Performance Optimization and Debugging Mobile Games

Lorenzo Dal Col
GPU Tools Product Manager

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The Architecture for the Digital World®

Agenda

1. Introduction to performance analysis with ARM® software tools
2. Analyse the performance of Epic Citadel
   - Software Profiling
   - GPU Profiling
   - Using the ARM® Mali™ GPU hardware counters to find the bottleneck
3. Debugging with Mali Graphics Debugger
   - Overdraw and frame analysis
4. Use cases from Gameloft
5. Q & A

Games and Demos

ARM

Importance of Analysis & Debug

- Mobile Platforms
  - Expectation of amazing console-like graphics and playing experience
  - Screen resolution beyond HD
  - Limited power budget

- Solution
  - ARM® Cortex® CPUs and Mali™ GPUs are designed for low power whilst providing innovative features to keep up performance
  - Software developers can be "smart" when developing apps
  - Good tools can do the heavy lifting

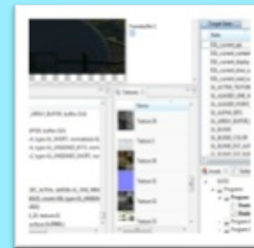
Performance Analysis & Debug

ARM® DS-5 Streamline Performance Analyzer

• System-wide performance analysis

• Combined ARM Cortex® Processors and Mali™ GPU visibility

• Optimize for performance & power across the system



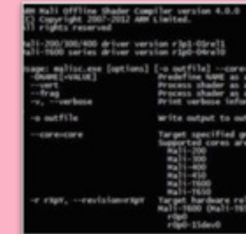
ARM Mali Graphics Debugger

• API Trace & Debug Tool

• Understand graphics and compute issues at the API level

• Debug and improve performance at frame level

• Support for OpenGL® ES 1,1, 2.0, 3.0 and OpenCL™ 1.1



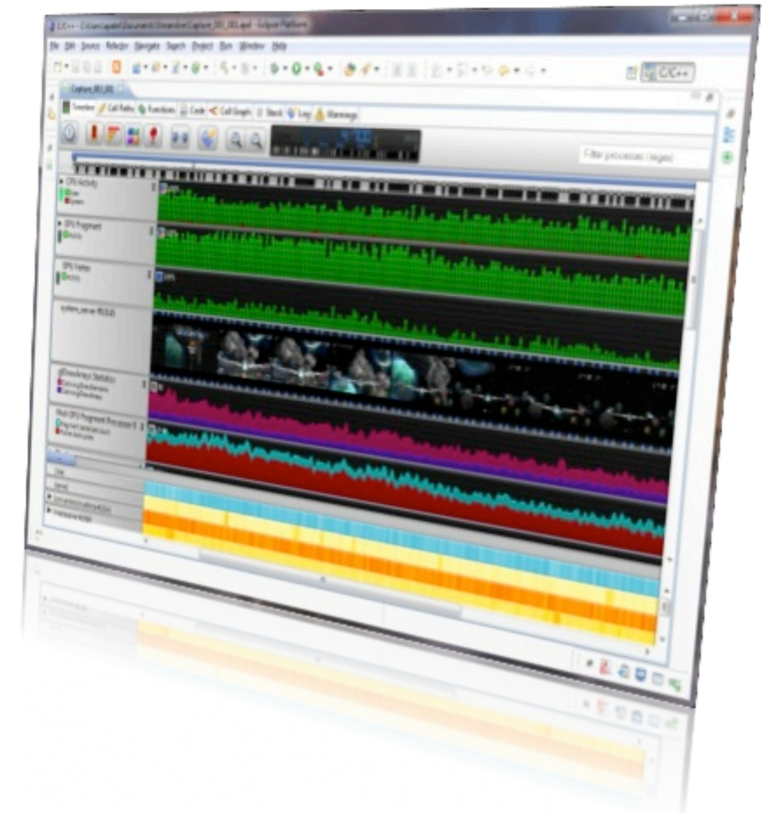
Offline Compilers

• Understand complexity of GLSL shaders and CL kernels

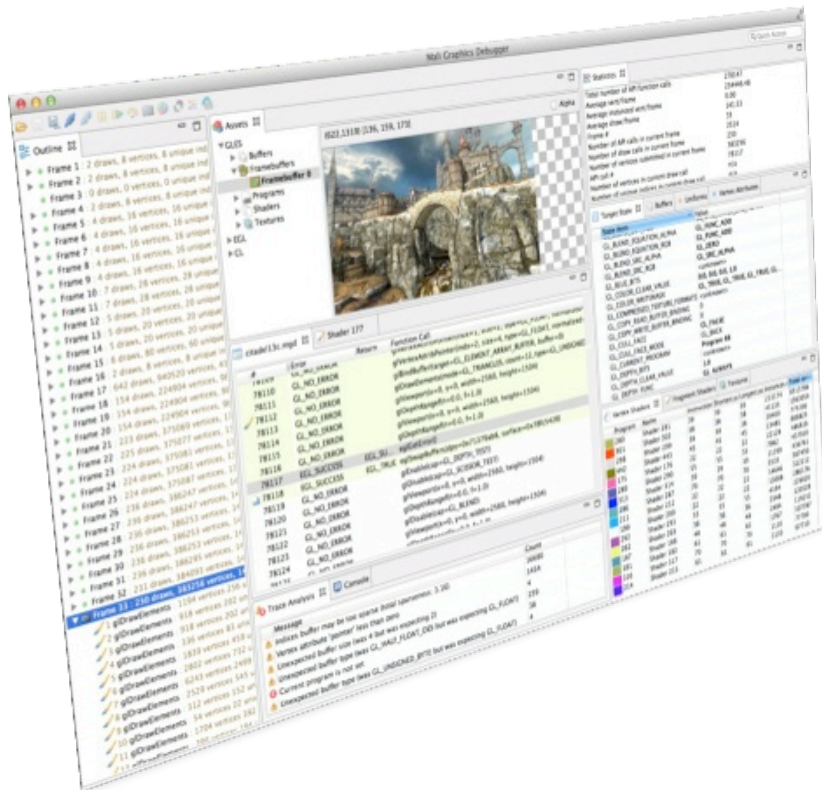
• Support for ARM Mali-4xx and Mali-T6xx GPU families

ARM® DS-5 Streamline Performance Analyzer

- System Wide Performance Analysis
  - Simultaneous visibility across ARM Cortex® processors & Mali™ GPUs
  - Support for graphics and GPU Compute performance analysis on Mali-T600 series
  - Timeline profiling of hardware counters for detailed analysis
  - Custom counters
  - Per-core/thread/process granularity
  - Frame buffer capture and display
- Optimize
  - Performance
  - Energy efficiency
  - Across the system



ARM® Mali™ Graphics Debugger



- Graphics debugging for content developers
- API level tracing
- Understand issues and causes at frame level
- Support for OpenGL® ES 2.0, 3.0, EGL™ & OpenCL™ 1.1
- Complimentary to DS-5 Streamline

v1.2.2 released in February
v1.3 will be available soon

ARM

Investigation with the ARM® Mali™ Graphics Debugger

Frame Outline

Assets View

Frame Statistics

States
Uniforms
Vertex Attributes
Buffers

Framebuffer /
Render Targets

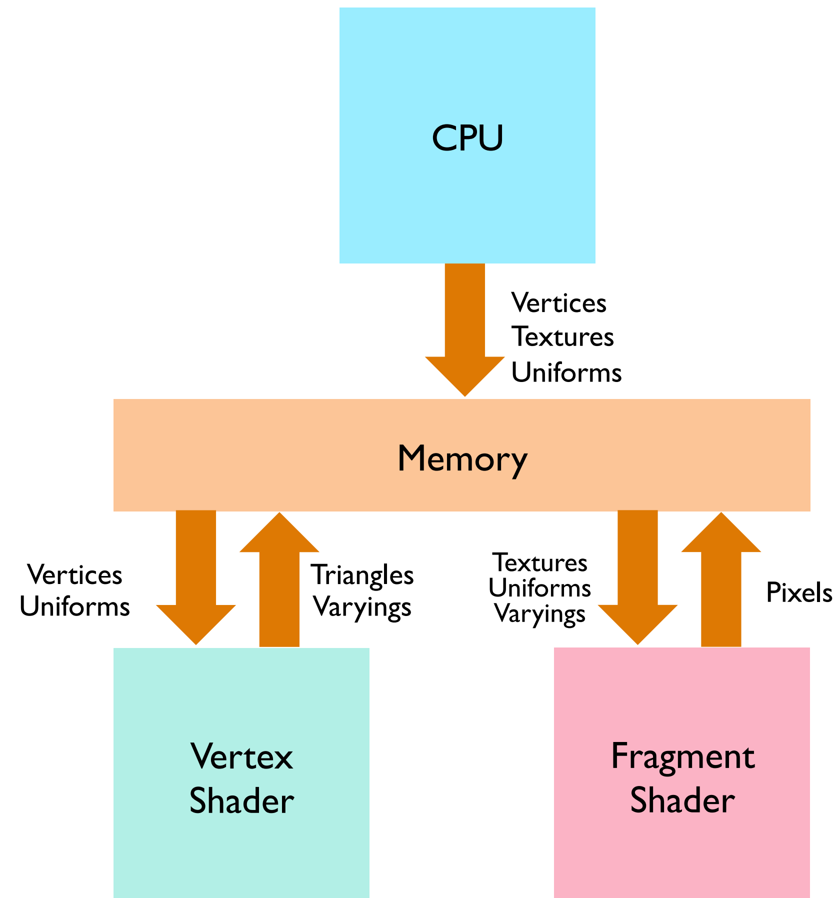
API Trace

Textures
Shaders

Dynamic Help

Main Bottlenecks

- **CPU**
  - Too many draw calls
  - Complex physics
- **Vertex processing**
  - Too many vertices
  - Too much computation per vertex
- **Fragment processing**
  - Too many fragments, overdraw
  - Too much computation per fragment
- **Bandwidth**
  - Big and uncompressed textures
  - High resolution framebuffer
- **Battery life**
  - Energy consumption strongly affects User Experience



ARM

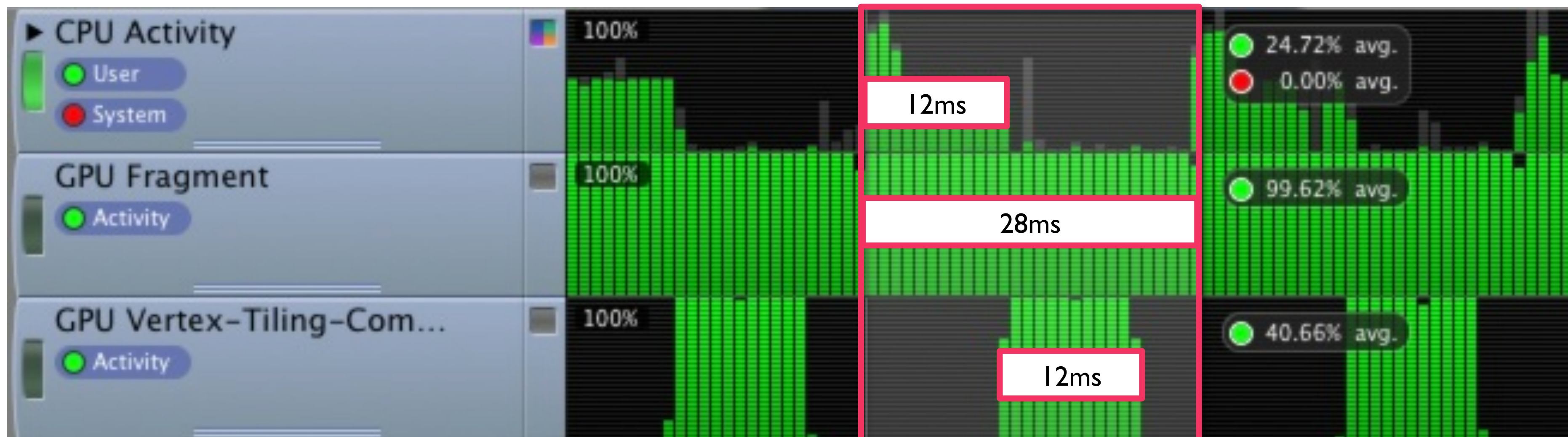
Epic Citadel

ARM

0.1s [1000ms]
CPU Activity
User
System
GPU Fragment
Activity
GPU Vertex-Tiling-Com...
Activity
Mali Job Manager Cycles
GPU cycles
JS0 cycles
JS1 cycles
JS2 cycles
Mali Arithmetic Pipe
A instructions
Mali Core Cycles
Fragment cycles
Tripipe cycles
Mali Load/Store Pipe
LS instruction issues
24.28% avg.
0.00% avg.
24.21% avg.
0.00% avg.
99.51% avg.
43.64% avg.
448,148,797
447,561,699
195,511,391
0
105,103,042
447,293,472
444,408,368
407,103,125
194,919,247
CPU Activity → User 24%
GPU Fragment → Activity 99%
GPU Vertex → Activity 44%
[idle]
[kernel]
[com.epicgames.EpicCitadel #1932]
[surfaceflinger #129]
[mediaserver #132]
[adbd #139]
[system_server #465]
[com.android.vending #1109]
[com.android.systemui #538]
[gatord #1990]

The Application is GPU bound

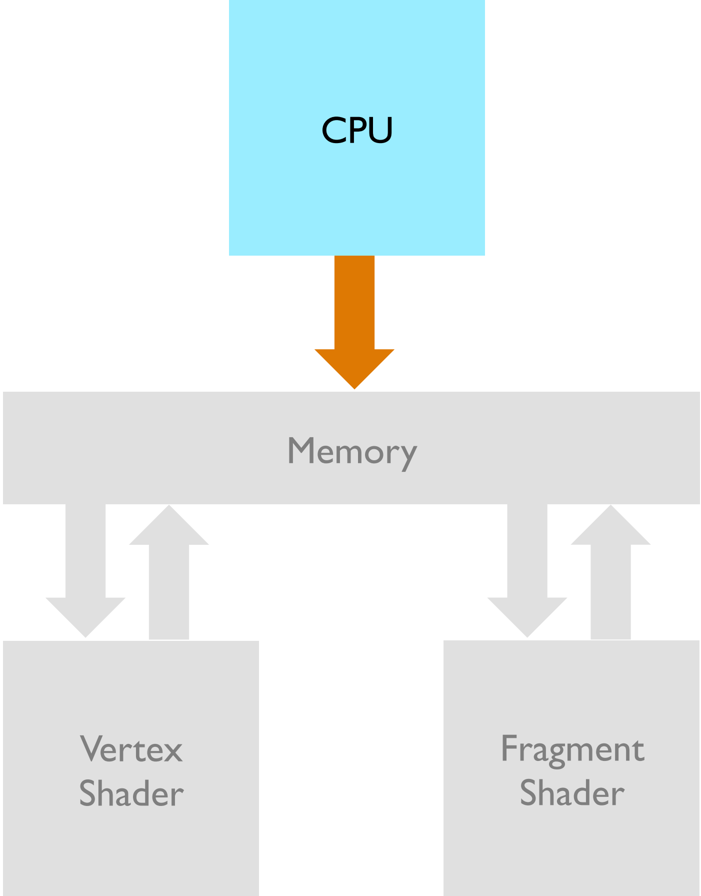
The CPU has to wait until the fragment processing has finished



While rendering the most complicated scene, the application is capable of 36 fps (29ms/frame)

ARM

CPU Bound

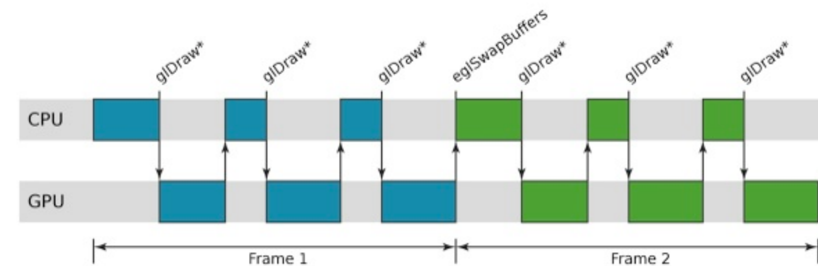


ARM

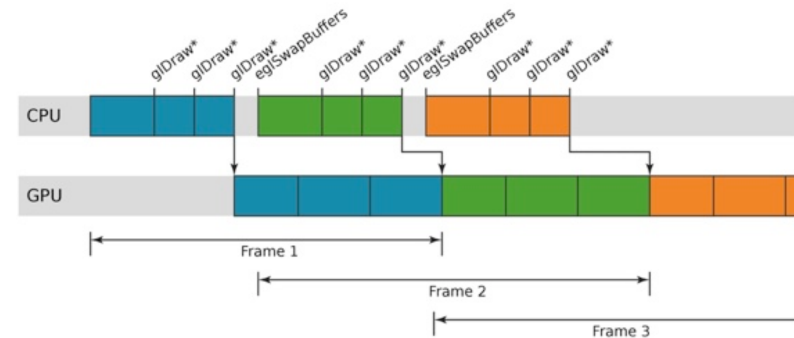
CPU Bound

- Mali GPU is a deferred architecture
  - Do not force a pipeline flush by reading back data (glReadPixels, glFinish, etc.)
  - Reduce the amount of draw calls
  - Try to combine your draw calls together
- Offload some of the work to the GPU
  - Move physics from CPU to GPU
- Avoid unnecessary OpenGL® ES calls (glGetError, redundant stage changes, etc.)

Synchronous Rendering



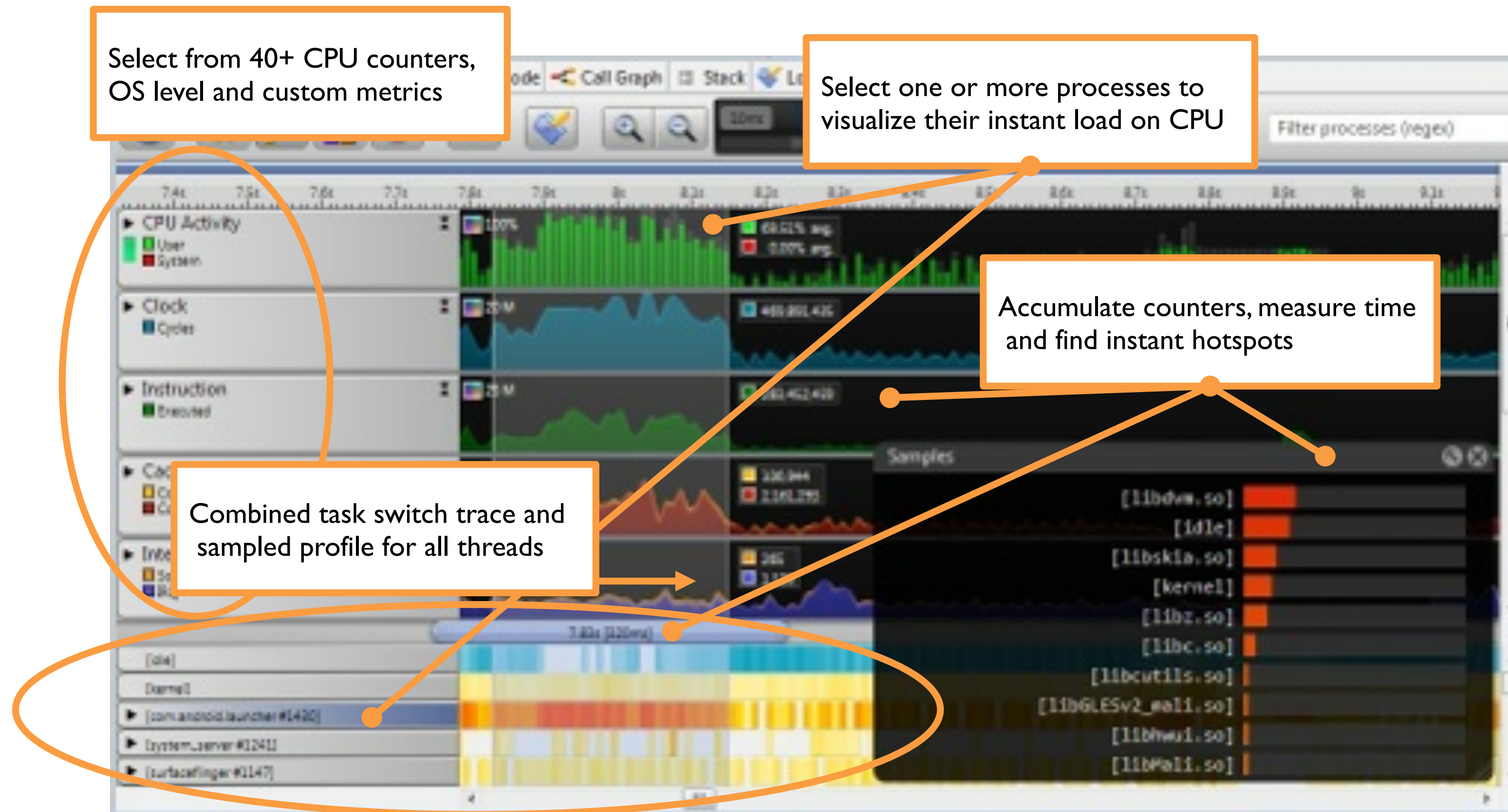
Deferred Rendering



ARM

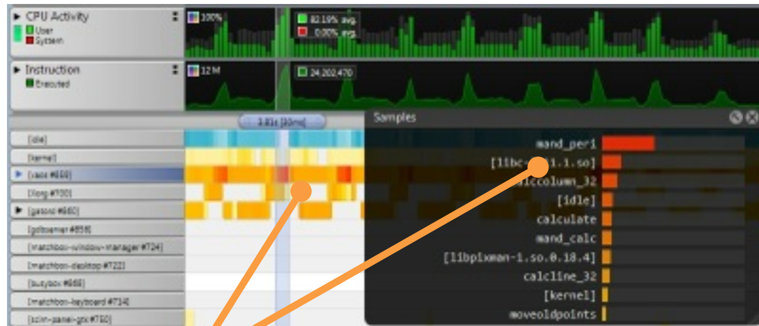
Timeline: The Big Picture

Find hotspots, system glitches, critical conditions at a glance



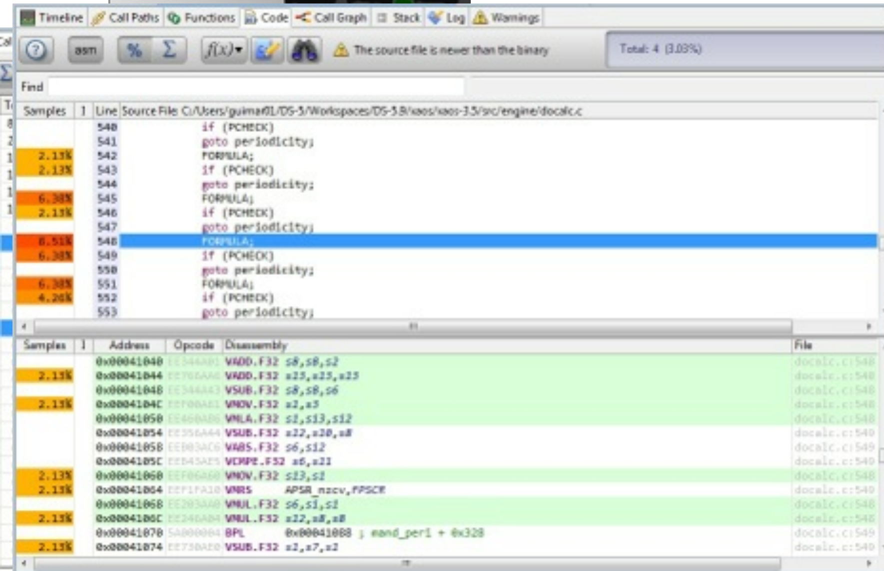
ARM

Drilldown Software Profiling



Quickly identify instant hotspots

Filter timeline data to generate focused software profile reports

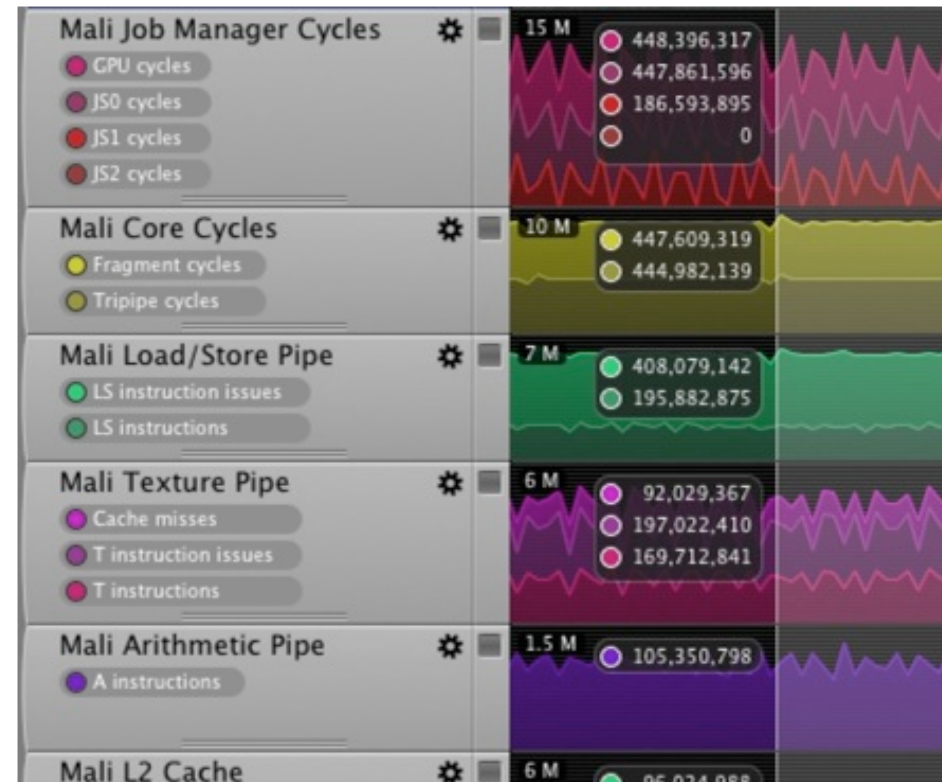


Click on the function name to go to source code level profile

GPU Activity Analysis

ARM® Mali™ GPU Hardware Counters

- Over the highlighted time of one second the GPU was active for 448m cycles (*Mali Job Manager Cycles* → *GPU cycles*)
- With this hardware, the maximum number of cycles is 450m
- A first pass of optimization would lead to a higher frame rate
- After reaching V-SYNC, optimization can lead to saving energy and to a longer play time

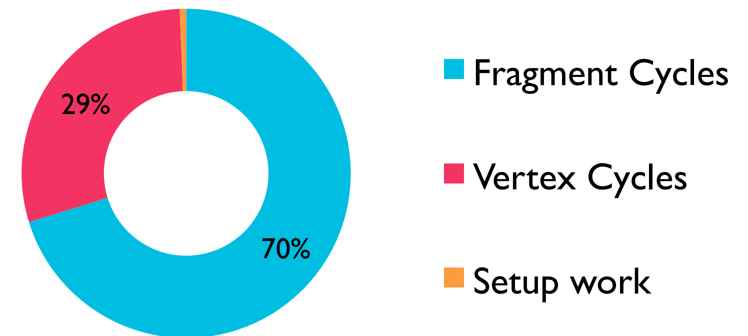


ARM

Vertex and Fragment Processing

- GPU is spending:
  - **186m** (29%) on vertex processing
    (*ARM® Mali™ Job Manager Cycles* → *JS1 cycles*)
  - **448m** (70%) on fragment processing
    (*Mali Job Manager Cycles* → *JS0 cycles*)

Ratio between vertex and fragment activity

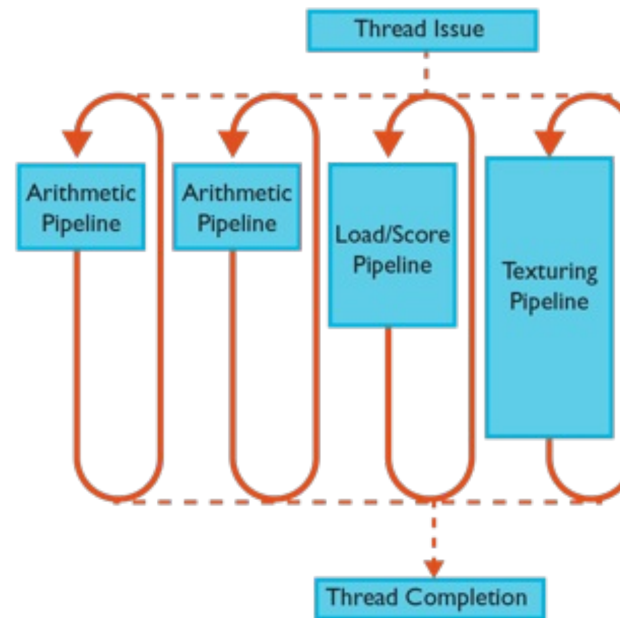


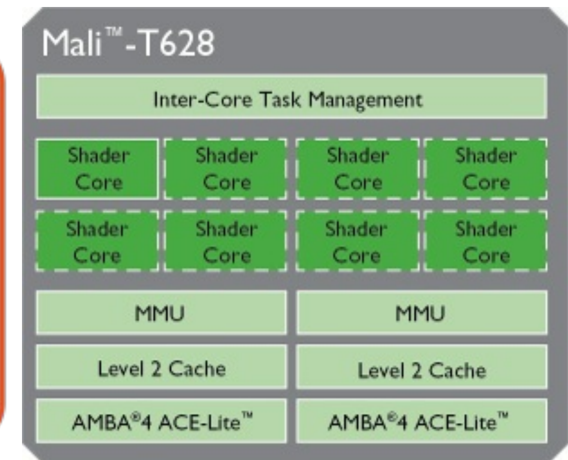
There might be an overhead in the job manager trying to optimize vertex list packing into jobs.

ARM

ARM® Mali™-T628 GPU Tripipe Cycles

- Arithmetic instructions
  - Math in the shaders
- Load & Store instructions
  - Uniforms, attributes and varyings
- Texture instructions
  - Texture sampling and filtering



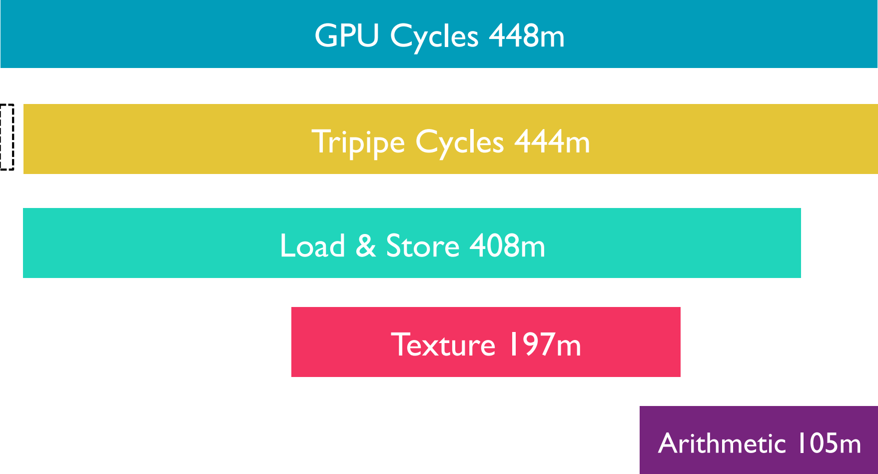


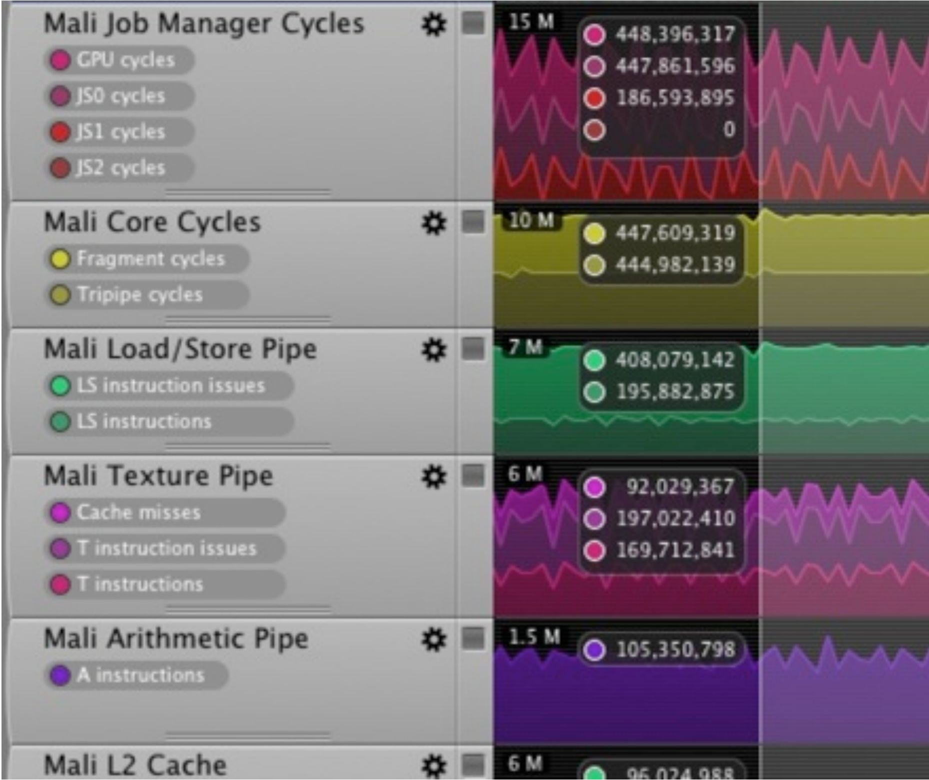
- Instructions can run in parallel
- Each one can be a bottleneck
- There are two arithmetic pipelines so we should aim to increase the arithmetic workload

ARM

Inspect the Tripipe Counters

Reduce the load on the L/S pipeline





ARM

Tripipe Counters

Cycles per instruction metrics

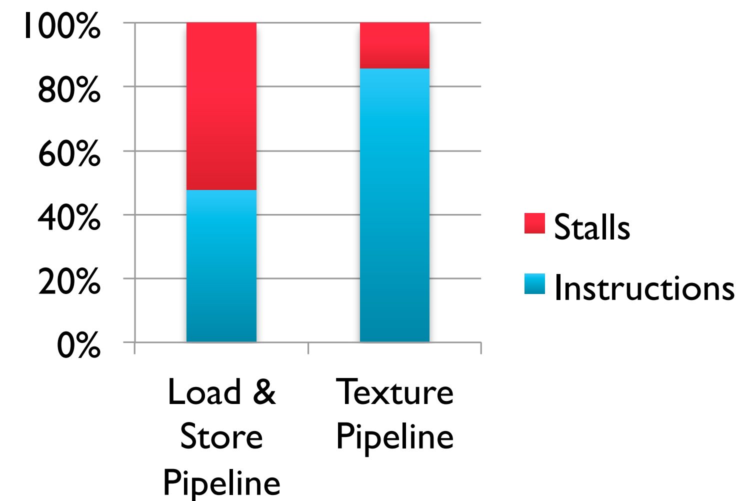
- It's easy to calculate a couple of CPI (cycles per instruction) metrics:

- For the load/store pipeline we have:

  408m (*Mali Load/Store Pipe → LS instruction issues*)
  / **195m** (*Mali Load/Store Pipe → LS instructions*)
  = 2.09 cycles/instruction

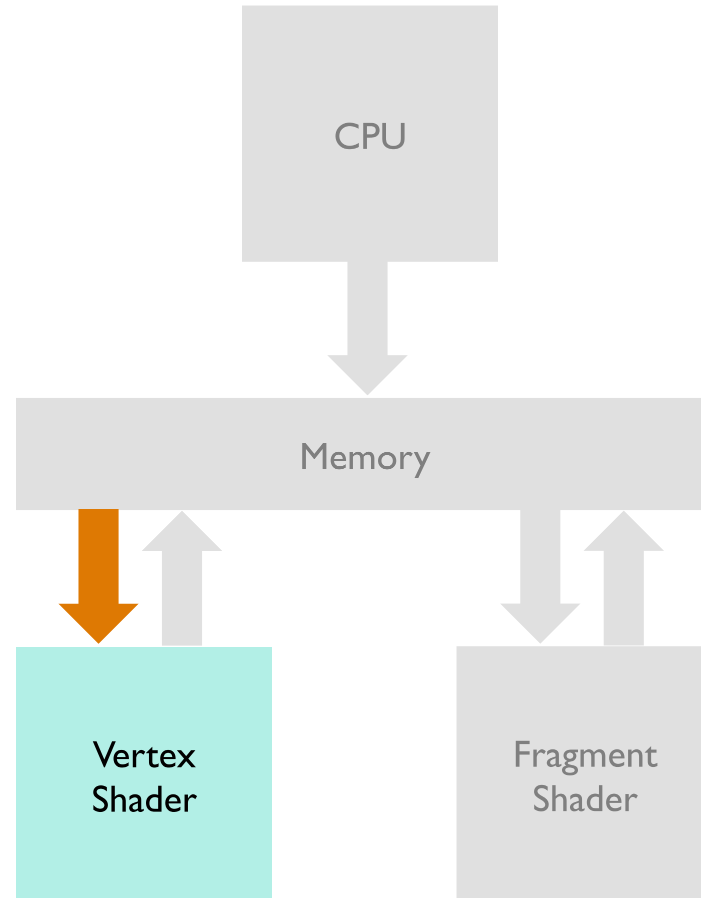
- For the texture pipeline we have:

  197m (*Mali Texture Pipe → T instruction issues*)
  / **169m** (*Mali Texture Pipe → T instructions*)
  = 1.16 cycles/instruction



ARM

Vertex Bound



ARM

Vertex Bound

- Get your artist to remove unnecessary vertices
- LOD switching
  - Only objects near the camera need to be in high detail
- Use culling
- Too many cycles in the vertex shader

Frame 33 : 230 draws, 383256 vertices, 142835 unique ind

1 glDrawElements : 1194 vertices 256 unique indices
2 glDrawElements : 918 vertices 202 unique indices
3 glDrawElements : 918 vertices 202 unique indices
4 glDrawElements : 336 vertices 83 unique indices
5 glDrawElements : 1839 vertices 459 unique indices
6 glDrawElements : 2802 vertices 732 unique indices
7 glDrawElements : 6243 vertices 2499 unique indices
8 glDrawElements : 2529 vertices 545 unique indices
9 glDrawElements : 312 vertices 152 unique indices
10 glDrawElements : 54 vertices 22 unique indices
11 glDrawElements : 1704 vertices 392 unique indices
12 glDrawElements : 396 vertices 194 unique indices
13 glDrawElements : 4038 vertices 1124 unique indices
14 glDrawElements : 8220 vertices 2198 unique indices
15 glDrawElements : 564 vertices 291 unique indices
16 glDrawElements : 528 vertices 233 unique indices
17 glDrawElements : 2166 vertices 681 unique indices
18 glDrawElements : 3858 vertices 2067 unique indices
19 glDrawElements : 702 vertices 468 unique indices
20 glDrawElements : 1671 vertices 808 unique indices
21 glDrawElements : 2322 vertices 836 unique indices
22 glDrawElements : 2277 vertices 917 unique indices
23 glDrawElements : 4251 vertices 1131 unique indices

Vertex Count and Shader Optimizations

Identify the top heavyweight vertex shaders

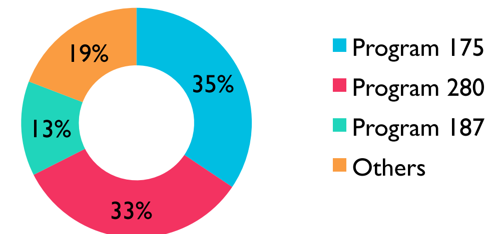
citadel13c.mgd | Shader 176

```
precision highp float;
float Square(float A)
{
return A * A;
}
vec2  Square( vec2  A)
{
return A * A;
}
vec3  Square( vec3  A)
{
return A * A;
}
vec4  Square( vec4  A)
{
return A * A;
}
float EncodeLightAttenuation(float InColor)
{
return sqrt(InColor);
}
vec4  EncodeLightAttenuation( vec4  InColor)
{
return sqrt(InColor);
}
uniform mat3 TextureTransform ;
void DummyPreprocessorFixFunction();
uniform mat4 LocalToWorld ;
uniform mat3 LocalToWorldRotation ;
uniform mat4 ViewProjection ;
uniform mat4 LocalToProjection ;
uniform vec4 FadeColorAndAmount ;
```

Assets | Vertex Shaders | Fragment Shaders | Textures

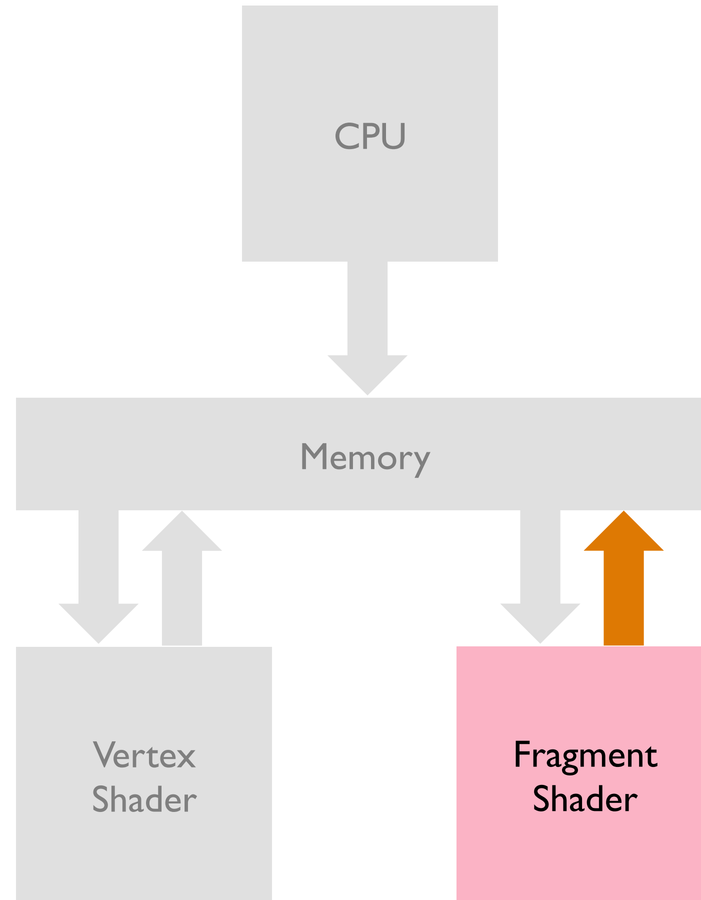
Program	Name	Instruction	Shortest p	Longest pa	Instances	Total cy
175	Shader 176	22	22	22	148500	3267000
280	Shader 281	39	39	39	80595	3143205
187	Shader 188	48	48	48	26328	1263744
181	Shader 182	61	61	61	11487	700707
211	Shader 212	22	22	22	14646	322212
289	Shader 290	55	55	55	5484	301620
298	Shader 299	38	38	38	5259	199842
208	Shader 209	22	22	22	4257	93654
214	Shader 215	61	61	61	1110	67710
73	Shader 74	20	20	20	2880	57600
262	Shader 263	36	36	36	1152	41472

Vertex Cycles Per Program



ARM

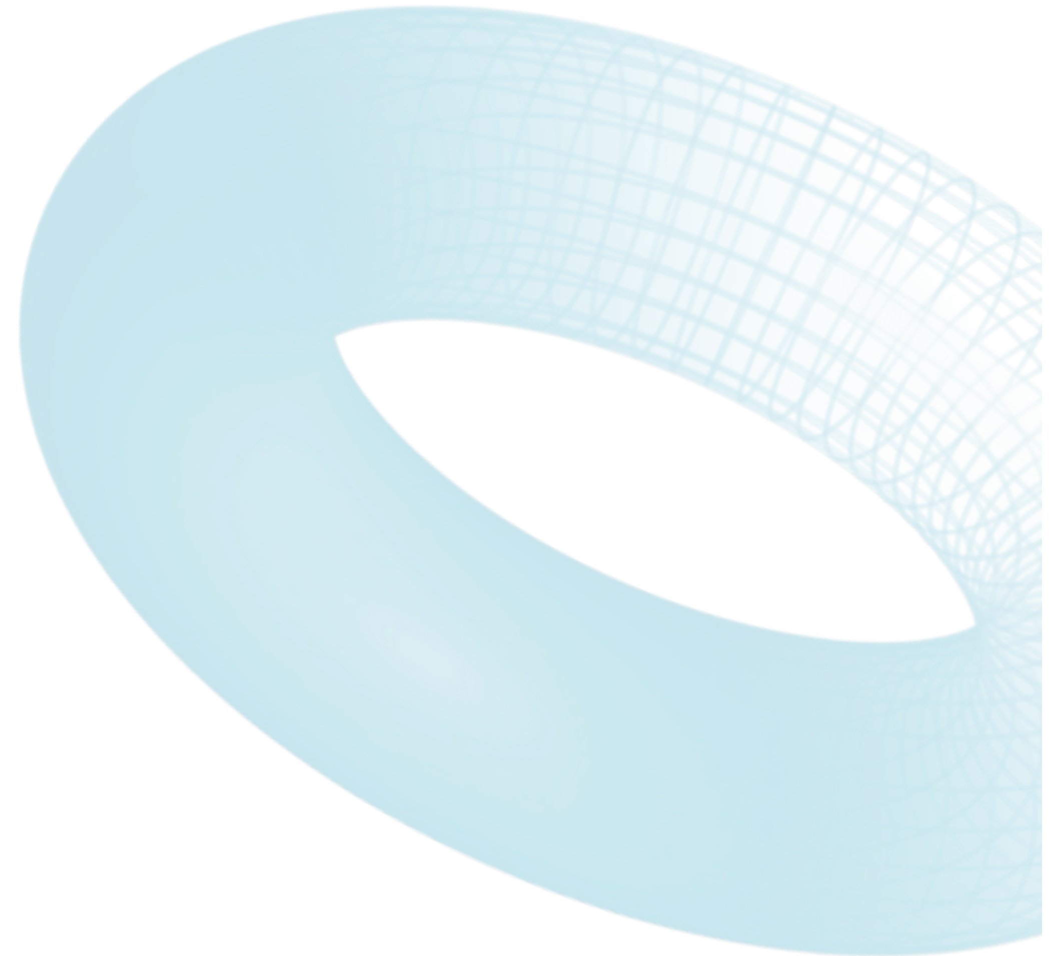
Fragment Bound



ARM

Fragment Bound

- Render to a smaller framebuffer
- Move computation from the fragment to the vertex shader (use HW interpolation)
- Drawing your objects front to back instead of back to front reduces overdraw
- Reduce the amount of transparency in the scene

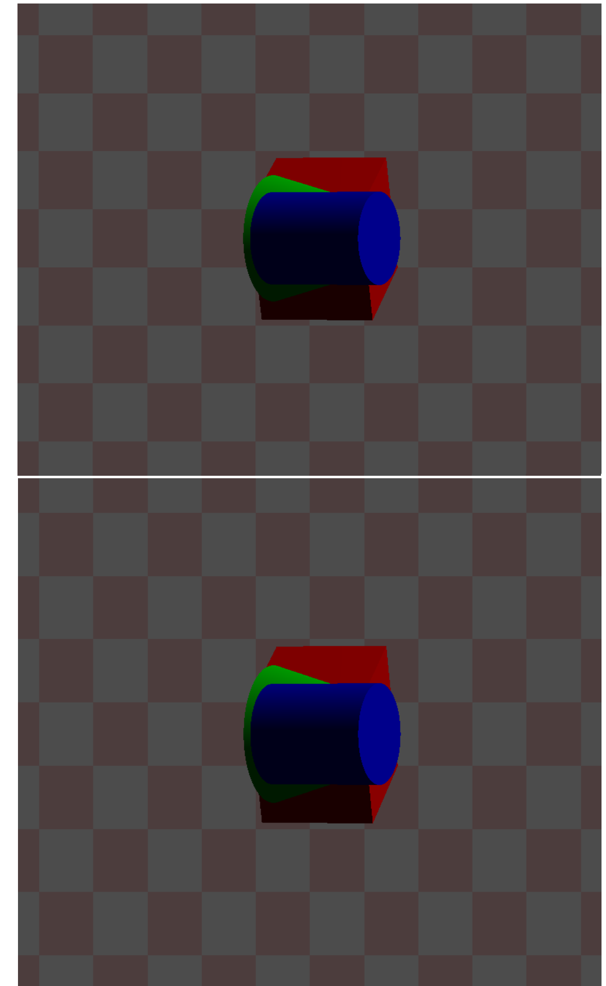


ARM

Overdraw

- This is when you draw to each pixel on the screen more than once
  - Drawing your objects front to back instead of back to front reduces overdraw
- The transparent objects must be drawn back to front for a correct ordering
  - Limiting the amount of transparency in the scene can help

- For OpenGL® ES 3.0, avoid modifying the depth buffer from the fragment shader or you will not benefit from the early Z testing, making the front to back sorting useless

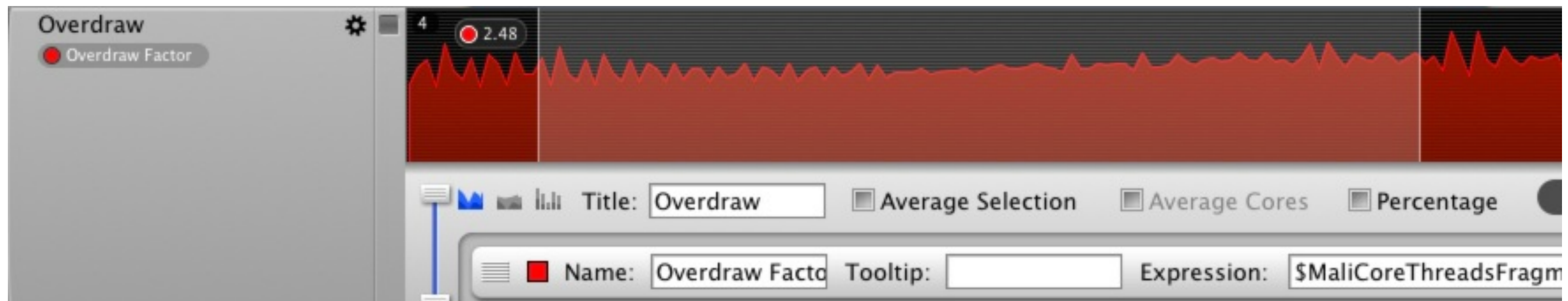


ARM

Overdraw Factor

- We divide the number of output pixels by the number of fragments, each rendered fragment corresponds to one fragment thread and each tile is 16x16 pixels, thus in our case:

90.7m (*Mali Core Threads* → *Fragment threads*)
/ 143K (*Mali Fragment Tasks* → *Tiles rendered*) x 256
= 2.48 threads/pixel



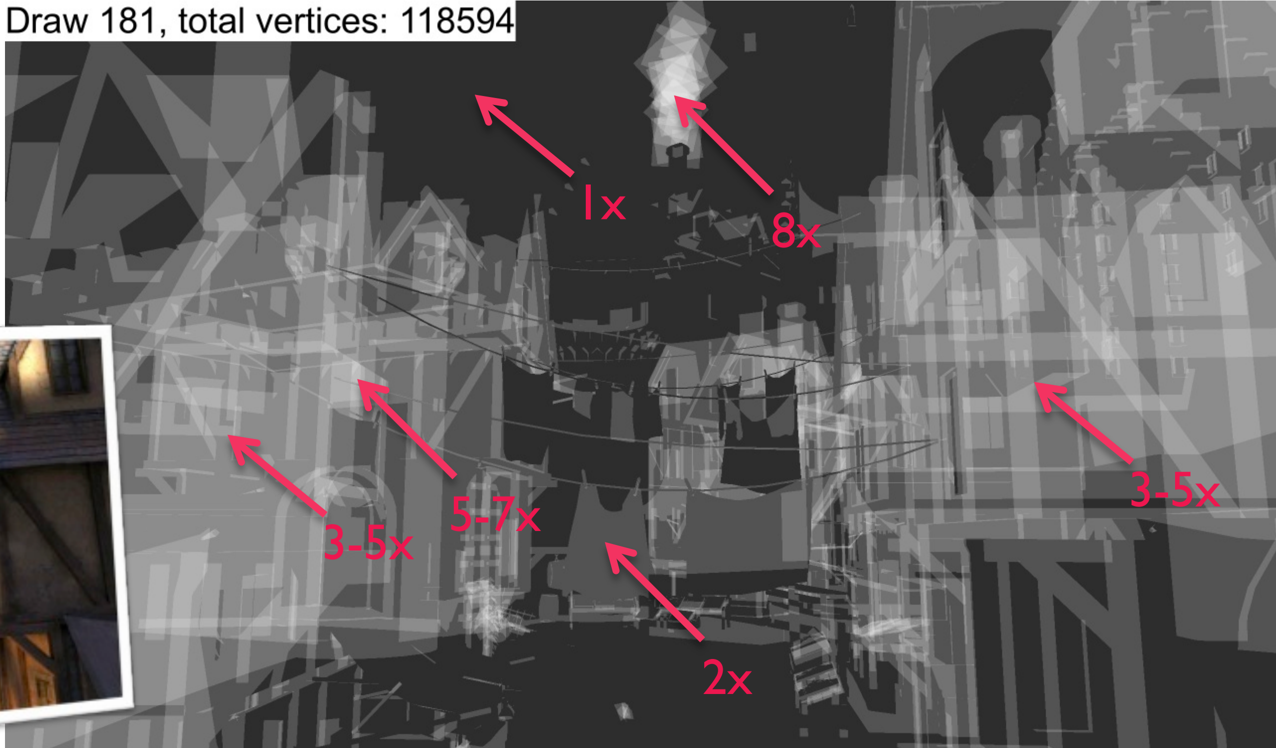
ARM

Frame Capture

ARM

Frame Analysis

Check the overdraw factor



ARM

Shader Map and Fragment Count

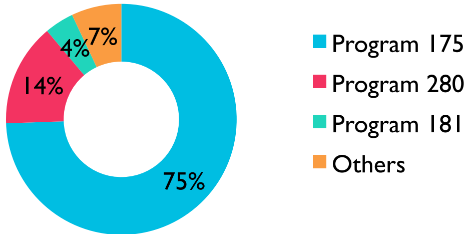
Identify the top heavyweight fragment shaders

Assets | Vertex Shaders | Fragment Shaders | Textures

Program	Name	Instructions	Shortest	Longest	Instances	Total cycles
175	Shader 177	5	5	5	7537773	37688865
280	Shader 282	5	5	5	1459254	7296270
181	Shader 183	5	5	5	415710	2078550
187	Shader 189	6	6	6	197329	1183974
73	Shader 75	4	4	4	279555	1118220
382	Shader 384	8	8	8	129913	1039304
289	Shader 291	6	6	6	16856	101136
208	Shader 210	7	3	6	7975	39875
262	Shader 264	5	5	5	6025	30125
400	Shader 402	5	5	5	914	4570

~10m instances
/ (2560×1600) pixel
= 2.44

Fragment Count Per Program



Shader Optimization

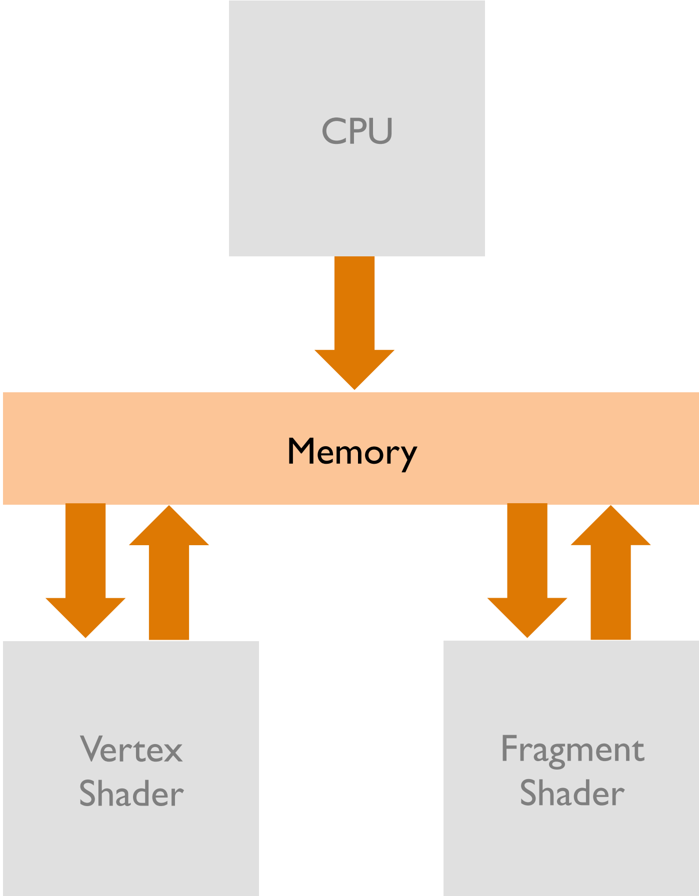
- Since the arithmetic workload is not very big, we should reduce the number of uniform and varyings and calculate them on-the-fly
- Reduce their size
- Reduce their precision: is highp always necessary?
- Use the Mali Offline Shader Compiler!
  - http://malideveloper.arm.com/develop-for-mali/tools/analysis-debug/mali-gpu-offline-shader-compiler/

citadel13c.mgd | Shader 177

```
uniform sampler2D TextureBase ;
varying highp vec4 UVBase ;
uniform sampler2D TextureLightmap ;
varying highp vec2 UVLightmap ;
varying lowp vec4 GlobalEffectColorAndAmount ;
void main()
{
lowp vec3 DebugColor;
highp vec2 FinalBaseUV = UVBase.xy;
highp vec2 TransformedFinalBaseUV = UVBase.zw;
highp vec2 BaseTextureCoord;
BaseTextureCoord = FinalBaseUV;
lowp vec4 BaseColor =  texture2D(TextureBase, BaseTextureCoord, -0.50 ) ;
lowp float AlphaVal = BaseColor.a;
{
}
ALPHAKILL( AlphaVal )
BaseColor.xyz =  BaseColor.xyz ;
lowp vec4 PolyColor = vec4(BaseColor.xyz, AlphaVal);
lowp  vec3  EnvironmentSpecular =  vec3 (0, 0, 0);
lowp vec3 TotalDiffuseLight = vec3( 0.0, 0.0, 0.0 );
PolyColor.rgb += EnvironmentSpecular;
lowp vec3 PreSpecularPolyColor = PolyColor.rgb;
{
lowp vec3 LightmapColor = texture2D( TextureLightmap, UVLightmap ).rgb;
LightmapColor =  LightmapColor ;
PolyColor.rgb = PolyColor.rgb * LightmapColor;
PolyColor.rgb += PolyColor.rgb;
}
PolyColor.xyz = (PolyColor.xyz * GlobalEffectColorAndAmount.w) + GlobalEffectColorAndAmou
;
PolyColor.xyz =  PolyColor.xyz ;
gl_FragColor =  PolyColor ;
}
```

ARM

Bandwidth Bound



ARM

Bandwidth

- When creating embedded graphics applications bandwidth is a scarce resource
  - A typical embedded device can handle 5.0 Gigabytes a second of bandwidth
  - A typical desktop GPU can do in excess of 100 Gigabytes a second

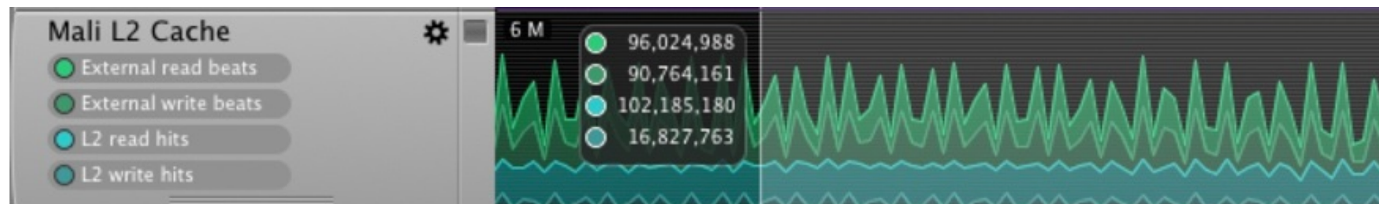
- The application is not bandwidth bound as it performs, over a period of one second:

(96m (*Mali L2 Cache → External read beats*) +

90.7m (*Mali L2 Cache → External write beats*)) x 16

~= 2.9 GB/s

- Since bandwidth usage is related to energy consumption it's always worth optimizing it



ARM

Bandwidth Bound

Vertices

- Reduce the number of vertices and varyings
- Interleave vertices, normals, texture coordinates
- Use Vertex Buffer Objects

Fragments

- Use texture compression
- Enable texture mipmapping

This will also cause a better cache utilization.

6	-6262.634, -4691.77...	0.34643...	1.82812...	137, 199, 233, 255
7	-6262.3794, -4696.2...	0.34936...	1.82812...	141, 140, 254, 255
8	-6260.96, -4721.509...	0.35571...	1.82812...	140, 45, 224, 255
9	-6260.889, -4722[illegible]	[illegible]	[illegible]	[illegible] 1, 145, 255
10	-6390.977, -4722[illegible]	[illegible]	[illegible]	[illegible] 3, 152, 255
11	-6391.1245, -472[illegible]	[illegible]	[illegible]	[illegible] 30, 208, 255
12	-6391.568, -4717[illegible]	[illegible]	[illegible]	[illegible], 109, 252, 255
13	-6261.173, -4717.64...	0.35278...	1.82812...	141, 109, 253, 255
30	-6390.977, -4722.63...	0.37231...	-9.99569...	132, 0, 127, 255
31	-6572.49, -4735.830...	0.38476...	0.23718...	149, 2, 127, 255
32	-6572.4927, -4735.8...	0.38183...	0.23742...	149, 3, 145, 255
33	-6390.977, -4722.63...	0.36938...	-9.99569...	135, 3, 152, 255
34	-6664.2188, -4760.8...	0.39672...	0.33959...	171, 8, 127, 255
35	-6664.222, -4760.90...	0.39453...	0.33959...	178, 12, 148, 255
36	-6783.513, -4827.17...	0.41210...	0.49975...	201, 26, 148, 255
37	-6783.5063, -4827.1...	0.41406...	0.49975...	196, 20, 127, 255
38	-6866.2744, -4896.6...	0.43188...	0.62255...	215, 35, 128, 255
39	-6866.309, -4896.70...	0.43017...	0.62255...	218, 40, 147, 255
40	-6932.6846, -4974.8...	0.44946...	0.70703...	229, 53, 147, 255
41	-6932.441, -4974.81...	0.45068...	0.70751...	228, 49, 129, 255
42	-6999.1626, -5076.3...	0.47216...	0.82861...	238, 64, 130, 255
43	-6999.5806, -5076.3...	0.47119...	0.82861...	239, 69, 147, 255
44	-6581.1475, -4706.2...	0.37060...	0.23742...	122, 216, 219, 255
45	-6394.6104, -4692.0...	0.35668...	-9.99569...	134, 230, 203, 255
46	-6394.081, -4696.53...	0.36010...	-9.99569...	144, 153, 251, 255

Indices sparseness: 1.47
bad for caching!

ARM

Texture Compression Formats

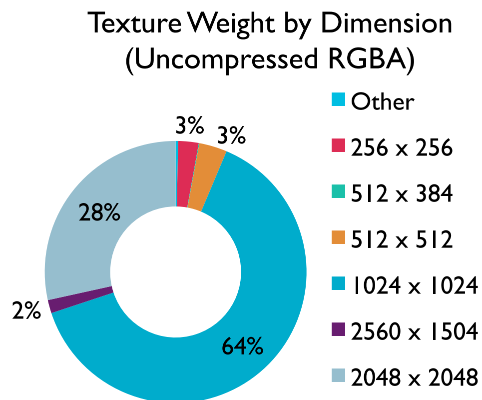
- ETC – ARM Mali-400 GPU
  - 4bpp
  - RGB No alpha channel
- ETC2 – ARM Mali-T604 GPU
  - 4bpp
  - Backward compatible
  - RGB also handles alpha & punch through
- ASTC – ARM Mali-T624 GPU and beyond
  - 0.8bpp to 8bpp
  - Supports RGB, RGB alpha, luminance, luminance alpha, normal maps
  - Also supports HDR
  - Also supports 3D textures

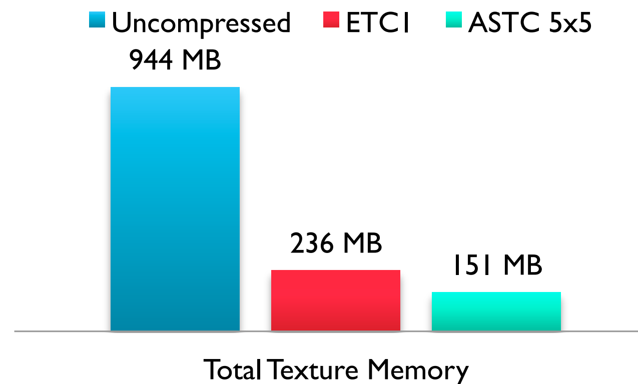
ARM

Textures

Save memory and bandwidth with texture compression

- The current most popular format is ETC Texture Compression
- But ASTC (Adaptive Scalable Texture Compression) can deliver < 1 bit/pixel





Assets | Vertex Shaders | Fragment Shaders | Textures

Name	Size	Format	Type
Texture 45	2048 x 2048	GL_RGBA	GL_UNSIGNED_BYTE
Texture 241	2048 x 2048	GL_ETC1_RGB8_OES	
Texture 243	2048 x 2048	GL_ETC1_RGB8_OES	
Texture 246	2048 x 2048	GL_ETC1_RGB8_OES	
Texture 259	2048 x 2048	GL_ETC1_RGB8_OES	
Texture 263	2048 x 2048	GL_ETC1_RGB8_OES	
Texture 267	2048 x 2048	GL_ETC1_RGB8_OES	
Texture 268	2048 x 2048	GL_ETC1_RGB8_OES	
Texture 270	2048 x 2048	GL_ETC1_RGB8_OES	
Texture 275	2048 x 2048	GL_ETC1_RGB8_OES	

ARM

Gameloft
Sample Cases

Iron Man 3

Improving Draw Calls and Rendering Techniques

ARM

Sorting Objects Before Rendering

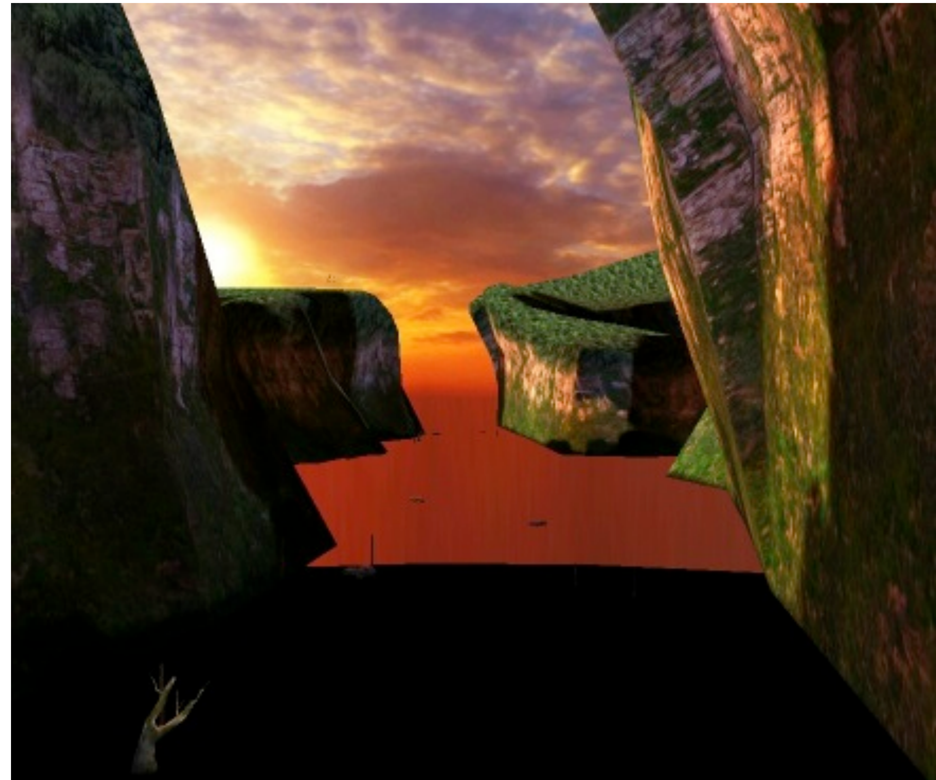
- Sorting methods reduce overdraw and material changes at the cost of CPU

- Sorting algorithms used for Iron Man 3:
  - Sorting by material
  - Sorting by distance

ARM

What Happens When No Sorting Is Applied?

- Mid-range device:
  - average 18 fps
  - constant micro-freezes
- Over 35 program changes per frame
- The skybox is rendered in the 27th draw call / 150
- There is a lot of overdraw



ARM

Material Sorting Results

- Reduced program changes to an average of 16
  - Micro-freezes are reduced
- Average 22 fps, smoother gameplay

ARM

Front to Back Sorting Results

- Sorting first by material, objects with the same material then sorted front to back
- Constant 24 fps
- The skybox is rendered in the 82nd draw call / 135, being the last opaque object

ARM

Asphalt 8

Effects, Draw Calls & Texture Data

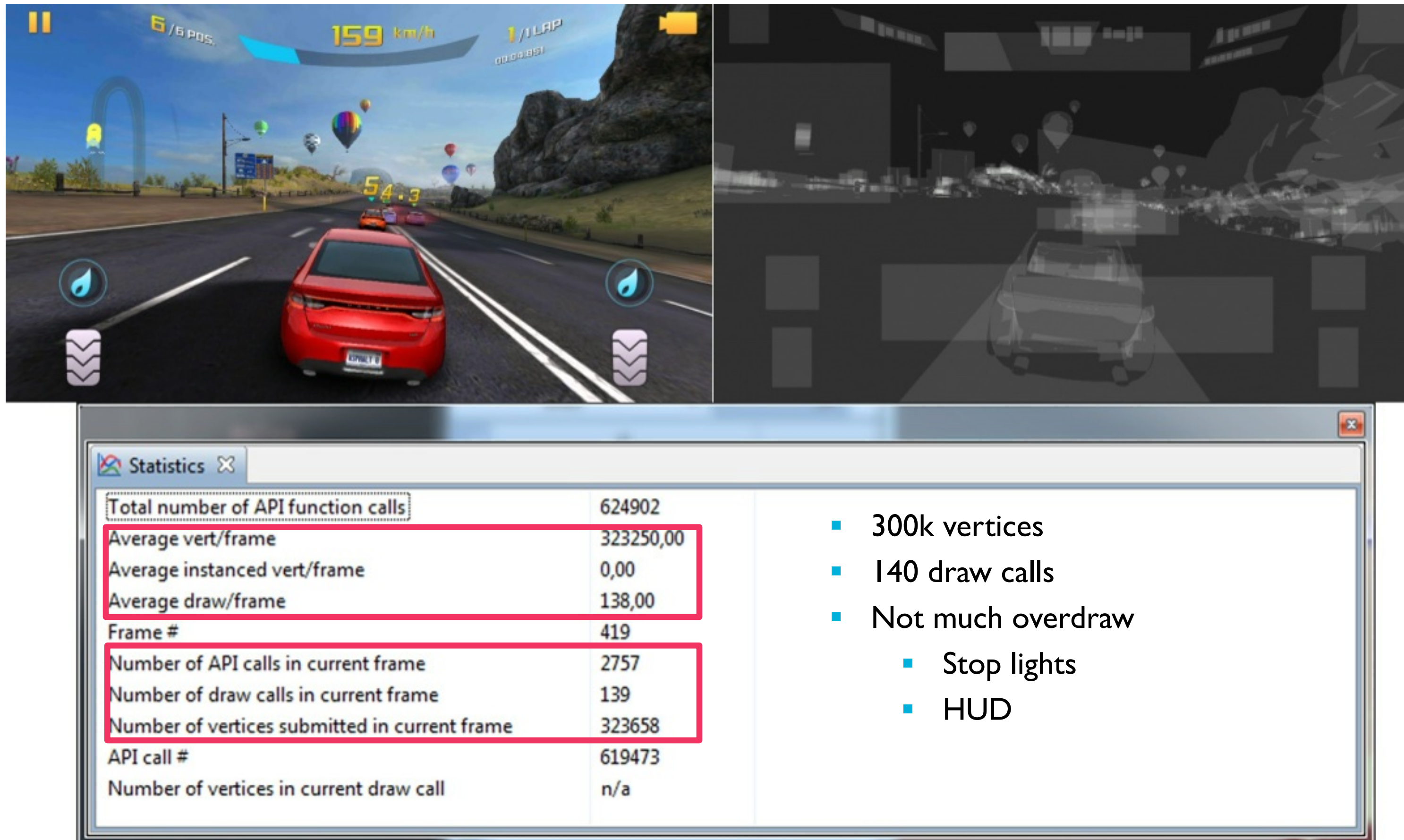
ARM

The Game

- Explosive action racing
  - Multiplayer
  - Physics engine
- Main FXs :
  - Realtime soft shadows
  - Realtime reflections
  - Paraboloid
  - Road reflections
  - Proxies
- Main post FXs:
  - Motion blur
  - Lens flare dirt
  - Color grading
  - Vigneting

ARM

ARM® Mali™ Graphics Debugger (on a Samsung Galaxy SIII)



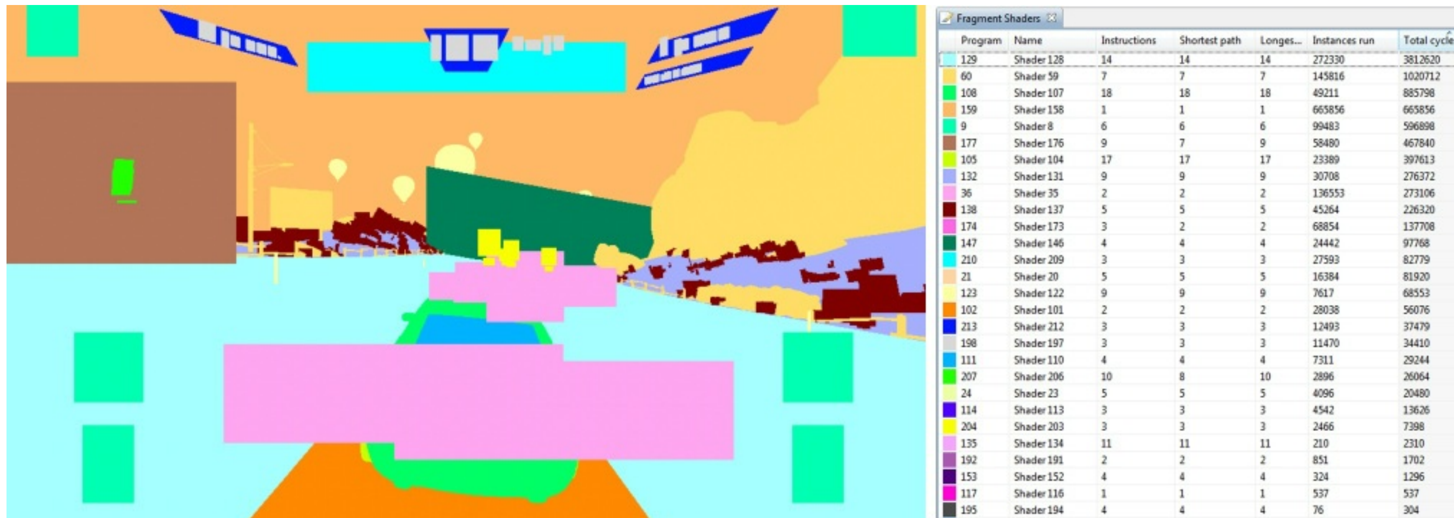
Statistics

Total number of API function calls	624902
Average vert/frame	323250,00
Average instanced vert/frame	0,00
Average draw/frame	138,00
Frame #	419
Number of API calls in current frame	2757
Number of draw calls in current frame	139
Number of vertices submitted in current frame	323658
API call #	619473
Number of vertices in current draw call	n/a

- 300k vertices
- 140 draw calls
- Not much overdraw
  - Stop lights
  - HUD

ARM

Mali Graphics Debugger (on a Samsung Galaxy SIII)



Fragment Shaders

Program	Name	Instructions	Shortest path	Longes...	Instances run	Total cycles
129	Shader 128	14	14	14	272330	3812620
60	Shader 59	7	7	7	145816	1020712
108	Shader 107	18	18	18	49211	885798
159	Shader 158	1	1	1	665856	665856
9	Shader 8	6	6	6	99483	596898
177	Shader 176	9	7	9	58480	467840
105	Shader 104	17	17	17	23389	397613
132	Shader 131	9	9	9	30708	276372
36	Shader 35	2	2	2	136553	273106
138	Shader 137	5	5	5	45264	226320
174	Shader 173	3	2	2	68854	137708
147	Shader 146	4	4	4	24442	97768
210	Shader 209	3	3	3	27593	82779
21	Shader 20	5	5	5	16384	81920
123	Shader 122	9	9	9	7617	68553
102	Shader 101	2	2	2	28038	56076
213	Shader 212	3	3	3	12493	37479
198	Shader 197	3	3	3	11470	34410
111	Shader 110	4	4	4	7311	29244
207	Shader 206	10	8	10	2896	26064
24	Shader 23	5	5	5	4096	20480
114	Shader 113	3	3	3	4542	13626
204	Shader 203	3	3	3	2466	7398
135	Shader 134	11	11	11	210	2310
192	Shader 191	2	2	2	851	1702
153	Shader 152	4	4	4	324	1296
117	Shader 116	1	1	1	537	537
195	Shader 194	4	4	4	76	304

- Post FXs disabled here
- Shaders covering large screen areas must be cheap:

```
• Road         => 14  cycles (specular / normal map)
• Rocks        => 7   cycles
• Sky          => 1   cycle
• Cars         => 18  cycles
• Lights/Smoke => 2/4 cycles
```

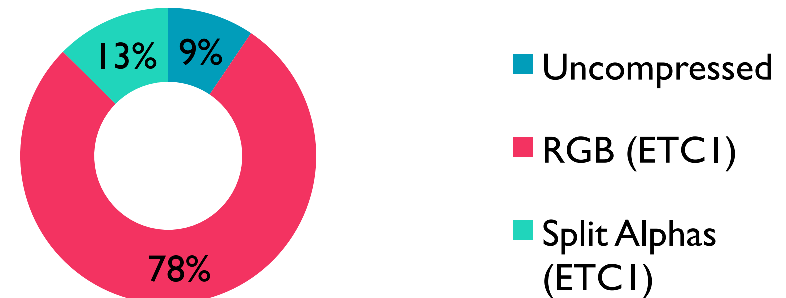

ARM

Iceland Track: Memory Usage

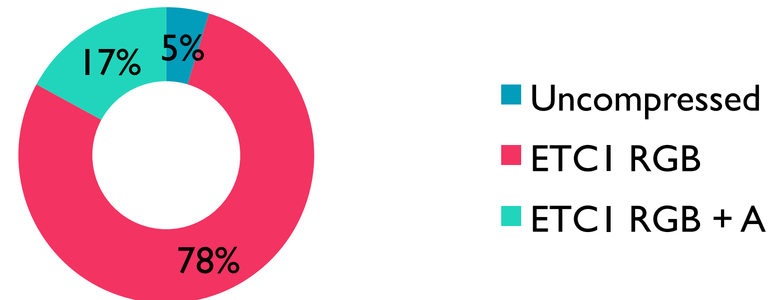
- Total : 127 MB
  - mipmaps not counted
- 13% of texture data is used for alphas

- One extra sampling operation in shaders:
  - More fragment instructions
  - Still better cache efficiency than uncompressed, but not as good as ETC1 RGB

Mem usage, Iceland track (MB)



After texture repartition



ARM

Summary

- Covered today:
  - Introduction to performance analysis
  - Software Profiling
  - GPU Profiling
  - Debugging with the ARM® Mali™ Graphics Debugger
- For more information:
  - malideveloper.arm.com
  - ds.arm.com
  - community.arm.com

- Covered today:
  - Performance analysis with ARM DS-5 Streamline
  - Software Profiling
  - GPU Profiling
  - Debugging with the ARM® Mali™ Graphics Debugger

Thank You

Any Questions?

malideveloper.arm.com

ds.arm.com

community.arm.com

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