Bringing AAA graphics to mobile platforms

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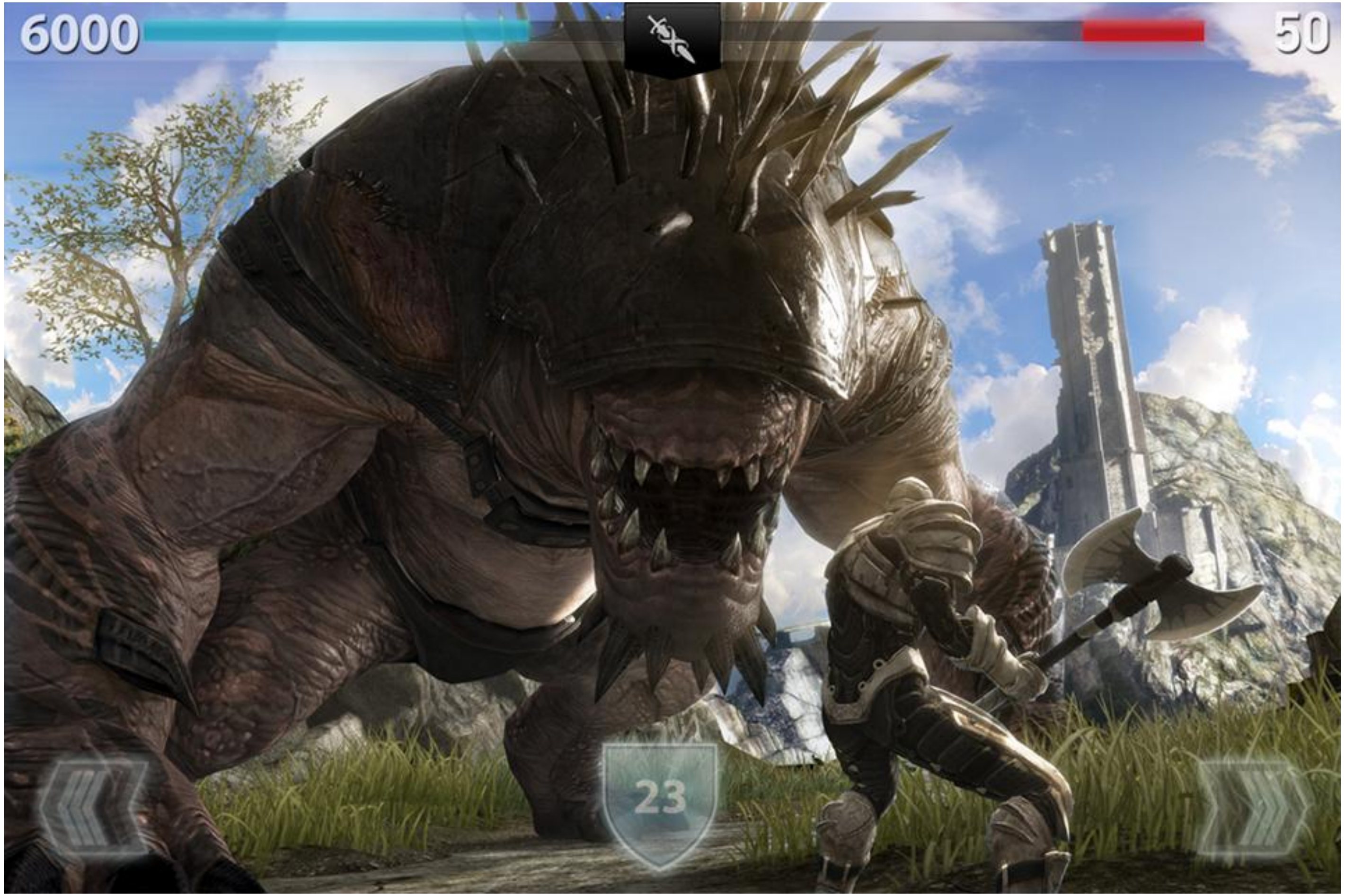
Who Am I

- A.k.a. "Smedis"
- Platform team at Epic Games
  - Unreal Engine
- 15 years in the industry
- 30 years of programming
- C64 demo scene

Content

- Hardware
  - How it works under the hood
  - Case study: **ImgTec SGX GPU**
- Software
  - How to apply this knowledge to bring console graphics to mobile platforms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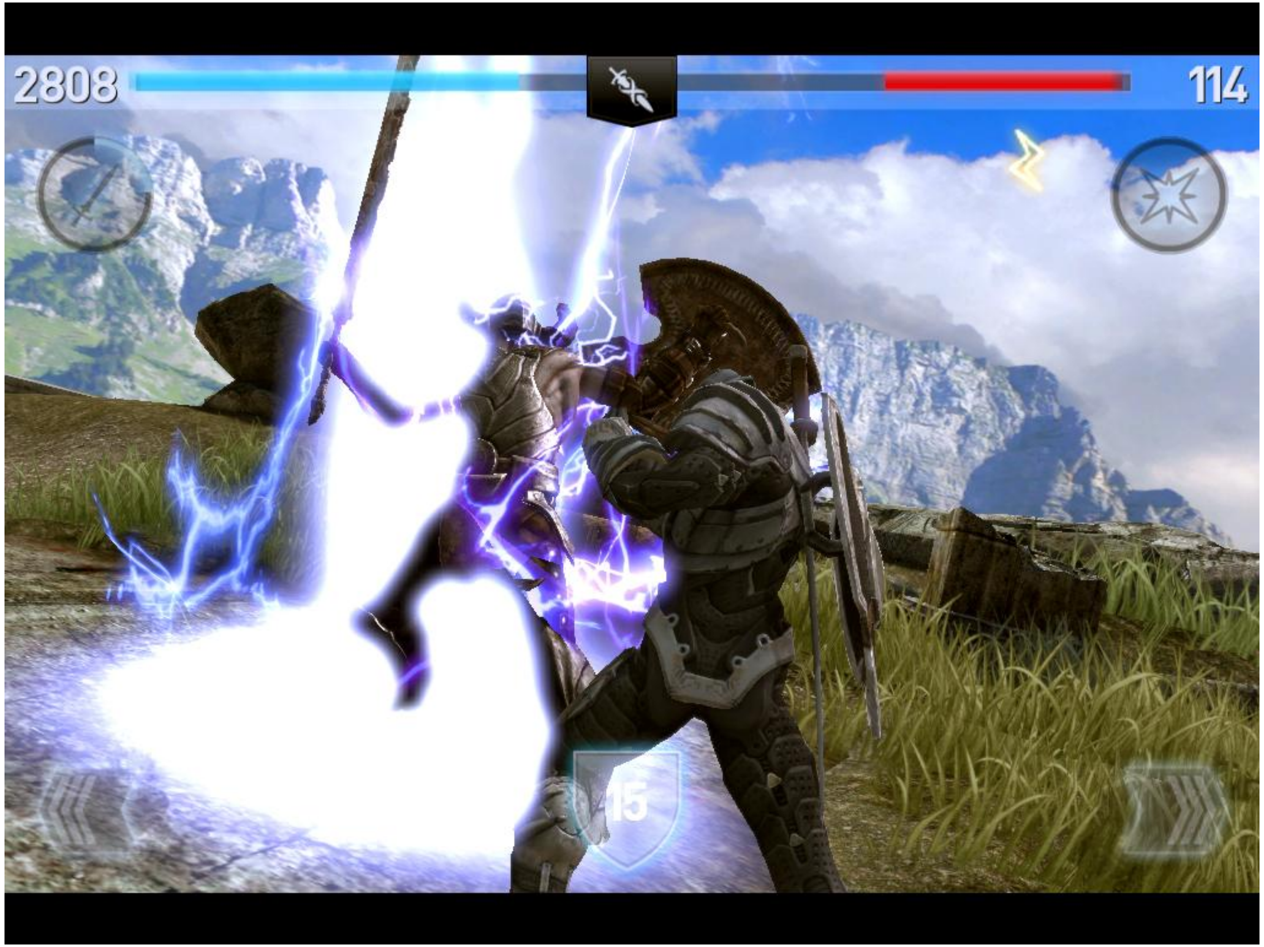
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Mobile Graphics Processors

- The feature support is there:
  - Shaders
  - Render to texture
  - Depth textures
  - MSAA
- But is the performance there?
  - Yes. And it keeps getting better!

Mobile GPU Architecture

- Tile-based deferred rendering GPU
  - Very different from desktop or consoles
  - Common on smartphones and tablets
  - **ImgTec SGX GPUs fall into this category**
  - There are other tile-based GPUs (e.g. ARM Mali)
- Other mobile GPU types
  - NVIDIA Tegra is more traditional

Tile-Based Mobile GPU

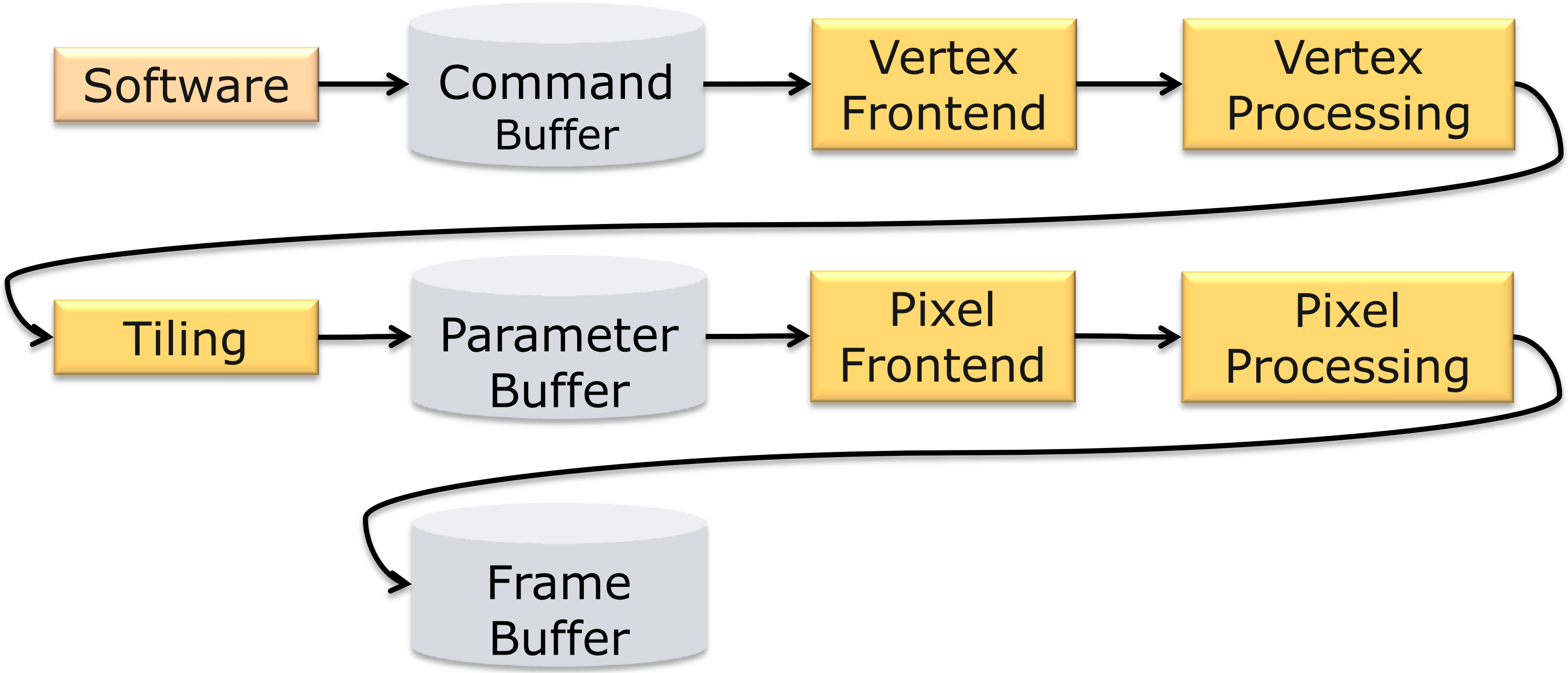
TLDR Summary:

- Split the screen into tiles
  - E.g. 16x16 or 32x32 pixels
- The GPU fits an entire tile on chip
- Process all drawcalls for one tile
  - Repeat for each tile to fill the screen
- Each tile is written to RAM as it finishes

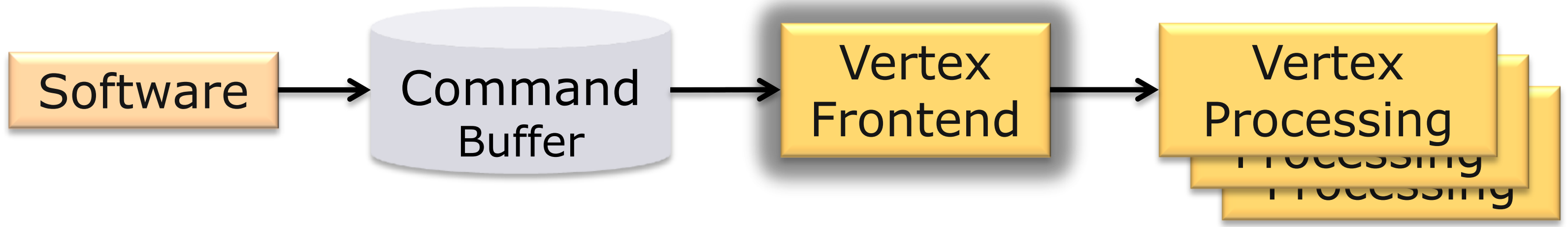
POWERED BY
UNREAL
TECHNOLOGY

(For illustration purposes only)

ImgTec Process

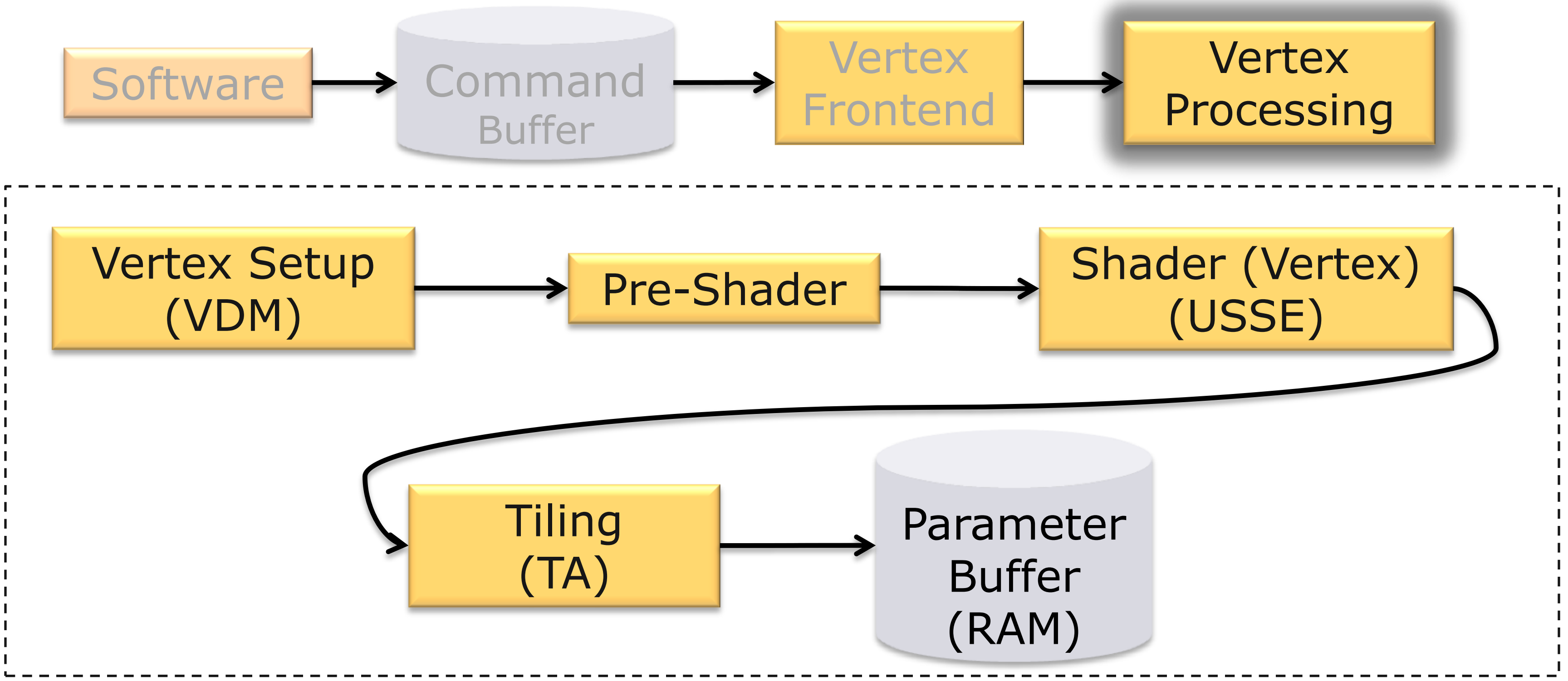


Vertex Frontend



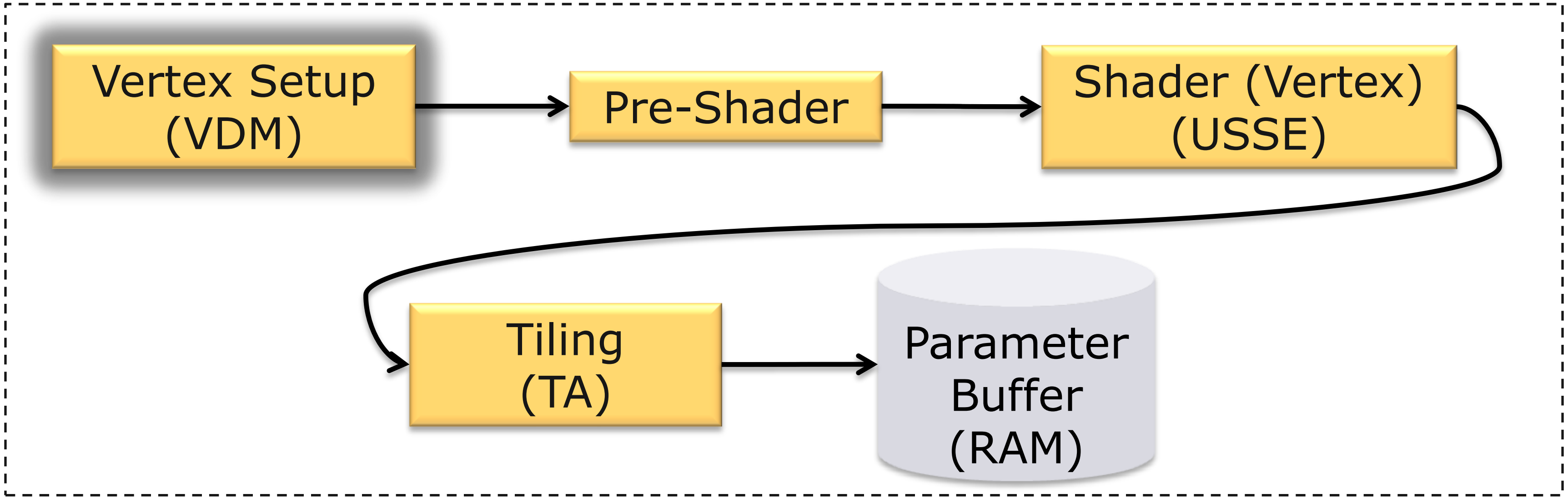
- Vertex Frontend reads from GPU command buffer
- Distributes vertex primitives to all GPU cores
  - Splits drawcalls into fixed chunks of vertices
  - GPU cores process vertices independently
  - Continues until the end of the scene

Vertex processing (Per GPU Core)



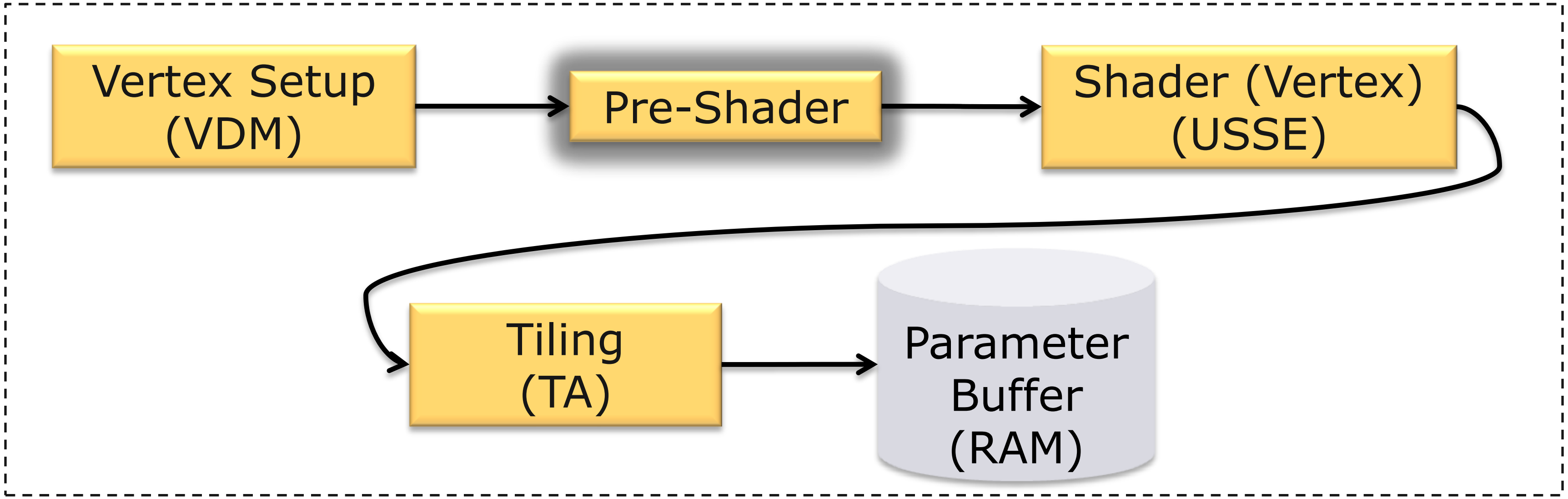
Vertex Setup

Receives commands from Vertex Frontend



Vertex Pre-Shader

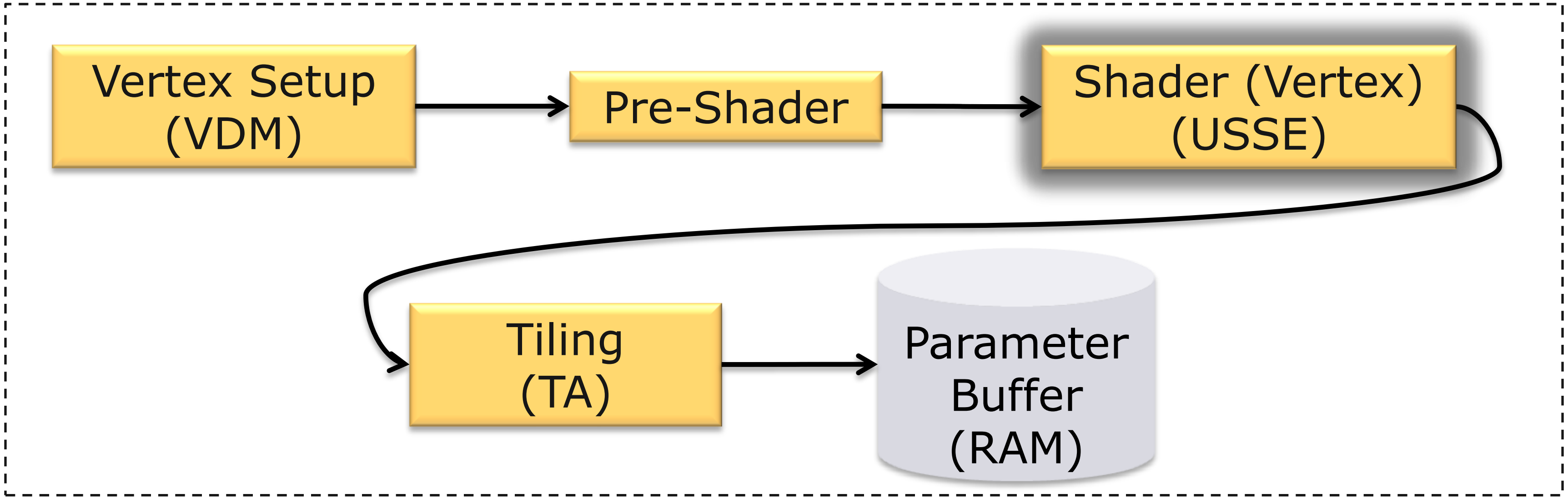
Fetches input data (attributes and uniforms)



Vertex Shader

Universal Scalable Shader Engine

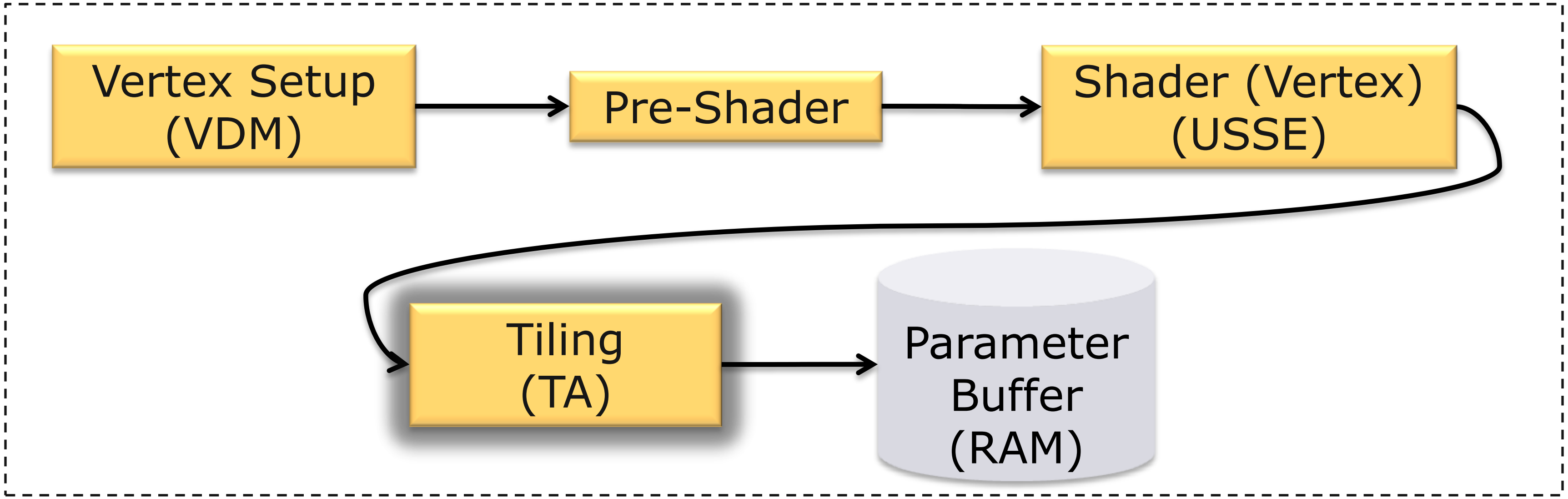
Executes the vertex shader program, multithreaded



Tiling

Optimizes vertex shader output

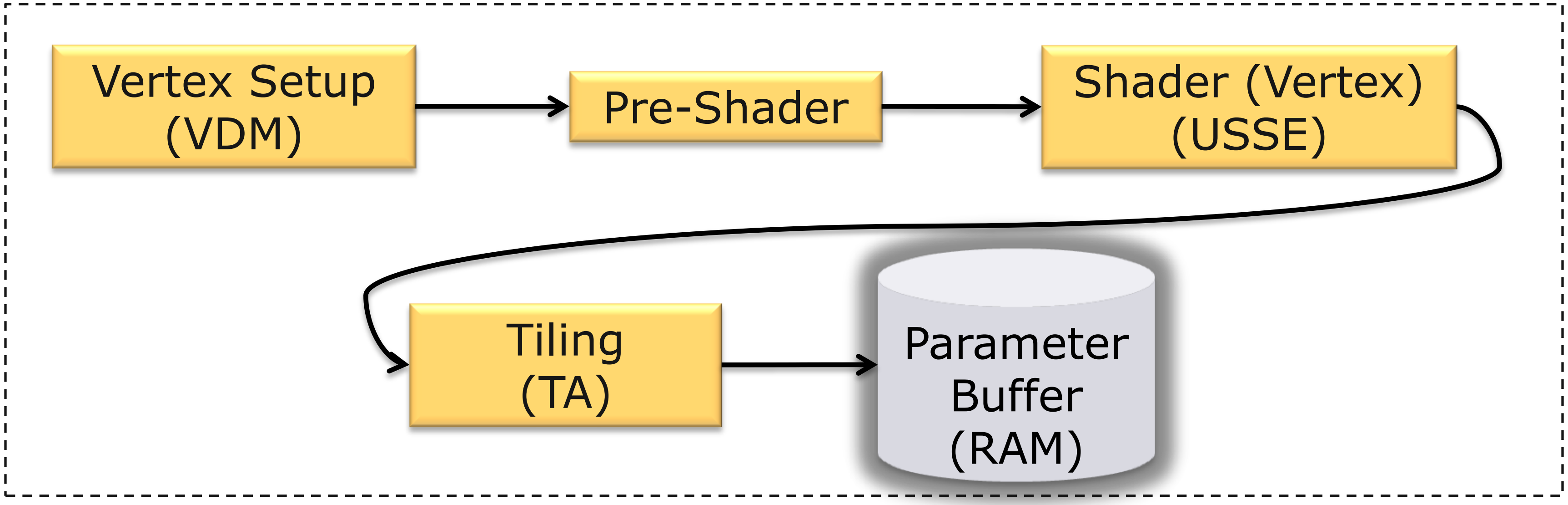
Bins resulting primitives into tile data



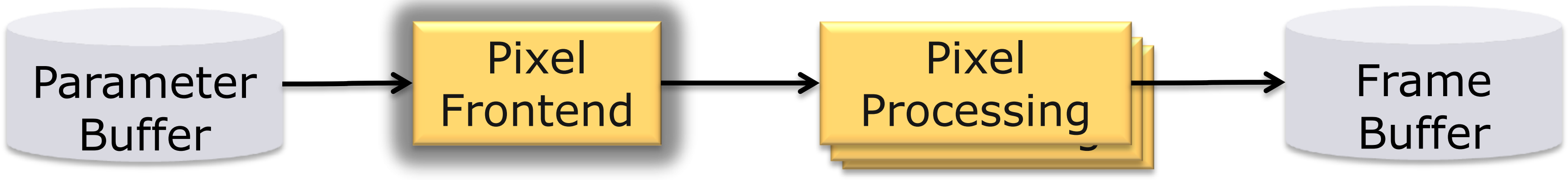
Parameter Buffer

Stored in system memory

You don't want to overflow this buffer!

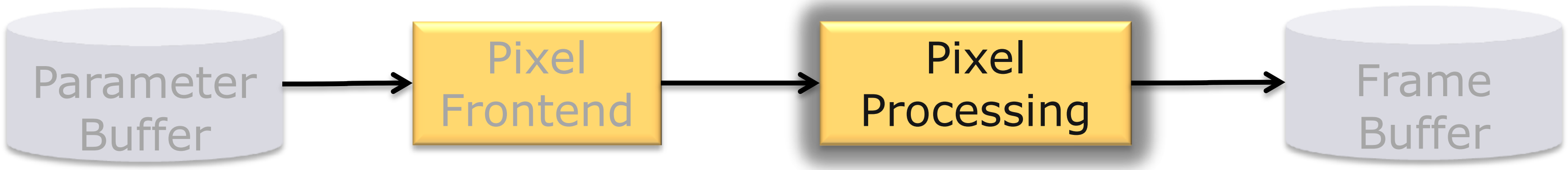


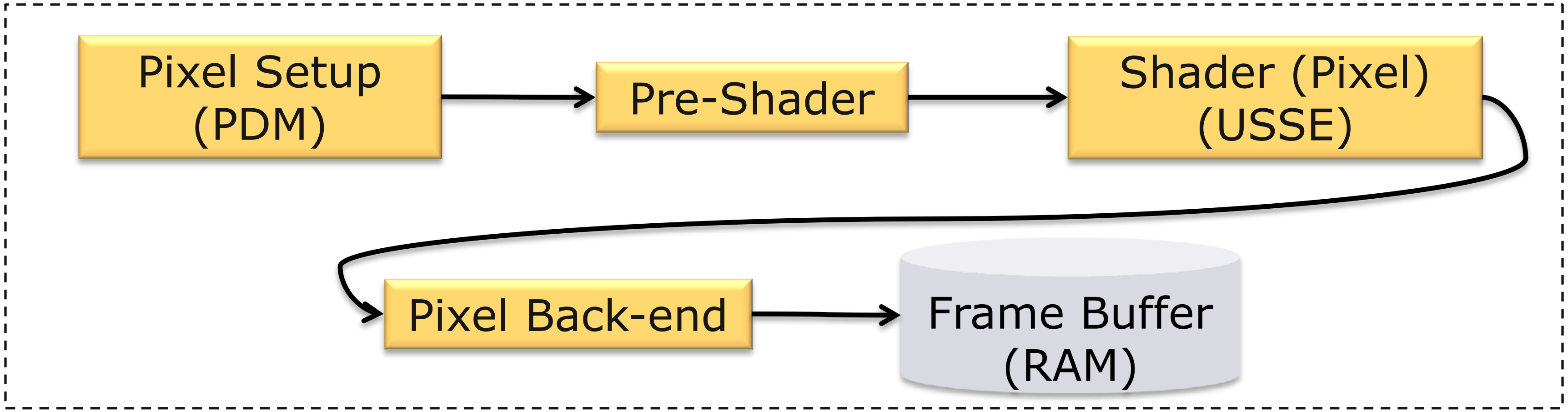
Pixel Frontend



- Reads Parameter Buffer
- Distributes pixel processing to all cores
  - One whole tile at a time
  - A tile is processed in full on one GPU core
  - Tiles are processed in parallel on multi-core GPUs

Pixel processing (Per GPU Core)





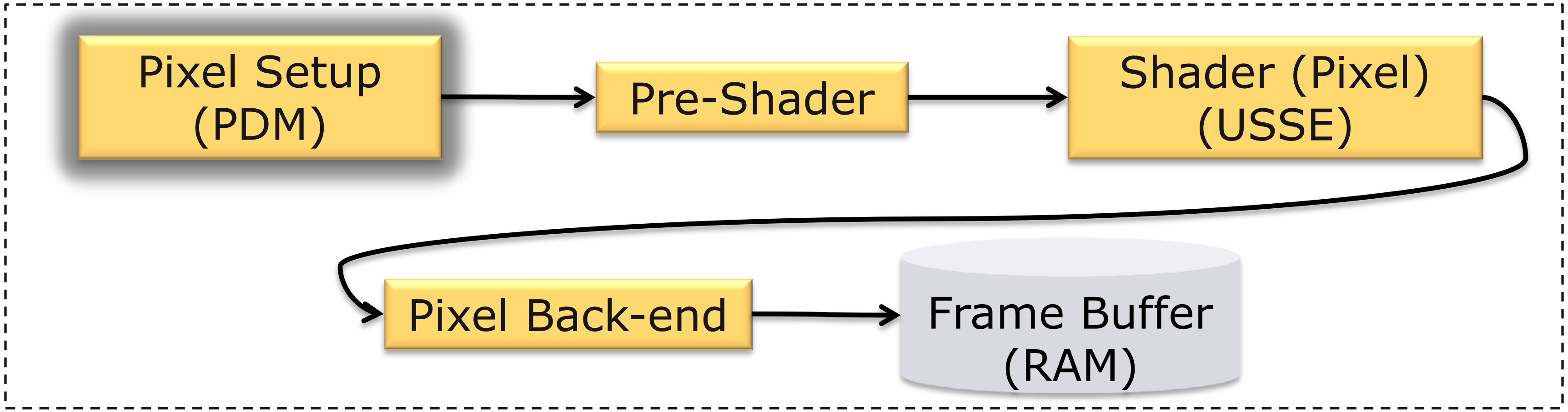
Pixel Setup

Receives tile commands from Pixel Frontend

Fetches vertexshader output from Parameter Buffer

Triangle rasterization; Calculate interpolator values

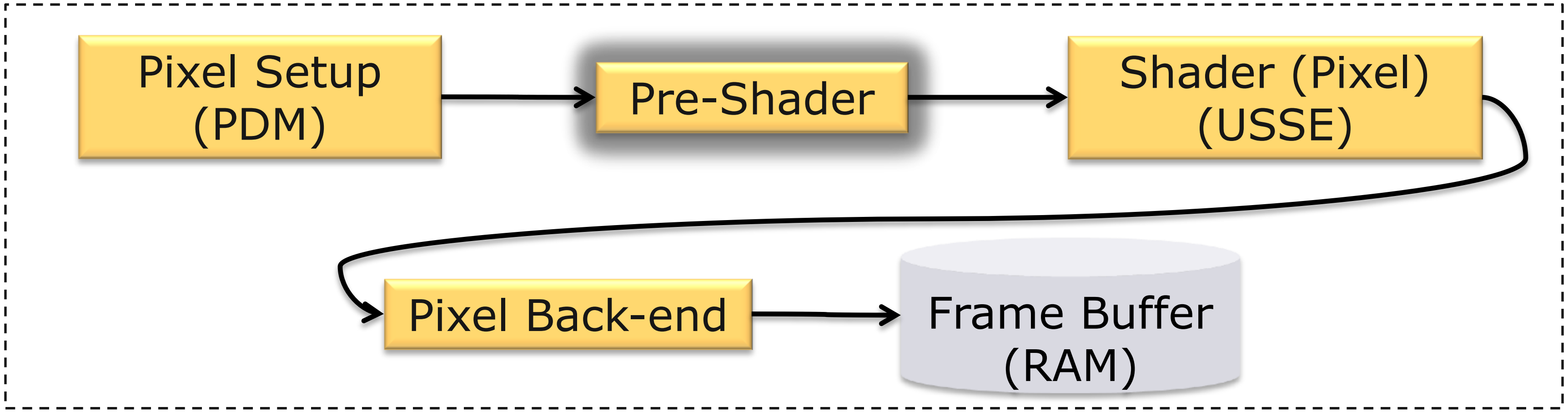
Depth/stencil test; **Hidden Surface Removal**



Pixel Pre-Shader

Fills in interpolator and uniform data

Kicks off non-dependent texture reads

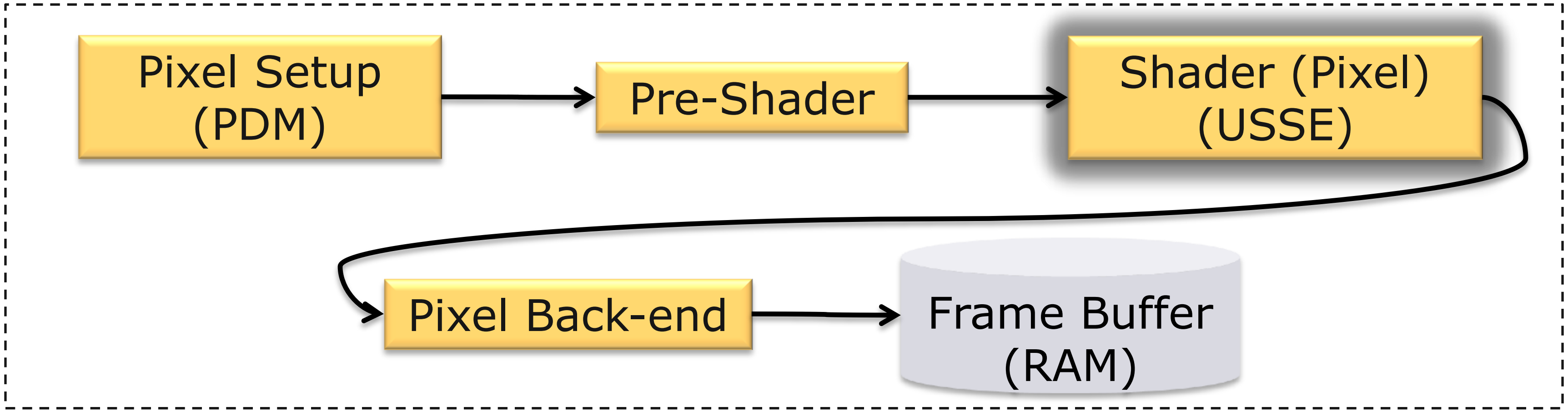


Pixel Shader

Multithreaded ALUs

Each thread can be vertices or pixels

Can have multiple USSEs in each GPU core

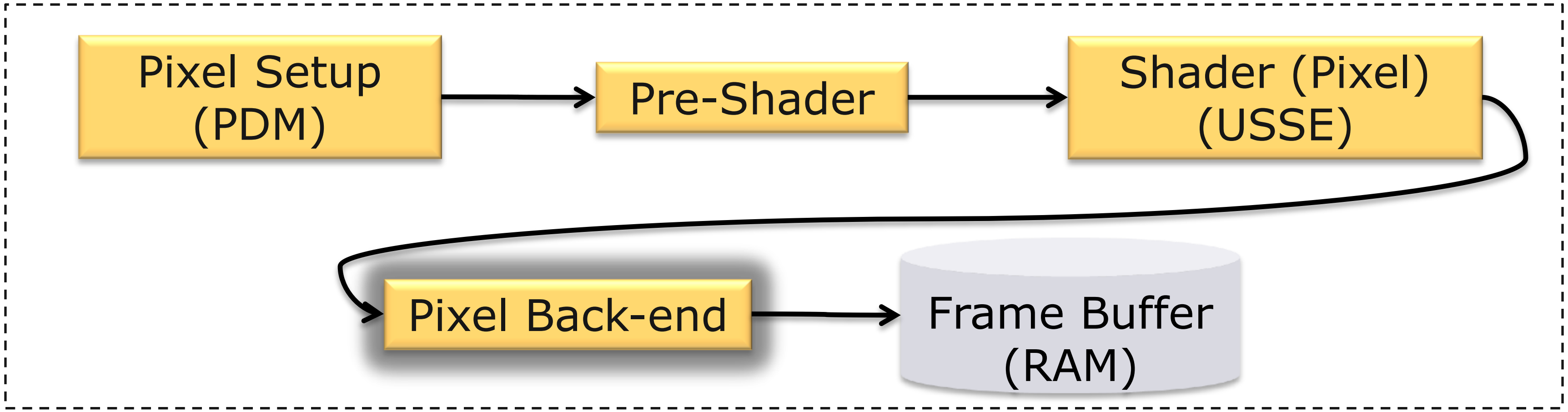


Pixel Back-end

Triggered when all pixels in the tile are finished

Performs data conversions, MSAA-downsampling

Writes finished tile color/depth/stencil to memory



Shader Unit Caveats

- Shader programs without dynamic flow-control:
  - 4 vertices/pixels per instruction
- Shader programs with dynamic flow-control:
  - 1 vertex/pixel per instruction
- Alpha-blending is in the shader
  - Not separate specialized hardware
  - Shader patching may occur when you switch state
  - (More on how to avoid shader patching later)

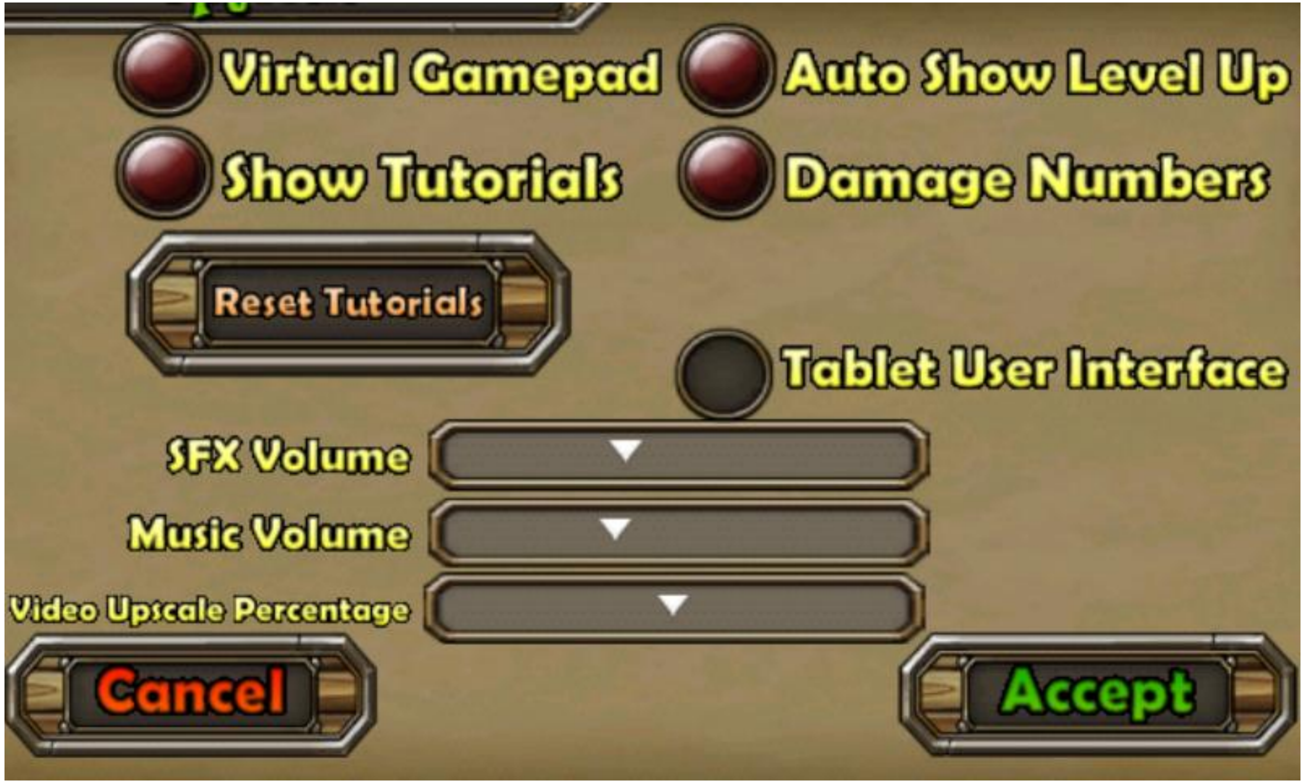
Rendering Techniques

- How to take advantage of this GPU?

Mobile is the new PC

- Wide feature and performance range
- Scalable graphics are back
- User graphics settings are back
  - Low/medium/high/ultra
  - Render buffer size scaling
- Testing 100 SKUs is back

Graphics Settings


Virtual Gamepad
Auto Show Level Up
Show Tutorials
Damage Numbers
Tablet User Interface
SFX Volume
Music Volume
Video Upscale Percentage

Render target is on die

- MSAA is cheap and use less memory
  - Only the resolved data in RAM
  - Have seen 0-5 ms cost for MSAA
  - Be wary of buffer restores (color or depth)
- No bandwidth cost for alpha-blend
- Cheap depth/stencil testing

“Free” hidden surface removal

- Specific to ImgTec SGX GPU
- Eliminates all background pixels
- Eliminates overdraw
- Only for opaque

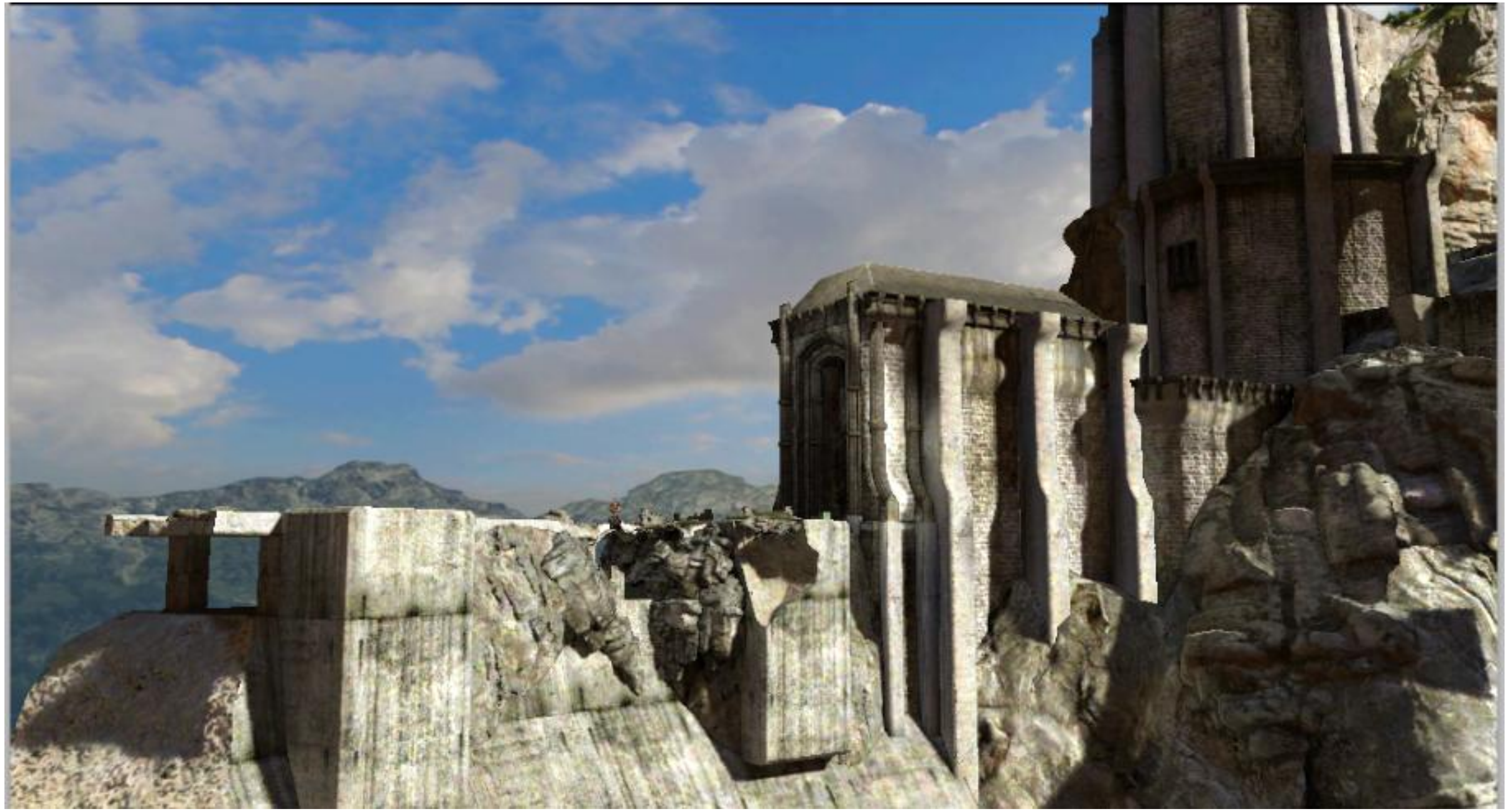
Mobile vs Console

- Very large CPU overhead for OpenGL ES API
  - Max CPU usage at 100-300 drawcalls
- Avoid too much data per scene
  - Parameter buffer between vertex & pixel processing
  - Save bandwidth and GPU flushes
- Shader patching
  - Some render states cause the shader to be modified and recompiled by the driver
  - E.g. alpha-blend settings, vertex input, color write masks, etc

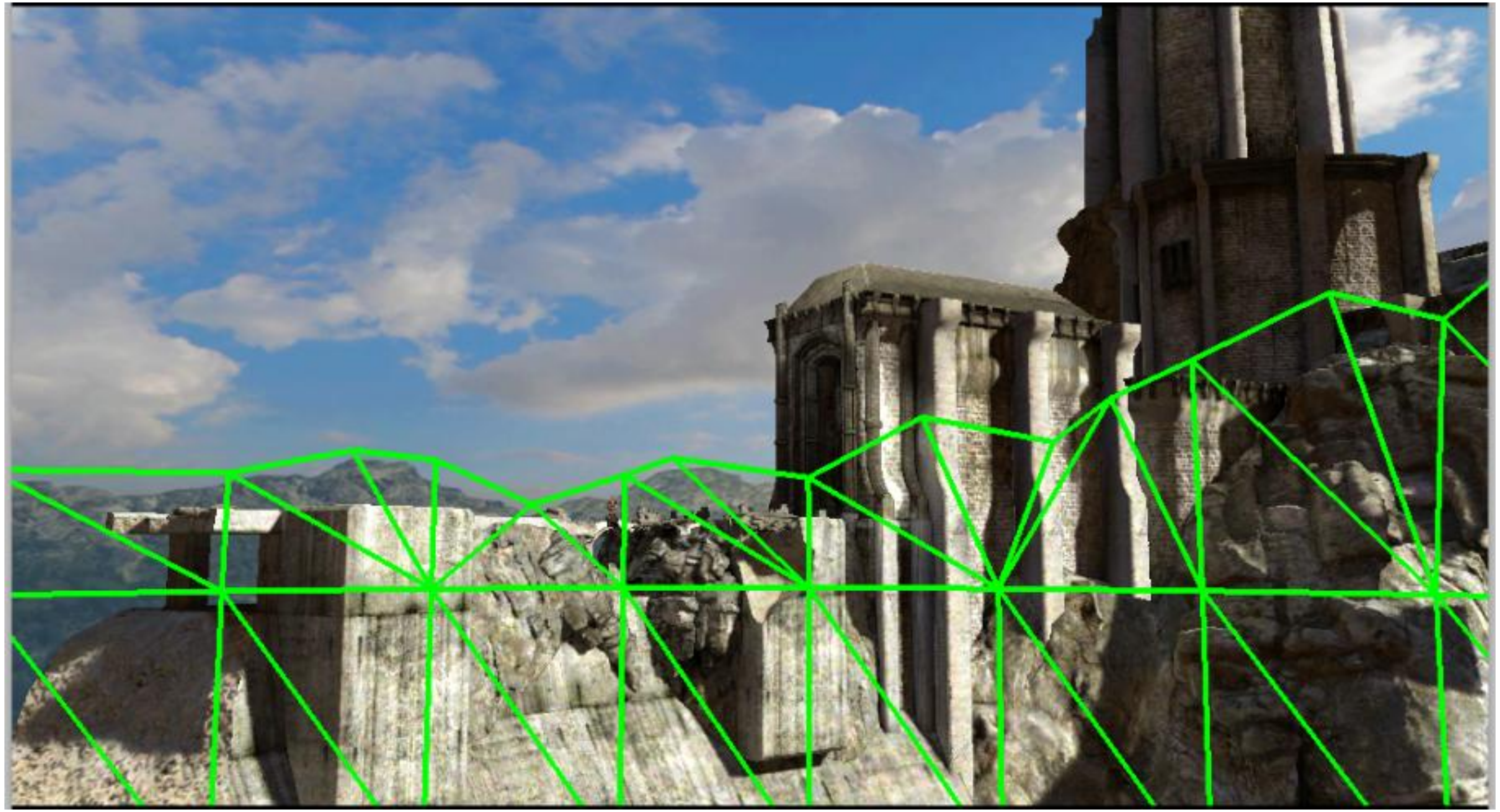
Alpha-test / Discard

- Conditional z-writes can be very slow
  - Instead of writing out Z ahead of time, the “Pixel setup” (PDM) won’t submit more fragments until the pixelshader has determined visibility for current pixels.
- Use alpha-blend instead of alpha-test
- Fit the geometry to visible pixels

Alpha-blended, form-fitted geometry



Alpha-blended, form-fitted geometry



Render Buffer Management (1 of 2)

- Each render target is a whole new scene
- Avoid switching render target back and forth!
- Can cause a full restore:
  - Copies full color/depth/stencil from RAM into Tile Memory at the beginning of the scene
- Can cause a full resolve:
  - Copies full color/depth/stencil from Tile Memory into RAM at the end of the scene

Render Buffer Management (2 of 2)

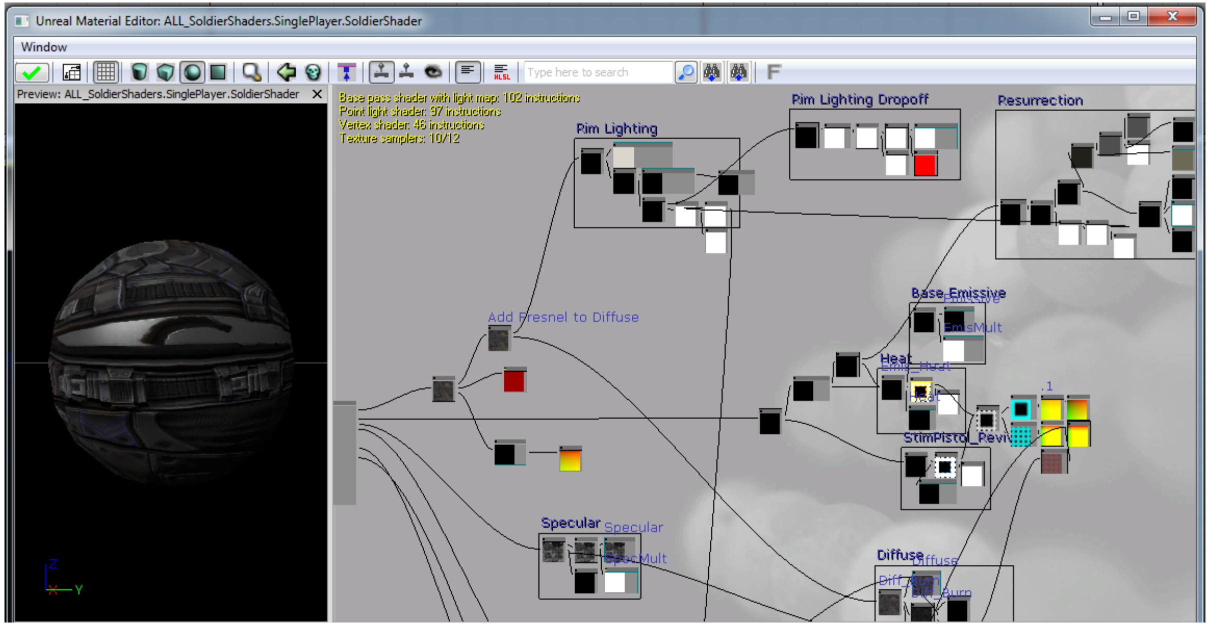
- Avoid buffer restore
  - Clear everything! Color/depth/stencil
  - A clear just sets some dirty bits in a register
- Avoid buffer resolve
  - Use discard extension (GL_EXT_discard_framebuffer)
  - See usage case for shadows
- Avoid unnecessarily different FBO combos
  - Don’t let the driver think it needs to start resolving and restoring any buffers!

Texture Lookups

- Don’t perform texture lookups in the pixel shader!
    - Let the “pre-shader” queue them up ahead of time
    - I.e. avoid dependent texture lookups
- Don’t manipulate texture coordinate with math
    - Move all math to vertex shader and pass down
- Don't use .zw components for texture coordinates
    - Will be handled as a dependent texture lookup
    - Only use .xy and pass other data in .zw

Mobile Material System

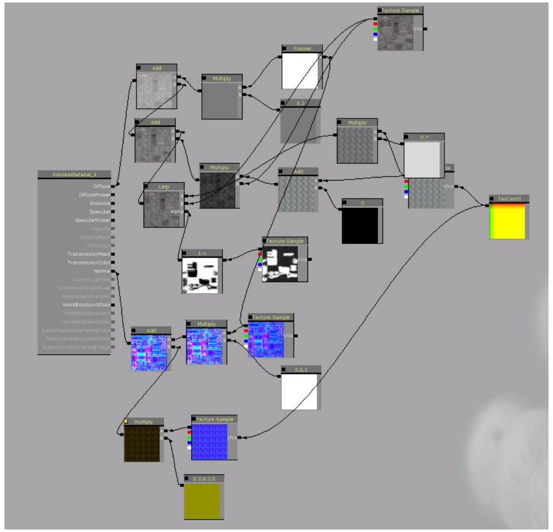
- Full Unreal Engine materials are too complicated

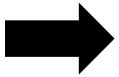

Unreal Material Editor: ALL_SoldierShaders.SinglePlayer.SoldierShader

Base pass shader with light map: 102 instructions
Point light shader: 97 instructions
Vertex shader: 46 instructions
Texture samplers: 10/12

Mobile Material System

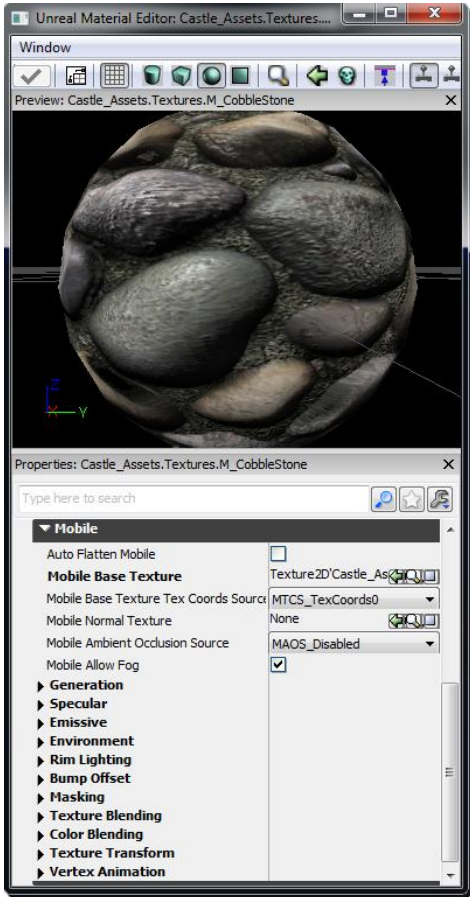
- Initial idea:
  - Pre-render into a single texture





Mobile Material System

- Current solution:
  - Pre-render components into separate textures
  - Add mobile-specific settings
  - Feature support driven by artists



Preview: Castle_Assets.Textures.M_CobbleStone

Properties: Castle_Assets.Textures.M_CobbleStone

Type here to search

▼ Mobile

Auto Flatten Mobile	☐
Mobile Base Texture	Texture2D'Castle_As
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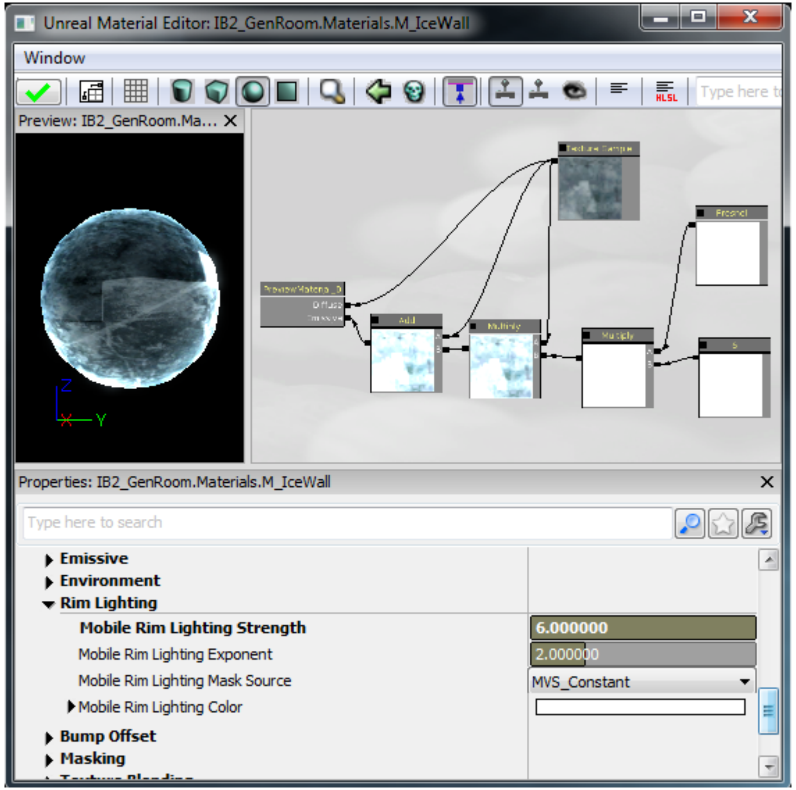
Mobile Normal Texture	None
Mobile Ambient Occlusion Source	MAOS_Disabled
Mobile Allow Fog	✓

- **Generation**
- **Specular**
- **Emissive**
- **Environment**
- **Rim Lighting**
- **Bump Offset**
- **Masking**
- **Texture Blending**
- **Color Blending**
- **Texture Transform**
- **Vertex Animation**

Mobile Material Shaders

- One hand-written ubershader
  - Lots of #ifdef for all features
  - Exposed as fixed settings in the artist UI
  - Checkboxes, lists, values, etc

Material Example: Rim Lighting



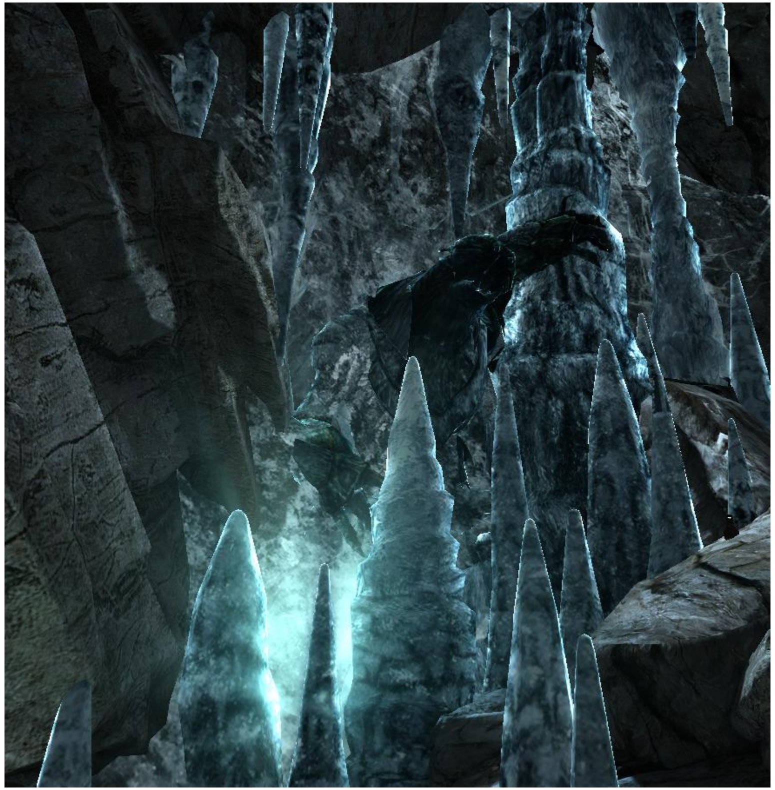
Properties: IB2_GenRoom.Materials.M_IceWall

Type here to search

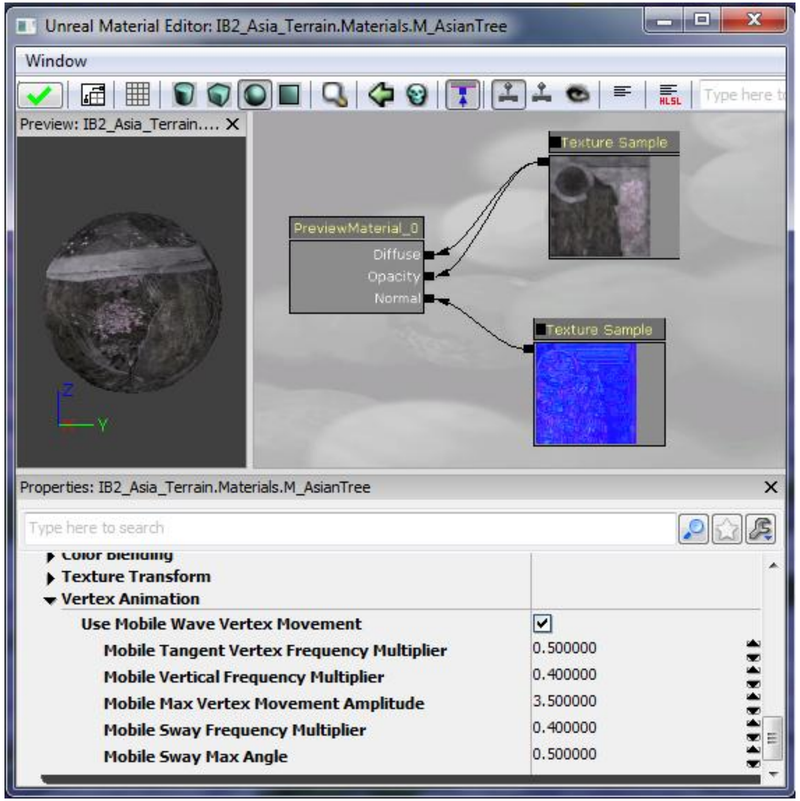
- Emissive
- Environment
- Rim Lighting

Mobile Rim Lighting Strength	6.000000
Mobile Rim Lighting Exponent	2.000000
Mobile Rim Lighting Mask Source	MVS_Constant
Mobile Rim Lighting Color	

- Bump Offset
- Masking
- Texture Blending



Material Example: Vertex Animation


Unreal Material Editor: IB2_Asia_Terrain.Materials.M_AsianTree
Window
Preview: IB2_Asia_Terrain....
Texture Sample
PreviewMaterial_0
Diffuse
Opacity
Normal
Texture Sample
Properties: IB2_Asia_Terrain.Materials.M_AsianTree
Type here to search
Color Blending
Texture Transform
Vertex Animation

Use Mobile Wave Vertex Movement	✓
Mobile Tangent Vertex Frequency Multiplier	0.500000
Mobile Vertical Frequency Multiplier	0.400000
Mobile Max Vertex Movement Amplitude	3.500000
Mobile Sway Frequency Multiplier	0.400000
Mobile Sway Max Angle	0.500000

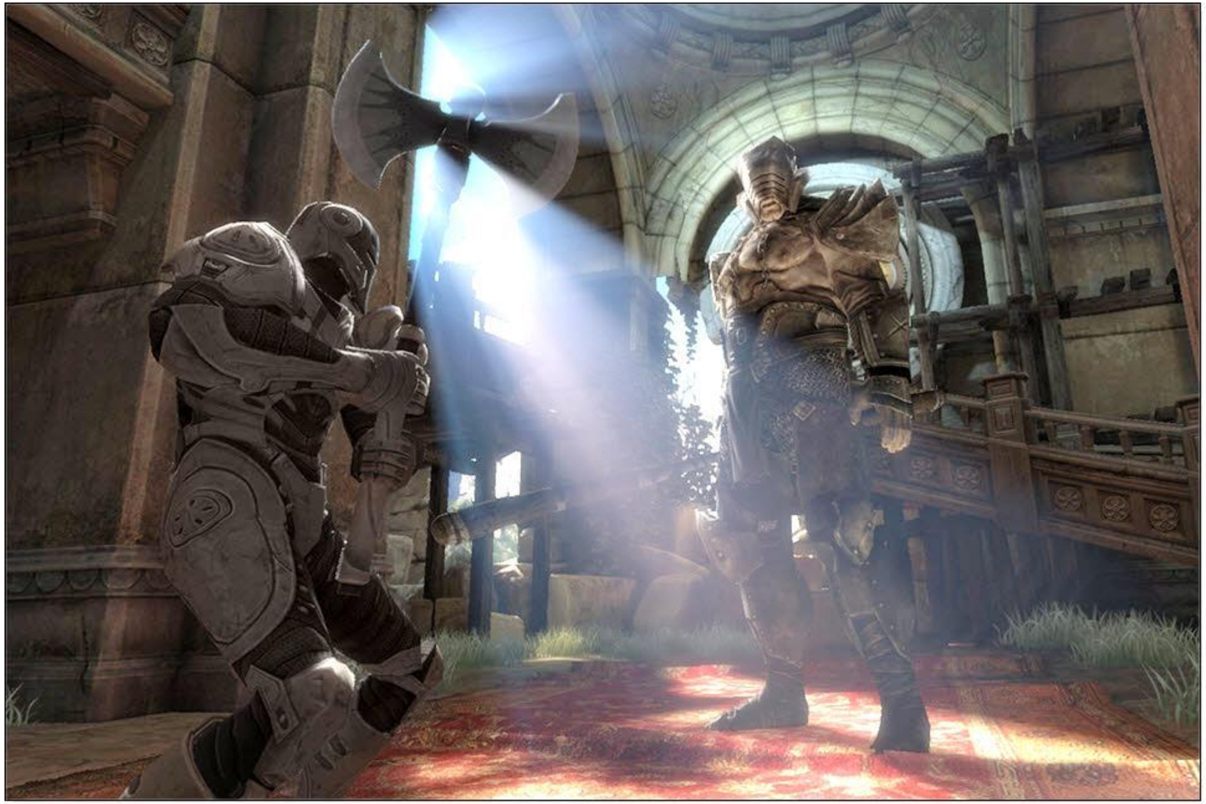
Shader Offline Processing

- Run C pre-processor offline
  - Reduces in-game compile time
  - Eliminates duplicates at off-line time

Shader Compiling

- Compile all shaders at startup
  - Avoids hitching at run-time
  - Compile on the GL thread, while loading on Game thread
- Compiling is not enough
  - Must issue dummy drawcalls!
  - Remember how certain states affect shaders!
  - May need experimenting to avoid shader patching
    E.g. alpha-blend states, color write masks

God Rays



God Rays

- Initially ported Xbox straight to PS Vita
  - Worked, but was very slow
- But for Infinity Blade II, on a cell phone!?
  - We first thought it was impossible
  - But let’s have a deeper look

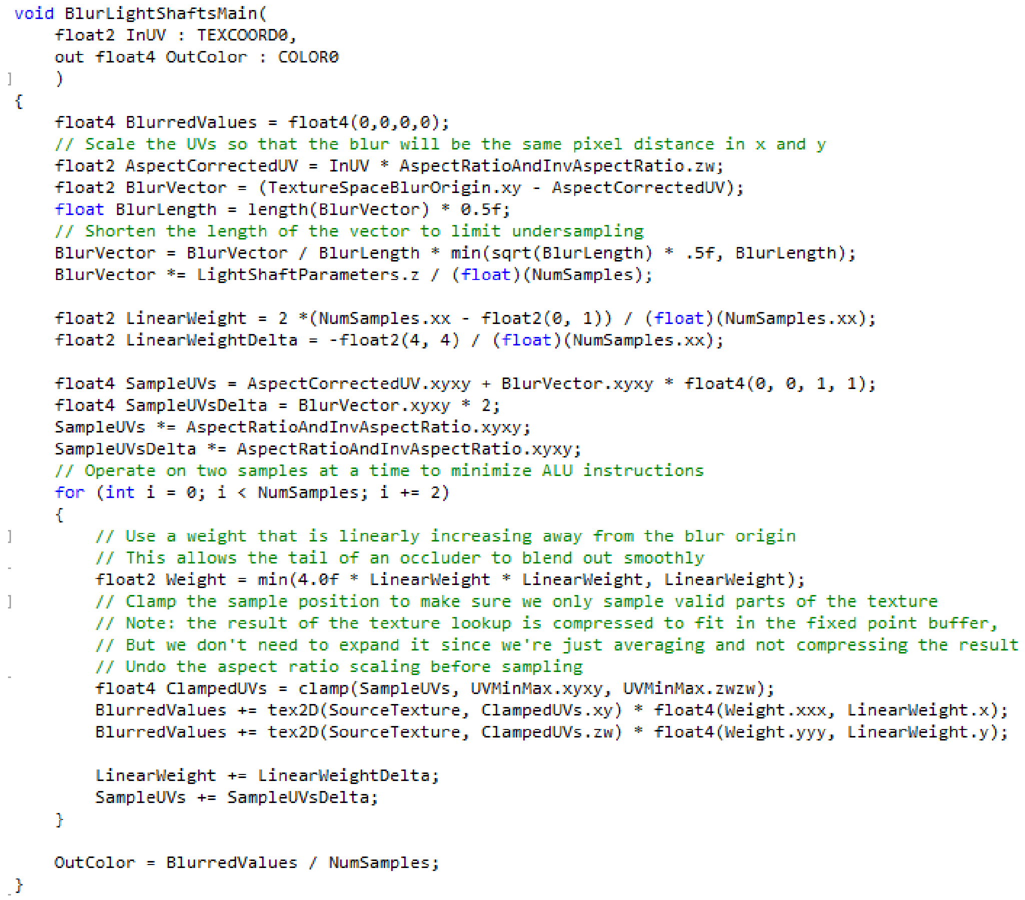
God Rays

- Port to OpenGL ES 2.0
- Use fewer texture lookups
  - Worse quality
  - And still very slow

Optimizations For Mobile

- Move all math to vertex shader
  - No dependent texture reads!
- Pass down data through interpolators
  - But, now we're out of interpolators ☹
- Split radial filter into 4 draw calls
  - 4 x 8 = 32 texture lookups total (equiv. 256)
- Went from 30 ms to 5 ms

Original Shader



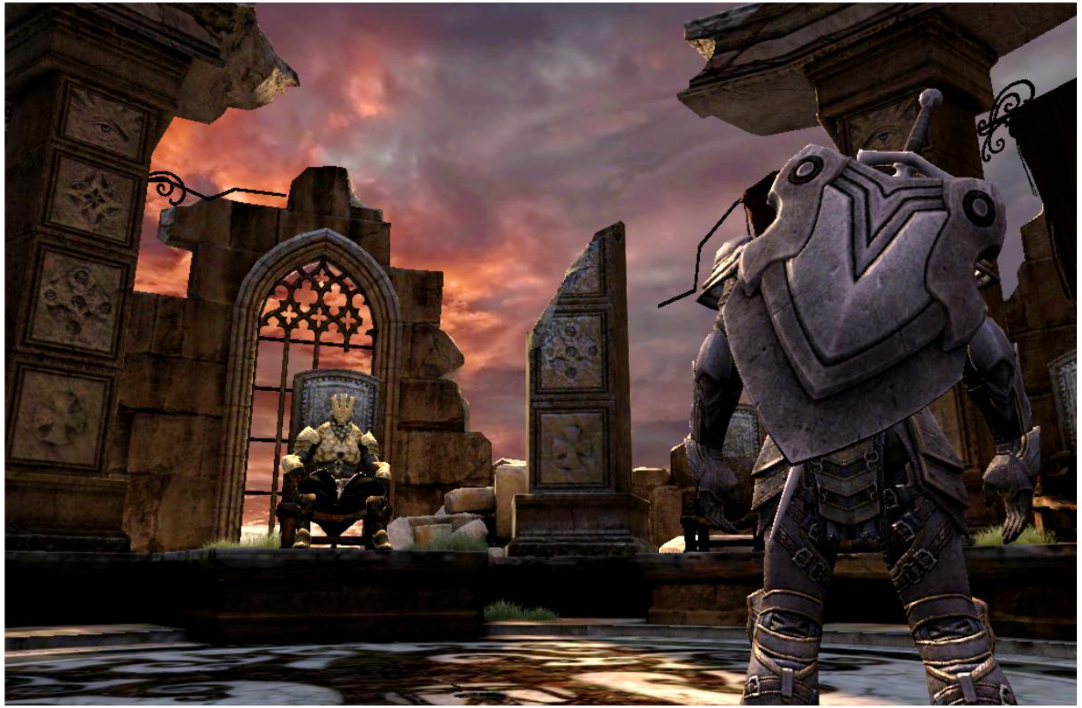
```
void BlurLightShaftsMain(
    float2 InUV : TEXCOORD0,
    out float4 OutColor : COLOR0
    )
{
    float4 BlurredValues = float4(0,0,0,0);
    // Scale the UVs so that the blur will be the same pixel distance in x and y
    float2 AspectCorrectedUV = InUV * AspectRatioAndInvAspectRatio.zw;
    float2 BlurVector = (TextureSpaceBlurOrigin.xy - AspectCorrectedUV);
    float BlurLength = length(BlurVector) * 0.5f;
    // Shorten the length of the vector to limit undersampling
    BlurVector = BlurVector / BlurLength * min(sqrt(BlurLength) * .5f, BlurLength);
    BlurVector *= LightShaftParameters.z / (float)(NumSamples);

    float2 LinearWeight = 2 *(NumSamples.xx - float2(0, 1)) / (float)(NumSamples.xx);
    float2 LinearWeightDelta = -float2(4, 4) / (float)(NumSamples.xx);

    float4 SampleUVs = AspectCorrectedUV.xyxy + BlurVector.xyxy * float4(0, 0, 1, 1);
    float4 SampleUVsDelta = BlurVector.xyxy * 2;
    SampleUVs *= AspectRatioAndInvAspectRatio.xyxy;
    SampleUVsDelta *= AspectRatioAndInvAspectRatio.xyxy;
    // Operate on two samples at a time to minimize ALU instructions
    for (int i = 0; i < NumSamples; i += 2)
    {
        // Use a weight that is linearly increasing away from the blur origin
        // This allows the tail of an occluder to blend out smoothly
        float2 Weight = min(4.0f * LinearWeight * LinearWeight, LinearWeight);
        // Clamp the sample position to make sure we only sample valid parts of the texture
        // Note: the result of the texture lookup is compressed to fit in the fixed point buffer,
        // But we don't need to expand it since we're just averaging and not compressing the result
        // Undo the aspect ratio scaling before sampling
        float4 ClampedUVs = clamp(SampleUVs, UVMinMax.xyxy, UVMinMax.zwzw);
        BlurredValues += tex2D(SourceTexture, ClampedUVs.xy) * float4(Weight.xxx, LinearWeight.x);
        BlurredValues += tex2D(SourceTexture, ClampedUVs.zw) * float4(Weight.yyy, LinearWeight.y);

        LinearWeight += LinearWeightDelta;
        SampleUVs += SampleUVsDelta;
    }

    OutColor = BlurredValues / NumSamples;
}
```

Mobile Shader

```
// BlurLightShaftsMain
void main()
{
    vec4 BlurredValues = vec4(0,0,0,0);
    BlurredValues += texture2D(SourceTexture, TexCoord0.xy);
    BlurredValues += texture2D(SourceTexture, TexCoord1.xy);
    BlurredValues += texture2D(SourceTexture, TexCoord2.xy);
    BlurredValues += texture2D(SourceTexture, TexCoord3.xy);
    BlurredValues += texture2D(SourceTexture, TexCoord4.xy);
    BlurredValues += texture2D(SourceTexture, TexCoord5.xy);
    BlurredValues += texture2D(SourceTexture, TexCoord6.xy);
    BlurredValues += texture2D(SourceTexture, TexCoord7.xy);
    gl_FragColor = BlurredValues / 16.0;
}
```

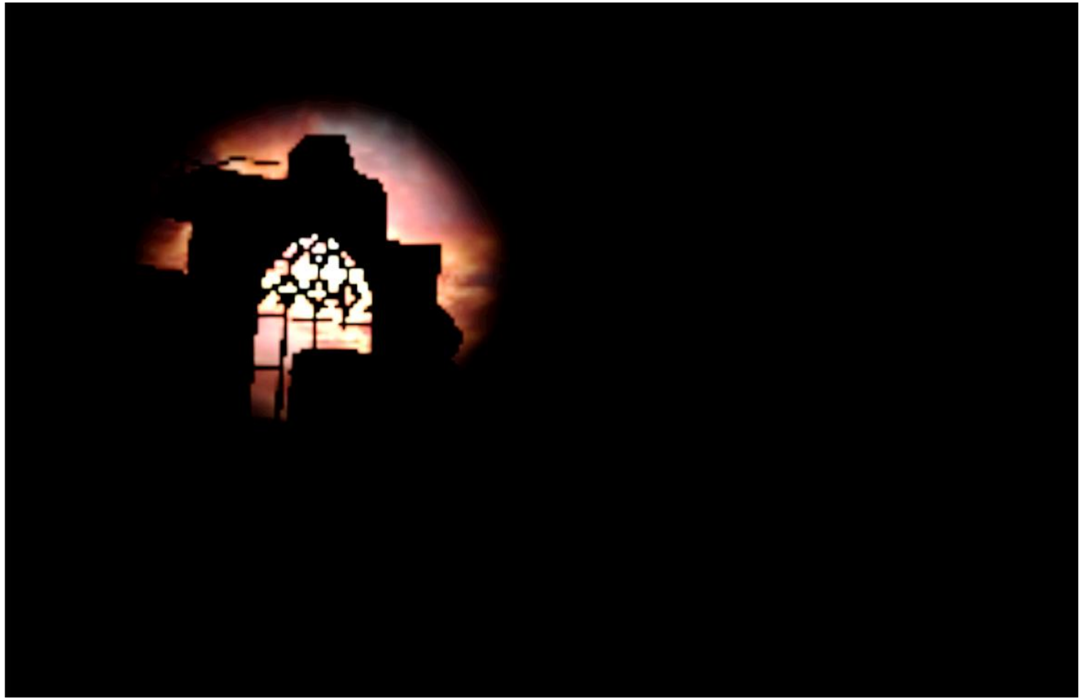
God Rays

- Original Scene
- No God Rays



1st Pass

- Downsample Scene
- Identify pixels
- RGB: Scene color
- A: Occlusion factor
- Resolve to texture:
    - "Unblurred source"

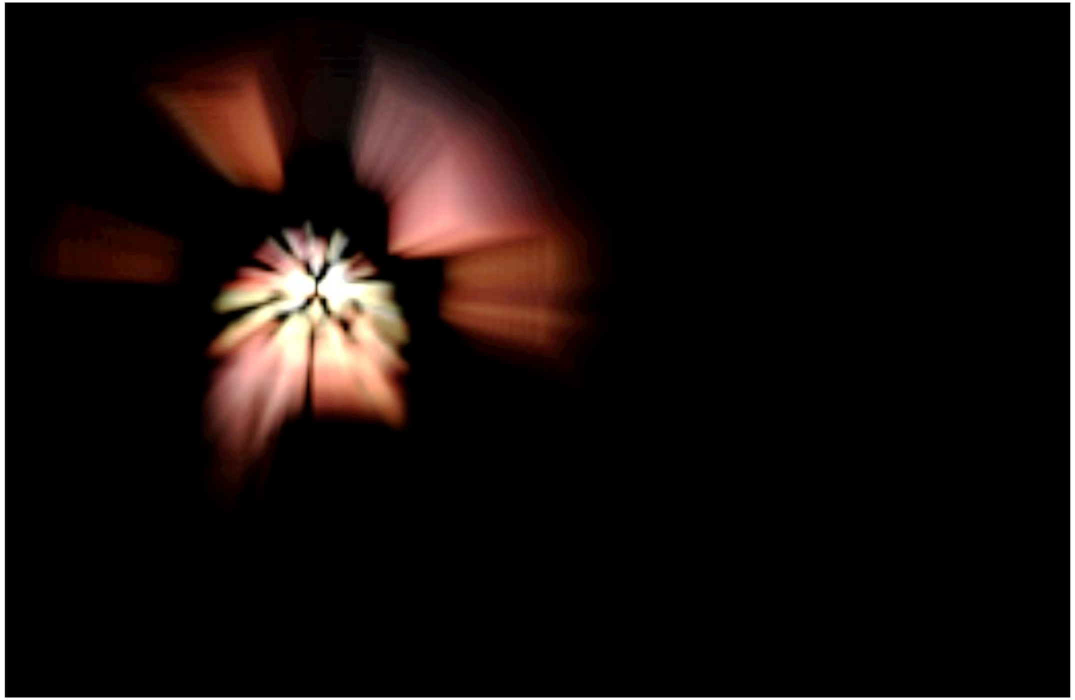


2nd Pass

- Average 8 lookups
  - From “Unblurred source”
  - 1st quarter vector
  - Uses 8 .xy interpolators
- Opaque draw call

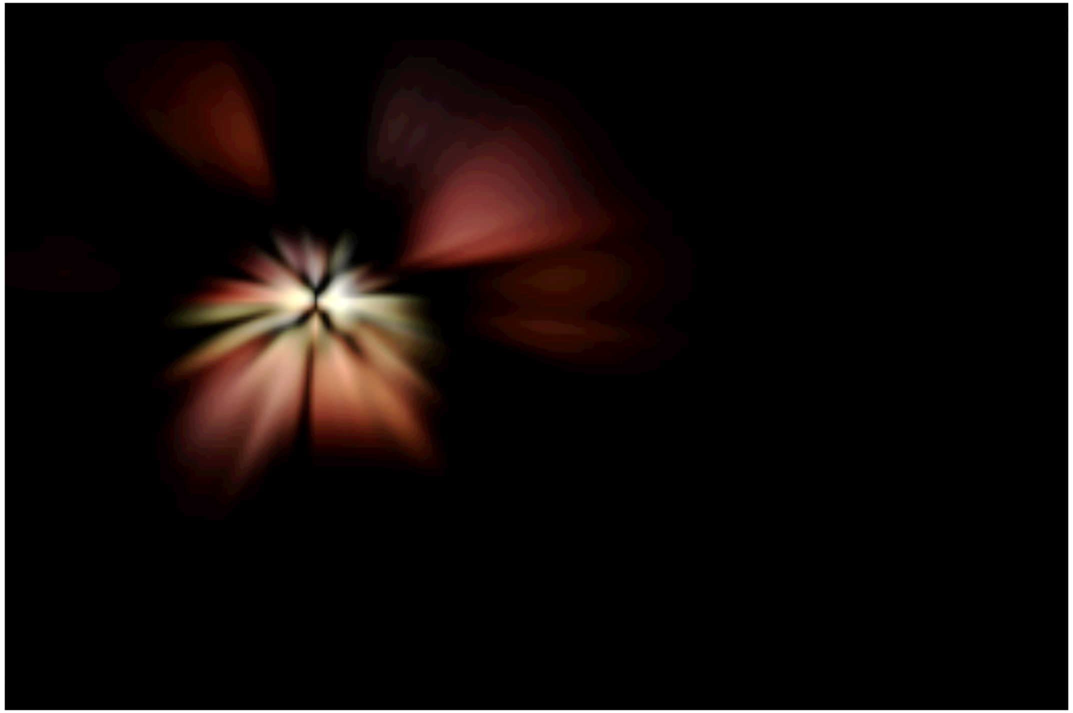
3rd Pass

- Average +8 lookups
  - From "Unblurred source"
  - 2nd quarter vector
  - Uses 8 .xy interpolators
- Additive draw call
- Resolve to texture:
  - *"Blurred source"*



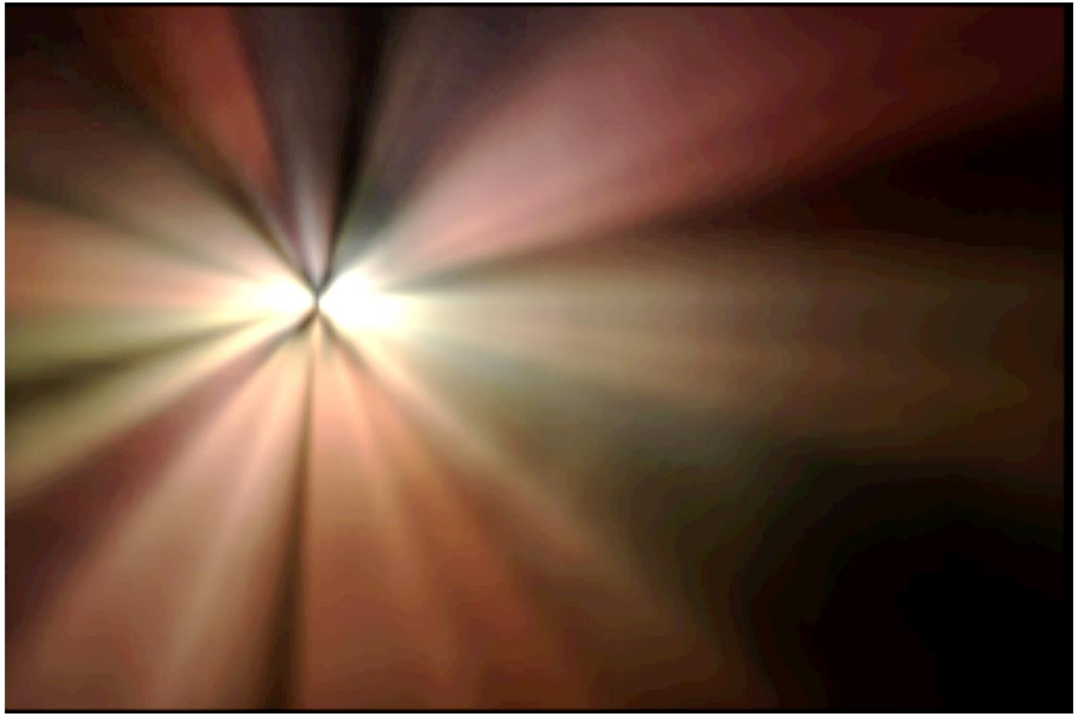
4th Pass

- Average 8 lookups
  - From "*Blurred source*"
  - 1st half vector
  - Uses 8 .xy interpolators
- Opaque draw call



5th Pass

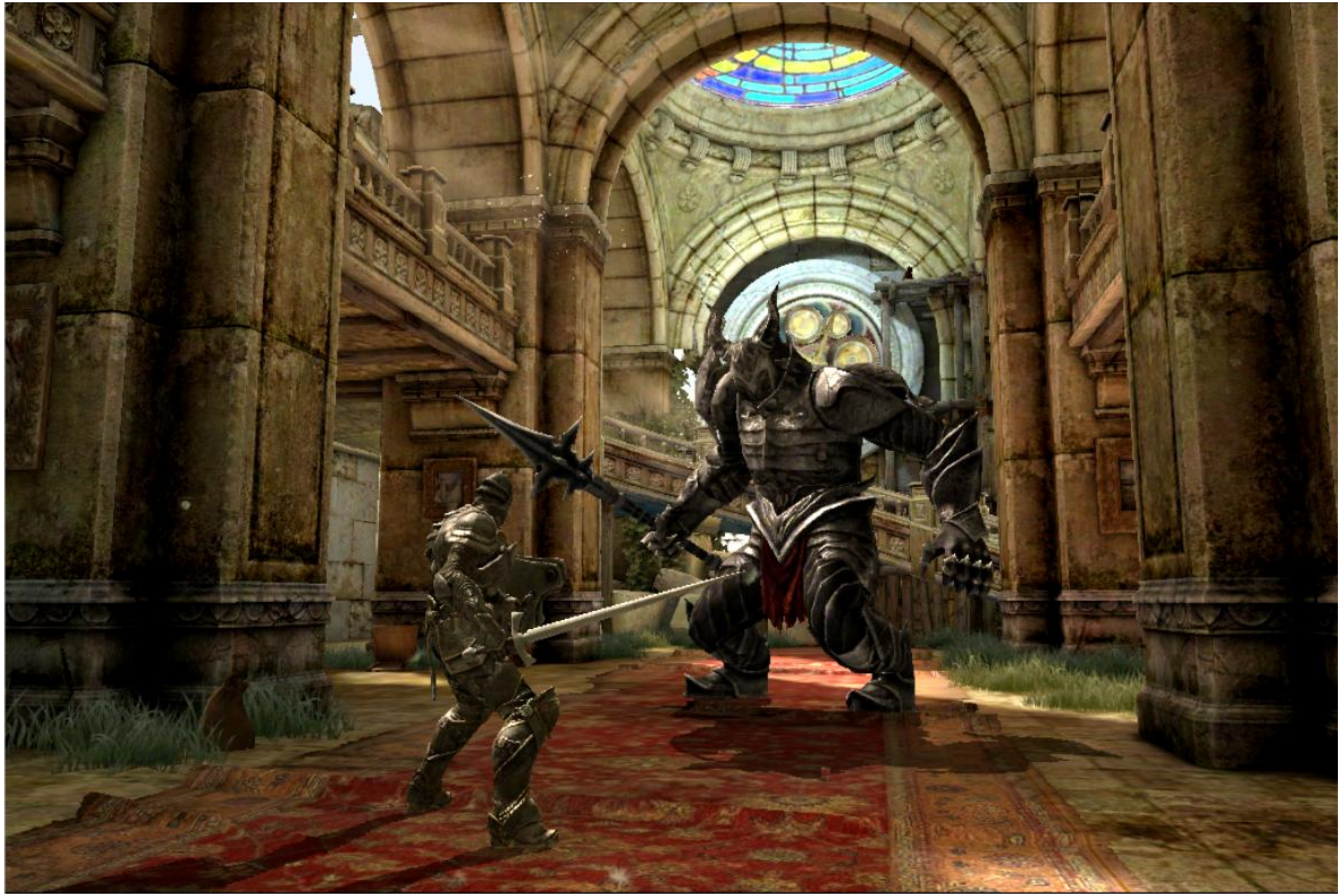
- Average +8 lookups
  - From "*Blurred source*"
  - 2nd half vector
  - Uses 8 .xy interpolators
- Additive draw call
- Resolve final result



6th Pass

- Clear the final buffer
  - Avoids buffer restore
- Opaque fullscreen
- Screenblend apply
  - Blend in pixelshader

Character Shadows

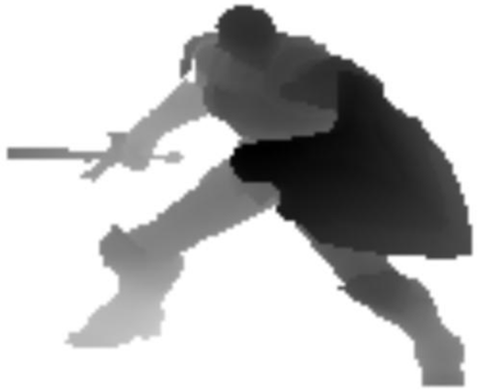


Character Shadows

- Ported one type of shadows from Xbox:
  - Projected, modulated dynamic shadows
- Fairly standard method
  - Generate shadow depth buffer
  - Stencil potential pixels
  - Compare shadow depth and scene depth
  - Darken affected pixels

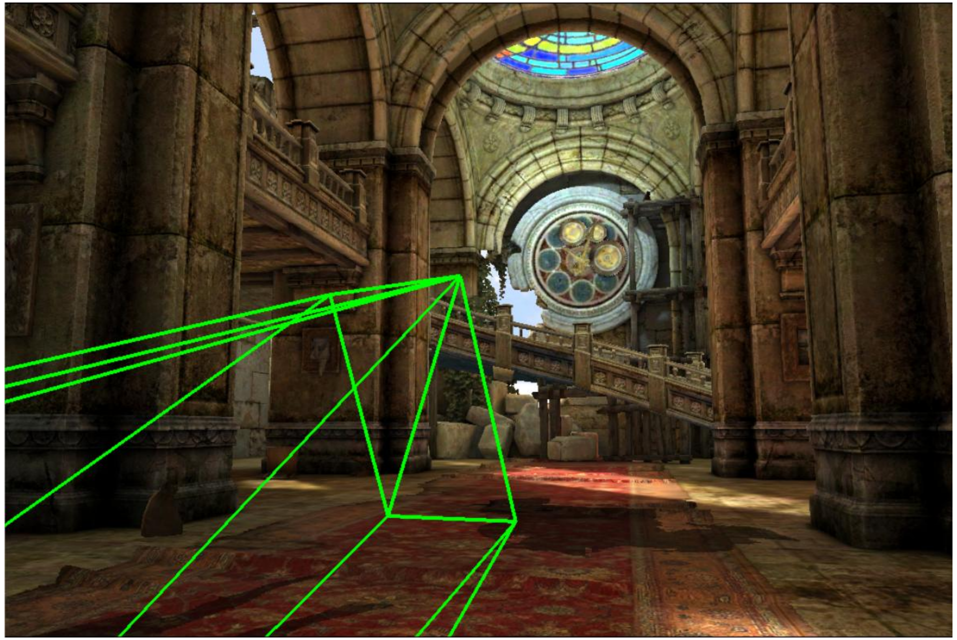
Character Shadows

1. Project character depth from light view



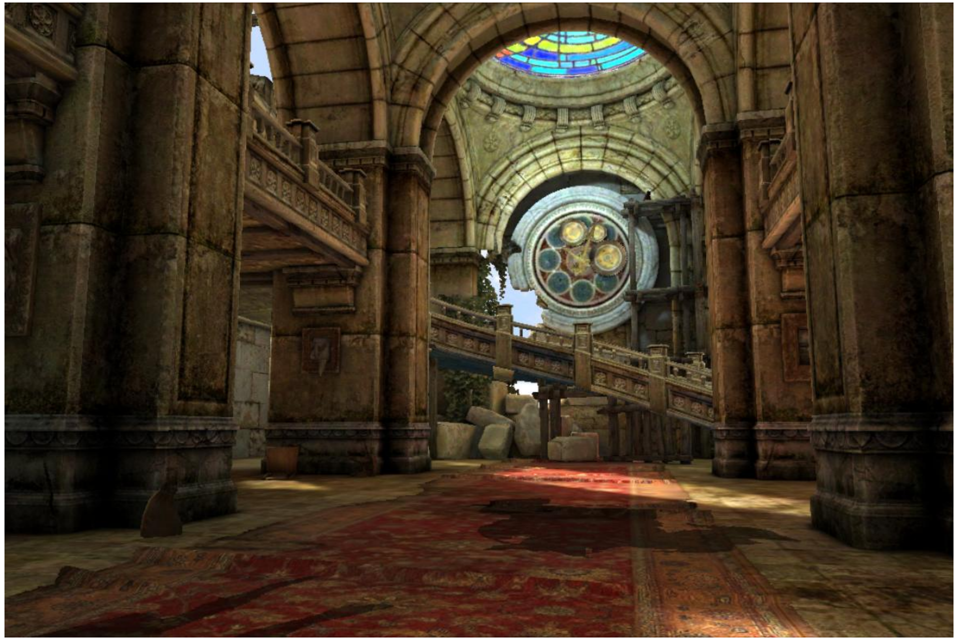
Character Shadows

2. Reproject into camera view



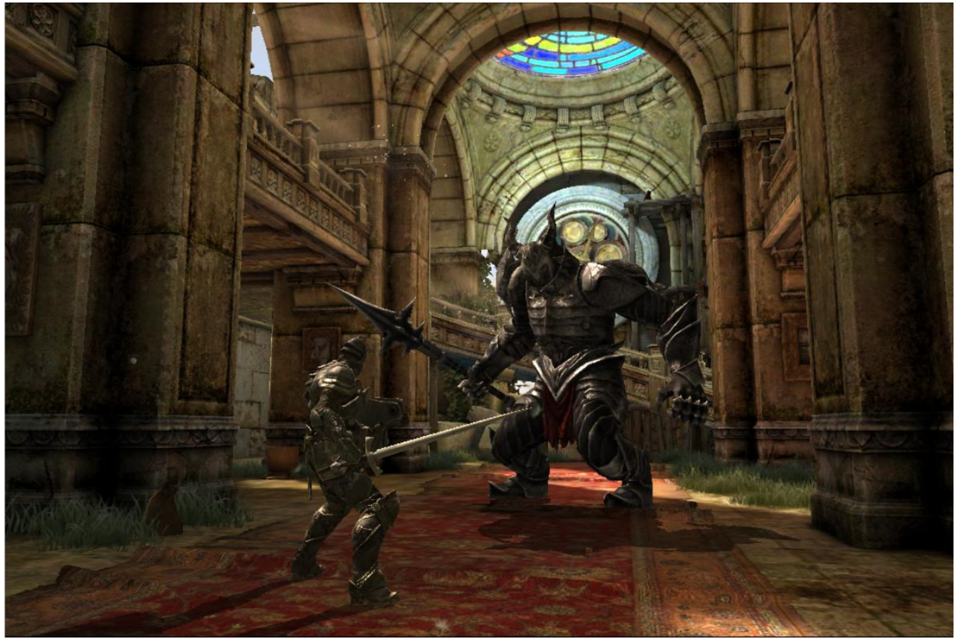
Character Shadows

3. Compare with SceneDepth and modulate



Character Shadows

4. Draw character on top (no self-shadow)



Shadow Optimizations (1 of 2)

- Shadow depth first in the frame
  - Avoids a rendertarget switch (resolve & restore!)
- Resolve SceneDepth just before shadows*
  - Write out tile depth to RAM to read as texture
  - Keep rendering in the same tile
  - Unfortunately no API for this in OpenGL ES

Shadow Optimizations (2 of 2)

- Optimize color buffer usage for shadow
  - We only need the depth buffer!
  - Unnecessary buffer, but required in OpenGL ES
  - Clear (avoid restore) and disable color writes
  - Use glDiscardFrameBuffer() to avoid resolve
  - Could encode depth in F16 / RGBA8 color instead
- Draw screen-space quad instead of cube
  - Avoids a dependent texture lookup

Tool Tips:

- Use an OpenGL ES wrapper on PC
  - Almost "WYSIWYG"
  - Debug in Visual Studio
- Apple Xcode GL debugger, iOS 5
  - Full capture of one frame
  - Shows each drawcall, states in separate pane
  - Shows all resources used by each drawcall
  - Shows shader source code + all uniform values

Next Generation

ImgTec “Rogue” (6xxx series):

20x

ImgTec 6xxx series

- 100+ GFLOPS (scalable to TFLOPS range)
- DirectX 10, OpenGL ES “Halti”
- PVRTC 2
- Improved memory bandwidth usage
- Improved latency hiding

Questions?

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EPIC GAMES