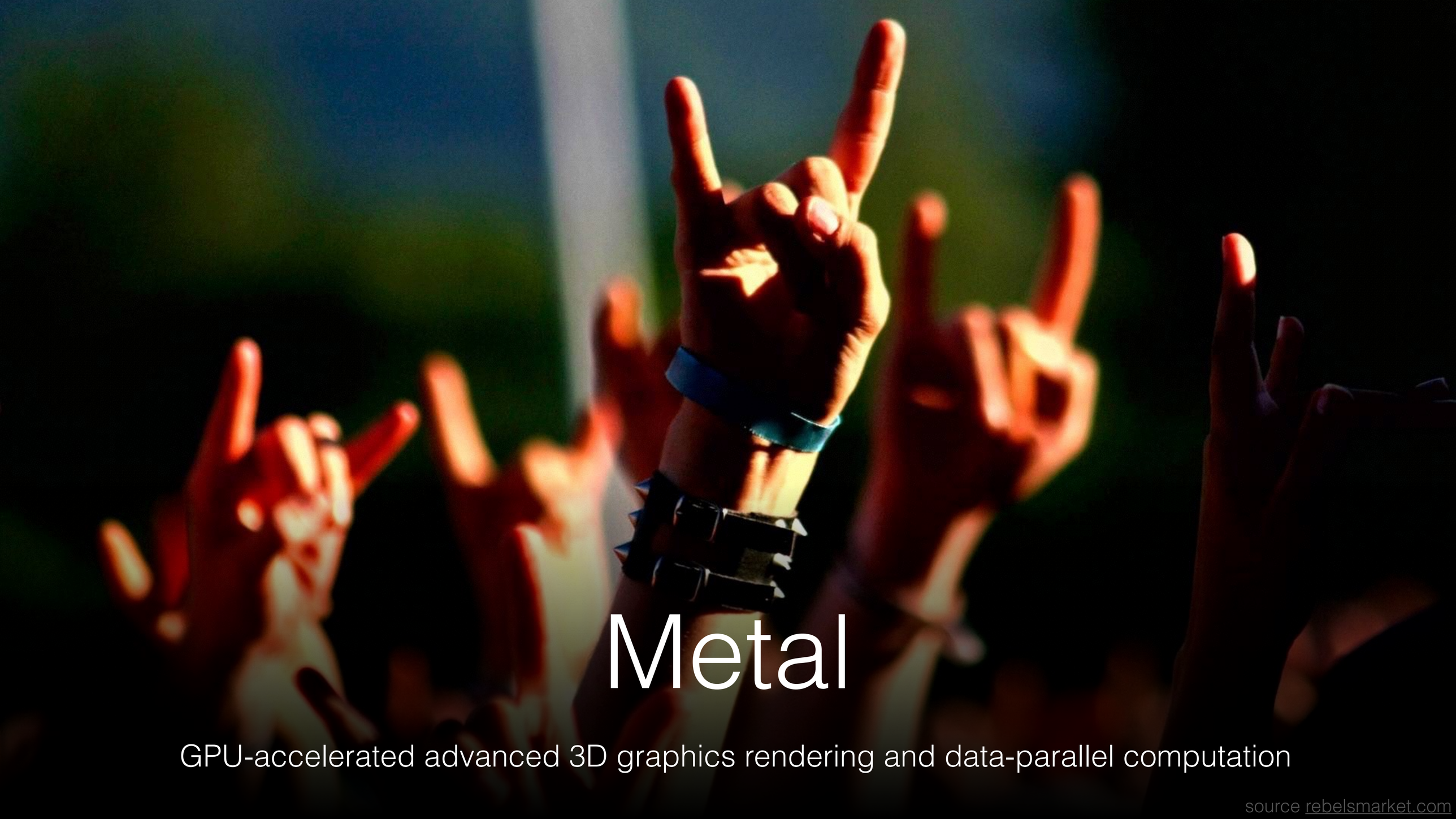
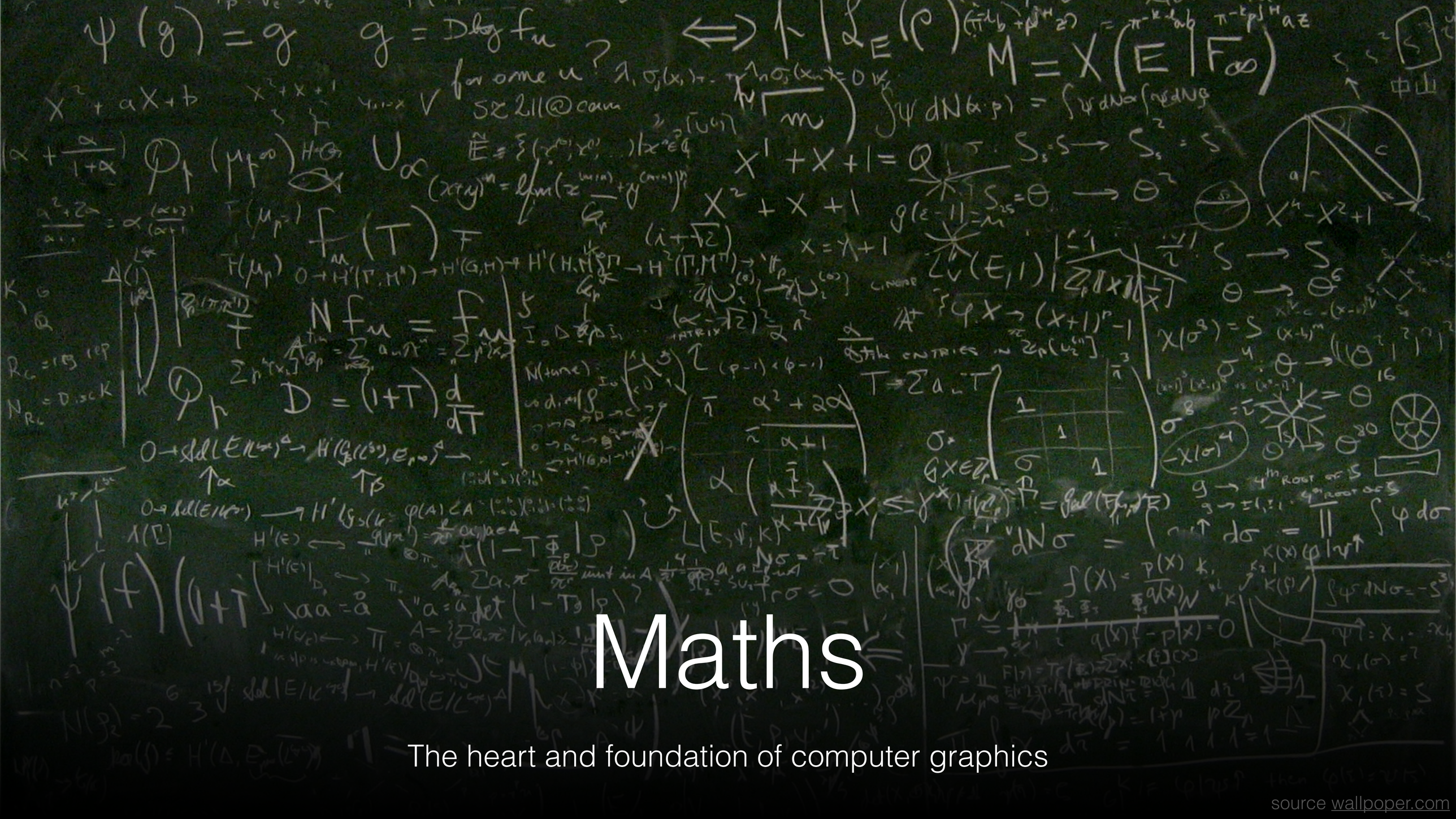


Metal

GPU-accelerated advanced 3D graphics rendering and data-parallel computation

source rebelsmarket.com



Maths

The heart and foundation of computer graphics

source wallpoper.com

Metalmatics

There are no computer graphics without mathematics

Rasterized 3D graphics requires algebra

- Vector operations
- Matrix operations
- Interpolation techniques

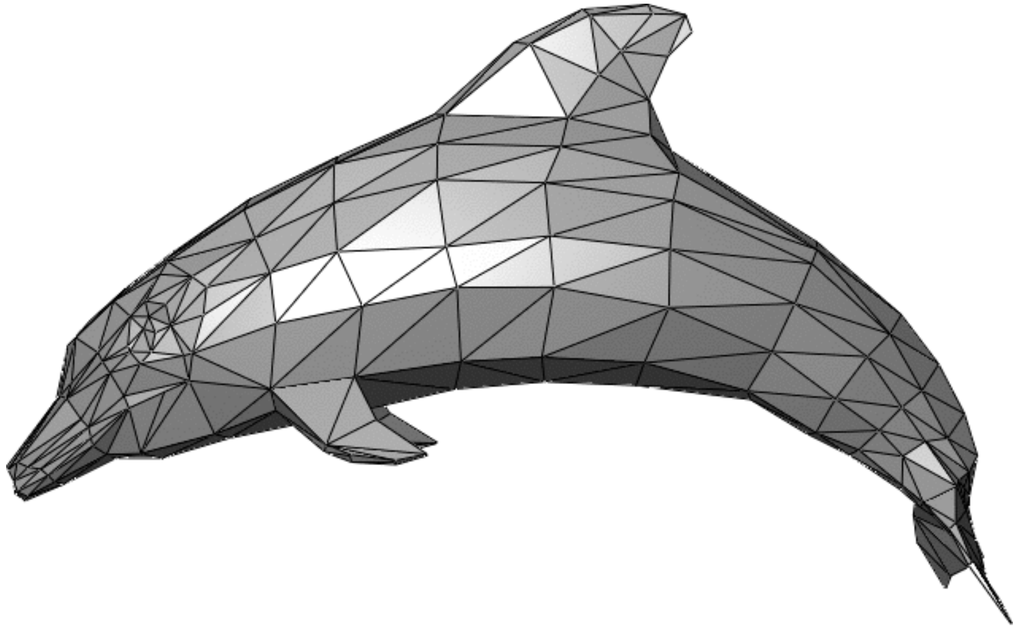
My first triangle

Why triangles?

Easiest surface that can be formed by straight lines

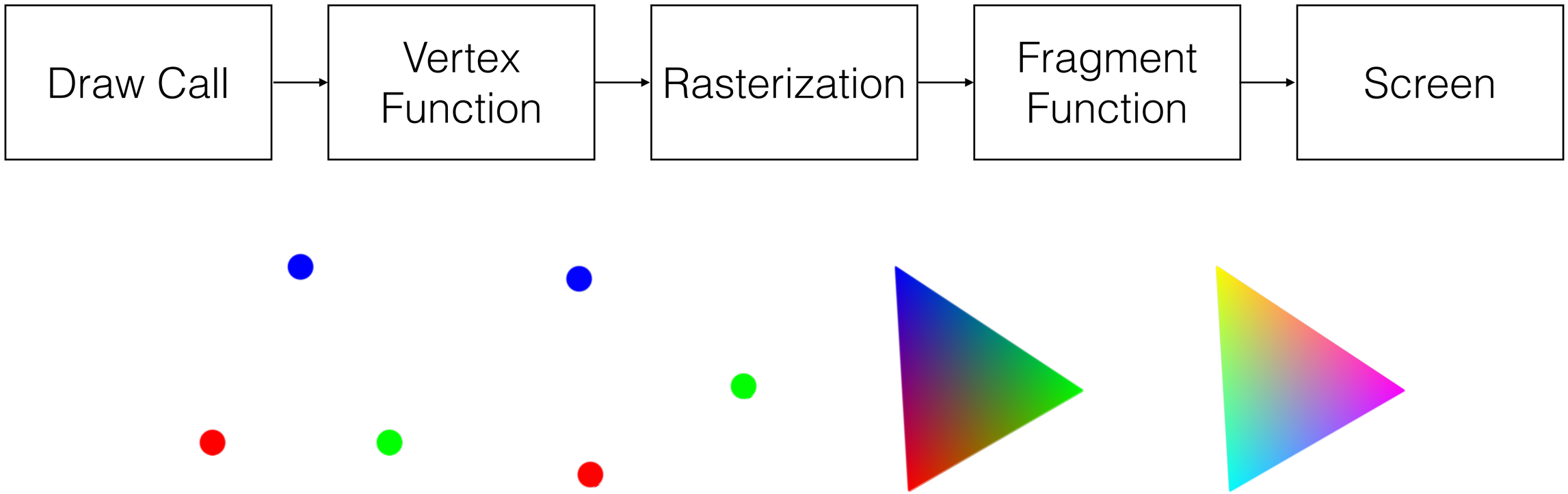
Other surfaces can be composed by a sequence of triangles

http://en.wikipedia.org/wiki/Polygon_mesh



source wikipedia.org

3D graphics pipeline



Draw Call

A collection of states to render our triangle

- Vertices
- Uniform data
- Vertex Function
- Fragment Function

Vertex (Vertices)

Structure that holds all the information of a triangle's corner

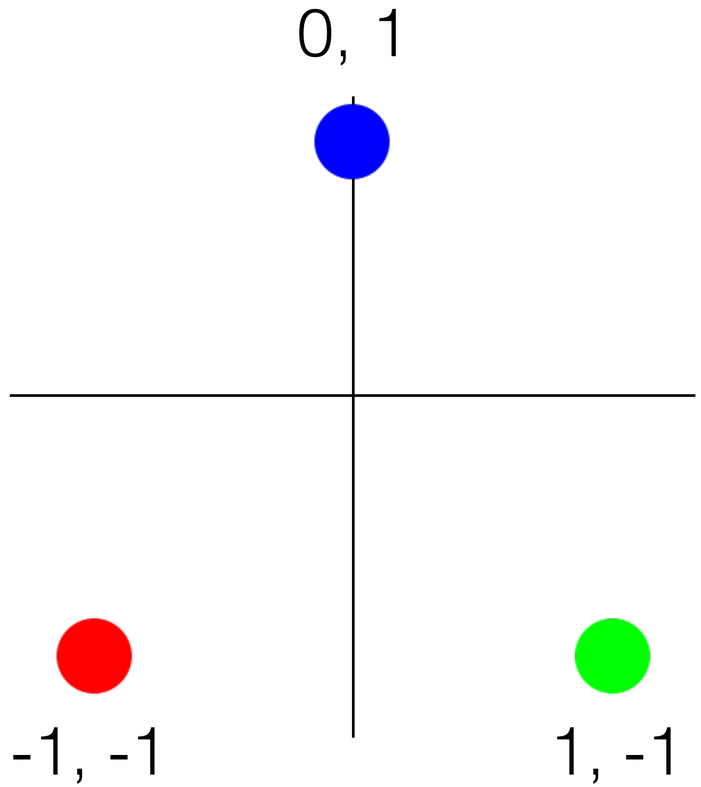
For our first triangle

- Position: `x, y`
- Color: `red, green, blue`

Vertex (Vertices)

```
struct Vertex {
   float x, y;
   float red, green, blue;
};

Vertex triangle[3] = {
   { -1.0, -1.0,   1.0, 0.0, 0.0 },
   {  1.0, -1.0,   0.0, 1.0, 0.0 },
   {  0.0,  1.0,   0.0, 0.0, 1.0 }
};
```



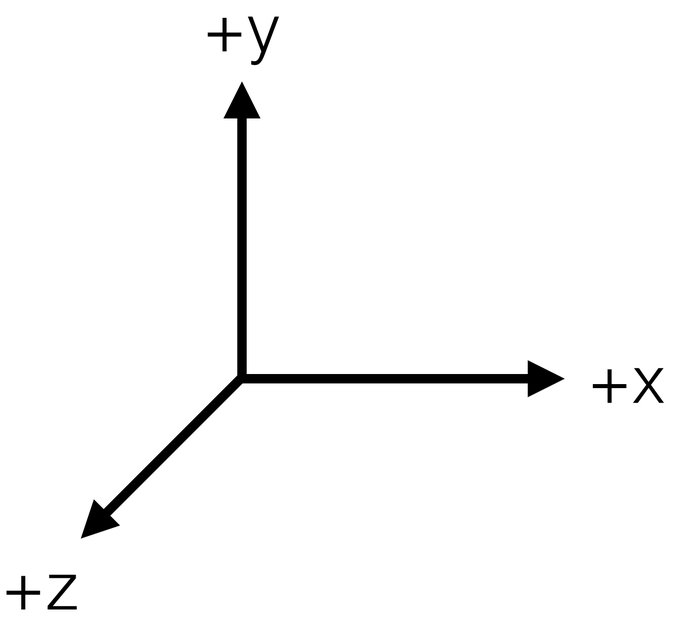
Coordinate System

Metal uses a right handed coordinate system

- Positive X axis points right
- Positive Y axis points up
- Positive Z axis point forward

Use your right hand for visualization

http://en.wikipedia.org/wiki/Coordinate_system



Uniform data

A structure that holds all data that is the same per draw call
For our triangle it is a rotation around the z-axis by angle α

```
struct Uniforms {
  float_matrix_4x4 transformation;
};

Uniforms uniform = {
  cos(a),  sin(a), 0.0, 0.0,
  -sin(a), cos(a), 0.0, 0.0,
  0.0,     0.0,    1.0, 0.0,
  0.0,     0.0,    0.0, 1.0
};
```

Transformation matrices

All transformations for 3D math can be expressed by a 4×4 matrix

easy to create

fast to apply (to each vertex)

http://en.wikipedia.org/wiki/Transformation_matrix

CGAffineTransform

Representation of a 2×3 matrix for 2D projection

```
CGAffineTransformIdentity

CGAffineTransformMakeRotation(angle)

CGAffineTransformMakeScale(x, y)

CGAffineTransformMakeTranslation(x, y)
```

Demo

Yes, it is Comic Sans

Vertex Function

Handles a single vertex

Called for each vertex in the draw call

Transforms the position to the final position

Optionally passes other uniforms to the fragment function

Vertex Function

```
struct Output {
  float4 position;
  float3 color;
};

Output vertexFunction(Vertex v, Uniforms u) {
  Output o;
  o.position = u.transform * v.position;
  o.color = v.color;
  return o;
}
```

Rasterization

Converts the transformed positions into fragments

A fragment is a future pixel

Interpolates the other vertex values (color)

http://en.wikipedia.org/wiki/Rasterisation

Fragment Function

Handles a single fragment

Called once per fragment

Converts the fragment into a pixel on the screen

Fragment Function

```
// Output of the Vertex Function without position
struct Input {
   float3 color;
};

float3 fragmentFunction(Input i) {
   float3 r;
   r = 1.0 - i.color;
   return r;
}
```

Homework

Write your own software rasterizer


API

What is Apple's Metal API?

The Metal framework supports GPU-accelerated advanced 3D graphics rendering and data-parallel computation workloads. Metal provides a modern and streamlined API for fine-grain, low-level control of the organization, processing, and submission of graphics and computation commands and the management of the associated data and resources for these commands. A primary goal of Metal is to minimize the CPU overhead necessary for executing these GPU workloads.

– Metal Programming Guide

Apple’s Graphics APIs

Is there room left for more graphics APIs?

CoreGraphics / Quartz

CoreImage

CoreText

OpenGL / OpenGLES

SpriteKit (2D) / SceneKit (3D)

Metal features

Designed for performance

- Reduce CPU overhead while maximizing the GPU performance

3D raster graphics pipeline

Parallel computing pipeline

- Replaces OpenCL (was never public on iOS)

Metal requirements

iOS8 only – Mac support would require unified RAM

ARM64 only – iPhone 5s, iPad Air, iPad mini with Retina Screen

Device only – no simulator support

Xcode 6

Metal API

Quite an unusual API for an Apple framework

1× Function

23× Classes (all helpers)

18× Protocols (core)

a few enumerations and type definitions

MTLDevice

First step is to get the GPU

```
id<MTLDevice> device = MTLCreateSystemDefaultDevice();
```

CAMetalLayer

Metal will draw to a layer, there is no UIMetalView

```
#import <QuartzCore/CAMetalLayer.h>

CAMetalLayer *layer = [CAMetalLayer layer];
layer.device = device;
layer.pixelFormat = MTLPixelFormatBGRA8Unorm;
layer.frame = self.view.layer.bounds;
[self.view.layer addSublayer:layer];
```

CAMetalDrawable

Request a drawable to render into

Might return nil when rendering too fast

```
id<CAMetalDrawable> drawable = layer.nextDrawable;
```

MTLBuffer

A buffer contains data that is shared between CPU and GPU

You are responsible for synchronized access!

```
id<MTLBuffer> vertexBuffer = [device
  newBufferWithBytes:vertices
  length:sizeof(vertices)
  options:MTLResourceOptionCPUCacheModeDefault];

id<MTLBuffer> uniformBuffer = [device
  newBufferWithBytes:uniforms
  length:sizeof(uniforms)
  options:MTLResourceOptionCPUCacheModeDefault];
```

MTLLibrary

A library is containing all the shaders (vertex and fragment functions)

There might be multiple libraries

```
id<MTLLibrary> library = [device newDefaultLibrary];
```

MTLFunction

MTLFunction (shader) is code that is executed on the GPU.

```
id<MTLFunction> vertexFunction = [library
newFunctionWithName:@"vertexFunction"];

id<MTLFunction> fragmentFunction = [library
newFunctionWithName:@"fragmentFunction"];
```

MTLCommandQueue

Command Queues execute Command Buffers in serial order

```
id<MTLCommandQueue> commandQueue =
   [device newCommandQueue];
```

MTLRenderPassDescriptor

Describes the buffer use to render to

```
MTLRenderPassDescriptor *renderPass =
   [MTLRenderPassDescriptor renderPassDescriptor];

renderPass.colorAttachments[0].texture = drawable.texture;
renderPass.colorAttachments[0].loadAction =
   MTLLoadActionClear;
renderPass.colorAttachments[0].clearColor =
   MTLClearColorMake(1.0f, 1.0f, 1.0f, 1.0f);
renderPass.colorAttachments[0].storeAction =
   MTLStoreActionStore;
```

MTLRenderPipelineDescriptor

Describes the pipeline that is used for rendering

Should be prepared in the setup phase

```
MTLRenderPipelineDescriptor *pipelineDesc =
   [[MTLRenderPipelineDescriptor alloc] init];

[pipelineDesc setVertexFunction:vertexFunction];
[pipelineDesc setFragmentFunction:fragmentFunction];

id<MTLRenderPipelineState> pipeline = [device
   newRenderPipelineStateWithDescriptor:pipelineDesc
   error:nil];
```

MTLCommandBuffer

Command Buffers hold series of Command Encoders

```
id<MTLCommandBuffer> commandBuffer = [commandQueue
commandBuffer];

// fill with Command Encoders (next slide)

[commandBuffer addCompletedHandler:…];

[commandBuffer presentDrawable:drawable];

[commandBuffer commit];
```

MTLCommandEncoder

Command Encoders hold a sequence of GPU instructions

```
id<MTLRenderCommandEncoder> commandEncoder = [commandBuffer
   renderCommandEncoderWithDescriptor:renderPass];

[commandEncoder setRenderPipelineState:pipeline];
[commandEncoder setVertexBuffer:vertices offset:0 atIndex:0];
[commandEncoder setVertexBuffer:uniforms offset:0 atIndex:1];

[commandEncoder drawPrimitives:MTLPrimitiveTypeTriangle
   vertexStart:0 vertexCount:3 instanceCount:1];

[commandEncoder endEncoding];
```

DEMO


LANGUAGE

Metal Shading Language

The shading language is C++11

- Custom standard library
- Math libraries
- Additional keywords

Restrictions

Some C++11 features are missing

- `new` and `delete` operator
- Exceptions
- Lambdas
- Exceptions
- `virtual` functions
- …

Benefits

Shared code between CPU and GPU

- Helpful for vertex and uniforms structs

Compiled with the clang toolchain

- Precompiled at compile time

Shared types

```
typedef struct {
    matrix_float4x4 transform;
} Uniforms;

typedef struct {
    packed_float2 position;
    packed_float3 color;
} Vertex;

typedef struct {
    float4 position [[ position ]];
    half4 color;
} Varyings;
```

Vertex Function

```
vertex Varyings vertexFunction(
   device Vertex* vertex_array [[ buffer(0) ]],
   constant Uniforms& uniforms [[ buffer(1) ]],
   unsigned int vid [[ vertex_id ]]
) {
   Varyings out;
   Vertex v = vertex_array[vid];

   float4 position = float4(v.position, 0.0, 1.0);
   out.position = uniforms.transform * position;
   out.color = half4(half3(v.color), 1.0);

   return out;
}
```

Fragment Function

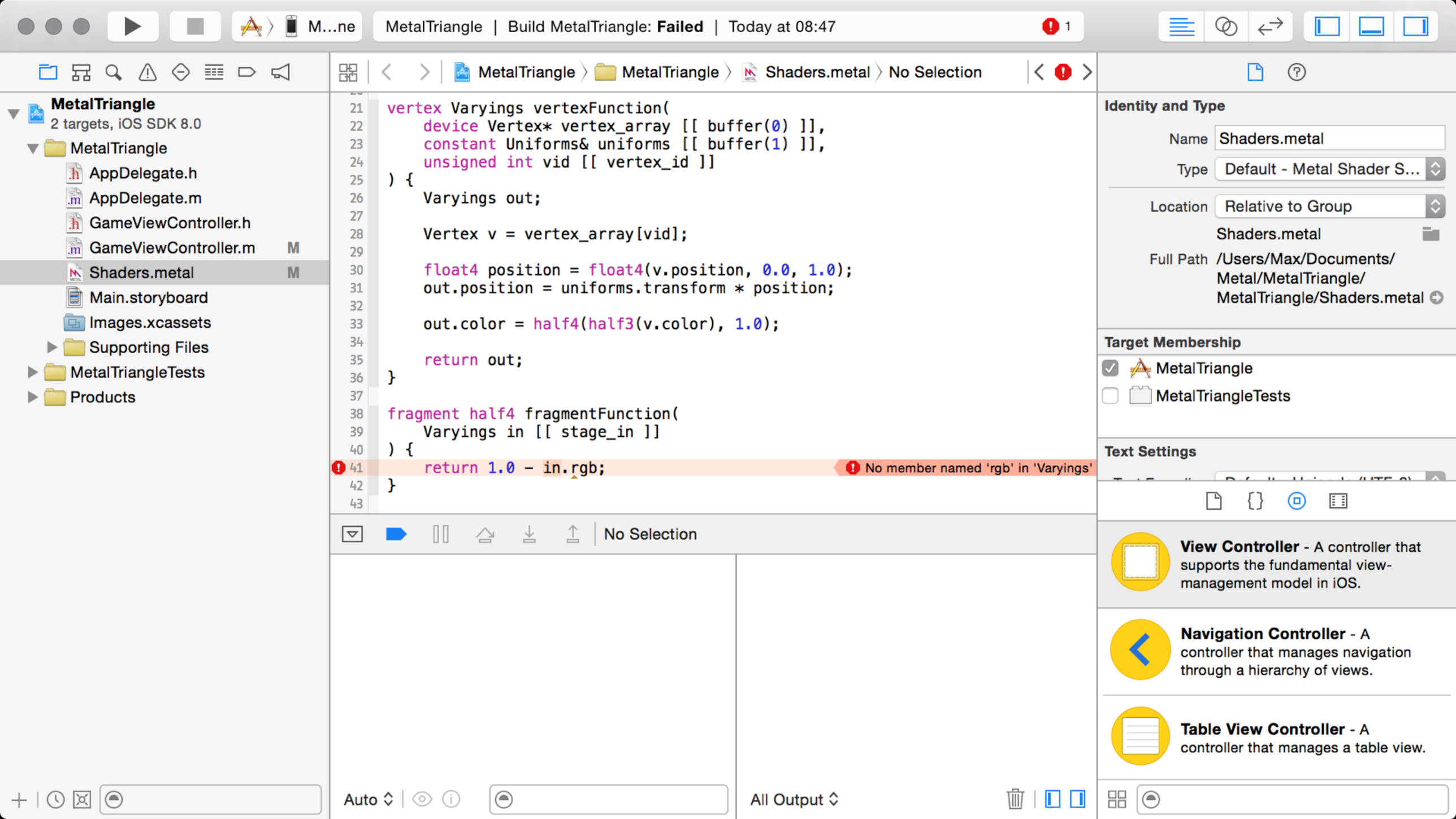
```
fragment half4 fragmentFunction(
  Varyings in [[ stage_in ]]
) {
    return 1.0 - in.color;
}
```

Kernel Function

```
kernel void kernelFunction(
  const device float *in0 [[ buffer(0) ]],
  const device float *in1 [[ buffer(1) ]],
  device float *out [[ buffer(2) ]],
  uint id [[ thread_position_in_grid ]]
) {
  out[id] = in0[id] + in1[id];
}
```

DEMO


TOOLS


MetalTriangle | Build MetalTriangle: Failed | Today at 08:47
MetalTriangle
2 targets, iOS SDK 8.0
MetalTriangle
AppDelegate.h
AppDelegate.m
GameViewController.h
GameViewController.m M
Shaders.metal M
Main.storyboard
Images.xcassets
Supporting Files
MetalTriangleTests
Products
MetalTriangle › MetalTriangle › Shaders.metal › No Selection
vertex Varyings vertexFunction(
device Vertex* vertex_array [[buffer(0)]],
constant Uniforms& uniforms [[buffer(1)]],
unsigned int vid [[vertex_id]]
) {
Varyings out;
Vertex v = vertex_array[vid];
float4 position = float4(v.position, 0.0, 1.0);
out.position = uniforms.transform * position;
out.color = half4(half3(v.color), 1.0);
return out;
}
fragment half4 fragmentFunction(
Varyings in [[stage_in]]
) {
return 1.0 - in.rgb;
No member named 'rgb' in 'Varyings'
}
No Selection
Auto
All Output
Identity and Type
Name Shaders.metal
Type Default - Metal Shader S...
Location Relative to Group
Shaders.metal
Full Path /Users/Max/Documents/Metal/MetalTriangle/MetalTriangle/Shaders.metal
Target Membership
MetalTriangle
MetalTriangleTests
Text Settings
View Controller - A controller that supports the fundamental view-management model in iOS.
Navigation Controller - A controller that manages navigation through a hierarchy of views.
Table View Controller - A controller that manages a table view.

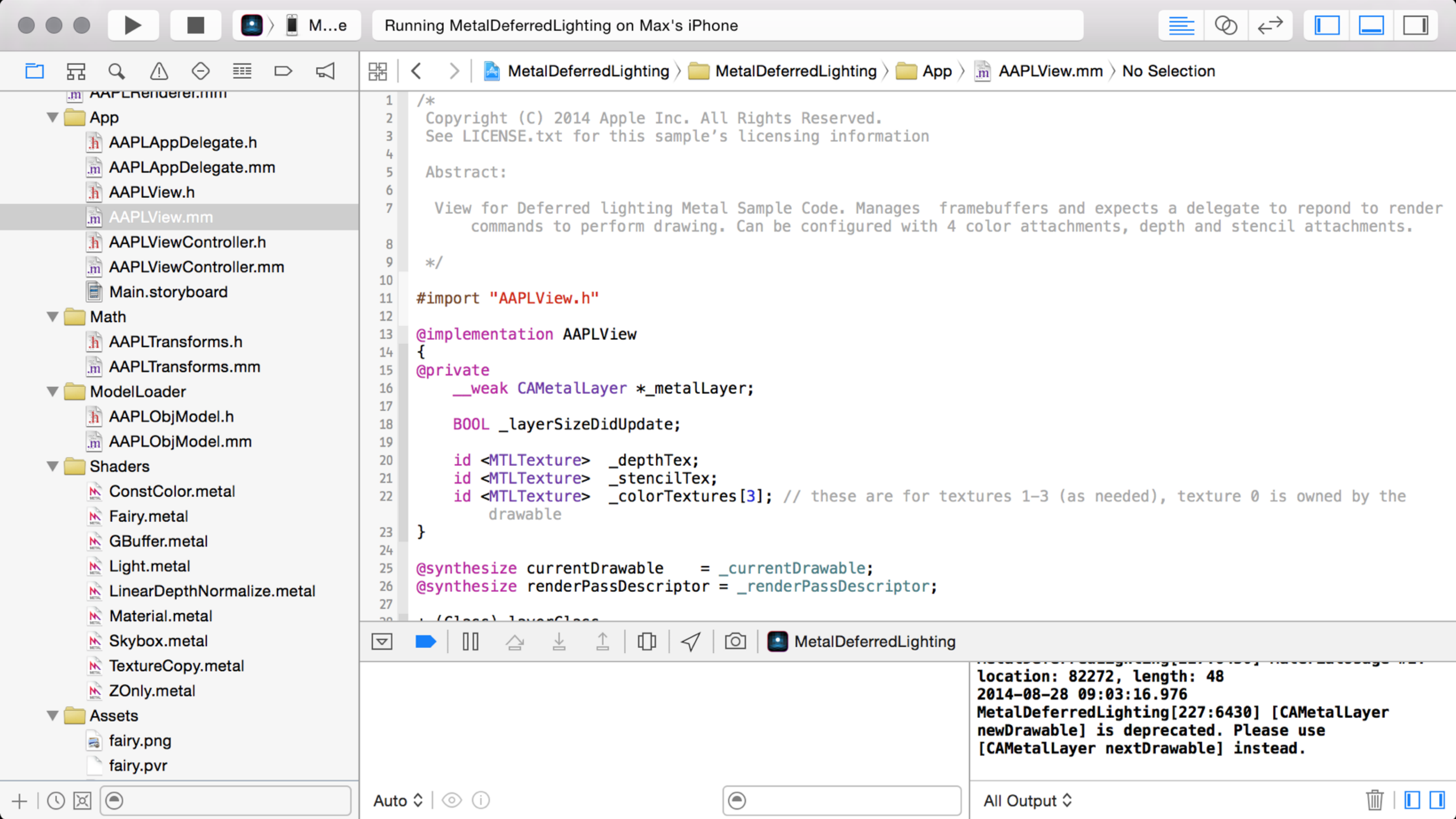
GPU Frame Debugger

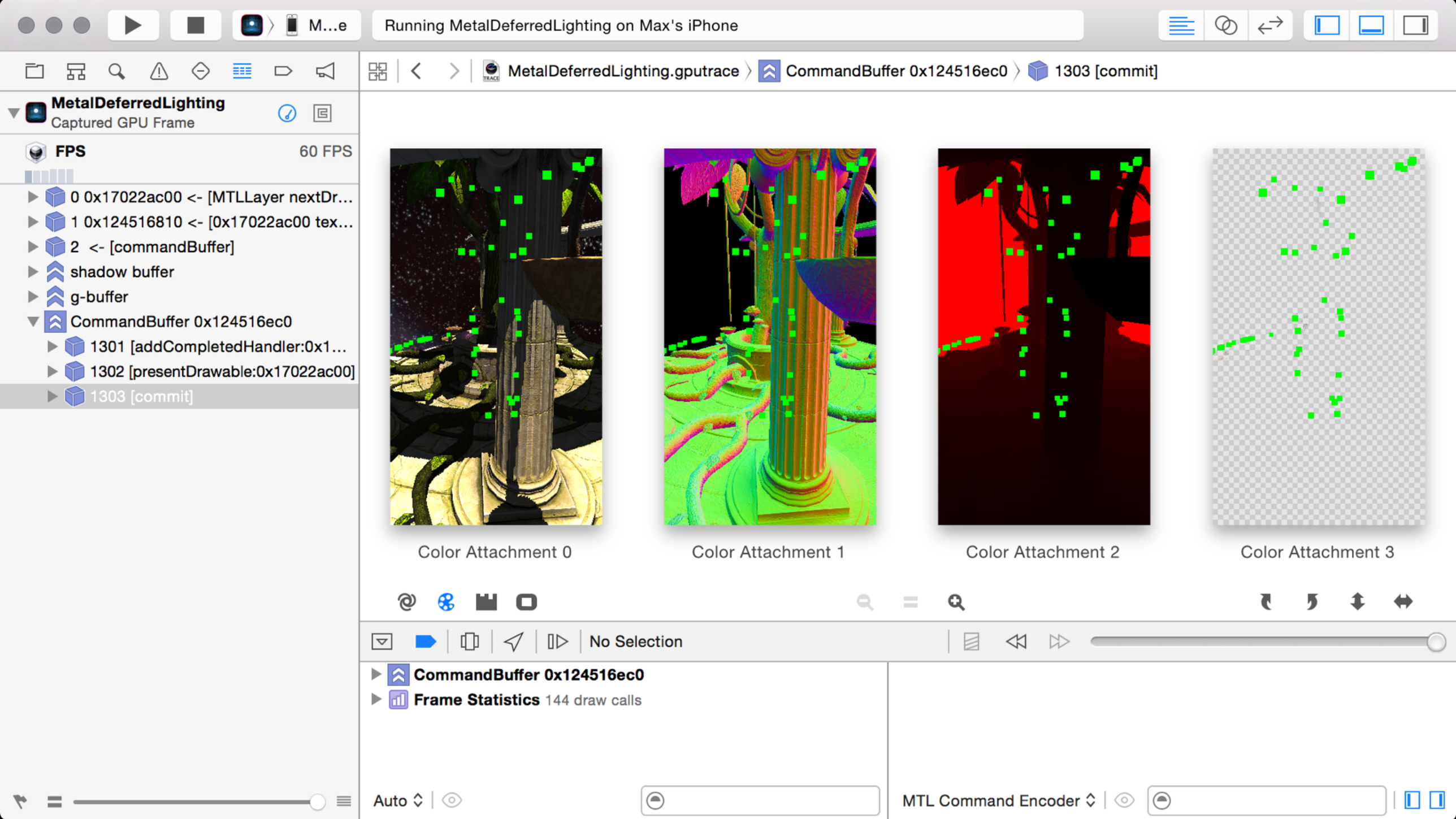
Inspect the state of the pipeline

Live edit shaders

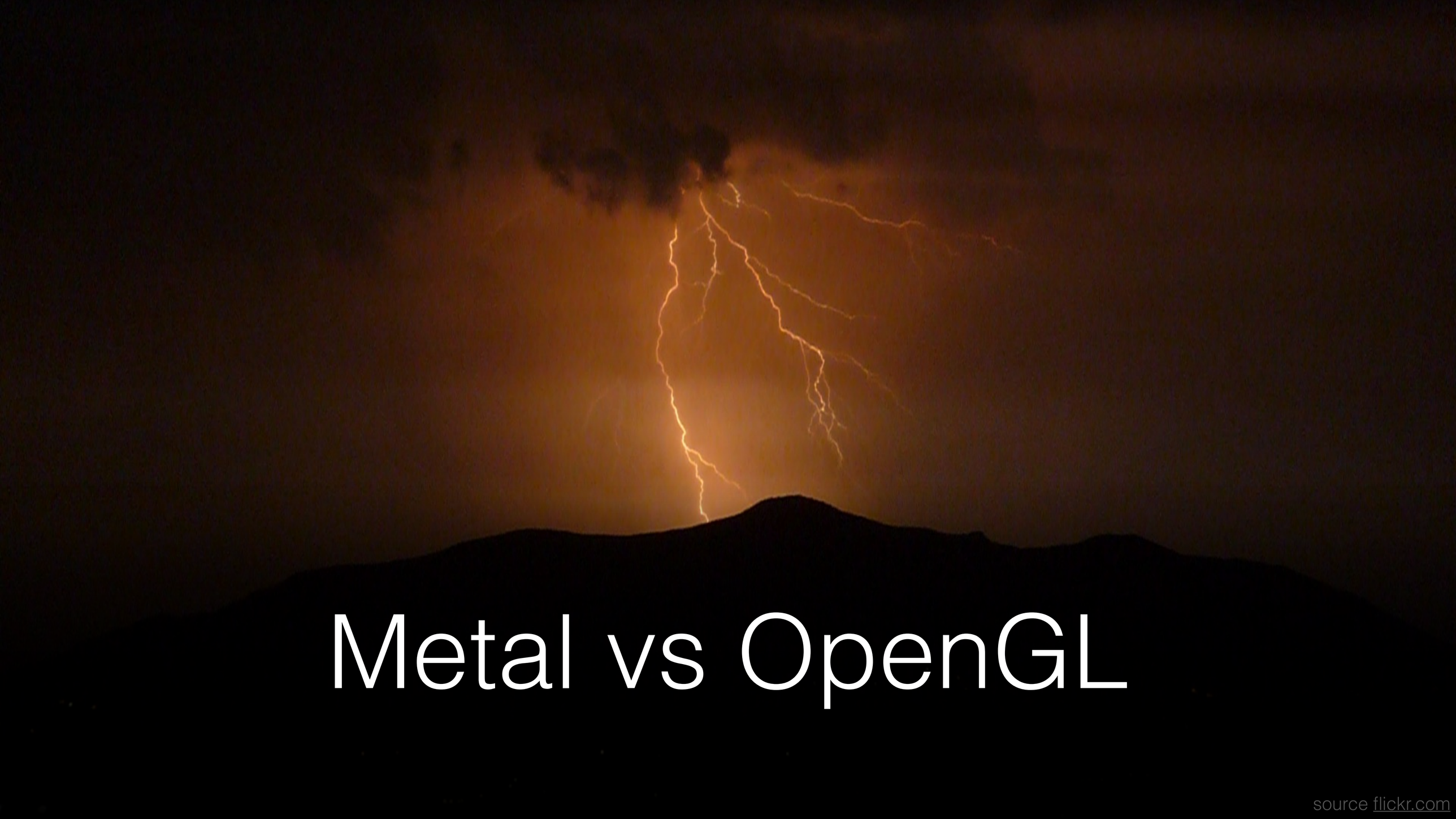
View buffers and textures

Also works for OpenGL ES on iOS


Running MetalDeferredLighting on Max's iPhone
MetalDeferredLighting
MetalDeferredLighting
App
AAPLView.mm
No Selection
App
AAPLAppDelegate.h
AAPLAppDelegate.mm
AAPLView.h
AAPLView.mm
AAPLViewController.h
AAPLViewController.mm
Main.storyboard
Math
AAPLTransforms.h
AAPLTransforms.mm
ModelLoader
AAPLObjModel.h
AAPLObjModel.mm
Shaders
ConstColor.metal
Fairy.metal
GBuffer.metal
Light.metal
LinearDepthNormalize.metal
Material.metal
Skybox.metal
TextureCopy.metal
ZOnly.metal
Assets
fairy.png
fairy.pvr
/*
Copyright (C) 2014 Apple Inc. All Rights Reserved.
See LICENSE.txt for this sample's licensing information
Abstract:
View for Deferred lighting Metal Sample Code. Manages framebuffers and expects a delegate to repond to render commands to perform drawing. Can be configured with 4 color attachments, depth and stencil attachments.
*/
#import "AAPLView.h"
@implementation AAPLView
{
@private
__weak CAMetalLayer *_metalLayer;
BOOL _layerSizeDidUpdate;
id <MTLTexture> _depthTex;
id <MTLTexture> _stencilTex;
id <MTLTexture> _colorTextures[3]; // these are for textures 1-3 (as needed), texture 0 is owned by the drawable
}
@synthesize currentDrawable = _currentDrawable;
@synthesize renderPassDescriptor = _renderPassDescriptor;
MetalDeferredLighting
location: 82272, length: 48
2014-08-28 09:03:16.976
MetalDeferredLighting[227:6430] [CAMetalLayer newDrawable] is deprecated. Please use [CAMetalLayer nextDrawable] instead.
Auto
All Output


M...e
Running MetalDeferredLighting on Max's iPhone
MetalDeferredLighting.gputrace
CommandBuffer 0x124516ec0
1303 [commit]
MetalDeferredLighting
Captured GPU Frame
FPS
60 FPS
0 0x17022ac00 <- [MTLLayer nextDr...
1 0x124516810 <- [0x17022ac00 tex...
2 <- [commandBuffer]
shadow buffer
g-buffer
CommandBuffer 0x124516ec0
1301 [addCompletedHandler:0x1...
1302 [presentDrawable:0x17022ac00]
1303 [commit]
Color Attachment 0
Color Attachment 1
Color Attachment 2
Color Attachment 3
No Selection
CommandBuffer 0x124516ec0
Frame Statistics 144 draw calls
Auto
MTL Command Encoder

Demo



Metal vs OpenGL

source flickr.com

OpenGL Problems

State validation ✓ done once at setup

Buffer copies ✓ no copies, but programmer is responsible for synchronizing

Runtime shader compilation ✓ can be done at compile time

Black screen ✗ random effects

When to use Metal

Indirectly when using a 3D engine

- Unity, Unreal, (SpriteKit, SceneKit)

Custom high-performance 3D engine

Parallel computation

- No OpenCL, only alternative is misusing OpenGL

source rebelsmarket.com