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Exploring Mobile vs. Desktop OpenGL Performance

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1.1 Introduction

The stunning rise of mobile platforms has opened a new market for new 3D applications and games where, excitingly, OpenGL ES is the *lingua franca* for graphics. However, mobile platforms and GPUs have performance profiles and characteristics that may be unfamiliar to desktop developers. Developers making the transition from desktop to mobile need to be aware of the limits and capabilities of mobile devices to create the best experience possible for the given hardware resources. This chapter surveys mobile GPU design decisions and constraints, then explores how these affect classic rendering paradigms.

First, we examine how mobile and desktop GPUs differ in design goals, scale and architecture. We then look at memory bandwidth consumption, which greatly affects performance and device power, and break it down into the contributions of display, composition, blending, texture access, and anti-aliasing. After that, our focus shifts towards optimizing fragment shading with limited compute power. We look at ways to eliminate shading work entirely if we can or to minimize it or render it more efficient if we can't.

Finally, we discuss the relationship between vertex and fragment shaders and how it is affected by different mobile GPU architectures, and end with some tips for optimizing vertex data for efficient reads and updates.

1.2 Important Differences and Constraints

1.2.1 Differences in Scale

Modern mobile devices are capable devices, but they face much greater limitations than desktop systems in terms of cost, chip die size, power consumption, and heat dissipation.

Power consumption is a major concern for mobile platforms that is much less pressing on desktop. Mobile devices must run off batteries small enough to fit in the body of the device, and a short battery life is frustrating and inconvenient to the user. Mobile hardware is built to use less power than desktop hardware via lower clock frequencies, narrower busses, smaller chips, smaller data formats, and by limiting redundant and speculative work. Display and network take a great deal of power, but OpenGL applications contribute to power consumption, especially through computation and through off-chip memory accesses.

Power consumption is doubly-impactful on mobile devices, since power consumed by the processor, GPU, and memory is largely dissipated as heat. Unlike desktop systems with active air cooling, good air circulation, and large heat sinks to radiate heat, mobile systems are usually passively cooled and have contrained bodies with little room for large sinks or radiating fins. Excess heat generation is not only potentially damaging to components, it's also noticeable and irritating to users of hand-held products.

Die size and cost are also greatly different between mobile and desktop. High-end desktop GPUs are some of the largest mainstream chips made, with over 3 billion transistors on recent models [Walton 10]. Both the large area and the effect of area on yield mean increased cost. A discrete GPU also means a separate package and mounting, and the expected cost increase. In mobile systems however, the GPU is usually one component on an integrated *System on a Chip (SoC)* designed for mobile and embedded applications, which means that a mobile GPU is a fraction of the cost and area of a desktop GPU.

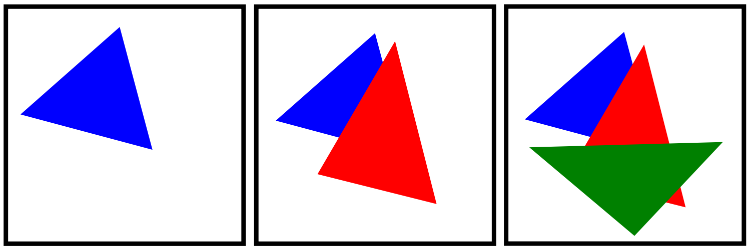
1.2.2 Differences in Rendering Architecture

Mobile and desktop GPUs don't differ only in scale. Mobile GPUs such as the Imagination Tech SGX543MP2 used in the Apple iPhone 4S/iPad 2 and the ARM Mali-400 used in the Samsung Galaxy S2 use a *tile-based* rendering architecture [Klug and Shimpi 11b]. In contrast, desktop GPUs from NVIDIA and ATI and mobile GPUs like the GeForce ULV GPU used in the Samsung Galaxy Tab 10.1 use *Immediate Mode Rendering (IMR)*.

In IMRs, vertices are transformed once and primitives are rasterized essentially in order. If a fragment passes depth-testing (assuming the platform has early-z), it will be shaded and will write to the framebuffer. However, a later fragment may over-write this pixel, nullifying the earlier work done and writing the framebuffer again. This behavior is known as overdraw. Even without overdraw, the depth buffer still must be read for later fragments generated at a pixel location in order to reject them.

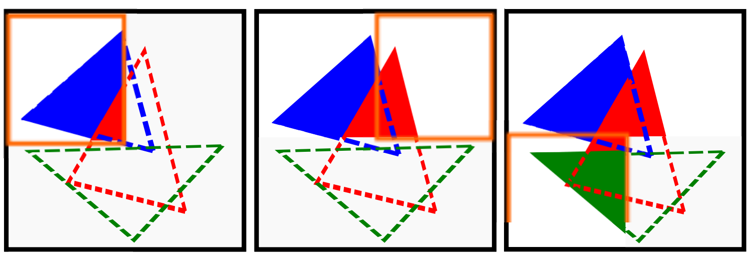
Tilers instead divide the framebuffer into tiles of pixels. All draw commands are buffered. At the end of the frame, for each tile, all geometry for the scene is re-rendered and rasterized into a framebuffer cache with that tile scissored out. Once all pixels have been resolved, the entire tile

Figure 1.1. IMRs render each primitive only once, and render the entire framebuffer in a single pass



is written out to memory. This saves redundant framebuffer writes and allows for fast depth-buffer access, since depth-testing and depth writes can be performed with the local framebuffer cache. The end goal is to limit the memory bandwidth consumed by color and depth buffer access.

Figure 1.2. Tiling architectures divide the scene into tiles, and render all primitives into each tile using a fast framebuffer cache.



Tiling doesn't come for free. The scene geometry must be re-transformed and clipped for each tile, so to maintain a balanced pipeline additional vertex processing power is needed. Bandwidth will also be spent re-reading vertex data for each tile. The digital logic for tiling, repeated vertex shading, and a fast framebuffer cache also takes transistors from raw fragment shading horsepower. Tiling also requires buffering commands deeply, leading to a more complicated hardware and driver implementation, and the fact that the rendering of each primitive cannot be neatly placed in single interval of time makes performance analysis more difficult. For more tips on performance tuning specific to tiling architectures, see *Performance Tuning for Tile-Based Architectures* [**?**]

There is an additional group of tilers which use *Tile-Based Deferred Rendering (TBDR)*, like the Imagination Tech SGX family. The idea is to rasterize all primitives in a tile before performing any fragment shading. This allows *Hidden Surface Removal (HSR)* and depth-testing to be performed in a fast framebuffer cache before any fragment shading work is done. Assuming opaque geometry, each pixel is then shaded and written to the framebuffer exactly once.

Architecturally, the mobile GPU landscape is not homogenous. Optimizations may affect the different architectures very differently, so it is important to test on multiple devices for cross-platform releases.

1.2.3 Differences in Memory Architecture

On desktop systems, middle-to-high-end GPUs are discrete devices which communicate with the rest of the system via a peripheral bus like *PCIe*, althought some desktop CPUs are now shipping with capable integrated GPUs, like the AMD Llano processors. For good performance, this means that GPUs must include their own dedicated memory, since accessing system memory through a peripheral bus for all memory accesses would be too slow in terms of bandwidth and latency. While this increases cost, it is an optimization opportunity since this memory and its configuration, controller, caching, and geometry can be optimized for graphics workloads.

For example, the NVIDIA *Fermi* architecture uses GDDR5 memory that is heavily partitioned [Walton 10] to allow for a wide memory interface. There are no other components competing for this bandwidth, since except for uploads from the rest of the system and scan-out for output devices, the GPU is the only user of this memory.

In mobile devices, on the other hand, the GPU is usually integrated into the same SoC as the CPU and other components. To save cost, power, die size, and package complexity, the GPU shares the RAM and memory interface with the other components. This is known as an *Unified Memory Architecture (UMA)*. A common memory type is the low-power LPDDR2, which has a 32-bit wide interface [Klug and Shimpi 11a]. Not only is this memory general-purpose, the GPU now shares bandwidth with other parts of the system like the CPU, network, camera, multimedia, and display, leaving less dedicated bandwidth available for rendering and composition.

There are some performance advantages to a unified memory architecture, besides the savings in cost and complexity. With discrete GPU's the peripheral bus could become a bottleneck for transfers, especially for non-PCIe buses with asymmetric speeds [Elhasson 05]. With a UMA, OpenGL client and server data are in fact stored in the same RAM. Even when it is not possible to directly access server-side data with `glMapBufferOES`, there are fewer performance cliffs lurking in transfers between OpenGL client and server data, and using client-side data for dynamic vertices or indices may not have as great a performance penalty. Data transfer and command latencies from the GPU to the CPU are also likely to be lessened.

One current limitation is that OpenGL ES does not yet have an extension for *Pixel Buffer Objects (PBO)*, meaning that pixel and texture data must be transferred synchronously. This makes the comparatively cheap bandwidth between client and server data less useful, and also makes streaming assets during run-time more difficult.

1.3 Reducing Memory Bandwidth

Memory bandwidth pressure is one of the major performance pressures on mobile devices, especially on games and other applications which also perform heavy amounts of CPU-side work during the frame, or in multimedia applications which have additional bandwidth clients besides the GPU and display.

Besides limiting performance, memory accesses external to the GPU consume a great deal of power, sometimes more than the computation itself. [Antochi 04].

Device	CPU Write Bandwidth	GPU Write Bandwidth
Motorola Xoom	2.6GBps	1.252GBps
Motorola Droid X	1.4GBps	6.8GBps
LG Thunderbolt	0.866GBps	0.518GBps
Dell Inspiron 520	4.8GBps	3.8GBps
Desktop System	14.2GBps	25.7GBps

Table 1.1. Write bandwidth for CPU and GPU on different devices. CPU write bandwidth estimated by *memset*. GPU bandwidth estimated by glClear followed by glFinish. Desktop system has an Intel Core 2 Quad and NVIDIA GeForce 8800 GTS. The desktop system has significantly more bandwidth available to the GPU than to the CPU, and CPU and GPU memory accesses do not interfere with each other. The Droid X GPU write bandwidth score is high enough that it may not actually be writing the framebuffer each time (ie coalescing redundant clears or setting a cleared flag)

1.3.1 Relative Display Sizes

Despite the tight power and cost constraints for mobile devices, the display resolutions of modern mobile devices are a considerable fraction of the resolutions of desktop displays. Even though the displays sizes are smaller, mobile devices often have a higher pixel density to be viewable at a close distance.

With the limited fragment shading throughput and memory bandwidth of mobile devices, these comparatively large display sizes mean that frag-

Device	Resolution	% of 1280x1024	% of 1920x1080
Motorola Xoom	1280x800	%78.13	%49.38
Apple iPad 2	1024x768	%58.63	%37.06
Apple iPhone 4S	960x640	%46.89	%29.63
Samsung Galaxy S2	800x480	%30.00	%18.52

Table 1.2. Resolution comparison of desktop and mobile panels

ment shading and full-screen or large-quad operations can easily become a bottleneck, since these requirements scale proportionally with the number of output pixels. Memory bandwidth is also a major power drain, making limiting bandwidth doubly important. Common large-quad operations include post-processing effects and user-interface composition.

Within mobile devices, there is also a large spread of resolution sizes , especially between tablets and phone form factors, so testing on multiple devices is important, for performance testing as well as application useabilty.

1.3.2 Framebuffer Bandwidth

Basic rendering can consume surprisingly significant amounts of memory bandwidth. Assume the framebuffer has 16-bit color with 16-bit depth [Android 11] and a 1024x768 resolution. Accessing every pixel in the framebuffer 60 times a second takes 94MBps of bandwidth. So to write all the pixels' colors every frame, at 60 frames a second, with 0% overdraw, takes 94MBps of bandwidth.

However, assuming an IMR architecture, to be able to render a scene, we also usually perform a depth-buffer read for each rendered pixel. Both the depth-buffer and the color buffer are also usually cleared each frame. And when applications write to the color buffer while rendering the scene, they also generally write the fragment depth to the depth-buffer.

The memory bandwidth consumption of the final framebuffer doesn't end when the application is done writing it either. After `eglSwapBuffers`, it may need to be composited by the platform-specific windowing system, and then scanned out to the display. Unlike desktop systems which often have dedicated graphics or framebuffer memory, this will also consume system memory bandwidth. This will consume an 94MBps of bandwidth just for scanout, or at least 288MBps with composition(read, write to composited framebuffer, and scan-out).

Thus with a depth and color clear, one depth buffer read, a depth and color buffer write, and display scanout, basic clear-fill-and-display operation consumes 564-752MBps of bandwidth, so even simple use cases consume a significant amount of memory bandwidth; anything interesting the application does only costs more bandwidth. If a 32-bit framebuffer is used, this number will be even greater. This can be a significant portion of the bandwidth available on a mobile device, see 1.1 for bandwidth measurements for some devices.

Tile-based architectures can consume less bandwidth for this basic operation since they ideally handle the depth and color clears and the depth buffer reads within the framebuffer cache. Use of the EXT_discard_framebuffer [Bowman 09] extension saves additional bandwidth because it means the calculated depth buffer never needs to be written back to external memory from the framebuffer cache once the frame is complete. So a tile-based architecture will consume at least 188-377 MBps for basic clear-fill-and-display operation.

Applications using a 32-bit framebuffer that may be bandwidth-bound should experiment with a lower-precision format. Since the output framebuffer is not often used in subsequent calculations, the loss of numerical precision is not propagated and magnified. One valid concern is banding or quantization of smooth gradients [Guy 10]. However, this may be more of an issue in photography and media applications rather than games and 3D applications, because of the nature of the produced content.

1.3.3 Texture Bandwidth

Since texture accesses are often performed at least once per-pixel, these can be another large source of bandwidth consumption.

One simple way to reduce bandwidth is to lower the texture resolution. Fewer texels, besides a smaller memory footprint, means better texture cache utilization and more efficient filtering. The framebuffer resolution usually can't be lowered, since native resolution is expected. Texture sizes are more flexible, particularly if they represent low-frequency signals like illumination. Low-frequency textures could even be demoted to vertex attributes, and interpolated. If assets have been ported from desktop, there may be room for optimization here.

For static textures, as opposed to textures drawn to by frequent offscreen rendering, texture compression is another great way to save bandwidth, loading-time, memory footprint, and disk space. Even though work must be done to decompress the texture data when it is used, the smaller size of compressed textures makes them friendlier to texture caching and memory bandwidth, increasing run-time performance.

One complication is that there are multiple incompatible formats for texture compression supported via OpenGL ES2 extensions. Example formats are ETC, available on most Android 2.2 devices, S3TC, available on NVIDIA Tegra, and PVRTC, available on ImaginationTech SGX [Motorola 11].

To support texture compression formats on multiple devices, an application must either package multiple versions of its assets and dynamically choose the correct ones, or perform the compression at run-time, load-time, or install-time. Performing the compression at run- or install-time must be done carefully to not slow down the application, and gives up the benefits of improved loading-time and disk-space, as well as reduced network bandwidth required to download the application. S3TC has compression ratios between 4:1 and 8:1, so the space and download savings lost are substantial. [Domine 00].

As for framebuffer bandwidth, using a texture format with lower precision, like RGB565, saves read bandwidth. Unlike texture compression, this applies to textures used as render targets as well.

1.3.4 Anti-Aliasing

Anti-aliasing improves image quality by refining edges that are jagged when rendered.*Super-sampling Anti-aliasing (SSAA)* consumes a large amount of extra bandwidth and fragment shading load, since it must render the scene to a larger, high-resolution buffer, then down-sample to the final image. *Multi-sample antialiasing (MSAA)* on the other hand rasterizes multiple samples per-pixel, and stores a depth and color for each sample. If all samples in a pixel are covered by the same primitive, the fragment shader will only be run once for that pixel, and the same color value will be writtenfor all samples in that pixel. These samples are then blended to compute the final image. [aths 03]

Though using MSAA creates little if any additional fragment shading work or texture read bandwidth consumption, it does use a significant amount of bandwidth to read and write multiple the samples for pixels. Tiling architectures may be able to store the samples in the framebuffer cache and perform this blending before writeback to system memory [Technologies 11]. Vendors may perform other optimizations like only storing multiple samples when there is non-trivial coverage information.

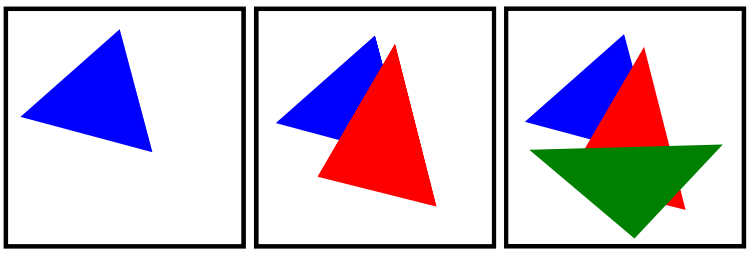
1.4 Reducing Fragment Workload

Due to the limited compute and bandwidth available on mobile devices with respect to the large number of pixels and the complexity of modern rendering, fragment shading is often a bottleneck for mobile GPUs. However, fragment shading can be improved in other ways than just simplifying shading.

1.4.1 Overdraw and Blending

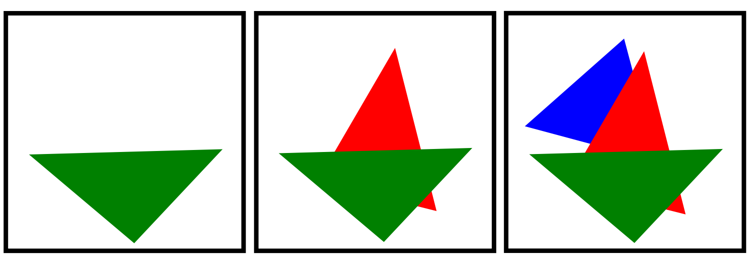
Overdraw is when pixels that have previously been shaded are overwritten by later fragments in a scene. On IMRs and tiling immediate-mode renderers, overdraw wastes completed fragment shading, since the previous computed pixel value is over-written and lost. On IMRS, this also results in an additional framebuffer write, when only one final pixel color needed to be written.

Figure 1.3. In this overdraw case, pixels that are covered by later primitives are shaded more than once



On IMR GPUs, this extra bandwidth consumption and fragment work can be limited by sorting and rendering geometry from front to back. This is especially practical for static geometry which can be processed into a spatial data structure during an asset export step. An additional heuristic for games is to render the player character first and the sky-box last. [Pranckevicius and Zioma 11].

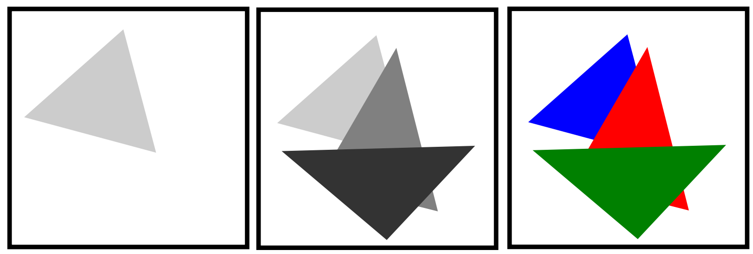
Figure 1.4. By ordering front to back, we no longer shade the covered pixels more than once



For batches where front-to-back object sorting is not practical, for example with complicated, interlocking geometry or heavy use of alpha-testing, a depth prepass can be used to eliminate redundant pixel calculations, at the cost of repeated vertex shading work, primitive assembly, and depth-buffer access.

The idea of a depth pre-pass is to bind a trivial fragment shader and render the scene with color writes disabled. Depth calculation, testing, and writes proceed as normal and the final pixel depth is resolved. The normal fragment shader is then bound and the scene is re-rendered. In this manner, only the final fragments that affect the scene color are rendered. This only works for opaque objects.

Figure 1.5. A depth pre-pass resolves ordering in the depth buffer before performing non-trivial fragment shading.



Even without overdraw, on IMRs heavy amounts of overlapping geometry can still be expensive because of the depth-buffer reads needed to reject pixels. Primitive assembly, rasterization, and the pixel reject rate can also become limiting for large areas like sky-boxes [Pranckevicius and Zioma 11].

One type of effect that can be particular expensive in terms of fragment shading and framebuffer bandwidth is particle effects rendered via multiple overlapping quads with blending. On IMRs, each layer of overlap requires a read and write of the existing framebuffer value. For all mobile GPUs, each layers adds additional fragment computation and blending. Some simple effects like a torch flame can be converted into an animated shader, for example by changing a texture offset each frame. Other effects, like a candle flame, can be done by rendering a mesh of dynamic data, instead of many overlapping billboarded quads. This reduces overlap and the resultant blending. When applicable, using opaque, alpha-tested sprites also eliminates the cost of blending.

1.4.2 Full-Screen Effects

Full-screen post-processing effects are a major tool for visual effects in modern games and graphics applications, and have been an area of innovation in recent years. Common applications of full-screen post-processing in games are motion-blur, depth-of-field, screen-space ambient occlusion, light bloom, color filtering, and tone-mapping. Other applications such as photo-editing tools may use full-screen or large-area effects for composition, blending, warping and filtering.

Full-screen post-processing is a powerful tool to create effects but it is an easy way to consume large amounts of bandwidth and fragment processing. Such effects should be carefully weighed for their worth, and are prime candidates for optimization.

A full-screen pass implies at least a read and write of the framebuffer at full resolution, which at 16-bit color and a 1024x768 resolution means 188MBps bandwidth. Even with tiling architectures, a post-processing pass means a round-trip to external memory. One way to optimize these effects is to remove the extra full-screen pass. Some post-processing effects such as color-filtering or tone-mapping that don't require knowledge of neighboring pixels or feedback from rendering may be merged into the fragment shaders for the objects themselves. This may require the use of *uber-shaders* or shader generation, to allow for natural editing of object fragment shaders while appending post-processing effects.

If the additional pass cannot be eliminated, then all layered full-screen post-processing effects can be coalesced into a single additional pass. Instead of multiple passes that each read the previous result from a texture and write out a new filtered value, each effect can pass its computed value to the next effect in the same shader. This saves redundant round-trips to framebuffer memory.

Device	GPU Arch	clear	vtx_lgt	frg_lgt	one_tap	five_tap
Motorola Xoom	IMR	626Mps	52.4MPps	24.08MPps	26.13MPps[1]	3.17MPps[1]
Motorola Droid X	TBDR	3670MPps	234MPps	62.9MPps	5.36MPps[1]	5.7MPps[1]
LG Thunderbolt	TB IMR	305MPps	48.7MPps		30MPps	20.36MPps
Dell Inspiron 520	IMR	1920MPps	231MPps	204MPps	139MPps	120MPps
Desktop System*	IMR	1380MPps	2950MPps	1920MPps	1730MPps	1290MPps

Table 1.3. Performance for different shading and pass configurations. All tests used 1024x1024 16-bit offscreen depth and color buffers as the main framebuffer, with a 32-bit RGBA intermediate color buffer and 16-bit depth buffer where applicable. *clear* performs color buffer clear operations. *vtx_lgt* renders a synthetic scene with lighting computed per-vertex, a per-pixel texture lookup, and 39200 triangles with 0% overdraw. *frg_lgt* uses the same scene and calculates the diffuse illumination in the fragment shader. *five_tap* and *one_tap* draw the vertex_lighting scene with five- and one- sample full-screen post-processing passes, respectively. All units are pixels per second. Desktop system has an Intel Core 2 Quad and NVIDIA 8800 GTS. The Droid X *clear* scores are high enough that it may not actually be writing the framebuffer each time (ie coalescing redundant clears or setting a cleared flag).

One limitation of OpenGL ES 2.0 is poor support for *Multiple Ren-*

der Targets (MRT), which allow multiple output buffers from a fragment shader. This makes deferred shading impractical, it relies on separate *geometry buffers* to store different geometry attributes, but without MRTs, this requires rendering a full pass of the scene for each. Even if MRTs were available however, the additional bandwidth cost of reading and writing multiple full-screen intermediate buffers make defered shading prohibitively expensive.

1.4.3 Off-screen Passes

Similar to full-screen effects are effects requiring off-screen render targets like environmental reflections, depth-map shadows, and light bloom.

Many of these effects require multiple samples of the off-screen image for a soft effect. Since these textures are rendering targets, they probably don't have full mipmap levels or optimal internal texture layouts for coherent read access, so eliminating the cost of multiple samples of a large texture is particularly important One way to optimize off-screen effects that require a blurred image is to take advantage of texture filtering hardware. Rather than rendering a large offscreen image, then taking multiple samples of a fragment shader, the scene can be rendered into a low-resolution offscreen target and blurred via texture filtering.

The main fragment shader for the scene can then bind that target as a texture and read from it with an appropriate texture-filtering mode such as GL_LINEAR. The smaller size of the offscreen target makes this strategy particularly cache-friendly. This may work well for light bloom and environmental reflection, for example. Depending on the effect, an additional Gaussian blurring pass on the off-screen target may be needed, but these can also be accelerated with texture filtering and separable kernels as well [Rideout].

Even when blurring due to texture filtering is not beneficial, reducing off-screen target resolution is an easy way to reduce the fragment workload and memory bandwidth without a serious visual impact for effects that only need low-frequency signals, like environmental reflections.

Whenever moving additional computations from a separate full-screen pass into the fragment shader of objects in the scene, it is important on non-tiled architectures to minimize over-draw to avoid wasted work. One advantage of full-screen post-processing in a separate pass is that each pixel is computed exactly once.

1.4.4 Shaving Fragment Work

One area of optimization with a significant amount of leverage is optimizing fragment shaders. Shaders tend to be fairly small and simple, but the sheer number of fragments and amount of floating-point computation makes non-trivial fragment shading a major bottleneck on both tiling and IMR GPUs. Optimizations here will probably have some effect on visual quality, but it may well be worth the gain in performance.

For static geometry and lighting, baking most of the illumination into light-maps saves computation at run-time, and allows the use of more advanced lighting techniques than would otherwise be affordable [Miller 99] [Unity 11]. Light-map generation and export does require a well-developed asset pipeline.

Another classic trick to avoid floating-point work and special functions in fragment shaders is to approximate a complicated function with a look-up texture [Pranckevicius 11]. This allows the use of much more elaborate BDRF's. This also allows for effects that would be difficult to achieve purely procedurally [Jason Mitchell 07]. 1D look-up textures may be particular cache-friendly, and with a smooth input parameter should have good locality of reference.

However, fragment shaders with multiple texture fetches may already be bound by texture fetch. Large amounts of state for each may also limit the maximum number of in-flight fragments due to register pressure, which affects the ability of the GPU to hide the latency of texture lookups.

1.4.5 Vertex vs. Fragment Work

Traditional IMR wisdom states that lifting computations like lighting, specularity, and normalization from per-fragment to per-vertex and then interpolating the results can save performance at the cost of image quality, and this is still true for IMRs.

However, for tilers, this performance wisdom is more dubious because tilers must perform all vertex computations for each tile [Apple 11]. Tilers are more likely to be vertex-bound, and Unity recommends 40k or less vertices on recent iOS devices, which use Imagination Tech SGX GPUs [Unity 11].

This means that heavy vertex shaders, even if they save fragment work, may be a performance drag on tiling architectures. This is particularly true for TBDRs since they perform little-to-no redundant fragment work. When working with IMRs, lifting computation from the fragment shader to the vertex shader is likely a performance win, and becoming vertex-bound is less of a concern.

Another consideration to the relationship between vertex and fragment shaders is that adding too many additional varyings can be a drag on performance, since they must all be interpolated, and a large amount of per-fragment memory may limit the number of fragments that can be in-flight at once. A large number of varyings may also thrash the post-transform cache, which stores the results of vertex shading, making vertex processing more expensive. So thinning the interface between vertex and fragment shading can be valuable.

Vertex processing is more of a bandwidth drain on tiling architectures, since the attributes probably are pulled again for each tile, unless they hit in a pre- or post- transform cache. To lower this bandwidth, use a lower-precision buffer format such as *OES_vertex_half_float*.

Interleaved vertex data, which interleaves the attributes for each vertex in the same buffer, is also more efficient for attribute fetch, since an entire vertex can be fetched in one linear read [Apple 11]. If there is a pre-transform vertex attribute cache, which stores fetched vertex attributes and the surrounding data, this will make more efficient use of it, since spatial locality in the cache means less data will have to be fetched from DRAM.

One caveat to interleaving vertex data is if the vertex data is partially dynamic. The most common case is when only positions are updated. A solution to separate the vertex data into "hot" attributes that are frequently updated and "cold" ones which are mostly static, and store them in separate buffers. This avoids inefficient updates to the "hot" attributes because of a large stride between vertices.

1.5 Conclusion

OpenGL ES is a fundamental component of the modern mobile experience, for UI rendering and composition, [Guy and Haase 11] and presents a huge market and potential impact for OpenGL developers. However, driven by explicit consumer demand for long battery life and slender devices on one hand, and large, brilliant displays with perfectly smooth rendering on the other, performance must be a dominant consideration during development. The wide range of devices in the market, differing in age, resolution, and capability, only make this more difficult.

One important question is if the significant difference in performance between mobile and desktop GPUs will continue to be a dominating consideration in application development, or if it is something that the steady march of semiconductor process and architectural improvements will soon make irrelevant. Looking at the projected roadmaps for mobile GPU vendors, the compute power of mobile GPUs should indeed climb over the next few years. However, other limits, including bandwidth and power consumption, are more fundamental and cannot be conquered as easily. Desktop and even laptop systems are less tightly constrained on those dimensions.

The expected workloads of mobile devices are also changing. Sprite-based games and 2D workloads are still very important, but several publishers have produced mobile ports of desktop game engines, and games with console or desktop levels of rich game worlds and visual quality. These games raise the bar for what is considered possible and now expected on mobile systems, and present challenges in terms of the amount of geometry, assets, and visual effects they require. The main strategy to deliver on these promises is a measured assessment of a platform's capabilities and limitations paired with an understanding and quantification of the costs of different effects and rendering techniques.

While developing a fast and efficient application for mobile devies takes thought, careful measurement and budgeting, and creative corner-cutting, with a consciousness to the costs and limitations involved, developers can deliver beautiful and compelling graphics and an experience users can barely believe is possible.

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