = gl_FragCoord.xy/u_resolution.xy;

    float scale = 2.0;
    float offset = 0.5;

    float angle = noise( st + u_time * 0.1 )*PI;
    float radius = offset;

    st *= scale;
    st += radius * vec2(cos(angle),sin(angle));

    vec4 color = texture2D(u_tex0,st);

    gl_FragColor = color;
}

```

5.2 Texture resolution

Aboves examples play well with squared images, where both sides are equal and match our squared billboard. But for non-squared images things can be a little more tricky, and unfortunatly centuries of picturical art and photography found more pleasant to the eye non-squared proportions for images.

How we can solve this problem? Well we need to know the original proportions of the image to know how to streatch the texture correctly in order to have the original *aspect ratio*. For that the texture width and height is pass to the shader as an *uniform*. Which in our example framework are pass as an *uniform* *vec2* with the same name of the texture followed with proposition *Resolution*. Once we have this information on the shader he can get the aspect ration by dividing the *width* for the *height* of the texture resolution. Finally by multiplying this ratio to the coordinates on y we will shrink these axis to match the original proportions.

Uncomment line 21 of the following code to see this in action.

```

// Author @patriciogv - 2015
// http://patriciogonzalezvivo.com

#ifndef GL_ES
precision mediump float;
#endif

uniform sampler2D u_tex0;

```

5 Image processing

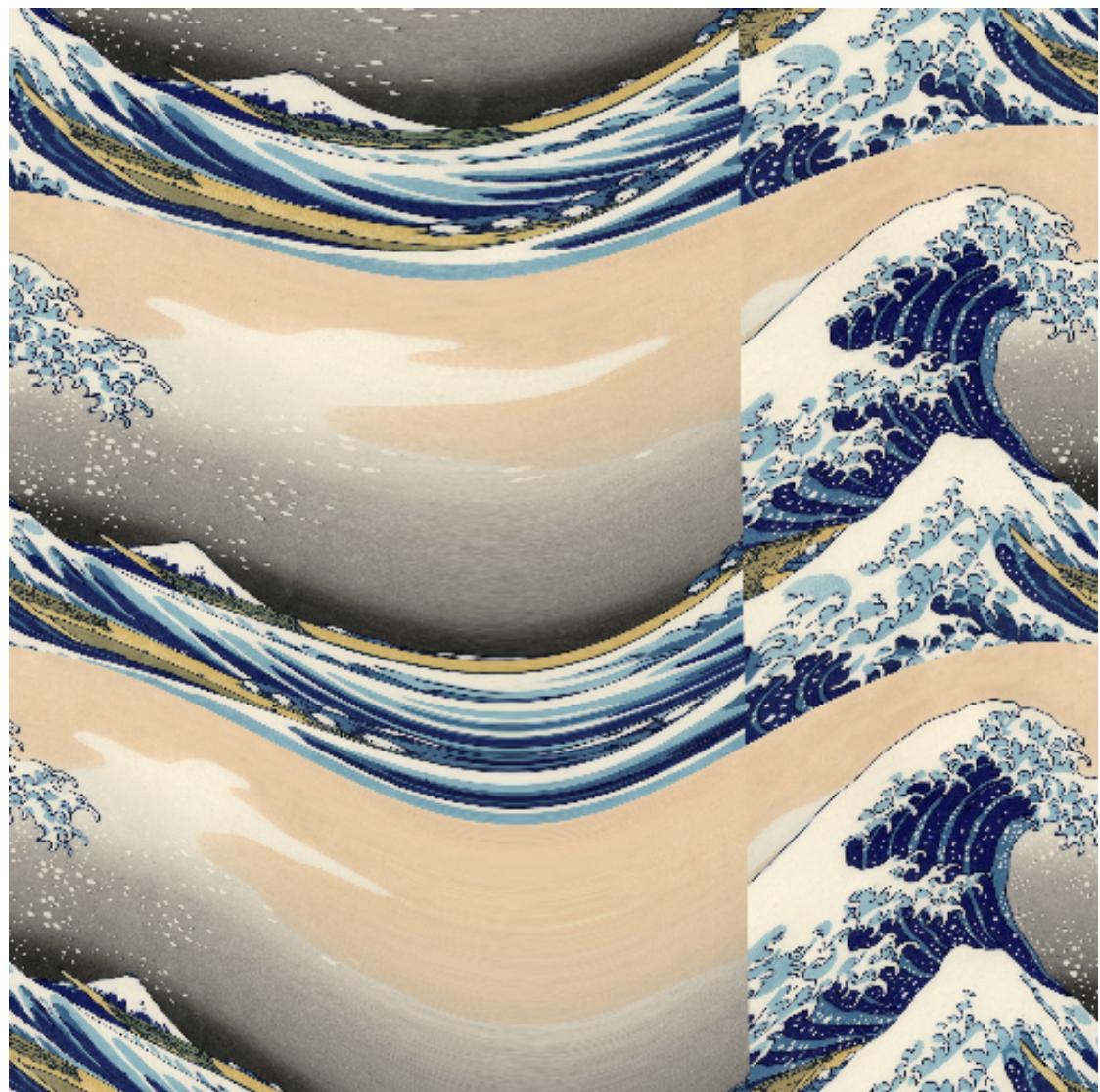


Figure 5.3:

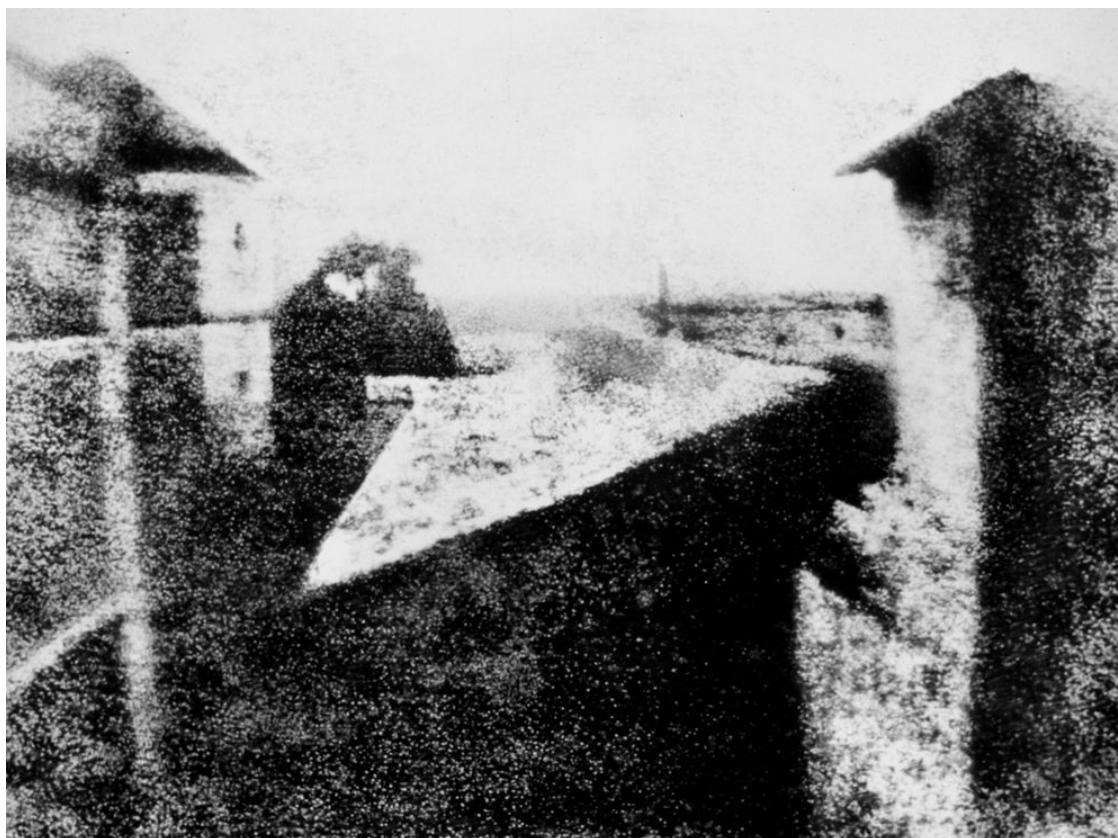


Figure 5.4: Joseph Nicéphore Niépce (1826)

5 Image processing

```
uniform vec2 u_tex0Resolution;

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

void main () {
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    vec4 color = vec4(0.0);

    // Fix the proportions by finding the aspect ration
    float aspect = u_tex0Resolution.x/u_tex0Resolution.y;
    // st.y *= aspect; // and then applying to it

    color = texture2D(u_tex0,st);

    gl_FragColor = color;
}
```

- What we need to do to center this image?

5.3 Digital upholstery

You may be thinking that this is unnesesary complicated... and you are probably right. Also this way of working with images leave a enought room to different hacks and creative tricks. Try to imagine that you are an upholster and by streaching and folding a fabric over a structure you can create better and new patterns and techniques.

This level of craftsmanship links back to some of the first optical experiments ever made. For example on games *sprite animations* are very common, and is inevitably to see on it reminicence to phenakistoscope, zoetrope and praxinoscope.

This could seam simple but the possibilities of modifing textures coordinates is enormous. For example: .

```
// Author @patriciogv - 2015
// http://patriciogonzalezvivo.com

#ifndef GL_ES
precision mediump float;
#endif

uniform sampler2D u_tex0;
uniform vec2 u_tex0Resolution;
```



Figure 5.5:

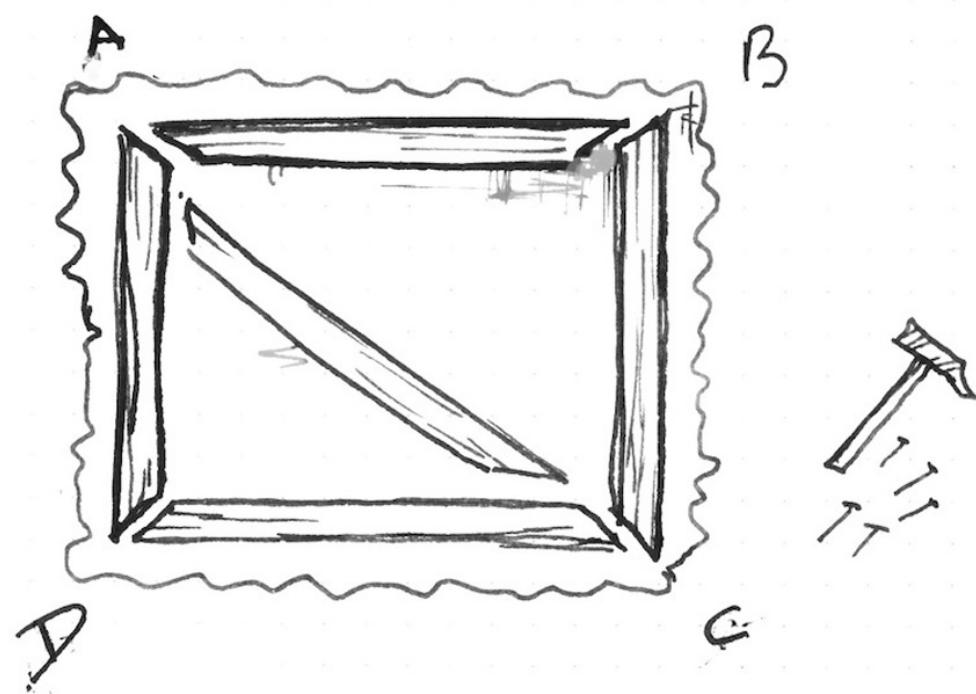


Figure 5.6:



Figure 5.7: Eadweard's Muybridge study of motion

5 Image processing

```
int col = 5;
int row = 4;

uniform vec2 u_resolution;
uniform vec2 u_mouse;
uniform float u_time;

void main () {
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    vec4 color = vec4(0.0);

    // Resolution of one frame
    vec2 fRes = u_resolution/vec2(float(col),float(row));

    // Normalize value of the frame resolution
    vec2 nRes = u_resolution/fRes;

    // Scale the coordinates to a single frame
    st = st/nRes;

    // Calculate the offset in cols and rows
    float timeX = u_time*15.;
    float timeY = floor(timeX/float(col));
    vec2 offset = vec2( floor(timeX)/nRes.x,
                        1.0-(floor(timeY)/nRes.y) );
    st = fract(st+offset);

    color = texture2D(u_tex0,st);

    gl_FragColor = color;
}
```

Now is your turn:

- Can you make a kaleidoscope using what we have learned?
- What other optical toys can you re-create using textures?

In the next chapters we will learn how to do some image processing using shaders. You will note that finally the complexity of shader makes sense, because was in a big sense designed to do this type of process. We will start doing some image operations!



Figure 5.8:

5.4 Image operations

5.4.1 Invert

```
// Author @patriciogu - 2015
// http://patriciogonzalezvivo.com

#ifndef GL_ES
precision mediump float;
#endif

uniform sampler2D u_tex0;

uniform float u_time;
uniform vec2 u_mouse;
uniform vec2 u_resolution;

void main (void) {
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    vec3 color = texture2D(u_tex0,st).rgb;

    // color = 1.0-color;

    gl_FragColor = vec4(color,1.0);
}
```

5.4.2 Add, Subtract, Multiply and others

```
// Author @patriciogu - 2015
// http://patriciogonzalezvivo.com

#ifndef GL_ES
precision mediump float;
#endif

uniform sampler2D u_tex0;
uniform sampler2D u_tex1;

uniform float u_time;
uniform vec2 u_mouse;
uniform vec2 u_resolution;

void main (void) {
```



Figure 5.9:



Figure 5.10:

```

vec2 st = gl_FragCoord.xy/u_resolution.xy;
vec3 color = vec3(0.);
vec3 colorA = texture2D(u_tex0,st).rgb;
vec3 colorB = texture2D(u_tex1,st).rgb;

color = colorA+colorB;      // Add
// color = colorA-colorB;    // Diff
// color = abs(colorA-colorB); // Abs Diff
// color = colorA*colorB;    // Mult
// color = colorA/colorB;    // Div
// color = max(colorA,colorB); // Ligther
// color = min(colorA,colorB); // Darker

gl_FragColor = vec4(color,1.0);
}
    
```

5.4.3 PS Blending modes

```

#ifndef GL_ES
precision mediump float;
#endif

#define BlendLinearDodgef          BlendAddf
#define BlendLinearBurnf           BlendSubtractf
    
```



Figure 5.11:

5 Image processing

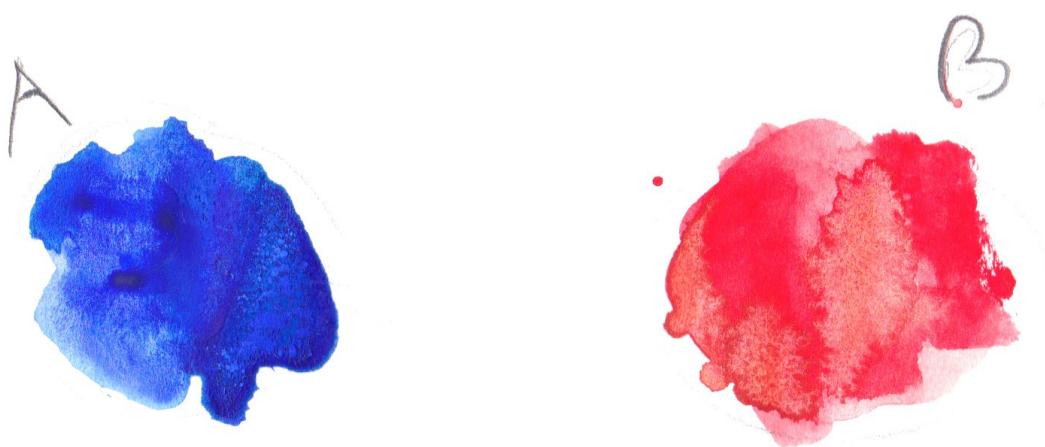


Figure 5.12:

```

#define BlendAddf(base, blend)
#define BlendSubtractf(base, blend)
#define BlendLightenf(base, blend)
#define BlendDarkenf(base, blend)
#define BlendLinearLightf(base, blend)
#define BlendScreenf(base, blend)
#define BlendOverlayf(base, blend)
#define BlendSoftLightf(base, blend)
#define BlendColorDodgef(base, blend)
#define BlendColorBurnf(base, blend)
#define BlendVividLightf(base, blend)
#define BlendPinLightf(base, blend)
#define BlendHardMixf(base, blend)
#define BlendReflectf(base, blend)

// Component wise blending
#define Blend(base, blend, funcf)

#define BlendNormal(base, blend)
#define BlendLighten
#define BlendDarken
#define BlendMultiply(base, blend)
#define BlendAverage(base, blend)
#define BlendAdd(base, blend)
#define BlendSubtract(base, blend)
#define BlendDifference(base, blend)
#define BlendNegation(base, blend)
#define BlendExclusion(base, blend)
#define BlendScreen(base, blend)
#define BlendOverlay(base, blend)
#define BlendSoftLight(base, blend)
#define BlendHardLight(base, blend)
#define BlendColorDodge(base, blend)
#define BlendColorBurn(base, blend)
#define BlendLinearDodge
#define BlendLinearBurn

#define BlendLinearLight(base, blend)
#define BlendVividLight(base, blend)
#define BlendPinLight(base, blend)
#define BlendHardMix(base, blend)
#define BlendReflect(base, blend)
#define BlendGlow(base, blend)
#define BlendPhoenix(base, blend)

min(base + blend, 1.0)
max(base + blend - 1.0, 0.0)
max(blend, base)
min(blend, base)
(blend < 0.5 ? BlendLinearBurnf(base, (2.0 * blend)) :
(1.0 - ((1.0 - base) * (1.0 - blend))))
(base < 0.5 ? (2.0 * base * blend) : (1.0 - 2.0 * (1.0 - base) * (1.0 - blend)))
((blend < 0.5) ? (2.0 * base * blend + base * base * (1.0 - base)) :
((blend == 1.0) ? blend : min(base / (1.0 - blend), 1.0)))
((blend == 0.0) ? blend : max((1.0 - ((1.0 - base) / (1.0 - blend))), 0.0))
((blend < 0.5) ? BlendColorBurnf(base, (2.0 * blend)) :
((blend < 0.5) ? BlendDarkenf(base, (2.0 * blend)) :
((BlendVividLightf(base, blend) < 0.5) ? 0.0 : 1.0)))
((blend == 1.0) ? blend : min(base * base / (1.0 - blend), 1.0))

vec3(funcf(base.r, blend.r), funcf(base.g, blend.g), funcf(base.b, blend.b))

(blend)
BlendLightenf
BlendDarkenf
(base * blend)
((base + blend) / 2.0)
min(base + blend, vec3(1.0))
max(base + blend - vec3(1.0), vec3(0.0))
abs(base - blend)
(vec3(1.0) - abs(vec3(1.0) - base - blend))
(base + blend - 2.0 * base * blend)
Blend(base, blend, BlendScreenf)
Blend(base, blend, BlendOverlayf)
Blend(base, blend, BlendSoftLightf)
BlendOverlay(blend, base)
Blend(base, blend, BlendColorDodgef)
Blend(base, blend, BlendColorBurnf)
BlendAdd
BlendSubtract

Blend(base, blend, BlendLinearLightf)
Blend(base, blend, BlendVividLightf)
Blend(base, blend, BlendPinLightf)
Blend(base, blend, BlendHardMixf)
Blend(base, blend, BlendReflectf)
BlendReflect(blend, base)
(min(base, blend) - max(base, blend) + vec3(1.0))

```

5 Image processing

```
#define BlendOpacity(base, blend, F, 0) (F(base, blend) * 0 + blend * (1.0 - 0))

uniform sampler2D u_tex0;
uniform sampler2D u_tex1;

uniform float u_time;
uniform vec2 u_mouse;
uniform vec2 u_resolution;

void main (void) {
    vec2 st = gl_FragCoord.xy/u_resolution.xy;
    vec3 color = vec3(0.0);

    vec3 colorA = texture2D(u_tex0,st).rgb;
    vec3 colorB = texture2D(u_tex1,st).rgb;

    color = BlendMultiply(colorA,colorB);
    // color = BlendAdd(colorA,colorB);
    // color = BlendLighten(colorA,colorB);
    // color = BlendDarken(colorA,colorB);
    // color = BlendAverage(colorA,colorB);
    // color = BlendSubtract(colorA,colorB);
    // color = BlendDifference(colorA,colorB);
    // color = BlendNegation(colorA,colorB);
    // color = BlendExclusion(colorA,colorB);
    // color = BlendScreen(colorA,colorB);
    // color = BlendOverlay(colorA,colorB);
    // color = BlendSoftLight(colorA,colorB);
    // color = BlendHardLight(colorA,colorB);
    // color = BlendColorDodge(colorA,colorB);
    // color = BlendColorBurn(colorA,colorB);
    // color = BlendLinearLight(colorA,colorB);
    // color = BlendVividLight(colorA,colorB);
    // color = BlendPinLight(colorA,colorB);
    // color = BlendHardMix(colorA,colorB);
    // color = BlendReflect(colorA,colorB);
    // color = BlendGlow(colorA,colorB);
    // color = BlendPhoenix(colorA,colorB);

    gl_FragColor = vec4(color,1.0);
}
```

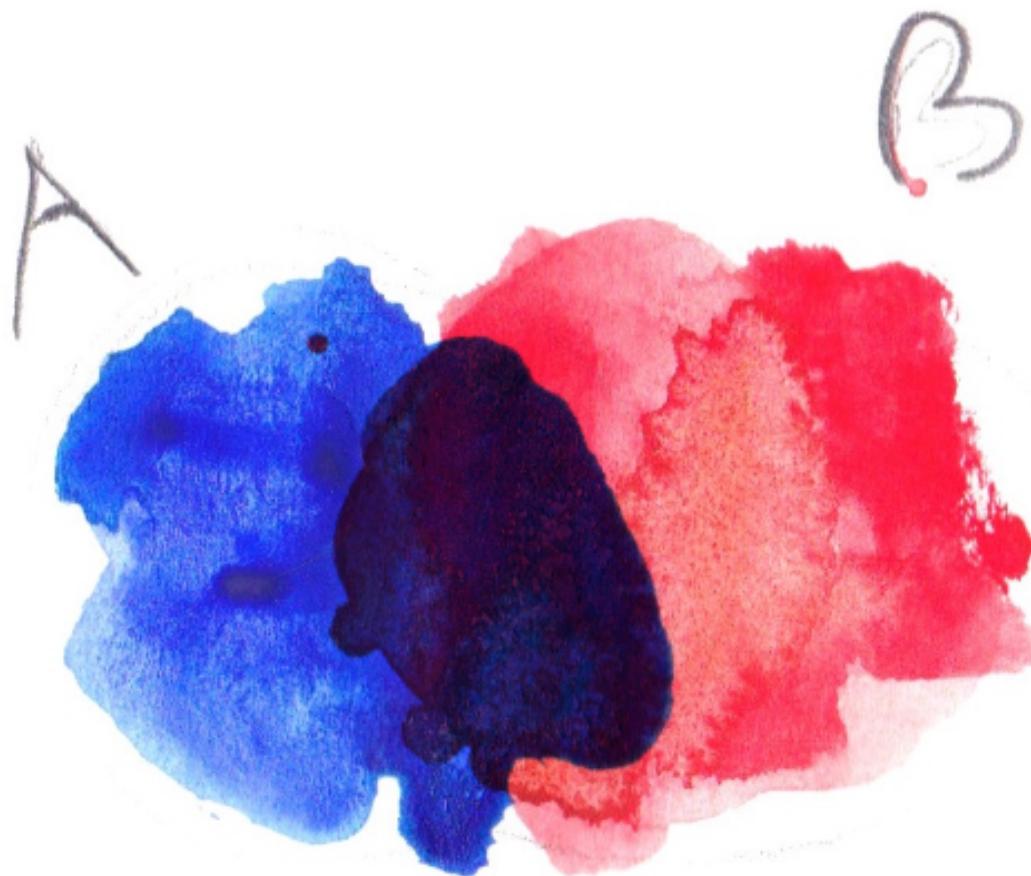


Figure 5.13:

5.5 Kernel convolutions

5.6 Filters

6 Appendix: Other ways to use this book

This book is designed to be navigated with a modern web browser that supports WebGL technology (Firefox, Chrome, Safari, between others). But you may encounter the situation that you don't have a computer with no GPU card or not internet. If that's the case the following sections can help you.

6.1 How can I navigate this book off-line?

Let's say you have a long trip and you want to use it to teach yourself some shaders. In that case you can make a local copy of this book on your computer and run a local server.

For that you only need Python 2.6 and a git client. On MacOS and RaspberryPi computers Python is installed by default but you still need to install a git client. For that:

In **MacOSX** be sure to have [homebrew](#) installed and then on your terminal do:

```
brew update  
brew upgrade  
brew install git
```

On **RaspberryPi** you need to do:

```
sudo apt-get update  
sudo apt-get upgrade  
sudo apt-get install git-core
```

Once you have everything installed you just need to do:

```
cd ~  
git clone --recursive https://github.com/patriciogonzalezvivo/thebookofshaders.git  
cd thebookofshaders  
git submodule foreach git pull  
php -S localhost:8000
```

Then open your browser to <http://localhost:8000/>

6.2 How to run the examples on a RaspberryPi?

A few years ago, taking for granted that everybody have a computer with a GPU was a long shot. Now, most computers have a graphic unit, but is a high bar for a requirement in for example a course or class.

Thanks to the [RaspberryPi project](#) a new type of small and cheap generation of computers (arround \$35 each) has found its way into classrooms. More importantly for the purposes of this book, the [RaspberryPi](#) comes with a decent Bradcom GPU card that can be accessed directly from the console. I made a [flexible GLSL live coding tool call glslViewer](#) that runs all the examples on this book. This program also is hable to update automatically the changes the user makes when they save it. What that means? you can edit the shader and every time you save it, the shader will be re-compile and rendered for you.

By making a local copy of the repository of this book (see the above section) and having [glslViewer installed](#), users can run the examples with `glslviewer`. Also by using the `-l` flag they can render the example on a corner of the screen while they modify it with any text editor (like `nano`, `pico`, `vi`, `vim` or `emacs`). This also works if the user is connected through ssh/sftp.

To install and set this all up on the RaspberryPi after installing the OS and logging in, type the following commands:

```
sudo apt-get update
sudo apt-get upgrade
sudo apt-get install git-core
cd ~
git clone http://github.com/patriciogonzalezvivo/glslViewer.git
cd glslViewer
make
make install
cd ~
git clone https://github.com/patriciogonzalezvivo/thebookofshaders.git
cd thebookofshaders
```

6.3 How to print this book?

Let's say you don't want to navigate or interact with the examples and you just want a good old fashion text book which you can read on the beach or on your commute to the city. In that case you can print this book.

6.3.0.1 Installing glslViewer

For printing this book you need first to parse it. For that you will need [glslViewer](#) a console shader tool that will compile and transform the shader examples into images.

In **MacOSX** get sure to have [homebrew](#) installed and then on your terminal do:

```
brew update
brew upgrade
brew tap homebrew/versions
brew install glfw3
cd ~
git clone http://github.com/patriciogonzalezvivo/glslViewer.git
cd glslViewer
make
make install
```

On **RaspberryPi** you need to do:

```
sudo apt-get update
sudo apt-get upgrade
sudo apt-get install git-core
cd ~
git clone http://github.com/patriciogonzalezvivo/glslViewer.git
cd glslViewer
make
make install
```

6.3.0.2 Installing Latex Engine and Pandoc

For parsing the Markdown chapters into Latex and then into a PDF file we will use Xetex Latex Engine and Pandoc.

In **MacOSX**:

Download and Install [basictex & MacTeX-Additions](#) and then install [Pandoc](#) by:

```
brew install pandoc
```

On **RaspberryPi**:

```
sudo apt-get install texlive-xetex pandoc
```

6.3.0.3 Compile the book into a pdf and print it

Now that you have all you need, it is time to clone [the repository of this book](#) and compile the book.

6 Appendix: Other ways to use this book

For that open your terminal once again and type:

```
cd ~  
git clone https://github.com/patriciogonzalezvivo/thebookofshaders.git  
cd thebookofshaders  
make
```

If everything goes well, you will see a `book.pdf` file which you can read on your favorite device or print.

7 List of Examples

The following is a list of examples present in this book.

7.0.1 Chapters examples

- Getting started
 - [Hello World](#)
 - * “Hello World!”
 - [Uniforms](#)
 - * `u_time`
 - * `gl_FragCoord`
- Algorithmic drawing
 - [Shaping functions](#)
 - * Linear Interpolation
 - * Exponential Interpolation
 - * Step function
 - * Smoothstep function
 - * Iñigo Quiles’s Impulse
 - * Iñigo Quiles’s Cubic Pulse
 - * Iñigo Quiles’s Exponential Step
 - * Iñigo Quiles’s Parabola
 - * Iñigo Quiles’s Power Curve
 - [Color](#)
 - * Mix
 - * Easing functions
 - * Gradient
 - * HSB
 - * HSB - Color Wheel
 - [Shapes](#)
 - * Rectangle: `making`, `function` and `distance-field`
 - * Circle: `making` and `function`
 - * [Batman](#)
 - * [Line](#)

7 List of Examples

- * Cross
- * Polar
- * Polar
- * Arrow
- Matrix
 - * cross
 - * translate
 - * rotate
 - * scale
- Patterns
 - * Grid: making, final, grid of + and fine grid
 - * Lines
 - * Checks
 - * Diamond tiles
 - * Bricks
 - * Dots: 0, 1, 2, 3, 4, 5 and marching dots
 - * Side grid
 - * Rotated tiles
 - * Nuts pattern
 - * Mirror tiles
 - * Zigzag
 - * Truchet
 - * Deco
 - * I Ching
- Generative designs
 - Random
 - * 1D Random
 - * 2D Random
 - * Random Mosaic
 - * Random Dots
 - * Random Truchet
 - * Ikeda's style: test pattern, wave,test pattern, data path and data defrag.
 - * Matrix
 - * Digits
 - * Random Grid
 - * Random Numbered Grid
 - * Random I Ching

7.0.2 Advance

- Moon

- [Matrix](#)
- [I Ching](#)
- Ikeda's series: [test pattern](#), [data path](#) and [data defrag](#), [digits](#), [radar](#), [numerical grid](#)

8 Glossary

8.1 By theme

- TYPES

void bool int float bvec2 bvec3 bvec4 ivec2 ivec3 ivec4 vec2 vec3 vec4 mat2 mat3 mat4
sampler2D samplerCube struct

- QUALIFIERS

attribute const uniform varying precision highp mediump lowp in out inout

- BUILT-IN VARIABLES

gl_Position gl_PointSize gl_PointCoord gl_FrontFacing gl_FragCoord gl_FragColor

- BUILT-IN CONSTANTS

gl_MaxVertexAttribs gl_MaxVaryingVectors gl_MaxVertexTextureImageUnits
gl_MaxCombinedTextureImageUnits gl_MaxTextureImageUnits gl_MaxFragmentUniformVectors
gl_MaxDrawBuffers

- ANGLE & TRIGONOMETRY FUNCTIONS

radians() degrees() sin() cos() tan() asin() acos() atan()

- EXPONENTIAL FUNCTIONS

pow() exp() log() exp2() log2() sqrt() inversesqrt()

- COMMON FUNCTIONS

abs() sign() floor() ceil() fract() mod() min() max() clamp() mix() step() smoothstep()

- GEOMETRIC FUNCTIONS

length() distance() dot() cross() normalize() faceforward() reflect() refract()

- MATRIX FUNCTIONS

matrixCompMult()

- VECTOR RELATIONAL FUNCTIONS

8 Glossary

lessThan() lessThanEqual() greaterThan() greaterThanEqual() equal() notEqual() any() all() not()

- TEXTURE LOOKUP FUNCTIONS

texture2D() textureCube()

8.2 Alphabetical

- A

abs() acos() all() any() asin() atan() attribute

- B

bool bvec2 bvec3 bvec4

- C

ceil() clamp() const cos() cross()

- D

degrees() dFdx() dFdy() distance() dot()

- E

equal() exp() exp2()

- F

faceforward() float floor() fract()

- G

greaterThan() greaterThanEqual() gl_FragColor gl_FragCoord gl_FrontFacing
gl_PointCoord gl_PointSize gl_Position gl_MaxCombinedTextureImageUnits
gl_MaxDrawBuffers gl_MaxFragmentUniformVectors gl_MaxVaryingVectors gl_MaxVertexAttribs
gl_MaxVertexTextureImageUnits gl_MaxTextureImageUnits

- H

highp

- I

in inout int inversesqrt() ivec2 ivec3 ivec4

- L

length() lessThan() lessThanEqual() log() log2() lowp

- M

matrixCompMult() mat2 mat3 mat4 max() mediump min() mix() mod()

- N

normalize() not() notEqual()

- O

out

- P

precision pow()

- R

radians() reflect() refract()

- S

sampler2D samplerCube sign() sin() smoothstep() sqrt() step() struct

- T

tan() texture2D() textureCube()

- U

uniform

- V

varying vec2 vec3 vec4 void