Next-gen Mobile Rendering

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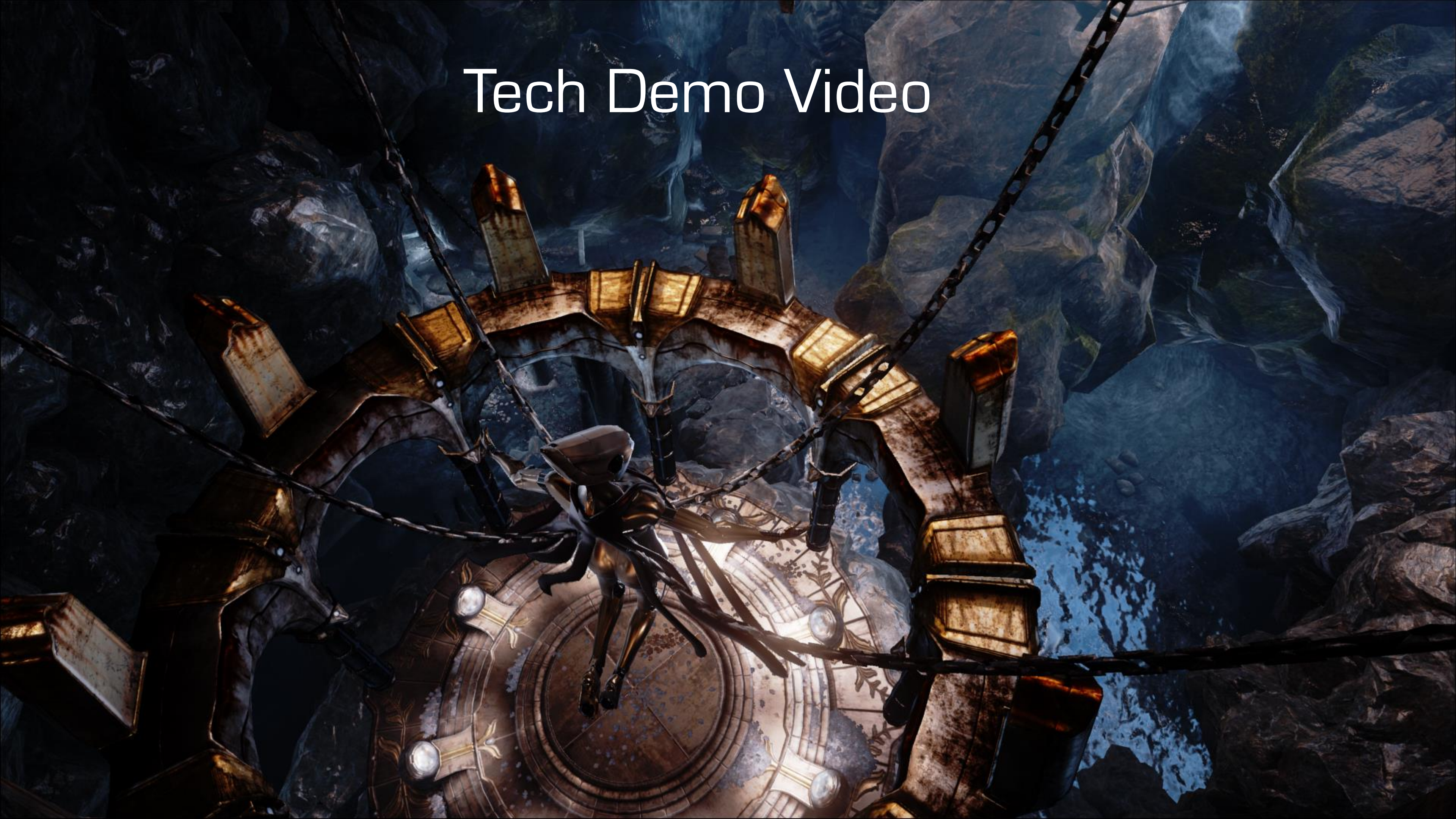
Introduction

- Niklas Smedberg, a.k.a. “Smedis”
  - 17 years in the game industry
  - Graphics programmer since the C64 demo scene
- Timothy Lottes
  - Industry background in games, GPU hardware, and movie special effects
  - Programming since days of the 80386 PCs

Content

- Hardware
  - How next-gen mobile hardware really works
  - Case study:
    - ImgTec Series 6 G6430 (“Rogue”)
    - Qualcomm Adreno 420 (Snapdragon 805)
- Software
  - Next-gen mobile rendering techniques in Unreal Engine 4
  - Bringing AAA PC graphics to mobile

Tech Demo Video



Next Generation Mobile Hardware

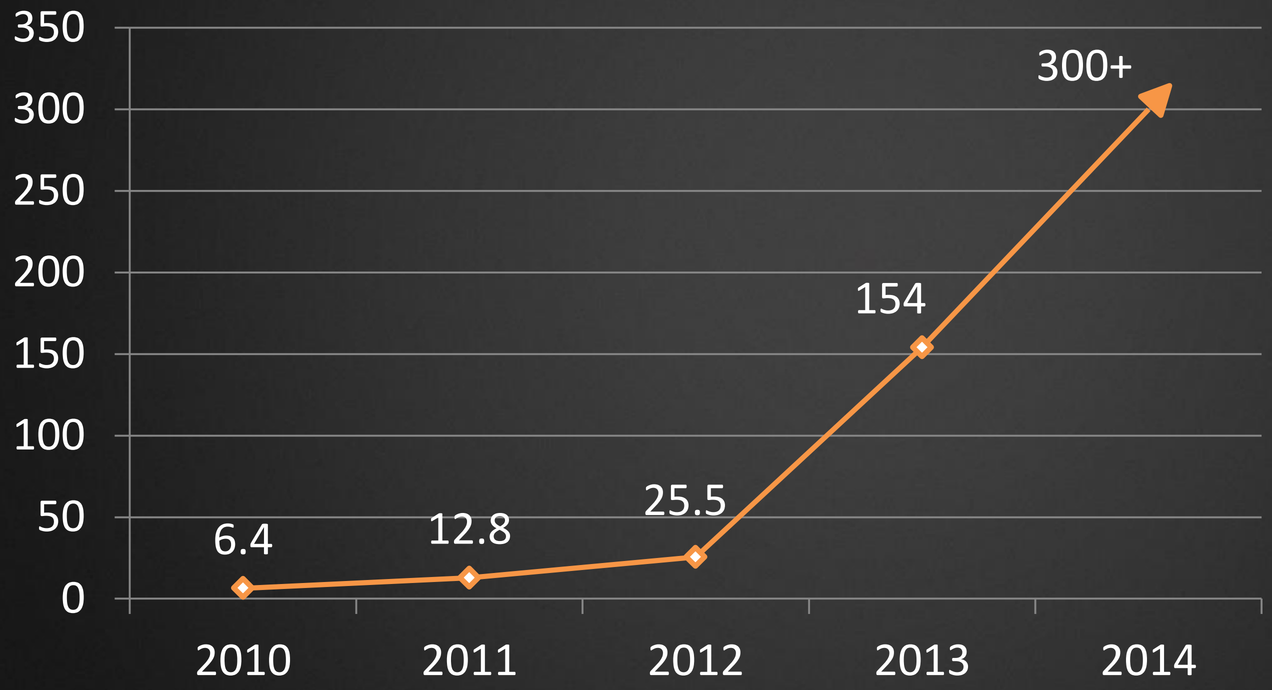
- Big leap in features and performance
- Full-featured (e.g. OpenGL ES Next, DirectX 10/11)
- Peak performance now comparable to consoles (Xbox 360/PS3)
  - About 300+ GFLOPS and 26 GB/s
- New goal: Bring AAA PC graphics to mobile

GDC 2012 vs. GDC 2014

- Next-gen performance?

20x ?

Performance Trends (FP16 GFLOPS)



2010 SGX 535

2011 SGX 543MP2

2012 SGX 543MP3

2013 G6430

2014 Adreno, K1, GX6650

Tile-based Mobile GPU

- Mobile GPUs are usually tile-based (next-gen too)

  Tile-based: ImgTec, Qualcomm*, ARM

  Direct: NVIDIA, Intel, Qualcomm*, Vivante

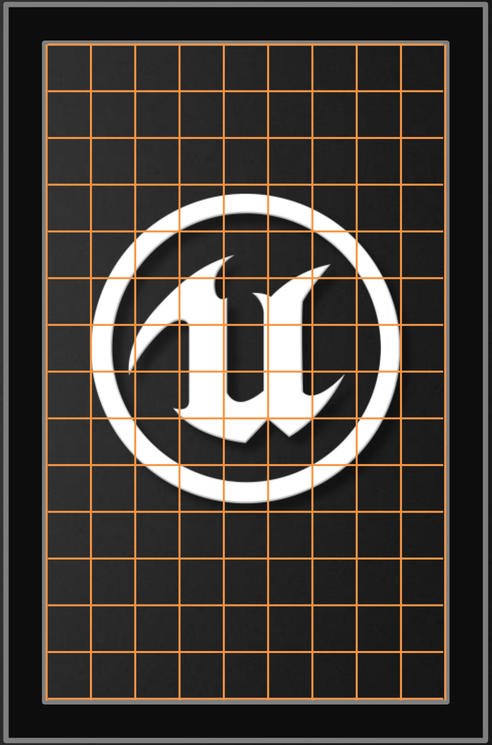
* Qualcomm Adreno can render either tile-based or direct to frame buffer

  – Extension: GL_QCOM_binning_control

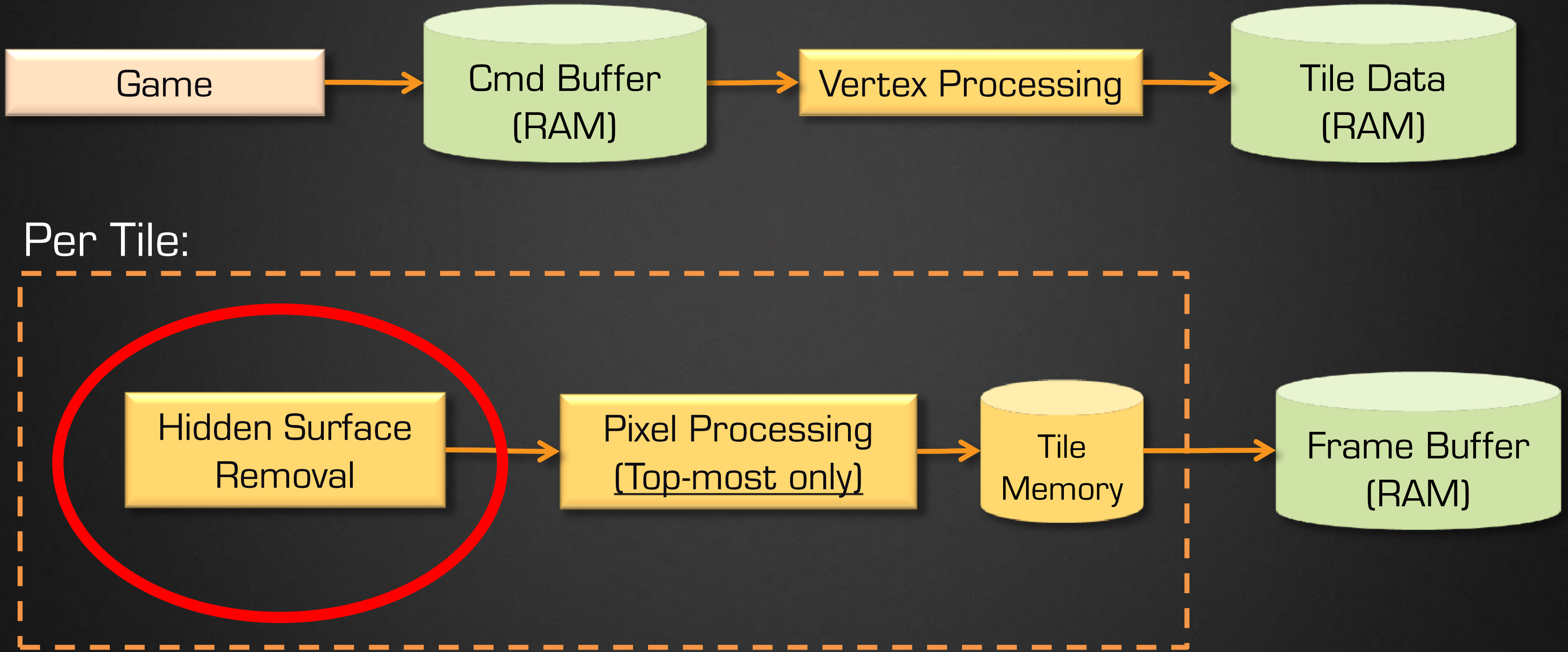
Tile-Based Mobile GPU

Summary:

- Split the screen into tiles
  - E.g. 32x32 pixels (ImgTec) or 300x300 (Qualcomm)
- The whole tile fits within GPU, on chip
- Process all drawcalls for one tile
  - Write out final tile results to RAM
- Repeat for each tile to fill the image in RAM

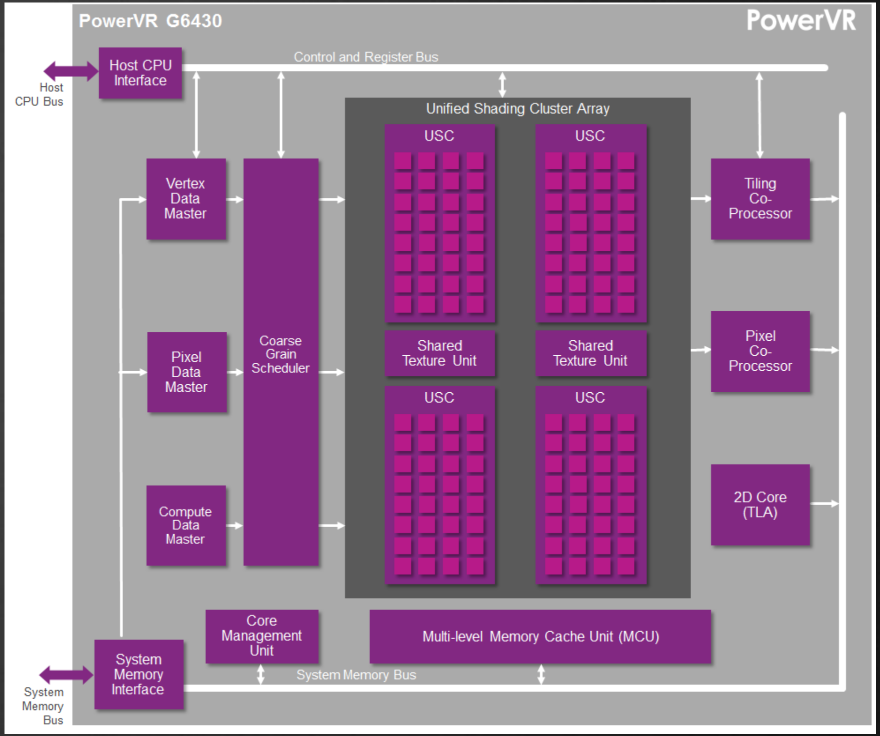


ImgTec Tile-based Rendering Process



ImgTec Series 6 G6430

- One GPU core
- Four shader units (USC)
  - 16-way scalar
- FP16: Two SOP per clock
  - (a*b + c*d)
- FP32: Two MADD per clock
  - (a*b + c)
- 154 GFLOPS @ 400 MHz
  - 16-bit floating point



ImgTec Series 6 vs SGX 5xx

- Each shader unit (USC) operates on multiple tiles in parallel
  - Don't need a whole separate GPU core for that anymore
  - Tiles are processed roughly left-to-right, top-to-bottom
- Throughput:
  - 48 FP16 scalars per clock
  - Compared to 4 floating point scalars per clock
- Parallelism:
  - 32 vertices/pixels per Wave
  - Compared to 4 (or 1) vertices/pixels per Thread

ImgTec Series 6: Improvements

- Supports OpenGL ES 3.0 and beyond
- Scalar, not vector
- No additional cost for dependent texture reads
  - Pixelshader math on texture coordinates
  - Texture coordinates can be in .zw (swizzle)
- Coherent dynamic flow control at full speed (not 1/4th speed)
- MRT support: 16 bytes per pixel in total
- FP16 is the minimum precision (no more lowp)

FP16 Is Faster Than FP32

- ImgTec Series 6: 50% faster
  - FP16 pipeline: Two SOP per clock
  - FP32 pipeline: Two MADD per clock
- ImgTec Series 6XT: 100% faster
  - FP16 pipeline: Four MADD per clock
  - FP32 pipeline: Two MADD per clock
- Qualcomm Snapdragon: 100% faster

Example: Scalar vs. Vector Performance

- GLSL shader source:

```
vec3 V = A * B  + C * D;
```

- Executed on SGX 543 GPU: (75% speed, .w component is wasted)

```
vec4 V' = A * B;
vec4 V = C * D + V';
```

- Executed on G6430 GPU: (Full speed)

```
half V.x = A.x * B.x + C.x * D.x;
half V.y = A.y * B.y + C.y * D.y;
half V.z = A.z * B.z + C.z * D.z;
```

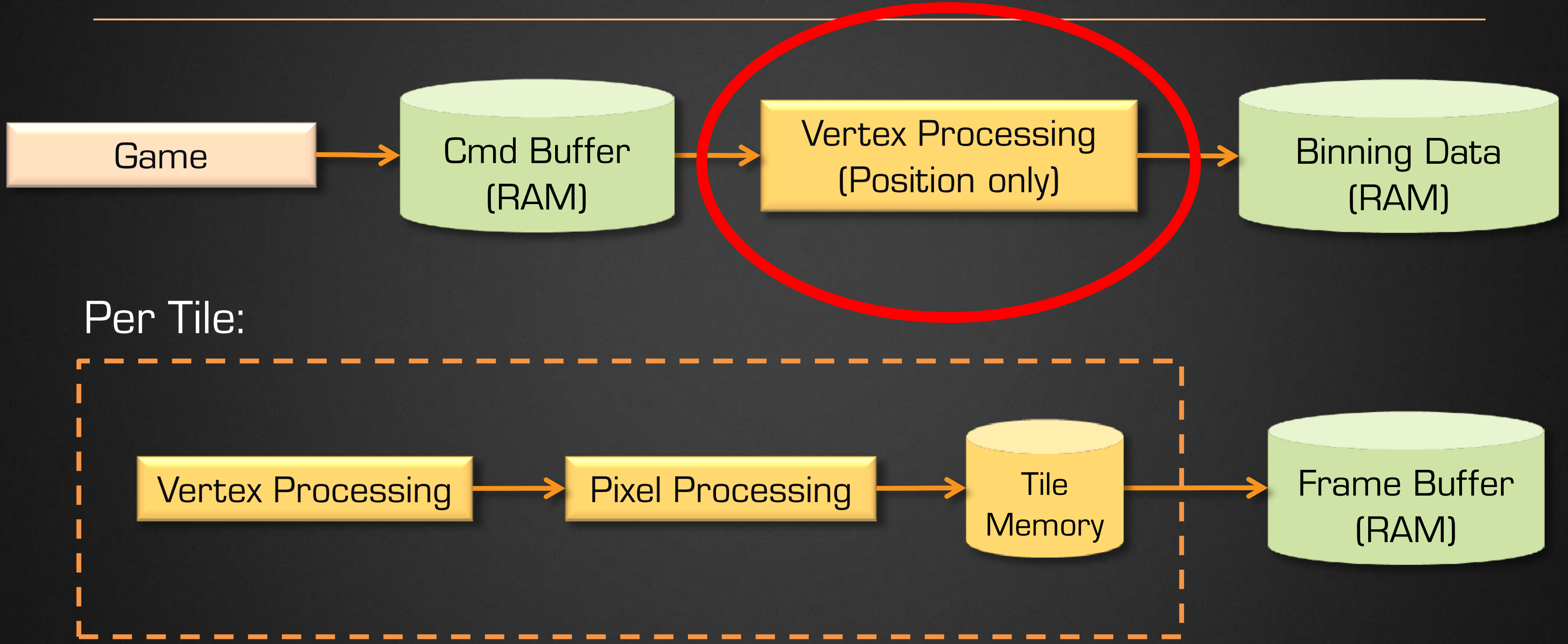
ImgTec Rendering Tips

- Hidden Surface Removal
  - For opaque only
  - Don’t keep alpha-test enabled all the time
  - Don’t keep “discard” keyword in shader source, even if it’s not used

- Group opaque drawcalls together

- Sort on state, not distance

Qualcomm Snapdragon Rendering Process



Qualcomm Snapdragon Rendering Tips

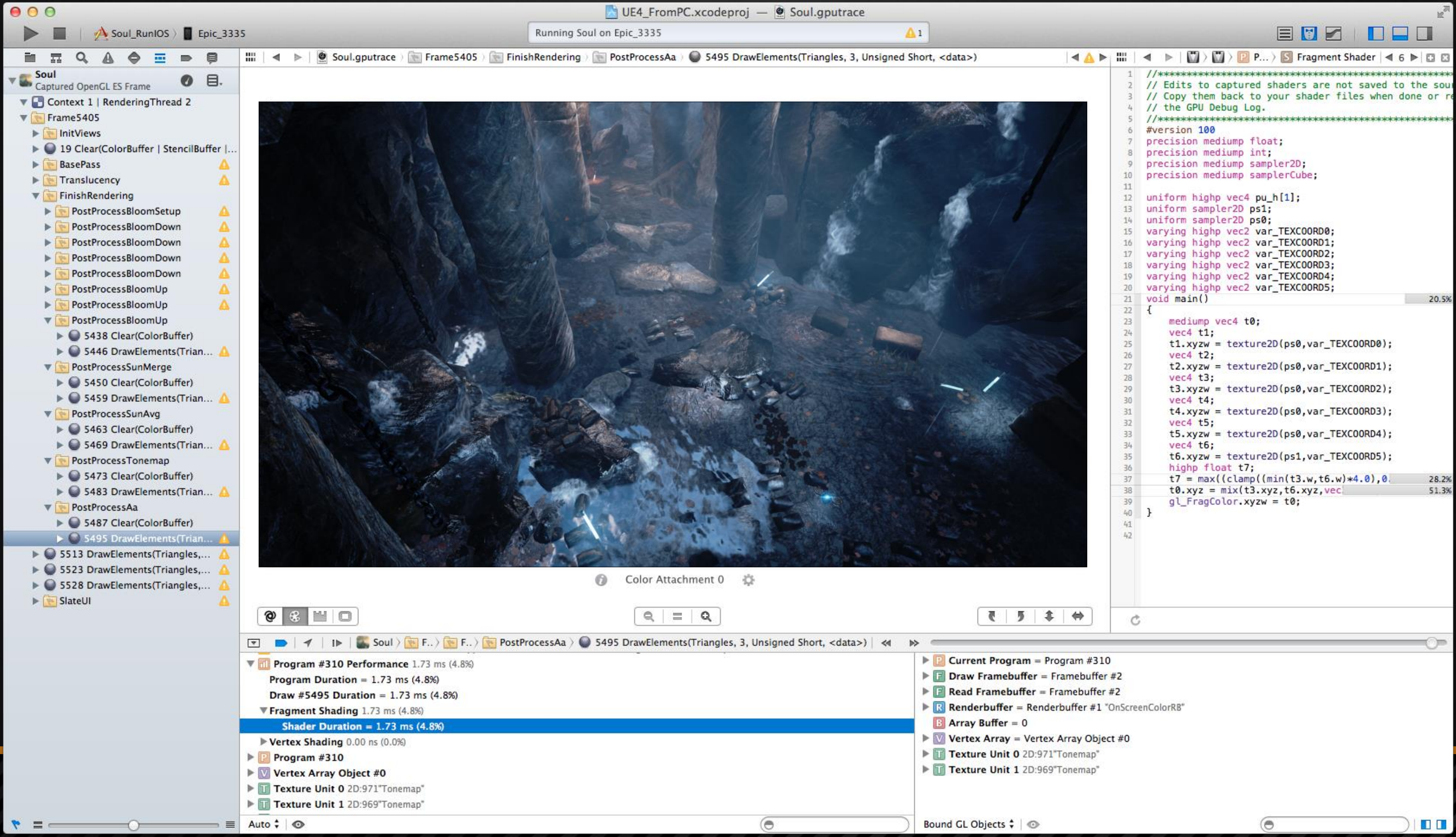
- Traditional handling of overdraw (via depth test)
  - Cull as much as you can on CPU, to avoid both CPU and GPU cost
  - Sort on distance (front to back) to maximize early z-rejection
- The Adreno SIMD is wide
  - Check your ALU utilization in the Adreno Profiler and optimize
  - Minimize temp register usage
  - Use long shaders with a lot of ALU instructions
  - Avoid dependent texture fetches (or cover the latency with a lot of ALUs)

Framebuffer Resolve/Restore

- Expensive to switch Frame Buffer Object on Tile-based GPUs
  - Saves the current FBO to RAM
  - Reloads the new FBO from RAM

Framebuffer Resolve/Restore

- Clear ALL FBO attachments after new frame/rendertarget
  - Clear after eglSwapBuffers / glBindFramebuffer
  - Avoids reloading FBO from RAM
  - NOTE: Do NOT do unnecessary clears on non-tile-based GPUs (e.g. NVIDIA)
- Discard unused attachments before new frame/rendertarget
  - Discard before eglSwapBuffers / glBindFramebuffer
  - Avoids saving unused FBO attachments to RAM
  - glDiscardFramebufferEXT / glInvalidateFramebuffer


UE4_FromPC.xcodeproj — Soul.gputrace
Soul_RunIOS
Epic_3335
Running Soul on Epic_3335
Soul.gputrace
Frame5405
FinishRendering
PostProcessAa
5495 DrawElements(Triangles, 3, Unsigned Short, <data>)
Fragment Shader
Soul
Captured OpenGL ES Frame
Context 1 | RenderingThread 2
Frame5405
InitViews
19 Clear(ColorBuffer | StencilBuffer |...
BasePass
Translucency
FinishRendering
PostProcessBloomSetup
PostProcessBloomDown
PostProcessBloomDown
PostProcessBloomDown
PostProcessBloomDown
PostProcessBloomUp
PostProcessBloomUp
PostProcessBloomUp
5438 Clear(ColorBuffer)
5446 DrawElements(Trian...
PostProcessSunMerge
5450 Clear(ColorBuffer)
5459 DrawElements(Trian...
PostProcessSunAvg
5463 Clear(ColorBuffer)
5469 DrawElements(Trian...
PostProcessTonemap
5473 Clear(ColorBuffer)
5483 DrawElements(Trian...
PostProcessAa
5487 Clear(ColorBuffer)
5495 DrawElements(Trian...
5513 DrawElements(Triangles,...
5523 DrawElements(Triangles,...
5528 DrawElements(Triangles,...
SlateUI
Color Attachment 0
// Edits to captured shaders are not saved to the sou
// Copy them back to your shader files when done or r
// the GPU Debug Log.
#version 100
precision mediump float;
precision mediump int;
precision mediump sampler2D;
precision mediump samplerCube;
uniform highp vec4 pu_h[1];
uniform sampler2D ps1;
uniform sampler2D ps0;
varying highp vec2 var_TEXCOORD0;
varying highp vec2 var_TEXCOORD1;
varying highp vec2 var_TEXCOORD2;
varying highp vec2 var_TEXCOORD3;
varying highp vec2 var_TEXCOORD4;
varying highp vec2 var_TEXCOORD5;
void main()
20.5%
{
mediump vec4 t0;
vec4 t1;
t1.xyzw = texture2D(ps0,var_TEXCOORD0);
vec4 t2;
t2.xyzw = texture2D(ps0,var_TEXCOORD1);
vec4 t3;
t3.xyzw = texture2D(ps0,var_TEXCOORD2);
vec4 t4;
t4.xyzw = texture2D(ps0,var_TEXCOORD3);
vec4 t5;
t5.xyzw = texture2D(ps0,var_TEXCOORD4);
vec4 t6;
t6.xyzw = texture2D(ps1,var_TEXCOORD5);
highp float t7;
t7 = max((clamp((min(t3.w,t6.w)*4.0),0.
28.2%
t0.xyz = mix(t3.xyz,t6.xyz,vec
51.3%
gl_FragColor.xyzw = t0;
}
Soul
PostProcessAa
5495 DrawElements(Triangles, 3, Unsigned Short, <data>)
Program #310 Performance 1.73 ms (4.8%)
Program Duration = 1.73 ms (4.8%)
Draw #5495 Duration = 1.73 ms (4.8%)
Fragment Shading 1.73 ms (4.8%)
Shader Duration = 1.73 ms (4.8%)
Vertex Shading 0.00 ns (0.0%)
Program #310
Vertex Array Object #0
Texture Unit 0 2D:971"Tonemap"
Texture Unit 1 2D:969"Tonemap"
Auto
Current Program = Program #310
Draw Framebuffer = Framebuffer #2
Read Framebuffer = Framebuffer #2
Renderbuffer = Renderbuffer #1 "OnScreenColorRB"
Array Buffer = 0
Vertex Array = Vertex Array Object #0
Texture Unit 0 2D:971"Tonemap"
Texture Unit 1 2D:969"Tonemap"
Bound GL Objects

Programmable Blending

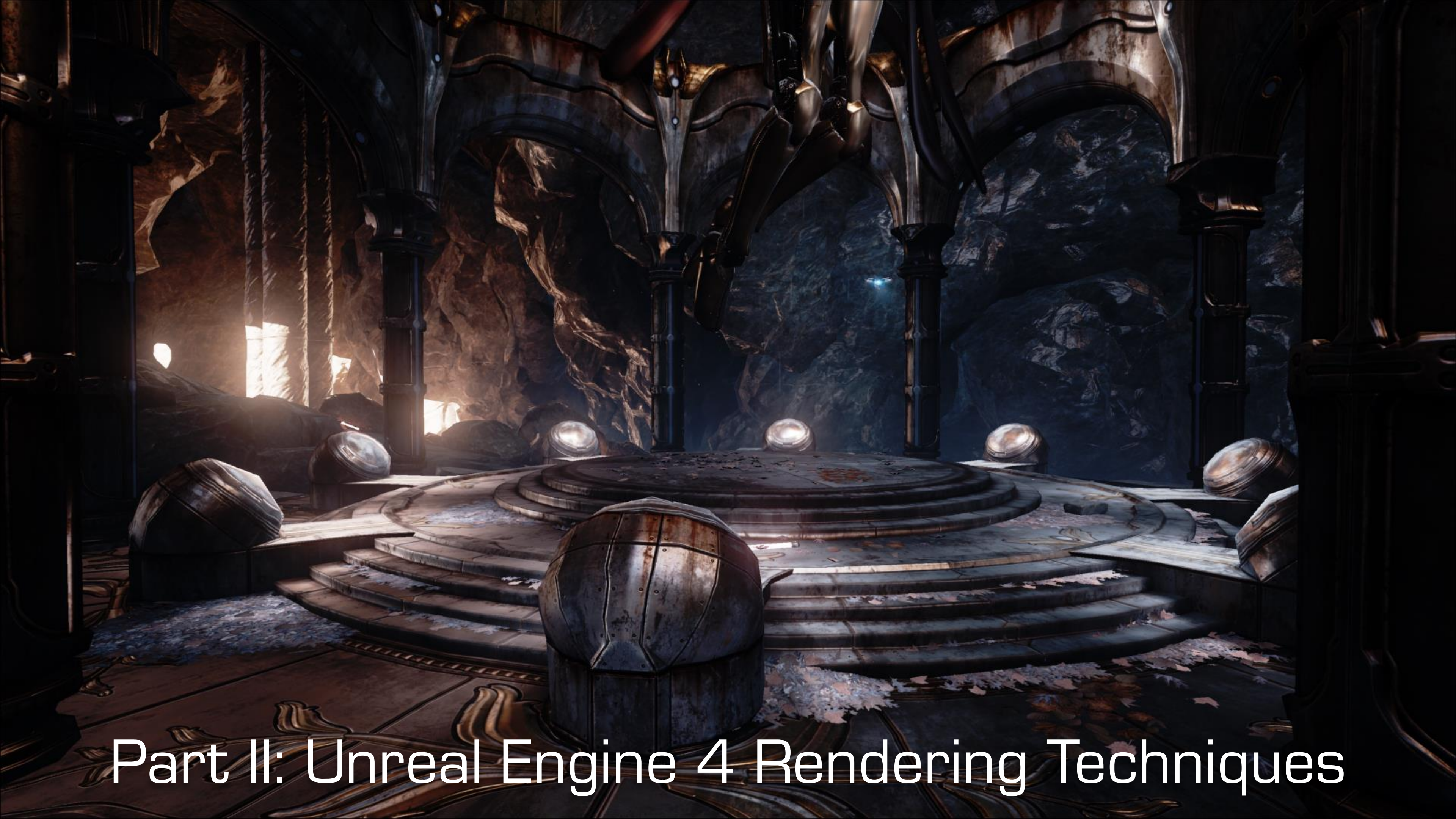
- GL_EXT_shader_framebuffer_fetch (gl_LastFragData)
- Reads current pixel background "for free"
- Potential uses:
  - Custom color blending
  - Blend by background depth value (depth in alpha)
    - E.g. Soft intersection against world geometry for particles
  - Deferred shading without resolving GBuffer
    - Stay on GPU and avoid expensive round-trip to RAM

Tips

- Think scalar! Avoid using unnecessary components
  - Avoid: (vec4*float)*float (8 MUL)
  - Use: vec4*(float*float) (5 MUL)
- Prefer 16-bit floating point operations (mediump)
- Leverage ALU to hide memory fetches
  - E.g. ALU can be faster than using lookup-textures

More Tips

- Don't switch back and forth between mediump/highp
  - ImgTec: Requires shader instructions to convert each time
  - Qualcomm: Many conversions are free
- Branch spatially coherent for many pixels
  - Uses predication to ignore invalid path



Part II: Unreal Engine 4 Rendering Techniques

Core Optimization: Opaque Draw Ordering

- All platforms,
  - 1. Group draws by material (shader) to reduce state changes
- Then for all platforms except ImgTec,
  - 2. Skybox last: 5 ms/frame savings (vs drawing skybox first)
  - 3. Sort groups nearest first : extra 3 ms/frame savings
  - 4. Sort inside groups nearest first : extra 7 ms/frame savings
- Timing from a UE4 map on a Qualcomm based device

Core Optimization: Render Resolution

- Reducing render resolution to get perf/pixel
  - Example Phone = 4.7 tex/ms/pixel at native 0.7 Mpix display
  - Example Tablet = 0.9 tex/ms/pixel at native 3.1 Mpix display
  - Example Last Gen Console = 3.9 tex/ms/pixel
    - at HDTV native 2.1 Mpix display

Comparison: PC

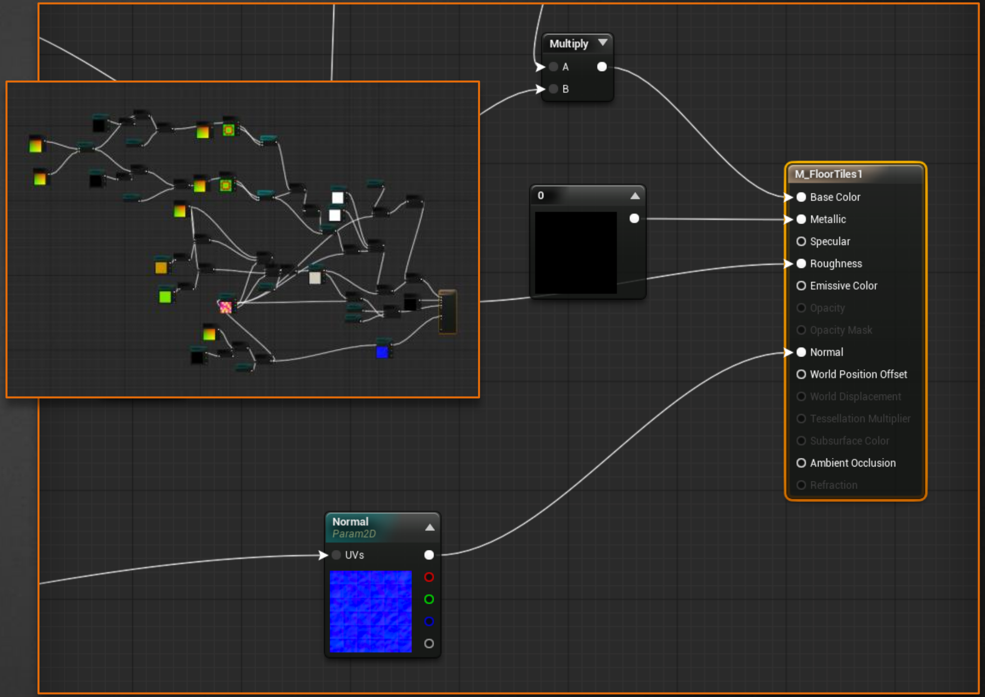
Comparison: Mobile

Authoring Consistency

- Core motivating factor in design
  - Authoring consistency between PC and Mobile
- Authoring environment for both platforms
  - Physically based shading model
  - High dynamic range linear color space
  - High quality post processing

Consistency: Material Editor

- One material for many platforms
  - Artist authored feature levels to scale shader perf from PC to mobile
- Using cross compiler tool to retarget HLSL into GLSL



Consistency: Physically Based Shading

- Same material model as PC
  - See "Real Shading in Unreal Engine 4" (Brian Karis) [1]
- Mobile adjustments
  - Analytic approximation of Environment BRDF (ALU instead of TEX)
  - Normalized Phong spec distribution (faster and still energy conserving)
- [1] http://blog.selfshadow.com/publications/s2013-shading-course/

Consistency: HDR Directional Lightmaps

- Pair of compressed textures
  - HDR color with log luma encoding
  - World space 1st order spherical harmonic luma directionality
- Optimized for Mobile and PVRTC compression
  - Mobile encoding lacks separately compressed encoding for alpha
  - Therefore mobile encoding for HDR color is different than PC
  - PC uses {RGB/Luma, LogLuma in Alpha}
  - Mobile uses {RGB/Luma * LogLuma, no Alpha}

Directional Light + SDF Shadows

Directional Light + SDF Shadows

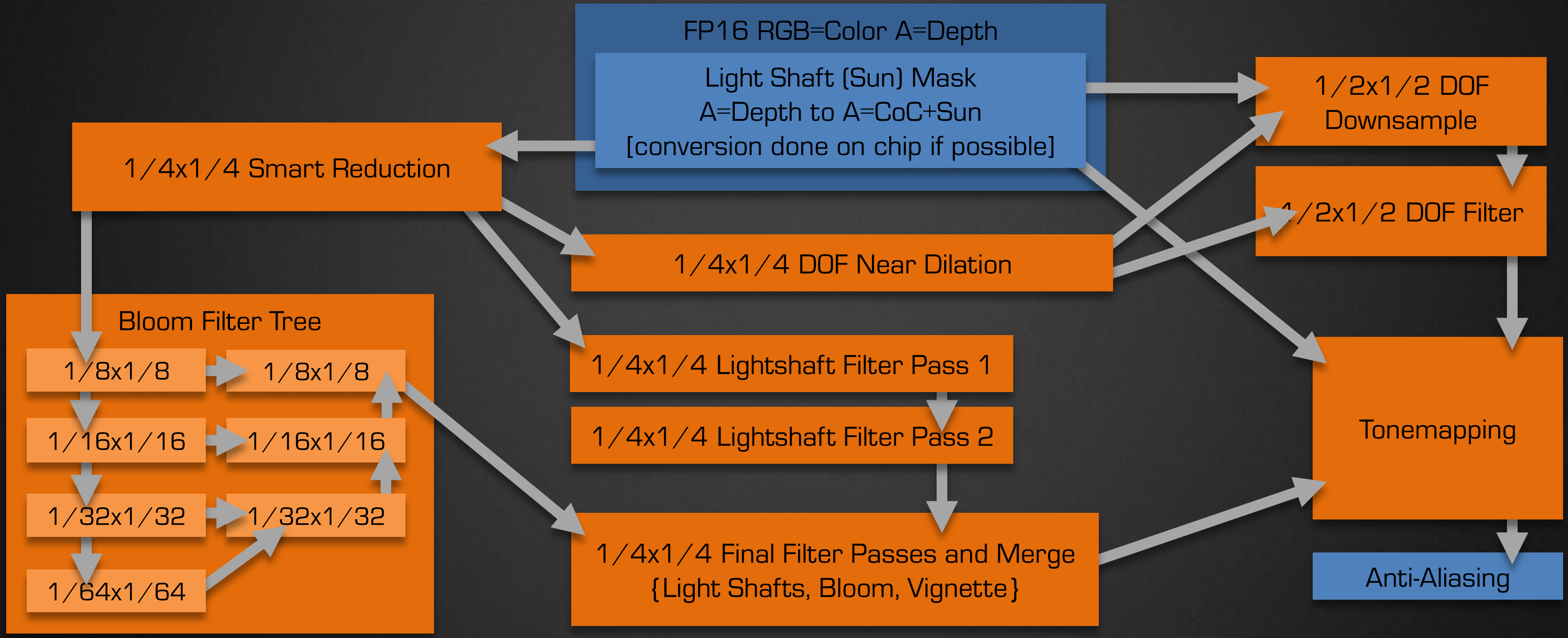
- UE4 mobile applies the primary directional light dynamically
- This light is shadowed by baked signed distance field (SDF) shadows
  - Uncompressed texture stores signed distance to nearest shadow transition

Image Based Lighting

Image Based Lighting

- Mip choice based on roughness
  - Same as PC, filtering same as PC
- PC uses FP16 IBL cubemaps
- Mobile uses Decode(RGBM)^2 IBL cubemap encoding
- PC blends multiple cubemaps per surface and provides parallax correction
- Mobile supports one infinite distance cubemap per object

Mobile Post Processing Pipeline



Mobile Depth of Field

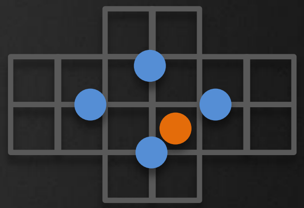
Mobile Depth of Field

- Special mobile algorithm
  - Uses 1/4 x 1/4 resolution near DOF dilation pass
    - Used to enable Bokeh to bleed out over background
  - DOF blur works at 1/2 x 1/2 resolution
    - Later applied to full resolution in tonemapping pass
    - Extra ultra fine blur tap taken in full resolution pass for better transitions

Mobile Depth of Field : Details

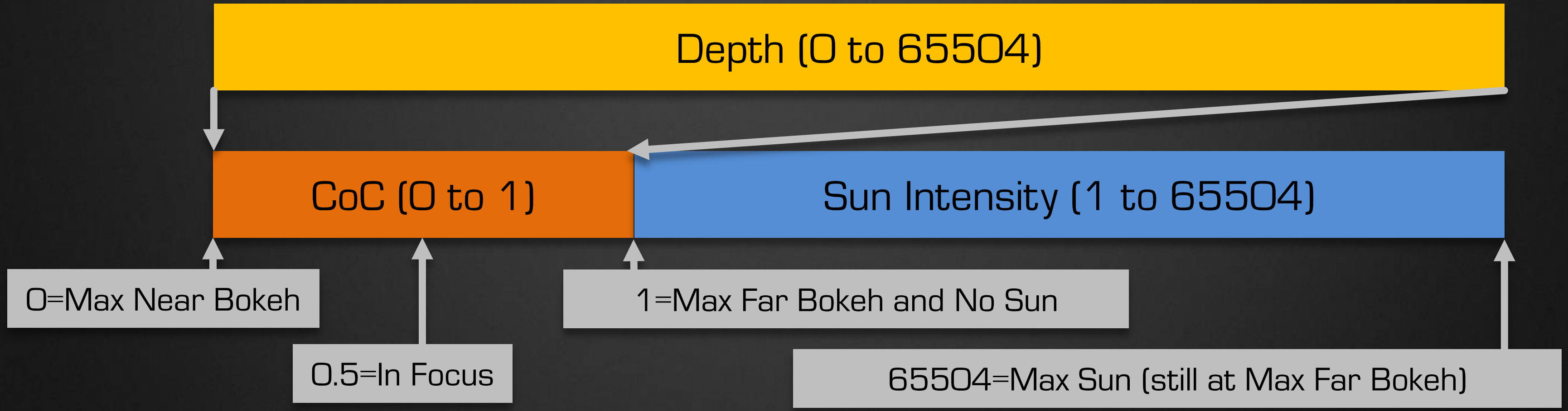
Mobile Depth of Field : Filtering

- Filtering is a weighted average of 4 taps
- 4 taps at different distance from pixel center
  - Enables smooth in-to-out-of-focus transition
  - Bokeh is slightly off center but covers 16 half res texels
- Remove color bleeding problems when bilinear filtering
  - Packed circle of confusion size in alpha
  - Pre-weighting color by alpha (undo weighting after fetch during filtering)
  - Watch out for lack of FP16 denormal support on mobile hardware!



Packed Circle of Confusion and Sun Intensity

- Optimization done for Depth of Field and Light Shafts
  - Represent sun intensity and circle of confusion (CoC) in one FP16 value
  - Saves needing an extra render target

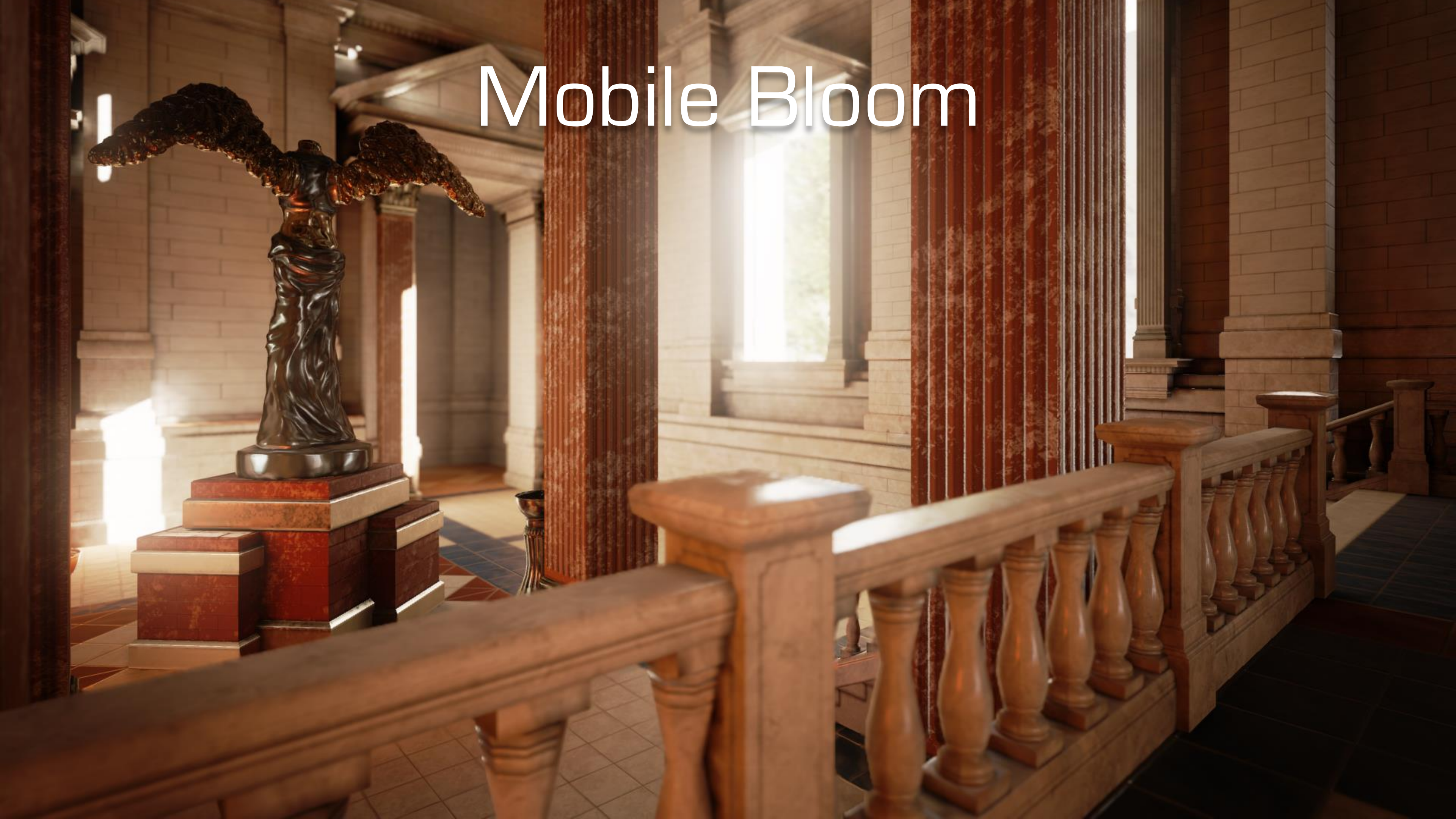


Vignette + Bloom + Light Shafts

Vignette + Bloom + Light Shafts : Optimized

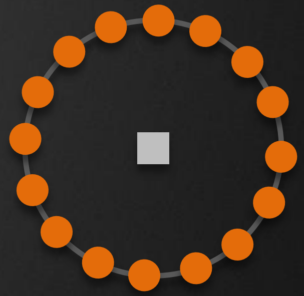
- Composited at 1/4 x 1/4 resolution
  - Using pre-multiplied alpha FP16
  - Composite shader does last bloom and light shaft filter pass too
    - Optimized to minimize resolves (or round trips off chip)
- 3 effects applied to scene with one full-res TEX fetch
  - Applied in the tonemapper pass

Mobile Bloom



Mobile Bloom

- Lower quality version which limits resolves to work around render target switch limits
  - Limited effect radius and less passes
- Faster and higher quality version for devices without need for the work around
  - Standard hierarchical algorithm with some optimizations
  - Down-sample from 1:1/4 res first (shared with light shaft)
  - Then down-sample in 1:1/2 resolution passes
  - Single pass circle based filter (instead of 2 pass Gaussian)
    - 15 taps on circle during down-sampling
    - 7 taps for both circles during up-sample+merge pass



Mobile Light Shafts

- Filters at 1/4 x 1/4 resolution
- Monochromatic with artist controlled tint on final composite
  - Bloom and light shaft down-sample pass shared
  - RGB = color for bloom, A = light shaft intensity
- Light shaft filter runs in tonemapped space (8-bit/channel)
  - Applied in linear (reverse tonemap before tint and composite)
- Filtering done by 3 passes of 8 taps

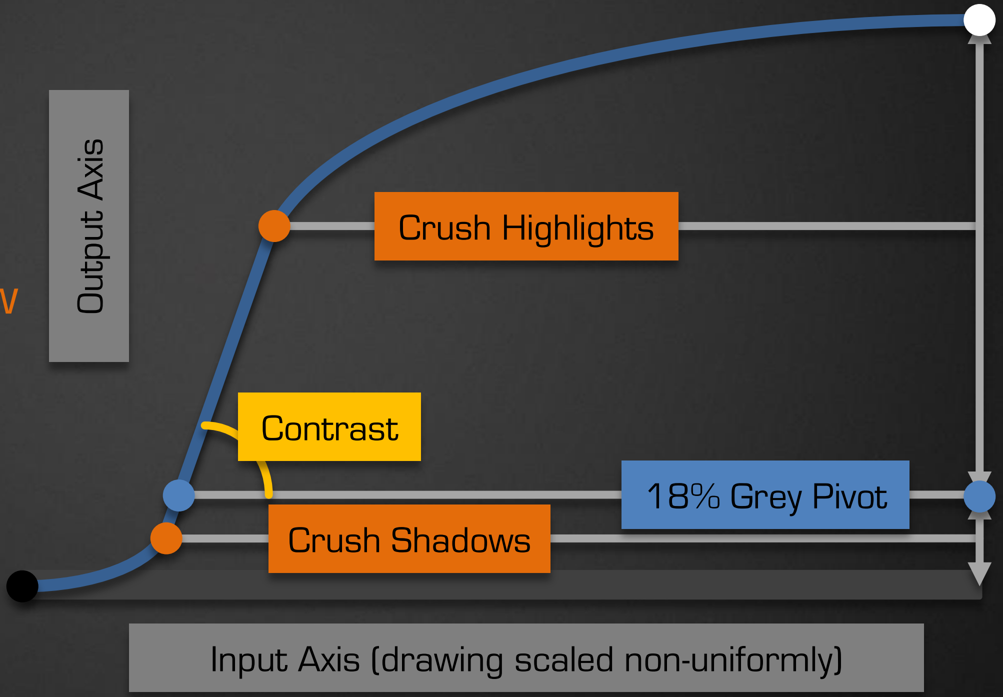
Film Post Tonemapping

Film Post Tonemapping : Details

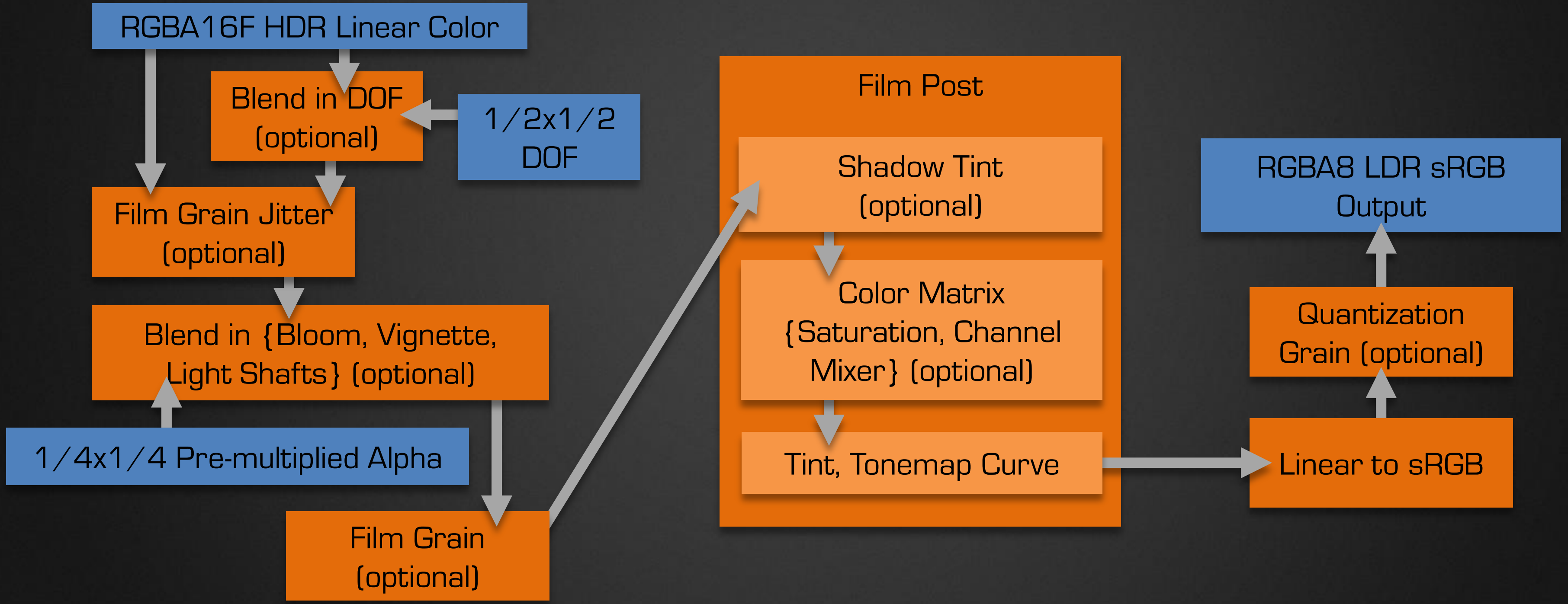
- Same controls as PC
  - Unused controls optimized out (shader permutations)
- Similar controls as high end photo editing software
- Applied in Linear HDR color space before tonemapping
  - Critical for high quality color
- White point and shadow color tint adjustment
- Saturation and channel mixer (applied as 3x3 color matrix)

Film Post Tonemapping : Curve

- 18% grey is the perceptual midpoint
- "Crush" controls film latitude (size of linear segment above and below 18% grey)
  - Higher latitude increases the region of the curve with no distortion on the ratio of color primaries
- Contrast controls slope of linear segment

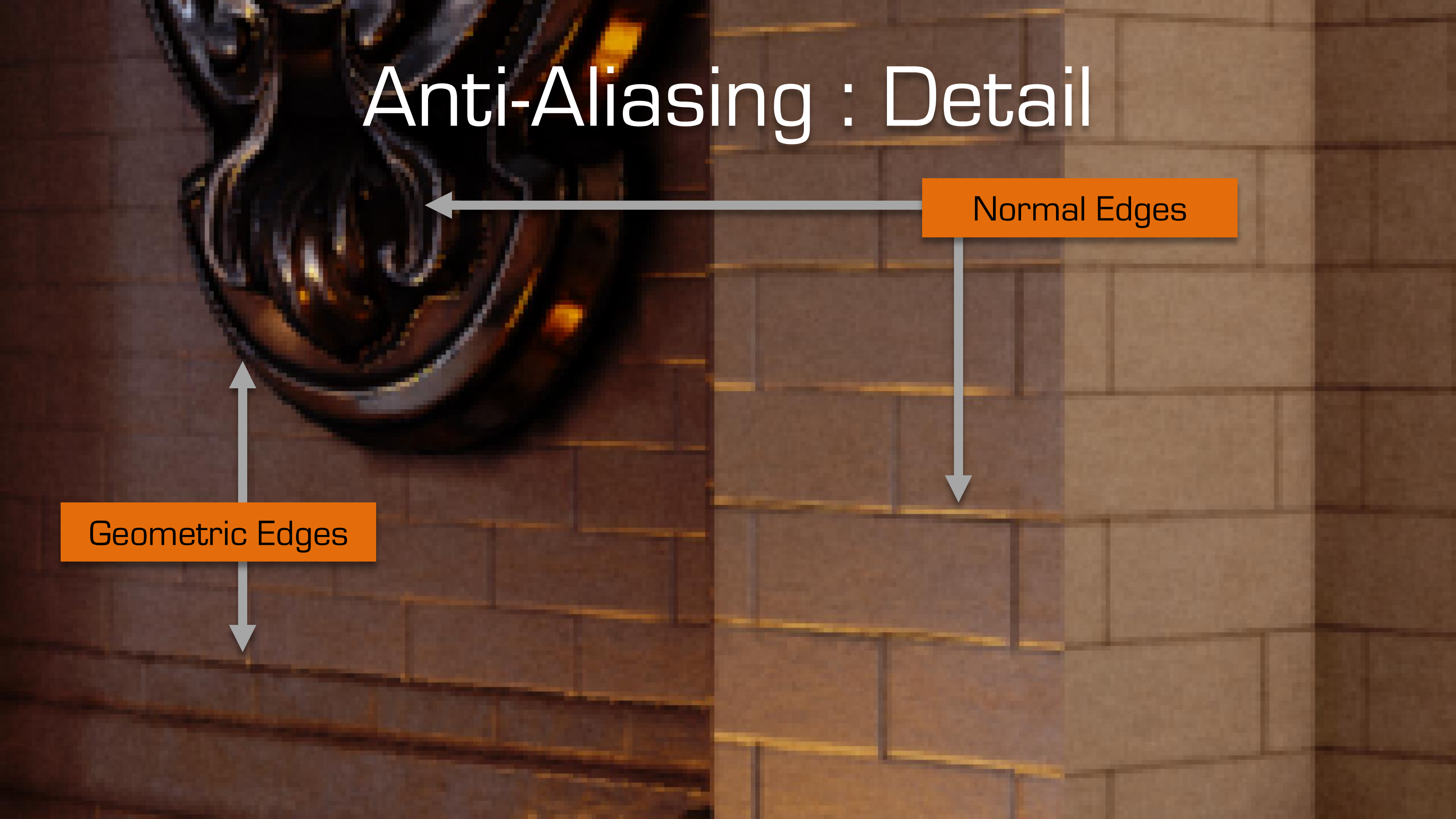


Film Post Tonemapping : Mobile Shader



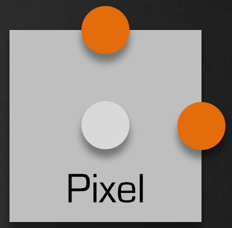
Anti-Aliasing

Anti-Aliasing : Detail



Anti-Aliasing

- Using a spatial & temporal anti-aliasing filter
  - 2x temporal super-sampling (higher quality surface shading)
  - Blending two jittered frames after tonemapping (32 bpp, perceptual colorspace)
    - With some special logic to remove ghosting/judder (not using motion reprojection)



- Not currently using MSAA
  - Needed super-sampled shading for HDR physically based shading model

Exposure Mosaic: Linear Blending at 32-bpp

- Used on GPUs without FP16 and without sRGB support to support linear blending
  - Supports {0.0 to 2.0} dynamic range
  - Mosaic mode simulates a 12-bit/channel linear framebuffer
  - Forward shading and linear blending with exposure mosaic based on gl_FragCoord
  - Demosaic in tonemapping pass

{0-2} dynamic range

{0-1/6} dynamic range

Exposure Mosaic: Output Quality


All Techniques Combined

And one more thing…

Unreal Engine 4

Full source code available now!

unrealengine.com

Includes all C++, shaders, tools, content

$19/mo

Bonus Slides

The following slides were not part of the live presentation . . .

GDC 2012 vs. GDC 2014:

SGX 543MP2:

- Two GPU cores
- Two SIMDs per core (vec4)
- Two MADD per clock
- 200 Mhz
- 13 GFLOPS

ImgTec G6430:

- One GPU core
- Four 16-way SIMDs (scalar)
- Two SOP per clock (FP16)
- 400 MHz
- 154 GFLOPS (FP16)

ImgTec Series 6: Latency Hiding

- Highly multithreaded to hide memory latency
  - Thousands of threads
  - Switch to new thread when kicking off a memory read
- Each SIMD has their own thread manager
- One Wave: 32 vertices/pixels, one instruction pointer
- Switching Wave is free (every two clock cycles)
  - Memory fetch
  - Branching
  - Other dependency