PowerVR Performance Recommendations

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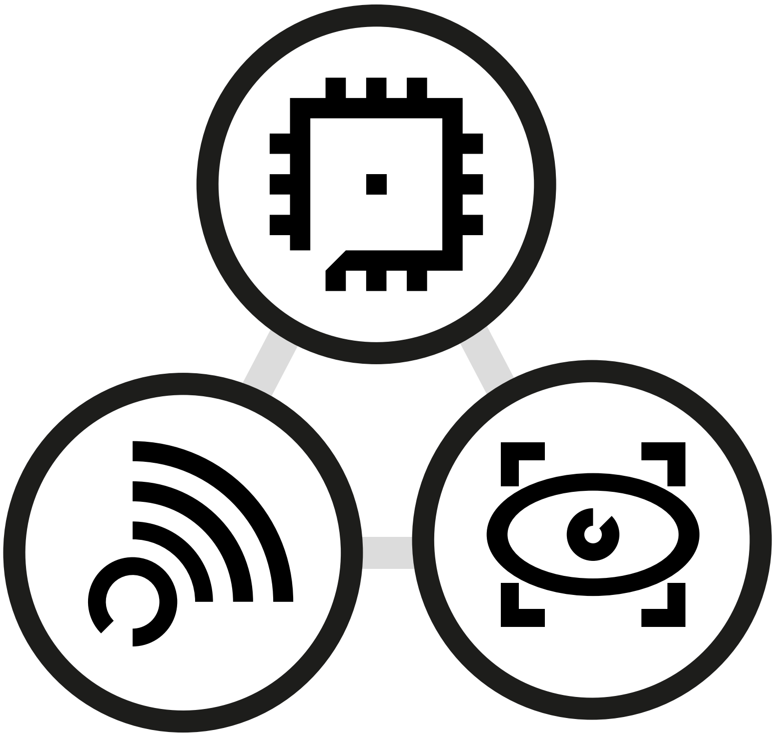

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1. PowerVR Performance Recommendations Introduction

What are the PowerVR Performance Recommendations?

These recommendations are aimed at developers who wish to get the best possible graphics performance from their applications running on PowerVR hardware. The recommendations range from the fairly high-level to very low-level, and have varying amounts of performance gain.

The reader is introduced to the *optimal development approach* when considering performance, including how to go about *analysing an application's performance*.

Further areas covered include:

- *Vulkan®-specific optimisations*
- *OpenGL® ES-specific optimisations*
- The best way to optimise:
  - *Geometry*
  - *Textures*
  - *Shaders*
- Optimisations for *specific techniques*, such as preferred *lighting* and *shadowing* solutions, *particle rendering*, *physically-based rendering*, and many more.
- Tips related to subjects such as *balancing workloads*, *on-chip memory performance*, and *register pressure*.

The PowerVR family

PowerVR SGX and PowerVR Rogue are graphics core architectures from Imagination Technologies designed specifically for shader-based APIs such as OpenGL® ES 2.0, 3.x, and Vulkan®. Due to their scalable architectures, the PowerVR family spans a huge performance range.

The Golden Rules

The Golden Rules are a set of more generic performance recommendations that all graphics developers should seek to implement, as well as observe as many of the techniques and principles mentioned. This should help produce well-behaved, high performance graphics applications.

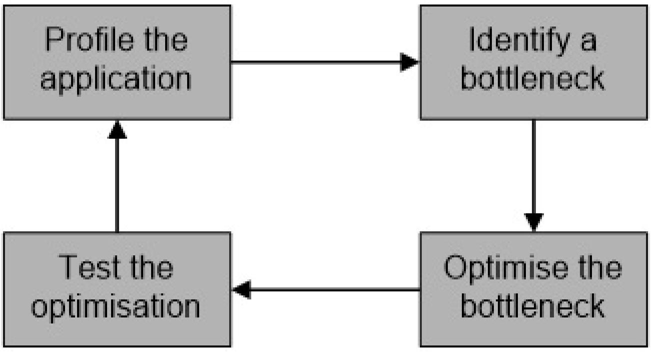
These rules can be found as part of the Introduction to PowerVR for Developers.

Optimal Development Approach

Cyclical profiling

It is crucial to follow these recommendations from the very start of development to save time and effort later.

Once an application is implemented to a near-final state, the Cyclical Profiling process shown below should be followed. The main benefit of this approach is that time is not wasted, and graphics quality is not comprised by making changes that do not benefit performance.



Understanding rendering bottlenecks

It is a common misconception that the same actions can speed up any application. For example:

- **Polygon count reduction**: If the bottleneck of the application is fragment processing or texture bandwidth, then the only result of this action will be to reduce the graphical quality of the application without improving rendering speed. If simpler models cause more of the render target to be covered by a material with complex fragments, then this can slow down an application.
- **Reduce rendering resolution**: If the fragment processing workload of the application is not the bottleneck, then this will also only serve to reduce the quality of the graphics in the application without improving performance.

It is only once the limiting factor of an application is determined by profiling with the correct tools that optimisation work should be applied. Once work has been done, then the application requires re-profiling in order to determine whether the work improved performance, and whether the bottleneck is still at the same stage of the graphics pipeline. It may be that the limiting stage in rendering is now at a different place and further optimisation should be targeted accordingly.

Some PowerVR-specific tools to consider for this purpose:

- *PVRTune* is a hardware profiler, giving real-time data on application performance, including access to hardware counters.
- *PVRMonitor* is a lightweight, fully-configurable Android overlay, giving quick access on-device to the same hardware counters as PVRTune.
- *PVRTrace/PVRCarbon* provides capture of API calls for further analysis.

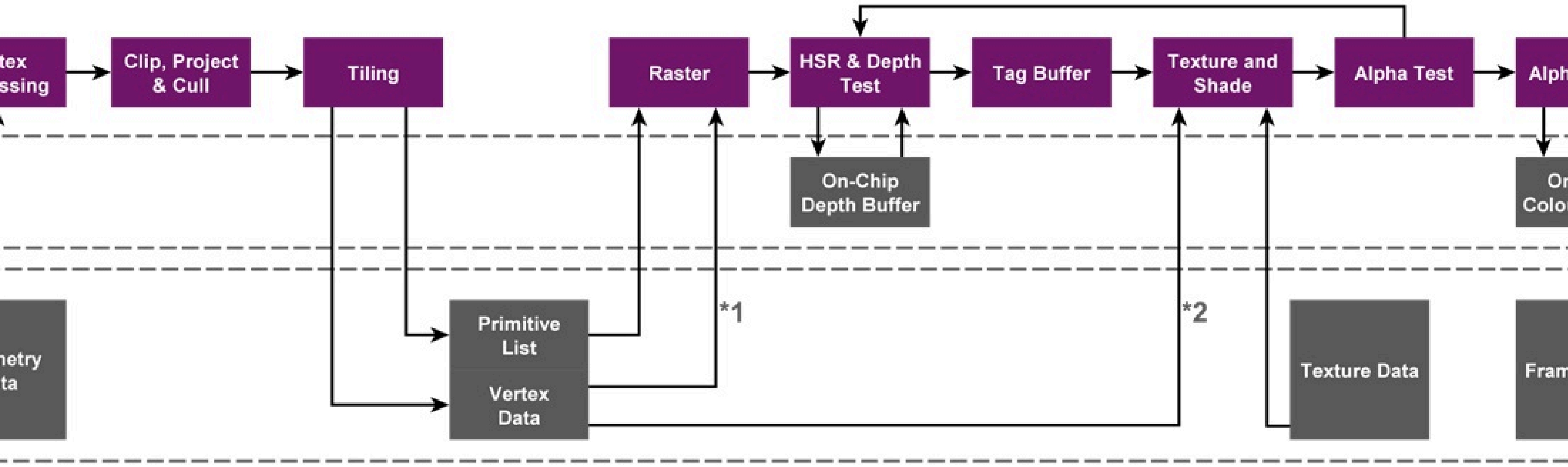
The full PowerVR Tools and SDK is available for download *here*.

Optimising Applications for PowerVR Graphics Cores

Before diving into tools or performance recommendations, it is important to consider the capabilities and characteristics of the target device.

Graphics architecture

A basic understanding of how API calls are processed by the driver, inserted into the graphics hardware's command stream, and converted into coloured pixels goes a long way. It provides an immediate appreciation of why certain graphics API calls are costly and how submitted calls will map to the graphics hardware's processing pipeline.



The following documents are recommended to become familiar with the PowerVR graphics architecture:

- *Introduction to PowerVR for Developers*
- *PowerVR Instruction Set Reference*

These documents are also packaged with the PowerVR SDK and Tools.

Mobile graphics APIs

Mobile graphics APIs are a subset of their desktop counterparts, with imposed restrictions and specific features to suit the performance characteristics of mobile devices and the batteries that power them. Although the latest APIs, such as OpenGL ES 3.2, Vulkan, and the Android Extension Pack, have brought many of the desktop and console features to low power devices, there are still differences that need to be considered.

Many of the recommendations in this document, as well as those in the Introduction to PowerVR for Developers and *PowerVR Supported Extensions* documents, apply to all mobile graphics architectures. These documents also detail PowerVR-specific behaviour and describe OpenGL ES extensions exposed by the PowerVR reference driver for advanced hardware features.

Thermal design power (embedded devices)

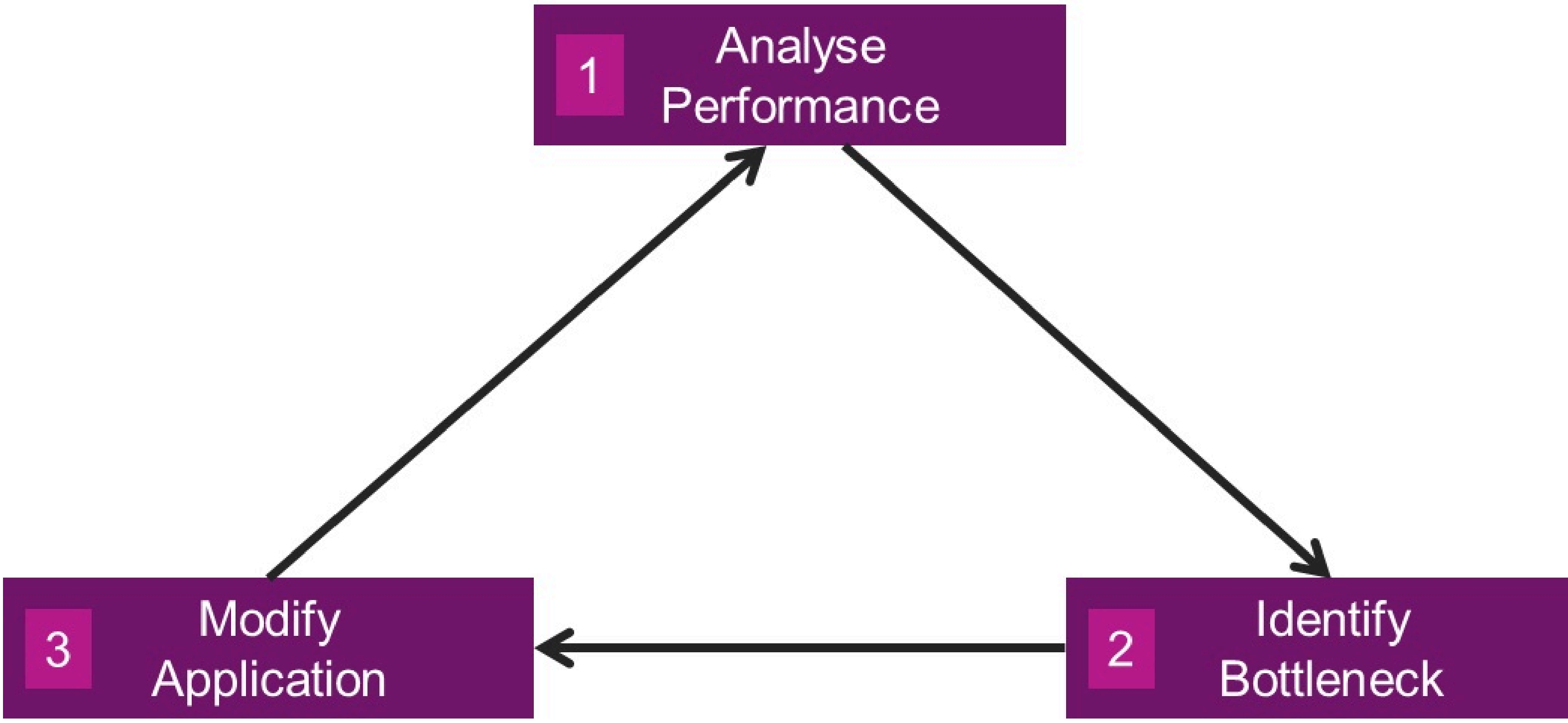
These recommendations for optimisations focus specifically on the PowerVR graphics core. However, reducing an application's workload on the CPU can be beneficial to the entire System on Chip (SoC) - which includes the graphics core. This is because the CPU and graphics core share Thermal Design Power (TDP), meaning a reduction in CPU workload can not only reduce power draw for the entire SoC, but also reduce thermal output. This will help to prevent thermal throttling which would reduce the amount of power being sent to the SoC, potentially increasing the performance of the graphics core.

One of the primary advantages of the Vulkan® API if used correctly is that it can reduce CPU workload. This is in part due to Vulkan drivers being very efficient and lightweight, which reduces overheads when using the API. This means that Vulkan has the potential to reduce the overall power consumption and thermal output of the entire SoC.

Analysing an Application's Performance

The process of optimising graphics applications

Optimising graphics applications seems like a straightforward process. Although the steps in the diagram below may seem obvious, both beginners and experienced developers have in the past made simple mistakes that have cost large amounts of development time to resolve. Developers tend to run their analysis tools, identify a bottleneck, modify their application and then consider the work done. However, one of the most important stages of optimisation is to verify the change has actually improved performance. Without analysing performance after a modification, it is easy for new, or possibly worse, bottlenecks to creep their way into a renderer.



The right tools for the job

The PowerVR SDK includes profilers, debuggers and a variety of other analysis tools to help developers track down issues. Here's a quick overview of the key utilities:

- *PVRMonitor*: Renders a real-time overlay of the CPU and graphics stats on Android devices with PowerVR graphics cores. Also available as plug-ins for Unity and Unreal.
- *PVRTune*: Remote graphics performance analyser, with a server on the target, and a GUI analysis tool on the development machine. Captures timing data and counters, such as hardware unit loads and throughput data, in real-time.
- *PVRShaderEditor*: Off-line shader editor and performance analyser. Generates disassembly in real-time for SGX and Rogue graphics cores.
- *PVRTrace*: OpenGL ES 1.x, 2.0 & 3.x capture and analysis tool. PVRCarbon brings Vulkan support.

For more information regarding our entire suite of development tools, please visit our *PowerVR Tools and SDK*.

2. Optimising Geometry

This section covers the best approaches for managing and storing vertex data. This includes how to decide on the degree of geometry complexity and what criteria to sort geometry on.

Choosing the Level of Geometry Complexity

An appropriate level of geometry complexity must be used for each object or portion of an object. Here are some examples of wasteful usage:

- using a large number of polygons on an object that will never cover more than a small area of the screen
- using polygons for detail that will never be seen due to camera angle, or culling
- using large numbers of primitives for objects that may be drawn with fewer primitives. For example, using hundreds of polygons to render a single quad.

Shader techniques such as bump mapping should be considered to minimise geometry complexity, but still maintain a high level of perceived detail. Other techniques such as Level of Detail should also be used. This is particularly true for things such as reflection passes where higher amounts of geometry may not be visible.

Optimising Vertex and Index Buffers

For optimal performance on PowerVR graphics cores, a mesh with static attribute data should:

- use indexed triangle lists
- interleave VBO attribute data
- not include unused attributes.

For optimal vertex shader execution performance, meshes transformed by the same vertex shader, even if compiled into different shader programs, must have the same VBO attribute data layout. On some devices, padding each vertex to 16-byte boundaries may also improve performance.

Generating optimal vertex and index buffers

When rendering large amounts of geometry, sub-optimal vertex and index buffers can affect performance dramatically. For optimal performance, vertex and index buffers need to be sorted so they become cache efficient. Our *PVRGeoPod* tool can be used for this purpose.

The *PVRGeoPod* GUI can be used to work with individual meshes. For batch processing, such as when automatically optimising meshes in a game engine, use the command-line version of PVRGeoPOD, or the *meshoptimizer* library. This library has many features including cache efficiency optimisation, view-independent overdraw optimisation, vertex fetch optimisation, and vertex quantisation. Please refer to the *project* on GitHub for instructions on how to use the tool.

Interleaving attributes

Two ways exist to store vertex data in memory. These are either:

- Data is stored with all the information, position, normals, and so on relevant to a given vertex in a single block. This is followed by all the information relevant to the next vertex.
- Data can be stored in a series of arrays, each containing all the information of a particular type for each vertex. For example, an array of positions or an array of normals.

The first of these two options is called interleaving. Usually data should be interleaved, as this provides better cache efficiency, and therefore better performance. However, two major caveats exist to this rule:

- Interleaving should not be used if several meshes share only some vertex attributes from an array of vertex attributes. In this case, separating the shared attributes into their own array may result in better performance, as opposed to duplicating the shared attributes in order to interleave them with the shared ones.
- Interleaving should also not be used if a single attribute will be updated frequently, outside of the graphics core, while the other attributes remain the same. In this instance, data that will not be updated should be interleaved, while data that will be updated is held in a separate array.

Vertex Buffer Objects in OpenGL ES

Vertex Buffer Objects (VBOs) are the preferred way of storing vertex and index data. VBO storage is managed by the driver, so there is no need to copy an array from the client side at every draw call, and the driver is able to perform some transparent optimisations.

All the vertex attributes that are required for a mesh should be packed into the same VBO unless a mixture of static and dynamic attributes are being used. Do not create a VBO for every mesh, as it is a good idea to group meshes that are always rendered together to minimise buffer rebinding. This also has the benefit of improving batching.

The graphics chip tends to process multiple frames at a time, so the driver has to internally allocate multiple buffers for dynamic VBOs so that each frame has a unique dynamic buffer associated with it. Due to this driver behaviour, it is generally better for performance if dynamic vertex data (data that changes on a per-frame basis) is split from the static vertex data and placed into a separate VBO. This means only the dynamic VBOs need to be resubmitted per frame, rather than the entire vertex data set.

If there is a mesh where only some of the vertex data is dynamic, such as a skinned character in a game, then a VBO should be created that contains the static data. Use calls to `glVertexAttribPointer` to resubmit the dynamic vertex data.

A VBO that will never change should always set the `STATIC_DRAW` flag, while a VBO whose contents will change should never set it.

An alternative approach to dynamically updating vertex data involves creating a type of ring buffer. In this scenario, all the vertex data is stored in a single buffer, and the API function `glMapBufferRange` is used to map portions of the buffer for updating. This allows the application to update vertex data stored in one region of a vertex buffer while the graphics core is drawing from a separate region of the same vertex buffer.

Note: Data should only be overwritten when it is no longer being used by the graphics core, meaning fences should be employed to determine when it is safe to update a region of buffer.

Choosing Attribute Data Types

When passing data into a shader, such as uniforms, varyings, or attributes, always consider their usage. If the data is intended to be used in maths operations then always use a floating point data type to prevent unnecessary type conversions between integer and float. If the data is intended to be used solely as an integer, such as an index to an array, then the data will not require a conversion.

Note: This implicit conversion is performed in the Unified Shader Core (USC) and costs a few additional cycles, and so should be avoided.

The throughput (ops/cycle) of various data types should also be considered.

From fastest to slowest:

- FP16 – *`mediump`*
- FP32 – *`highp`*
- INT

The conversion will be performed if the application uses an integer attribute type in a floating point operation, otherwise there is no additional cost associated with integer types.

The choice of attribute data type is a trade-off between shader cycles, bandwidth/ storage requirements, and precision. It is important that type conversion is considered as bandwidth is always at a premium.

There are a couple of exceptions to this rule:

- The data type 10F11F11F will require conversion to be performed by the hardware.
- The data type 8-bit S/UNORM may not require conversion, depending on the hardware being deployed to.

Precision requirements should be checked carefully. The byte and short types are often sufficient, even for position information. For example, scaled to a range of 10m, the short types give a precision of 150 μm. Scaling and biasing those attribute values to fit a certain range can often be folded into other vertex shader calculations, such as multiplied into a transformation matrix.

Determining Optimal Draw Call Size

When using the OpenGL ES API, draw calls should contain a significant amount of work for the graphics core to process through the number of vertices, heavy shader arithmetic computation, or both. This negates the API overhead incurred by calling the function in the first place. Many light draw calls with little work for the graphics core to process each time can incur unnecessary overhead, and potentially lead to a CPU bottleneck.

When an application uses the Vulkan API correctly, this issue is much less critical due to the API being much more efficient. Command buffer submission results in significantly less driver overhead compared to OpenGL ES.

Triangle Size

On PowerVR hardware, an application should try to avoid small triangle sizes, in terms of pixel coverage (area), especially dipping below 32 pixels per primitive. Rendering triangles smaller than this size will impact the efficiency of rasterization, which could potentially lead to a bottleneck.

Submitting many tiny triangles will likely result in the hardware spending a large percentage of time processing them in the vertex stage, due to the number of triangles rather than size. This is specifically with the tile accelerator (TA) fixed function hardware, which could potentially result in a TA bottleneck. Many small triangles will result in an increased number of accesses to the parameter buffer, which is located in system memory. This will increase the memory bandwidth footprint.

Note: Sub-pixel triangles (triangles that cover less than a single pixel) will be discarded by the hardware.

What is the Parameter Buffer?

The Tile Accelerator (TA) on PowerVR graphics cores generates a list containing pointers to each vertex passed in from the application. This structure determines which tile each vertex resides in. This list is called the parameter buffer (PB) and is stored in system memory along with the vertex data.

Advantages of Face Culling

An application should enable face culling wherever possible, and correctly set the appropriate face to be culled. Enabling face culling significantly reduces the amount of load on the graphics hardware. This is due to the significant reduction in the number of polygons that must be processed by hardware. The tiling hardware (TA) does not need to bin as many triangles and the ISP does not need to rasterize as many triangles. This can help performance significantly on highly complex workloads with many hundreds of thousands or millions of polygons, and reduce the likelihood of bottlenecks in these fixed function pipeline stages.

Z Pre-pass and PowerVR

On PowerVR hardware there is no performance benefit to rendering a low-poly geometry Z pre-pass to save fragment processing later. Performing this operation would be a waste of clock cycles and memory bandwidth. The PowerVR hidden surface removal (HSR) hardware will detect and remove occluded (opaque) geometry from the pipeline automatically during rasterization, before fragment processing begins.

Sorting Geometry Effectively on PowerVR

Distance

On PowerVR hardware there is no performance benefit to be gained by sorting opaque geometry based on distance from the camera. The Hidden Surface Removal (HSR) hardware will detect and remove occluded (opaque) geometry from the pipeline automatically before fragment processing begins. Performing this operation would be a waste of resources.

However, for blended geometry, sorting is necessary to get the correct results, and for alpha-tested geometry it may actually be beneficial to sort. If the application uses opaque, alpha-tested and alpha-blended objects in a scene, then it is advised that the application renders the opaque objects first, followed by the alpha-tested objects, and finally the transparent geometry.

Render state

There are performance gains to be had by sorting geometry based on render state, for example common materials, shaders, render targets, or resources. Sorting the geometry based on this method can significantly reduce the amount of resources that are switched (operations which may incur significant overheads) by the driver during rendering of the frame. This can reduce the amount of work that the driver performs, therefore reducing CPU workload. It can also reduce the amount of time the graphics core spends idle waiting for resources to be ready before being able to render.

Render to texture

For maximised performance, the preferred method for rendering to textures in OpenGL ES is through the use of frame buffer objects (FBOs) with textures as attachments.

An application should always render to frame buffer objects (FBO) in series, which means submitting all calls for one FBO before moving to the next. This serves to significantly reduce unnecessary system memory bandwidth usage, caused by flushing partially completed renders to system memory when the target FBO is changed, and it will also minimise state changes. For optimal performance, attachments should be unique to each FBO, and attachments should not be added or removed once the FBO has been created.

Note: PowerVR hardware exposes a unique extension to efficiently perform down sampling on frame buffer attachments, see *Framebuffer down sampling* for further information.

3. Optimising Textures

This section covers advice on how to use textures optimally on PowerVR hardware to improve application performance.

Choosing Appropriate Texture Sizes

It is a common misconception that bigger textures always look better. A 1024x1024 texture that never takes up more than a 32x32 area of the screen is a waste of both storage space and reduces cache efficiency. A texture's size should be based on its usage. There should be a one pixel to one texel mapping when the object that it is mapped to is viewed from the closest allowable distance.

Before considering reducing the resolution of texture assets to save storage space, apply texture compression. If the quality of the lossy texture compression is unacceptable, consider using an 8 or 16-bit per pixel uncompressed format. If the storage space for the assets still needs to be reduced, then consider reducing the resolution of the images.

Demystifying NPOT

If a 2D texture has dimensions which are a power-of-two (width and height are 2^n and 2^m for some m and n), then the texture is known as a POT texture (power-of-two). If they are not, it is known as an NPOT texture (non-power-of-two). This section seeks to clarify the status of NPOT textures in OpenGL ES.

OpenGL ES support

NPOT textures are supported as required by the OpenGL ES specifications. However:

- NPOT textures are not supported in OpenGL ES 1.1 implementations.
- NPOT textures are supported in OpenGL ES 2.0 implementations, but only with the wrap mode of `GL_CLAMP_TO_EDGE`.
  - The default wrap mode in OpenGL ES 2.0 is `GL_REPEAT`. This must be specifically overridden in an application to `GL_CLAMP_TO_EDGE` for NPOT textures to function correctly.
  - If this wrap mode is not correctly set, then an invalid texture error will occur. Likewise, a driver error may occur at runtime on newer drivers, to highlight the need to set a wrap mode.

GL_IMG_texture_npot

An extension exists (`GL_IMG_texture_npot`) to provide some of the functionality found outside of the core OpenGL ES specification. This extension allows the use of the following filters for NPOT textures:

- `LINEAR_MIPMAP_NEAREST`
- `LINEAR_MIPMAP_LINEAR`

- `NEAREST_MIPMAP_NEAREST`
- `NEAREST_MIPMAP_LINEAR`

It also allows the calling of `glGenerateMipmapOES` with an NPOT texture to generate NPOT mipmaps. Like all other OpenGL ES extensions, the application should check for this extension's presence before attempting to load and use it.

Guidelines

Additional points to consider when using NPOT textures:

- POT textures should be favoured over NPOT textures for the majority of use cases, as this gives the best opportunity for the hardware and driver to work optimally.
- A 512x128 texture will qualify as a POT texture, not an NPOT texture, where rectangular POT textures are fully supported.
- 2D applications should see little performance loss from the use of NPOT textures other than possibly at upload time. 2D applications could be a browser or other application rendering UI elements, where an NPOT texture is displayed with a one-to-one texel to pixel mapping.
- To ensure that texture upload can be optimally performed by the hardware, use textures where both dimensions are multiples of 32 pixels.

The use of NPOT textures may cause a drop in performance during 3D rendering. This can vary depending upon mipmap levels, size of the texture, texture usage, and the target platform.

Texture Compression using PVRTC

Modern applications have become graphically intensive. Certain types of software, such as games or navigation aids, often need large amounts of textures to represent a scene with satisfying quality. Texture compression can save or allow better use of bandwidth, power, and memory without noticeably losing graphical quality and should be used as much as possible.

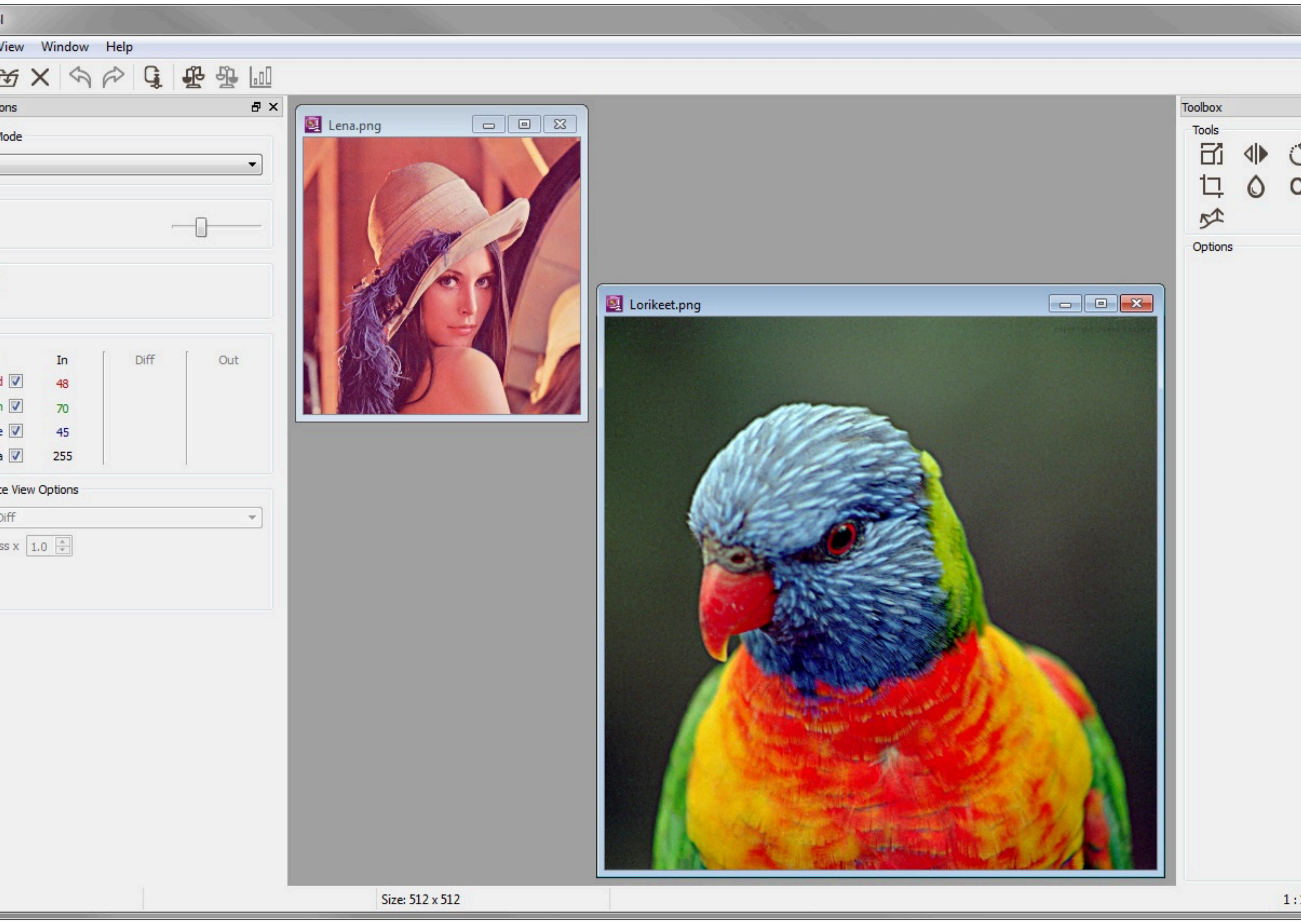
PowerVR hardware offers a specific proprietary form of texture compression called PVRTC. It uses a sophisticated amplitude modulation scheme to compress textures. Texture data is encoded as two low-resolution images along with a full resolution, low bit-precision modulation signal. More information can be found in the whitepaper:

- Fenney, S. (2003) 'Texture Compression Using Low-Frequency Signal Modulation' *SIGGRAPH Conference*.

PVRTC supports both opaque (RGB) and translucent (RGBA) textures, unlike other formats such as S3TC that require a dedicated, larger form to support full alpha channels. It also boasts a very high image quality for competitive compression ratios of 4 bits per pixel (PVRTC 4bpp) and 2 bits per pixel (PVRTC 2bpp).

PVRTexTool

PVRTexTool is a utility for compressing textures, which ensures the lowest possible texture memory overhead at application run-time. The PVRTexTool package includes a library, command-line and GUI tools, and a set of plug-ins. Plug-ins are available for Autodesk 3ds Max, Autodesk Maya, and Adobe Photoshop.



Each component is capable of converting to a variety of popular compressed texture formats such as PVRTC and ETC, as well as all core texture formats for a variety of different APIs. They also include a number of advanced features to pre-process the image data, for example border generation, colour bleeding, and normal map generation.

Textures can be saved to DDS, KTX, or PVR. PVR is Imagination's PowerVR Texture Container format which benefits from:

- Full public specification
- Support for custom metadata
- Complete and optimised resource loading code with other PVR tools.

Key features of PVRTexTool include:

- Supports all core texture formats in OpenGL ES, Vulkan, and DirectX 11.1
- PVRTC, ASTC, ETC, and DXT texture compression
- Outputs to PVR, KTX, or DDS files
- Pre-processing textures for efficient rendering
- Normal map generation
- Composition and visualisation of cube maps
- Optimised font to texture creation
- Creation of texture arrays

For more information and to download the latest version of PVRTexTool, please visit our page *here*.

Note: Texture arrays are allocated as contiguous blocks of memory. In OpenGL ES (only) modifying any texel within any element of the array will cause the driver to ghost the entire texture array. The KHR_debug logging will report when these ghosting events occur. In Vulkan, all synchronisation is under the application's control.

Why use PVRTC?

In any given situation, the best texture format to use is the one that gives the required image quality at the highest rate of compression. The smaller the size of the texture data, the less bandwidth is required for texture fetches. This reduces power consumption, can increase performance, and allows for more textures to be used for the same budget.

The smallest RGB and RGBA format currently available on all PowerVR Graphics Cores is PVRTC 2bpp, and therefore it should be considered for every texture in an application. Larger formats such as PVRTC 4bpp should only be used if the image quality provided by a particular PVRTC 2bpp image does not have sufficient quality. On the latest PowerVR graphics cores, ASTC compression is also available.

Performance improvement

The smaller memory footprint of PVRTC means less data is transferred from memory to the Graphics Core allowing for major bandwidth savings. In situations where memory bandwidth is the limiting factor in an application's performance, PVRTC can provide a significant boost. PVRTC also improves cache efficiency, because it takes less space to store the data in the cache. This can reduce the number of cache evictions and improve cache hit-rate.

Power consumption

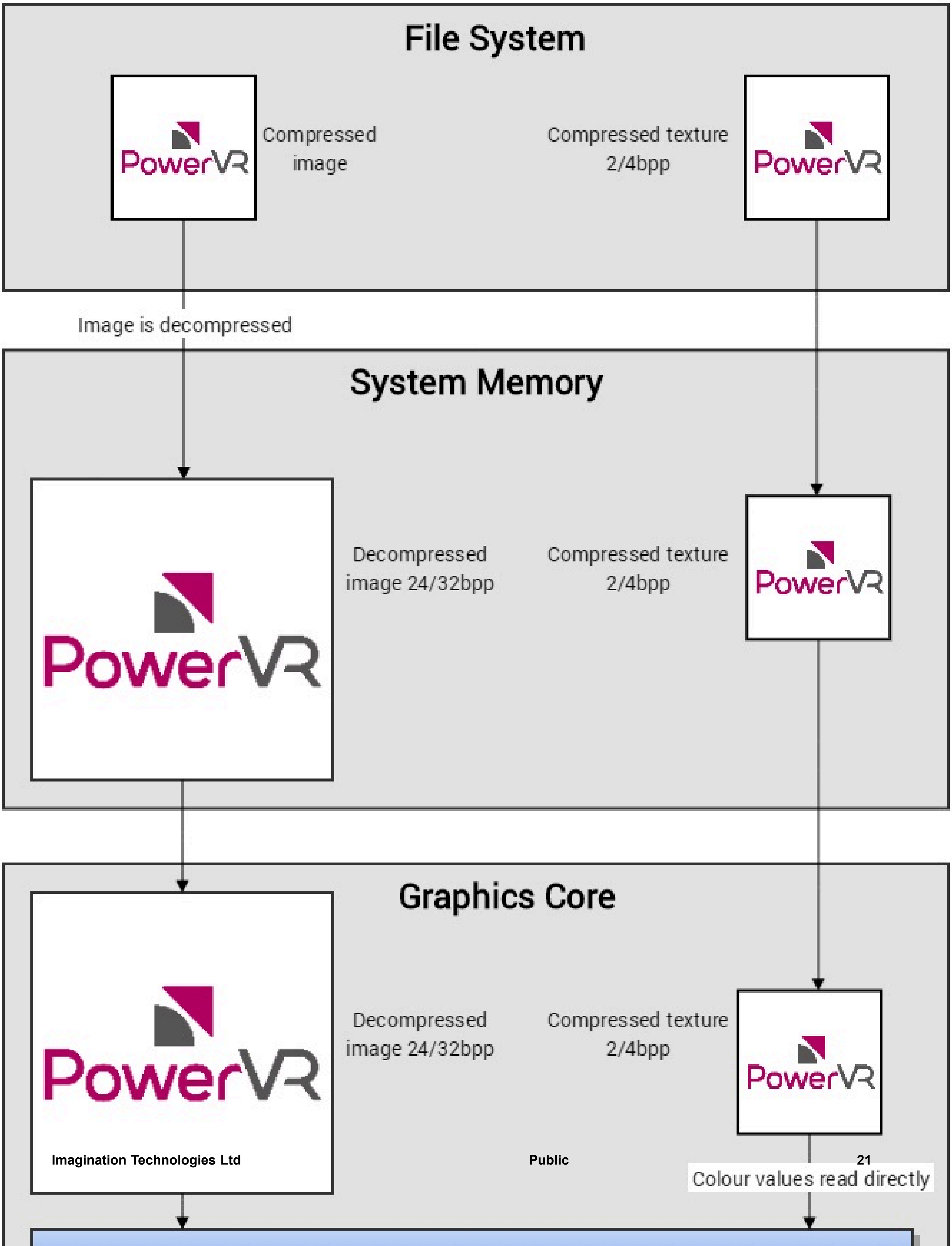
Memory accesses are one of the primary causes of increased power consumption on mobile devices where battery life is of the utmost importance. The bandwidth savings and better cache performance resulting from the use of PVRTC both contribute to decreasing the quantity and magnitude of memory accesses. These in turn reduce the power consumption of an application.

Image file compression versus texture compression

Developers are familiar with compressed image file formats such as JPG or jpg. It is important to be aware of the distinction between these forms of storage compression, and the texture compression discussed in this document.

The primary requirement of storage compression schemes is that files compressed using them should occupy as small an amount of storage in a file system as possible. There is no requirement that the data stays compressed while in use. The result is that storage-based image file formats tend to produce very small file sizes, often for very high (or lossless) image quality, but at the cost of immediate decompression on use. This immediate decompression, usually to 24/32bpp, means that the image while small on disk, consumes large amounts of bandwidth and memory at runtime.

Texture compression schemes such as PVRTC are designed to be directly usable by the graphics core. The texture data exists in storage in memory, and is transferred to the graphics hardware itself in the compressed format. The only step in which full-precision colour values are extracted from a compressed state is when dedicated texture sampling hardware inside the graphics accelerator passes texel values to the shader processing units.


File System
Compressed image
Compressed texture 2/4bpp
Image is decompressed
System Memory
Decompressed image 24/32bpp
Compressed texture 2/4bpp
Graphics Core
Decompressed image 24/32bpp
Compressed texture 2/4bpp
Colour values read directly

This allows all the advantages mentioned above, but puts some limits on the form the compression technique may take. To allow for direct use by the graphics accelerator, a texture format should be optimised for random access, with a minimal size of data from which to retrieve each texel's values. Consequently, texture compression schemes are usually fixed bitrate with very high data locality. Image file formats are not constrained by these requirements, and can often achieve higher compression ratios and image quality for a given data size.

Using Mipmapping to Improve Quality and Performance

Mipmaps are smaller, pre-filtered variants of a texture image, representing different Levels of Detail (LOD) of a texture. A minification filter mode that uses mipmaps must be used. The graphics core can then be set up to automatically calculate which LOD comes closest to mapping the texels of a mipmap to pixels in the render target, and use the right mipmap for texturing.

Advantages

Using mipmaps has two important advantages:

- Increases performance by massively improving texture cache efficiency, especially in cases of strong minification.
- Improves image quality by countering the aliasing that is caused by the under-sampling of textures that do not use mipmapping.

The single limitation of mipmapping is that it requires approximately a third more texture memory per image. Depending on the situation, this cost may be minor when compared to the benefits in terms of rendering speed and image quality.

There are some exceptions where mipmaps should not be used. Specifically, mipmapping should not be used where filtering cannot be applied sensibly, such as for textures that contain non-image data such as indices or depth textures. It should also be avoided for textures that are never minified, for example with UI elements where texels are always mapped one-to-one to pixels.

Generation

Ideally mipmaps should be created offline using a tool like *PVRTexTool*, which is available as part of the PowerVR Graphics SDK. It is possible to generate mipmaps at runtime, which can be useful for updating the mipmaps for a render to texture target. In OpenGL ES this can be achieved using the function `glGenerateMipmap`. In Vulkan there is no such built in function, and they must be generated manually.

This will not work with PVRTC textures which must have their mipmaps generated offline. A decision must be made as to which cost is the most appropriate - the storage cost of offline generation, or the runtime cost (and increased code complexity in the case of Vulkan) of generating mipmaps at runtime.

Filtering

The lack of filtering between mipmap levels can lead to visible seams at mipmap transitions, in the form of an artefact known as mipmap banding. Tri-linear filtering can be enabled by setting the filter mode as follows:

- OpenGL ES - use `GL_LINEAR_MIPMAP_LINEAR`.
- Vulkan - use `VK_SAMPLER_MIPMAP_MODE_LINEAR`.

This can effectively eliminate these seams, for a price (see *Texture Filtering*), which achieves an even higher image quality.

Texture Sampling

Texture filtering

Texture filtering can be used to increase the image quality of textures used in 3D scenes. However, as the complexity of the filtering used increases, so will the associated cost as more samples are required.

There are several common techniques employed for texture filtering. These include, in order of increasing image quality, but also increasing cost:

1. nearest
2. bilinear
3. cubic
4. tri-linear
5. anisotropic

Performance can be gained by using an appropriate level of filtering, following the principle of "good enough". For instance, not using anisotropic if tri-linear is acceptable, or not using tri-linear if bilinear is acceptable.

Filtering works by either taking a single sample in the case of nearest filtering, or by taking multiple samples involving multiple texture fetch operations. These are then combined (interpolated) in order to produce as good a sampling value as possible to use in fragment calculations.

Retrieving multiple values requires more data to be fetched, possibly from disparate areas of memory, and so cache performance and bandwidth use can be affected. For instance, when tri-linear filtering is used, eight texel fetches are required, compared to only four for bilinear filtering or one for nearest filtering. This means the texture processing unit in the graphics core must spend more time and bandwidth fetching and filtering the required data as the complexity of the filtering increases.

The graphics core will attempt to hide memory access by scheduling USC tasks. If there is not enough work to hide the memory latency, then the texture fetches may cause the processing of a fragment to stall while the data is fetched from system memory. If the data is already in cache, then memory latency is much less an issue. More complex filtering techniques will result in additional data being transferred across the system memory bus in order to render a frame.

Note: When performing independent texture reads, texture sampling can begin before the execution of a shader. Therefore the latency of the texture fetch can be avoided, as the data is ready before shader execution.

On PowerVR hardware, bilinear filtering is always hardware accelerated, including shadow sampling. This is sampling a texture with depth comparison activated - `sampler2DShadow`. In the case of shadow sampling, the depth comparison operation is performed in software with USC instructions appended (patched) to the fragment shader. The exact cost of the depth comparison operation will vary depending on the exact hardware the application is deployed to. The cost of the operation can be determined by using *PVRShaderEditor* and setting the appropriate GLSL compiler.

Texel fetch

In certain cases, performing a `texelFetch` operation can be considerably faster than calling the texture function. For example, take the case of an application performing an expensive sampling operation such as anisotropic filtering. It will likely be faster to perform a `texelFetch` operation over a `texture` operation, although this should be verified through profiling.

On PowerVR hardware, both operations are driven by dedicated hardware known as the Texture Processing Unit (TPU). In some special cases `texelFetch` may translate to a DMA operation.

Dependent texture read

A dependent texture read is a texture read in which the texture co-ordinates depend on some calculation within the shader instead of on a varying. As the values of this calculation cannot be known ahead of time, it is not possible to pre-fetch texture data, and so stalls in shader processing occur.

Vertex shader texture lookups always count as dependent texture reads, as do texture reads in fragment shaders where the texture read is based on the `.zw` channels of a varying. On some driver and platform revisions `Texture2DProj()` also qualifies as a dependent texture read if given a `Vec3` or a `Vec4` with an invalid `w`.

The cost associated with a dependent texture read can be written off to some extent by hardware thread scheduling, particularly if the shader in question involves a lot of mathematical calculations. This process involves the thread scheduler suspending the current thread and swapping in another thread to process on the USC. This swapped thread will process as much as possible, with the original thread being swapped back once the texture fetch is complete.

Note: While the hardware will do its best to hide memory latency, dependent texture reads should be avoided wherever possible for good performance.

Dependent texture reads are significantly more efficient on PowerVR Rogue Graphics Cores than SGX. However, there are still small performance gains to be had. For this reason, applications should always calculate coordinates before fragment shader execution, unless the algorithm relies on this functionality.

Wide floating point textures

For textures that exceed 32-bits per texel, every additional 32-bits is counted as a separate texture read. This also applies to half float textures with three or four components, as well as float textures with two or more components. These larger formats should be avoided unless necessary for a particular effect.

Related Concepts

Do Use Level of Detail (LoD)

Uploading Textures Efficiently

When a non-compressed texture is uploaded to the graphics hardware, the input data is in linear scan-line format; a compressed texture is uploaded block-by-block. Internally, PowerVR hardware uses its own layout to improve memory access locality and improve cache efficiency. Reformatting of the data is done on-chip by dedicated hardware and is therefore very fast. However, it is still recommended that a few steps be taken to minimise the cost of this reformat.

These steps are as follows:

- Textures should be uploaded during non-performance critical periods, such as initialisation. This helps avoid the frame rate dips associated with additional texture loading.
- Avoid uploading texture data mid-frame to a texture object that has already been used for that frame.
- Consider performing a warm-up step after texture uploads have been performed. Once again, this helps avoid the frame rate dips associated with texture loading.

Texture warm-up

The warm-up step mentioned before ensures that textures are fully uploaded immediately. By default, `glTexImage2D` does not perform all the processing required to upload immediately. Instead, the texture is fully uploaded the first time it is used. It is possible to force an upload by drawing a series of triangles off screen or otherwise obscured with the texture object in question bound and so marked for use. Performing this for all textures in a scene will avoid the cost and potential stutters when they are uploaded on first use.

Texture formats and precision

Textures should be read as `lowp` (see *Samplers*). The exceptions to this are half float textures which should be read as `mediump` , and float and depth textures which should be read as `highp` .

Mathematical Look-ups in Textures

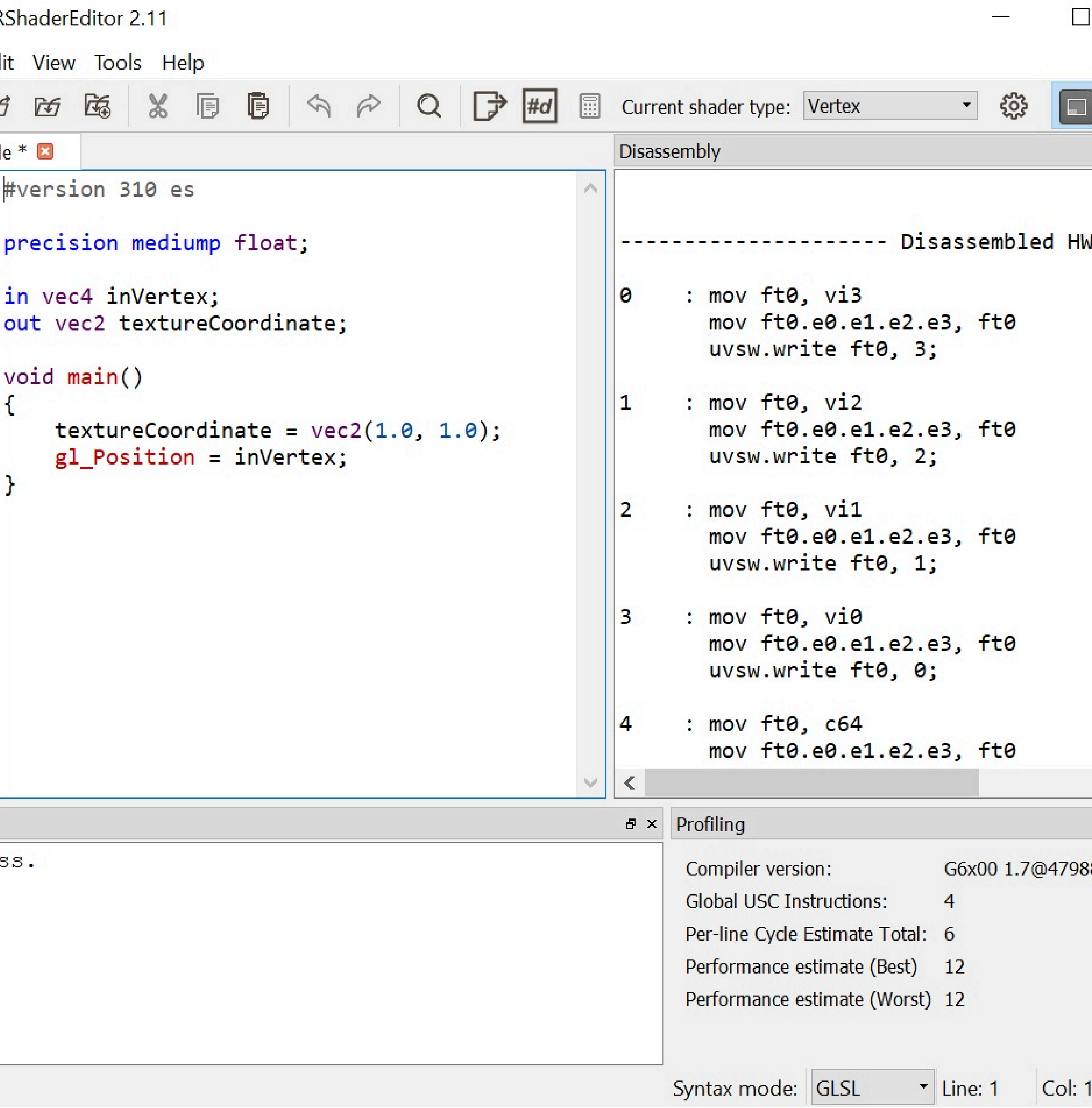
Sometimes it can be a good idea to encode the results of a complex function into a texture and use it as a look-up table instead of performing the calculations in a shader. However, this will only provide a boost in performance if a bottleneck has been identified in the processing of the shader in question, and bandwidth is free to perform the texture lookup. If the function parameters and therefore the texture coordinates in the look-up table vary wildly between adjacent fragments, then cache efficiency will suffer. As a significant amount of work must be saved for this to be an optimisation, profiling should be performed to determine if the results of using look-up tables are acceptable.

4. Optimising Shaders

This section covers advice on optimising shaders to improve performance, particularly on PowerVR hardware.

PVRShader Editor

PVRShaderEditor helps developers understand what is happening when optimising shaders. This GUI-based tool provides a wide range of off-line performance analysis data as shaders are being written.



Current shader type: Vertex

```
#version 310 es

precision mediump float;

in vec4 inVertex;
out vec2 textureCoordinate;

void main()
{
    textureCoordinate = vec2(1.0, 1.0);
    gl_Position = inVertex;
}
```

```
-------------------- Disassembled HW

0    : mov ft0, vi3
       mov ft0.e0.e1.e2.e3, ft0
       uvsw.write ft0, 3;

1    : mov ft0, vi2
       mov ft0.e0.e1.e2.e3, ft0
       uvsw.write ft0, 2;

2    : mov ft0, vi1
       mov ft0.e0.e1.e2.e3, ft0
       uvsw.write ft0, 1;

3    : mov ft0, vi0
       mov ft0.e0.e1.e2.e3, ft0
       uvsw.write ft0, 0;

4    : mov ft0, c64
       mov ft0.e0.e1.e2.e3, ft0
```

Compiler version:	G6x00 1.7@4798
Global USC Instructions:	4
Per-line Cycle Estimate Total:	6
Performance estimate (Best)	12
Performance estimate (Worst)	12

Syntax mode: GLSL Line: 1 Col: 1

Shader disassembly for PowerVR Rogue graphics cores is provided within the tool. It is possible to see the exact unified shader core (USC) instructions that have been generated by the compiler for the shader in question.

Key features of the tool include:

- Syntax highlighting for GLSL ES, GLSL, PFX, HLSL and OpenCL Kernels
- Support for PowerVR SGX and Rogue offline GLSL ES compilers
- Per-line cycle count estimates
- Simulated performance estimates (PowerVR Series5 and Series5XT graphics cores only)
- Full dissembled USC code, including FP16 disassembly
- Supports Khronos reference GLSL compiler (optionally compiled to SPIR-V).

To find out more and to download the latest version of PVRShaderEditor, please visit our page *here*.

GLSL Optimiser

GLSL Optimiser is a stand-alone C++ library, based on the Mesa GLSL compiler that is used in the many game engines to optimise GLSL shaders for mobile platforms. The tool can be found on GitHub *here*.

GLSL optimiser can automatically perform some graphics-core-independent GLSL shader optimisations. The tool will not perform any hardware-specific optimisations, but rather generic optimisations which will likely (but not always) improve performance on most platforms. To verify any shader optimisations performed by the tool, use *PVRShaderEditor*.

Choose the Right Algorithm

For complex shaders that run for more than a few cycles, picking the right algorithm is usually more important than low-level optimisations. It is highly recommended that a fast, well-designed algorithm be favoured over small performance tweaks to a poor algorithm. Although increasingly powerful, mobile graphics hardware is not designed to handle some of the latest techniques in desktop and console shaders. Therefore, a reduction in complexity will likely be needed from some of these techniques for mobile shader implementations.

Know Your Spaces

A common mistake in vertex shaders is to perform unnecessary transformations between model space, world space, view space, and clip space. If the model-world transformation is a rigid body transformation (only consisting of of rotations, translations, mirroring, lighting, or similar) then calculations can be performed directly in model space.

Transforming uniforms such as light positions and directions to model space is a per-mesh operation. This is as opposed to transforming the vertex position to world or view space once per vertex, which is an optimisation. In cases where a particular space must be used, for example, for cube map reflections, it is often best to use this single space throughout.

Flow Control

PowerVR hardware offers full support for flow control in both vertex and fragment shaders without the need to explicitly enable an extension.

- *Static flow control* refers to when conditional execution depends on the value of a uniform variable. The same shader execution path is applied to all vertex or fragment instances in a draw call.
- *Dynamic flow control* refers to conditional execution based on per-fragment or per-vertex data, such as textures or vertex attributes.

Static flow control can be used to combine many shaders into one big uber-shader. Thorough profiling should be done when taking this approach, as a performance advantage may not be gained. A better solution when an uber-shader is desired is to use pre-processor defines to create separate shaders from one larger shader at build time. This effectively creates many smaller shaders from a single original source file.

Using dynamic branching in a shader has a non-constant overhead that depends on the exact shader code. Dynamic branching is therefore unpredictable in its effect on performance.

The following specific points should be considered:

- Make use of conditionals to skip unnecessary operations when the condition is met in a significant number of cases.
- Do not branch to discard ().
- **Series5 and Series5XT only**: Avoid branching to a texture read as samplers in dynamic branches qualify as dependent texture reads, and will harm performance.

Discard

Applications should avoid the use of the discard operation in the fragment shader, as doing so will not improve performance. This is because some of the benefits of our TBDR architecture will be lost when discard is used, so if possible prefer alpha blending over discard.

Note: This is a general problem across many tile based platforms and applies to many mobile/embedded graphics cores, not just PowerVR devices.

Shader group vote – OpenGL ES

OpenGL ES 3.0 provides a new extension `GL_EXT_shader_group_vote`. This extension is designed to allow divergent code, such as branching, in shader programs to be optimised. Consider how the graphics core (a SIMD processor) executes shaders which are commonly grouped together, into a set of shader invocations that all must take the same code path. In compute this is known as a local work group.

In the code snippet below, if even a single shader in the local work group diverges from all other active shaders in the local work group with a true condition, then all other threads in local work group must also execute the `do_fast_path()` code path. This will usually leave most threads in the local work group dormant. Once the function do_fast_path() returns, all active shaders in the local work group must then also execute the do_general_path() code path, meaning the local work group executes both code paths.

```
if (condition)
    result = do_fast_path();
else
    result = do_general_path();
```

With the same example but using the allInvocationsEXT function (see below), the allInvocationsEXT function will return the same value for all invocations of the shader in the local work group. This means the group will either execute the do_fast_path() or the do_general_path() but not both paths. It achieves this by computing the Boolean value across the local work group. The implementation uses this result to decide which path to take for all active threads in the local work group.

```
if (allInvocationEXT(condition))
    result = do_fast_path();
else
    result = do_general_path();
```

The GL_EXT_shader_group_vote extension exposes three new built-in shader functions:

- bool anyInvocationEXT(bool value) - returns true if value is true for at least one active invocation in the local work group.
- bool allInvocationsEXT(bool value) - returns true if value is true for all active invocations in the local work group.
- bool allInvocationsEqualEXT(bool value) - returns true if value is the same for all active invocations in the group.

Further details on this extension can be found on the Khronos® extensions page *here*.

Demystifying Precision

PowerVR hardware is designed with support for the multiple precision features of graphics APIs such as OpenGL ES and Vulkan. Three precision modifiers are included in the API spec for OpenGL ES 2.0 onwards and Vulkan, namely mediump, highp, and lowp. Lower precision calculations can be performed faster, but need to be used carefully to avoid trouble with visible artefacts being introduced. The best method of arriving at the right precision for a given value is to begin with lowp or mediump for everything (except samplers) then increase the precision of specific variables until the visual output is as desired.

Highp

Float variables with the highp precision modifier will be represented as 32 bit floating point (FP32) values, where integer values range from 2^{31}-1 to -2^{31}.

This precision should be used for all position calculations, including world, view, and projection matrices, as well as any bone matrices used for skinning where the precision, or range, of mediump is not sufficient. It should also be used for any scalar calculations that use complex built-in functions such as sin, cos, pow, and log.

Mediump

Variables declared with the mediump modifier are represented as 16 bit floating point (FP16) values covering the range [-65504.0, 65504.0]. The integer values cover the range [2^{15}-1, -2^{15}].

Applications should use FP16 wherever appropriate as it typically offers a performance improvement over FP32, and should be considered wherever FP32 would normally be used. This is as long as the precision is sufficient and the maximum and minimum values will not overflow, as visual artefacts may be introduced.

Using medium precision (FP16) in shaders can result in a significant improvement in performance over high precision (FP32). This is due to the dedicated FP16 Sum of Products (SOP) arithmetic pipeline, which can perform two SOP operations in parallel per cycle, theoretically doubling the throughput of floating point operations. The FP16 SOP pipeline is available on most PowerVR Rogue graphics cores – depending on the exact variant.

Some Rogue cores, such as Series6 XT, also provide a FP16 SOP/MAD (Sum of Products, Multiply-Add) arithmetic pipeline. This can perform four SOP/MAD operations in parallel per cycle, again significantly improving performance compared to high precision.

Verify the improvements of using medium precision by opening the shader in *PVRShaderEditor* and selecting the appropriate compiler for the target device.

Lowp

SGX

A variable declared with the lowp modifier will use a 10 bit fixed point format on SGX allowing values in the range [-2, 2] to be represented to a precision of 1/256. The integer values are in the range of [2^9 -1, -2^9]. This precision is useful for representing colours and any data read from low precision textures, such as normals from a normal map. Care must be taken not to overflow the maximum or minimum value of lowp precision, especially with intermediate results.

Rogue

On PowerVR Rogue devices lowp is represented as a 16 bit floating point value, meaning lowp and mediump have identical representations as far as the hardware is concerned.

Swizzling

Swizzling is the act of accessing or reordering the components of a vector out of order. Some examples of swizzling can be found next:

```
a = var.brg;   // Swizzled - Out of order access
b = vec3(var.g, var.b, var.r);   // Swizzled - Out of order access
c = vec3(vec4);       // Not swizzled - Dropping a component does not change
// access order
d.gr = a.gr + b.gr    // Not swizzled - This will be optimized to a
```

```
// non-swizzled form
```

Swizzling costs performance on Series5 (lowp only) and Series5XT (all precisions) due to the additional work required to reorder vector components. As PowerVR Rogue is scalar based, swizzling is a significantly cheaper operation.

Attributes

The per-vertex attributes passed to a vertex shader should use a precision appropriate to the data-type being passed in. For example, `highp` would not be required for a float whose maximum value never goes above 2 and for which a precision of 1/256 would be acceptable.

Varyings

Varyings represent the outputs from the vertex shader which are interpolated across a triangle and then fed into the fragment shader. Varyings are significantly cheaper than performing per-fragment operations to calculate data that could have been passed in from a vertex shader via a varying.

Keep the following considerations in mind when using varyings:

- Each varying requires additional space in the parameter buffer, and additional processing time to perform interpolation.
- Varying outputs are stored in registers. Having too many may introduce register pressure and potentially reduce shader occupancy. This will reduce the maximum number of concurrent shader executions per Unified Shader Core (USC).

Packing varyings

Packing multiple varyings together, for example packing two `Vec2` into a single `Vec4`, should suffer no performance penalty and will save varyings. Exclusively on PowerVR Series5 and Series5XT, co-ordinate varyings which are packed into the `.zw` channel of a `Vec4` will always be treated as a dependent texture read and should be avoided (see *Dependent Texture Read*).

Samplers

Samplers are used to sample from a texture bound to a certain texture unit. The default precision for sampler variables is `lowp`, and usually this is good enough.

Two main exceptions exist to the `lowp` rule:

- If the sampler will be used to read from either a depth or float texture, then it should be declared with `highp`.
- If the sampler will be used to read from a half float texture, then it should be declared as `mediump`.

Uniforms

Uniform variables represent values that are constant for all vertices or fragments processed as part of a draw call. They should be used to pass data that can be computed once on the CPU, and then not changed for the duration of a draw call. Unlike attributes and varyings, uniform variables may be declared as arrays. Using uniforms is significantly cheaper than using varyings; however keep the following considerations in mind when using uniforms:

- A certain number of uniforms (uniform storage varies between graphics cores) can be stored in registers on-chip. Large uniform arrays will be stored in system memory and accessing them comes at a bandwidth and execution time cost.
- Redundant uniform updates in between draw calls should be avoided.

Constant calculations

The PowerVR shader compiler can extract calculations based on constant values (for example uniforms) from the shader and perform these calculations once per draw call.

Conversion costs

When performing arithmetic operations on multiple precisions within the same calculation, it is likely that values will have to be packed or unpacked. Packing is the act of taking a higher precision value and placing into a lower precision variable while unpacking is the reverse and involves taking a lower precision value and placing it into a higher precision variable.

Where possible, precisions should be kept the same for an entire calculation as each pack and unpack has a cost associated with it. This cost can be further reduced by writing shaders in such a way that:

- All higher precision calculations are performed together, at the top of the shader.
- All lower precision calculations are performed at the bottom.

This ensures that variables are not repeatedly packed and unpacked. It also ensures that variables are not all unpacked into `highp` therefore losing any benefit of using lower precision.

Using fixed point values in an arithmetic operation will result in the graphics core performing a type conversion. This should be avoided as additional cycles will be introduced to the shader.

Scalar Operations

It is very easy to accidentally vectorise a calculation. Be wary of vectorising scalar operations where it cost more cycles for the same output. For example:

```
highp vec4 v1, v2;
highp float x, y;
// Bad
v2 = (v1 * x) * y; // vector * scalar followed by vector * scalar totals eight scalar muladds
// Good
v2 = v1 * (x * y); // scalar * scalar followed by vector * scalar totals five scalar muladds
```

Constant Data in Shaders

If used correctly, the `const` keyword can provide a significant performance boost. For example, a shader that declares a `const` array outside of the `main()` block can perform significantly better than the same shader with the array not marked as `const`, even if the array could be treated as such.

Another example would be the use of a `const` value to reference an array member. In this example, if the value is `const` , the graphics core can know ahead of time that the number will not change, and data can be pre-fetched prior to the shader being run.

Geometry / Tessellation Shaders

Tessellation and geometry shaders should be avoided if possible, as the hardware will be required to bin (place into tiles) many more vertices which are produced by these pipeline stages. This results in many more writes to the parameter buffer which is located off-chip in system memory.

Geometry and tessellation will usually result in increased pressure on the rasterization hardware, due to the increased number of triangles. The exact impact on performance will depend on the exact graphics core that the application is being deployed to.

Profiling with *PVRTune* would reveal the impact of using geometry and/or tessellation shaders.

If an application must use tessellation and/or geometry shaders on PowerVR hardware, the shaders may be hardware accelerated, may be emulated, or may not be supported at all.

This depends on the exact graphics core that the application is being deployed to:

- Series 6XE graphics cores do not support either the tessellation or geometry shader extension, and therefore these stages in the graphics pipeline are not available on this platform.
- Series 6, Series 6XT, Series 7XE and Series 8XE graphics cores have native support (hardware acceleration) for geometry shaders, and provide execution of tessellation shaders through software emulation.
- Series 7XT and Series 8XT graphics cores provide native support (hardware acceleration) for both geometry and tessellation shaders.

While geometry shaders are not optimal when used to introduce new geometry, they can be used to cull geometry, which may result in some moderate performance gains. This should be verified through profiling using our *PVRTune* tool which is available in our SDK.

5. Optimising Specific Techniques

This section covers ways of optimising various techniques to improve application performance particularly when using PowerVR hardware.

Using Multiple Render Targets Efficiently

Multiple Render Targets (MRTs) are available in a variety of APIs, and are supported on PowerVR Rogue hardware. MRTs allow developers to render images to multiple render target textures at once. These textures can then be used as inputs to other shaders, applied to a 3D model, presented to the screen and so on. A common use case for MRTs is deferred shading, whereby the lighting calculations are stored in multiple render targets, and then used to light the scene after it has been drawn.

Tile based architectures such as PowerVR hardware can efficiently use render targets by storing per-pixel render target data for a single tile (32 x 32 pixels) entirely in on-chip memory, also known as Pixel Local Storage (PLS). This has the advantage of significantly reducing system memory access compared to immediate mode renderers.

On most PowerVR devices the recommended maximum size per pixel for a render target is 128 bits plus a depth attachment. On some graphics cores the amount of available memory for PLS may be increased to 256 bits plus a depth attachment.

It is highly recommended that applications do not exceed the amount of available per-pixel storage as this will result in the render target data being spilled out into system memory. This is extremely expensive as the render target data will need to be read for each fragment from system memory when a shader accesses the data stored in the render target. This essentially negates one of the main benefits of tile based rendering, and costs huge amounts of memory bandwidth and performance.

Exceeding the per-pixel storage will also likely result in reduced Unified Shader Cluster (USC) occupancy. Therefore, the maximum number of active threads (shaders) executing in parallel per USC will be severely limited, resulting in reduced efficiency and performance.

On PowerVR hardware, applications can use a variety of render target formats. If the per-pixel render target data can fit into on-chip memory, then all texture accesses are handled by the on-chip memory bus, and therefore all formats equally provide the same performance. This is because no transactions from system memory to the chip are required to load and store the data.

In addition to memory transaction and performance considerations, when render targets spill in system memory, not all render target formats will be supported at full rate over the system memory bus. Therefore, transfer rates may be further reduced depending on the format and the Texture Processing Unit (TPU) available in the graphics core.

The transfer rates are as follows:

- `RGBA8` can be accessed at full rate.

- RGB10A2 can be accessed at almost full rate.
- RG11B10 can be accessed at half rate.
- RGBA16F can be accessed at half rate.
- RGBA32F can be accessed at quarter rate (no bilinear filtering).

Recommended HDR texture formats

There are several texture formats available which can be used to store HDR texture data. Each format has its benefits and drawbacks. *This section* discusses several HDR suitable texture formats that are currently available to use.

The appropriate HDR texture format will depend on several factors such as available memory bandwidth, precision (quality), alpha support and so on.

For HDR texture formats which are natively supported by the hardware, use either RGB10A2, or RGBA16F which has increased bandwidth. These textures provide a good balance between quality, performance (filtering), and memory bandwidth usage.

RGBM and RGBdiv8

Both RGBM and RGBdiv8 texture formats require the developer to implement encoding and decoding functionality into the shader, as these formats are not natively supported by the hardware. This costs additional USC cycles, so if an application is USC limited it should not employ these formats.

These formats do have the advantage that they cost very little in terms of memory bandwidth as they cost the same bandwidth as RGBA8. Therefore, if an application is bound by memory bandwidth, it may be useful to explore these formats. Further information on the RGBM format can be found *here*.

Recommended HDR Texture Formats

The following table details various attributes of HDR suitable texture formats:

Table 1: HDR suitable texture formats

Texture Format	Bandwidth Cost	USC Cost	Filtering	Precision	Alpha
RGB10A2	Same as RGBA8	None	Hardware accelerated, slightly slower than RGBA8	RGB channels have greater precision over RGBA8 at the cost of alpha precision	Supports alpha - only four unique values
RGBA16F	2x RGBA8	None	Hardware accelerated but performs at half the rate of RGBA8	Far greater precision than RGBA8 - 2^{16} values per channel	Supports alpha
RG11B10F	2x RGBA8 (internally stored as RGBA16F)	None	Hardware accelerated but performs at half the rate of RGBA8	Same as RGBA16F	Does not have an alpha channel

Texture Format	Bandwidth Cost	USC Cost	Filtering	Precision	Alpha
RGBA32F	4x RGBA8	None	Hardware accelerated but performs at quarter the rate of RGBA8 and only supports nearest sampling	Vastly greater precision than any other format - 2^{32} values per channel	Supports alpha
RGBM (RGBA8)	Same as RGBA8	Moderate USC cost for encoding / decoding the data	Hardware does not natively support filtering on this format	Encoding algorithm improves the range of values that can be represented by the RGB channels compared to standard RGBA8	No alpha sacrificed to provide improved RGB range
RGBdiv8 (RGBA8)	Same as RGBA8	Slightly more complex than RGBM to encode / decode the data	Hardware does not natively support filtering on this format	Encoding algorithm improves the range of values that can be represented by the RGB channels compared to standard RGBA8	No alpha sacrificed to provide improved RGB range

Preferred Lighting Solution

There are several lighting techniques which an application may use, each with their own costs and benefits. Choosing the most optimal algorithm for the task may improve performance significantly.

Here are the common lighting techniques and their usage scenarios:

- Forward shading is the recommended method to be used for a small number of light sources. Small is fewer than ten point lights, anything more and deferred will be faster.
- Traditional deferred shading is the recommended method to be used for many light sources. This technique is highly efficient on PowerVR hardware, because the per pixel data for the tile stored in the G-buffer render targets can be stored in on-chip memory (Pixel Local Storage). As a result, the fragment shaders can reuse the data already stored in on-chip memory, significantly reducing accesses to system memory and significantly improving performance.
- For all compute based techniques such as tiled deferred and forward+, note that the contents of the G-buffer will need to be written out to system memory. This is costly for almost all mobile and embedded platforms including PowerVR graphics cores, due to the limited amount of system memory bandwidth available.

Preferred Shadowing Solution

There are many techniques for creating shadows. One technique that performs exceptionally well on PowerVR hardware is stencil shadowing, as the hardware is very good at handling stencil buffers. The data is stored in on-chip memory and never has to be written out to system memory, so if hard shadows are acceptable then employ a stencil shadowing algorithm.

Techniques that require results to be written to off-chip memory, such as shadow mapping, will usually perform worse than techniques that can be computed entirely in on-chip memory.

MSAA Performance

On PowerVR hardware, Multi-Sampled Anti-Aliasing (MSAA) can be performed directly in on-chip memory before being written out to system memory, which saves valuable memory bandwidth. MSAA is considered to cost relatively little performance. This is true for typical games and UIs, which have low geometry counts but very complex shaders. The complex shaders typically hide the cost of MSAA and have a reduced blend workload.

2x MSAA is virtually free on most PowerVR graphics cores (Rogue onwards), while 4x MSAA+ will noticeably impact performance. This is partly due to the increased on-chip memory footprint, which results in a reduction in tile dimensions (for instance 32 x 32 -> 32 x 16 -> 16 x 16 pixels) as the number of samples taken increases. This in turn results in an increased number of tiles that need to be processed by the tile accelerator hardware, which then increases the vertex stages overall processing cost.

The concept of *good enough* should be followed in determining how much anti-aliasing is enough. An application may only require 2x MSAA to look good enough, while performing comfortably at a consistent 60 FPS. In some cases, there may be no need for anti-aliasing to be used at all, for example when the target device's display has high pixels per-inch (PPI).

Performing MSAA becomes costlier when there is an alpha blended edge, resulting in the graphics core marking the pixels on the edge to *on edge blend*. *On edge blend* is a costly operation, as the blending is performed for each sample by a shader in software. In contrast, *on opaque edge* is performed by dedicated hardware, and is a much cheaper operation as a result. *On edge blend* is also sticky, which means that once an on-screen pixel is marked, all subsequent blended pixels are blended by a shader, rather than by dedicated hardware.

To mitigate these costs, submit all opaque geometry first, which keeps the pixels *off edge* for as long as possible. Be extremely reserved with the use of blending, as blending has lots of performance implications, not just for MSAA.

Preferred Analytical AA Solution

Analytical anti-aliasing algorithms, such as fast approximate anti-aliasing (FXAA) or sub-pixel morphological anti-aliasing (SMAA) are shader-based techniques. These types of anti-aliasing techniques use analytics to detect and blur sharp geometric features. They are post-processing algorithms which are performed in screen space, and usually have a fixed cost, such as a full-screen pass. They do require more memory bandwidth, which is usually at a premium on mobile and embedded devices.

On PowerVR hardware the recommended analytical anti-aliasing solutions are as follows (best to worst performance):

- Fast approXimate Anti-Aliasing (*FXAA*) – single full screen pass
- Conservative Morphological Anti-Aliasing (*CMAA*)
- Morphological Anti-Aliasing (*MLAA*)
- Sub-pixel Morphological Anti-Aliasing (*SMAA*).

Screen Space Ambient Occlusion

Screen Space Ambient Occlusion (SSAO) is a technique used for efficiently approximating how each point in the scene is affected by ambient light. SSAO is implemented in a fragment shader, which executes once per fragment - a single full screen pass. In its simplest form, the algorithm samples the depth buffer (stored in a texture) around the current pixel and attempts to estimate the occlusion for the current fragment. However, this approach results in hundreds of random accesses to the depth texture stored in system memory, which will inevitably thrash the cache and result in poor performance.

If an application implements SSAO, it is recommended that the algorithm implements a form of hierarchical-Z buffer (Hi-Z, HZB) optimisation. Briefly, this involves performing a hierarchical Z pre-pass to build a mipchain for the hardware calculated depth buffer. Building the depth mipchain involves progressively taking either the minimum or maximum depth value for a tile of pixels (for example, 4 x 4) and storing the value in the next mip level.

Hierarchical Z-buffer optimisation significantly improves the rate of convergence for ray intersection by reducing the number of steps to find an intersection, and significantly improves cache efficiency. This is because a small region defining the working area at each level of the mipchain will likely reside in cache, which significantly reduces accesses to system memory. Overall this results in improved performance and massively reduced system memory bandwidth. A white paper explaining one such approach can be found *here*.

Ray-Marching

If an application implements a ray-marching graphical effect such as Screen Space Reflections (SSR), the algorithm should implement an optimal sampling technique which takes as few samples as possible to achieve the desired quality. One possible approach to reducing the number of samples is to perform the ray marching in a half-screen resolution buffer – in other words, down sampled. PowerVR hardware exposes an extension in OpenGL ES for hardware-accelerated down sampling, see *Frame Buffer Down Sampling*. This approach could also be coupled with a hierarchical-Z buffer (similar to the technique discussed *above*) to accelerate the ray marching further.

In place of the relatively expensive ray marching algorithms, consider using a parallax corrected local cube map method. This could be used as either a fall-back technique, or even as the main technique as it may be good enough visually for the application, and is considerably cheaper to perform. Also consider simple, cheap, planar reflections for flat surfaces.

An article discussing an optimal SSR technique can be found *here* and an article discussing a local cube map can be found *here*.

Separable Kernels

Many post-processing techniques such as full screen blur with a Gaussian blur, or gather and scatter operations like motion blur, depth of field, and bloom can be implemented with multiple separated kernels. The downside to using a multi-pass algorithm is that they can be very inefficient in terms of memory bandwidth. This is due to increased round trips to system memory; write-out, read-back, write-out, read-back, and so on. This results in significantly increased memory bandwidth usage and power consumption, and may result in poor performance.

The alternative solution is to use a single kernel (single pass – brute force) to achieve the desired graphical effect. However, condensing the algorithm into that single pass may result in worse performance than the multi-pass technique. This is because the algorithm may require many more samples when performing in single pass mode to achieve the same level of quality. This will result in increased system memory bandwidth usage over the multi-pass.

An example of this is Gaussian blur, which is commonly implemented as a multi-pass technique with a horizontal and vertical pass. This substantially simplifies the complexity of the algorithm when compared to a single pass approach, which requires significantly more samples. There are full screen blur techniques that work with a single pass which have been proven to be efficient, such as Epic’s single pass circular based filter algorithm, instead of a two-pass Gaussian. More information can be found *here*.

To choose the ideal single or multi-pass algorithm, profile the algorithm to determine which technique provides the most efficient usage of system memory bandwidth and USC.

Efficient Sprite Rendering

Rendering sprites efficiently may seem like a trivial exercise. However, without careful consideration an application may be unresponsive and sluggish due to poor graphics performance. Traditional sprite rendering tends to see textures drawn using alpha blending on to quads. These quads will consist of large areas of alpha, either completely transparent (alpha value of zero), or partial alpha. Areas which are completely transparent are traditionally discarded using either the discard keyword or alpha testing, while areas of partial alpha undergo blending. Both have some form of impact on performance versus fully opaque objects, meaning that a large number of sprites being drawn inefficiently can seriously harm performance.

The `discard` keyword () should be avoided in favour of the much faster alpha blending.

Even when favouring alpha blending, performance can still be affected if there are many sprites. One method to minimise the impact of several layers of blended sprites is to increase the geometry complexity of the sprites, to reduce the amount of wasted transparent fragments. For example, if a sprite is circular in shape and is rendered using the most optimal fitting quad, 22% of the fragments processed are redundant. Significant performance improvements can be gained by reducing the wasted transparency by increasing geometry complexity.

PowerVR hardware has excellent vertex processing capabilities and is designed to handle large amounts of geometry data, far more than what is present in most sprite-based applications. Therefore, increasing complexity should have minimal performance impact, and any impact this may have is most likely outweighed by the savings of rendering less transparency. If the complexity is increased with the previous case of a perfectly fitting quad around a circular sprite to that of a dodecagon (twelve-sided polygon) the amount of wasted fragment processing can be reduced to just 3%.

The formula below demonstrates increasing complexity and reducing processing.

Assuming radius $\boldsymbol{r}$ of 64

$$A = 1 - \frac{\pi r^2}{(2r)^2}$$

$$A = 0.214$$

$$A = \mathbf{21.4\%}$$

vs

$$A = 1 - \frac{\pi r^2}{12\left(2 - \sqrt{3}\right) r^2}$$

$$A = 0.029$$

$$A = \mathbf{2.9\%}$$

Also consider splitting opaque and alpha blended objects, such as UI elements, that appear in the scene into separate draw submissions.

For the rasterization to be performed as efficiently as possible, the elements should be rendered in the following order:

1. opaque scene elements
2. alpha blended scene elements
3. alpha blended UI elements

On-Chip Memory Performance

Every PowerVR Rogue (and later) architecture GPU contains some amount of on-chip memory, typically 256 bits on high end GPUs and 128 bits on low end GPUs. The depth buffer is stored separately and does not count toward the on-chip memory. This memory is used to accelerate some of the per-fragment fixed-function pipeline such as alpha blending, depth testing, and stencil testing. It can also be used programmatically via the Pixel Local Storage extension in OpenGL, and Vulkan's subpass functionality.

Important: Tailoring algorithms around this high performance on-chip memory is key to achieving the maximum amount of performance on PowerVR.

While on-chip memory is fast and should be used as much as possible, the following should be considered:

- On-chip memory has a finite amount of bandwidth.
- Bits used for storage cannot be used elsewhere, such as for register space.

The Developer Technology team tested the performance of the on-chip memory by modifying the *Deferred Shading* example from the PowerVR SDK to use increasing amounts of on-chip memory. The GPU used was a PowerVR GX6250 GPU. The results can be found in the table below.

Table 2: On-chip memory performance results on PowerVR GX6250

Configuration	GX6250 time/frame (ms)
96bit + D32	20
128bit + D32	21
160bit + D32	23
192bit + D32	24
224bit + D32	28
256bit + D32	29
288bit + D32	39

The much higher 10ms gap at the last step is proof that the GX6250 has 256bits of on-chip memory. The increasing frametime as the on-chip memory usage goes up indicates that it has a finite amount of bandwidth.

Therefore, it is advisable to keep G-buffers as small as possible, and within the limits of the target GPU.

Optimising Register Pressure on PowerVR

Like any other GPU architecture, PowerVR has a limited amount of register space to use. Failure to stay within the bounds of available register space could cause register spilling, which may result in sub-optimal performance.

There are several ways to improve this:

- The number of registers used at any time is equal to the number of variables a shader invocation needs to "remember" at that specific moment. Therefore, register pressure can be minimised by keeping global variable usage to a minimum, and also by making sure local variables stay in scope as little as possible.
- The PowerVR Rogue architecture has scalar ALUs. Therefore, if the last components are not needed, it is better to work with two or three component vectors, rather than four. This also applies to matrix operations - for example, when transforming a three-component vector, it is better to use a 3x3 matrix to save register space. This also applies if the `w` component will be `0`. And finally, affine transformations usually only require a 4x3 matrix (rotate, scale, translate) as the last column is always `(0,0,0,1)`.
- The PowerVR Rogue architecture is particularly good at handling FP16 operations, as often this results in twice as many instructions executed in a single cycle.

FP16 math also has the advantage that two variables can be packed into a single FP32 register. Therefore, FP16 is not only faster, but also results in less register pressure.

Attention: Minimising the use of branching is recommended. On most GPU architectures, branching is always costly as GPUs are designed to handle data parallel workloads. Branching not only results in extra cycles consumed, but also comes with increased register pressure.

Optimal Depth Buffer Usage for Large-scale Games

With large-scale scene rendering, developers often decide to use a 32-bit floating point depth buffer format, rather than the usual 24-bit integer format. However, against expectations, this does not result in noticeable precision improvement when using a standard perspective projection, because the 32-bit floating point format only has 23-bits of mantissa.

One solution is to change the depth buffer mapping to ensure the depth values are distributed more evenly. This requires changing OpenGL's default clip space Z projection, which maps values to `[-1...1]` range, to `[0...1]` using the `GL_EXT_clip_control` extension. Depth buffers must then be cleared to zero, and depth comparison will need to be changed to `GL_GREATER`. Finally, the projection matrix needs to be changed so that far values are projected to `0` and near values are projected to `1`.

With this method, the usual `D24S8` format may be enough for most games. For even more precision, use a `D32F` with a separate stencil buffer, although this will use more memory.

Balancing Workloads on PowerVR to Eliminate Bottlenecks

Application developers often face the problem of a performance bottleneck, and sometimes it can be challenging to eliminate these without reducing application quality. These performance bottlenecks are often a result of excessively heavy usage of one of the GPU's processing capabilities. For example, an application might use very ALU-heavy shaders. However, while some parts of the GPU are fully utilised, other parts of the GPU may remain under-utilised or almost idle.

One solution is to balance the GPU workloads to ensure all the GPU is reasonably well-utilised. This means shifting the workload from one part of the GPU to another. This balancing work may depend on the GPU's capabilities, so different optimisations may be required for low-end GPUs compared to high-end GPUs.

The following resources are distinguishable on PowerVR:

- ALU (shader processing load)
- texturing load
- ISP load
- renderer active
- tiler active.

Using *PVRTune* or *PVRMonitor*, it is possible to observe the usage values for these resources. If one or more resource is discovered to be a bottleneck, and others are under-utilised, then it is worth investigating possible optimisation strategies.

Here are some examples of optimisation strategies:

- ALU utilisation can be traded for texturing load if some of the equations are precalculated, and the result is stored in a lookup table (LUT).
- Texturing load can be traded for ALU utilisation by replacing texture fetches with procedural texture functions.
- The number of shader invocations can be reduced by using depth and stencil testing to reject some pixels. This reduces the texturing load or ALU utilisation depending on the bottleneck.
- ALU based alpha testing can be traded for a depth prepass and depth testing. This doubles draw call and geometry costs, but it can significantly reduce ALU utilisation and register pressure.
- Alpha testing and noise functions are usually used in combination to achieve a level-of-detail transition effect. This is often quite ALU-heavy. ALU can be traded for ISP in this scenario by running a stencil prepass.
- Visual fidelity can be increased by either running more complex shaders and using higher resolution textures, or by increasing the polygon count. In certain cases when the render utilisation is already almost at maximum, it may be sensible to add more polygon complexity rather than fragment heavy effects.

Optimal Particle Rendering on PowerVR

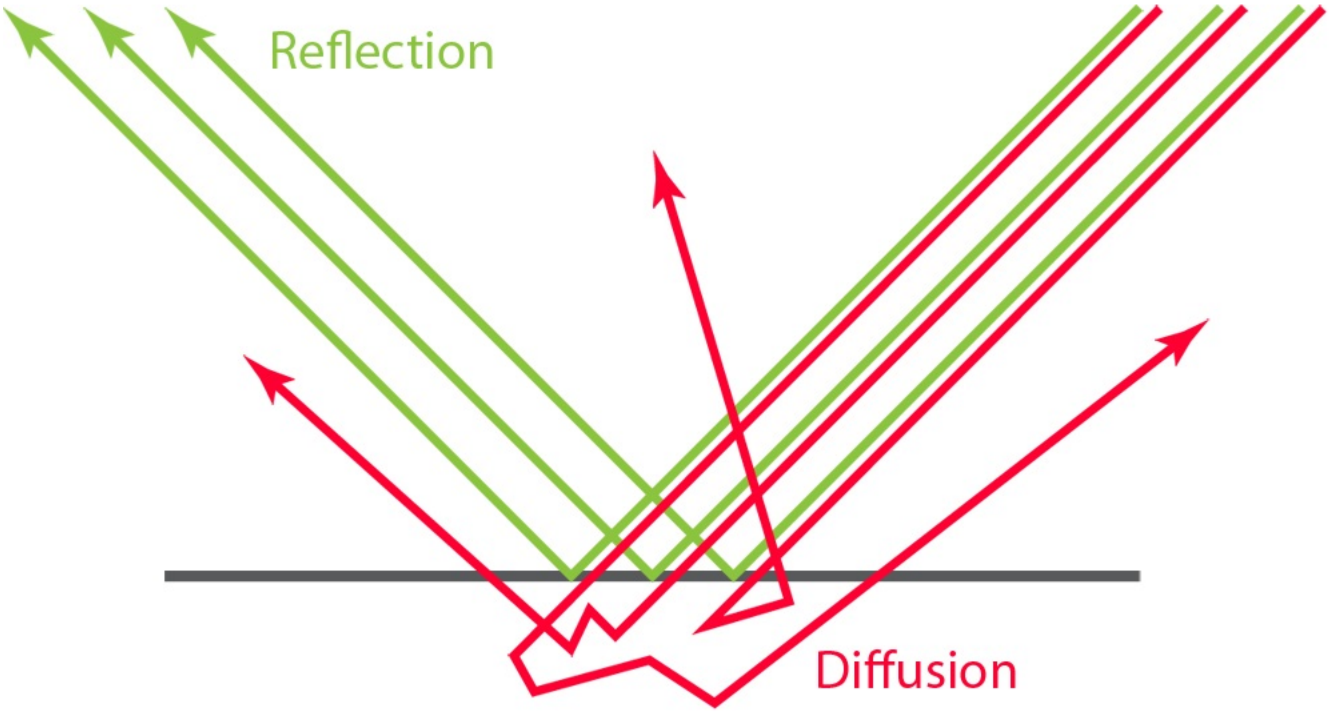
Game developers like to use particle systems extensively to add effects such as smoke, dust, and dirt to their games. These particle systems usually consist of many 2D quads that sample a texture and use alpha blending to composite them. This can be a good solution for implementing some of these effects, but it can come with a significant performance impact if used carelessly. In particular, lots of alpha-blended particles can cause a massive overdraw issue, which means the GPU has to rasterize many more fragments for each pixel than usual. This issue may be present for even small amounts of particles if their on-screen size is large. *PVRTune* or *PVRMonitor* can be used to check the current overdraw value, which needs to be kept as low as possible.

If a performance bottleneck happens only due to an out-of-control overdraw issue, the following suggestions may help:

- Reduce the number of particles used if at all possible.
- Use meshes for particles that closely follow the opaque-transparent edges within the texture used, such as a circular mesh for a puff of smoke. This way, completely transparent parts will not be causing unnecessary overdraw.
- For particles, it may not be important to have crisp textures in the distance, so anisotropic filtering could be disabled.

Physically Based Rendering and Per-Pixel LOD - Rogue Performance

Physically Based Rendering (PBR) is a forward and deferred render compatible lighting model that aims to better represent real world light behaviour. It is costlier to calculate than traditional diffuse, specular, and ambient lighting, but it is very appealing to artists as it makes it easier to specify complex material properties. PBR art pipelines are rapidly becoming the norm in AAA titles.



Per-pixel texture LOD

PBR pairs each object in a scene with a roughness/gloss map. This texture allows artists to alter the surface roughness and glossiness across an object, rather than having the same surface roughness or glossiness over the whole object. An example use is to add areas of dull rust to a shiny pistol, or to describe the properties of a rubber grip, all within a single draw call.

To add an element of reflectivity, environment maps are applied to all objects. Each environment map contains progressively blurrier surfaces towards the bottom of the chain. The sampled roughness value is used to calculate which mip level of the environment map should be sampled.

Why is this approach a problem for Rogue?

Rogue subdivides a fragment shader USC task into 2×2 blocks of spatially aligned pixels. A primary reason for doing this is so gradients can be calculated across a pixel-quad to determine how texture filtering should be applied. It is also optimised for the standard rendering case where a LOD value is calculated for a pixel-quad based on the calculated gradients. This allows the graphics core to batch texture sample operations for the pixel-quad into a single TPU request.

When texture LOD is specified per-pixel, passed in via a varying, the graphics core assumes that each pixel in the quad has a unique LOD. This causes the USC to issue a TPU request for each pixel instead of the entire quad (USC instruction – pplod) which in turn causes one quarter TPU throughput. This behaviour could lead to a memory bandwidth bottleneck in some applications.

Detailed further down is an example fragment shader. This example shows how an application can get around this behaviour by using branching and performing bilinear filtering in software. By branching to a textureLod operation with a constant value as the LOD parameter, the compiler will no longer make assumptions about the LOD of each pixel. Therefore, the compiler will not automatically fetch a sample per pixel in the pixel group.

Note: The workaround described below increases the number of USC instructions significantly. Therefore, it is important to profile the application before implementing the workaround. If the application is bandwidth or USC-limited, this workaround may negatively impact performance. Decreasing memory bandwidth in an application that is USC-limited would yield no performance benefits.

The workaround

There is a GLSL workaround (shown below) to avoid the one-quarter speed path. However, it introduces dynamic branching and additional instructions.

```
#version 310 es
in mediump float LOD;
in mediump vec3 TexCoords;

uniform lowp samplerCube EnvMap;
layout (location = 0) out lowp vec4 oColour;

mediump vec4 envSample(lowp samplerCube envMap_, mediump vec3 texCoords_, mediump float LOD_)
{
    mediump vec4 mip0;
    mediump vec4 mip1;

    if(LOD_ <= 4.0)
    {
        if(LOD_ <= 2.0)
            mip1 = textureLod(envMap_, texCoords_, 1.0);
        else // LOD_ > 2.0
            mip1 = textureLod(envMap_, texCoords_, 3.0);
    }
    else // LOD_ > 4.0
    {
        if(LOD_ <= 6.0)
            mip1 = textureLod(envMap_, texCoords_, 5.0);
        else // LOD > 6.0
            mip1 = textureLod(envMap_, texCoords_, 7.0);
    }

    if(LOD_ <= 3.0)
    {
        if(LOD_ <= 1.0)
            mip0 = textureLod(envMap_, texCoords_, 0.0);
        else // LOD_ > 1.0
            mip0 = textureLod(envMap_, texCoords_, 2.0);
    }
    else // LOD_ > 3.0
    {
        if(LOD_ <= 5.0)
            mip0 = textureLod(envMap_, texCoords_, 4.0);
        else // LOD_ > 5.0
            mip0 = textureLod(envMap_, texCoords_, 6.0);
    }

    bool isEven = ((int(LOD_) & 1) == 0);
    mediump float fractVal = fract(LOD_);
    mediump float invFractVal = 1.0 - fractVal;
    mediump float mixVal = isEven ? fractVal : invFractVal;
    return mix(mip0, mip1, mixVal);
}

void main()
{
    oColour = envSample(EnvMap, TexCoords, LOD);
}
```

6. OpenGL ES-Specific Optimisations

This section covers advice and suggestions about optimising various aspects of OpenGL ES applications.

Using glClears and glColorMask on PowerVR

An application must avoid a partial clear (partial colour mask) at the start of a frame for two important reasons:

1. The previous frame must be read in. This is performed by a full screen primitive reading it in as a texture.
2. This texture must be masked out by the partial clear, which is done by submitting another full screen primitive as a blend.

This will result in two overdraws before work on the frame begins. If the colour mask is changed to full and `glClear`, this counts as a state change for the colour mask. A state change requires a flush to be performed on the tile accelerator, and the clear becomes another full screen primitive. This adds the second overdraw.

In the case of one full clear (no partial colour masks) at the start of frame, the fast clear path is followed. This marks the whole frame as a set colour and does nothing, so no full screen primitive is required, resulting in no pixels being drawn at all.

Note: *PVRTrace GUI* emulates this behaviour.

Invalidating frame buffer attachments

There is a way to prevent unnecessary memory transfers when rendering to a frame buffer object using the OpenGL ES API. The application should invalidate frame buffers using the function `glInvalidateFramebuffer`, for example `GL_DEPTH_ATTATCHMENT` or `GL_STENCIL_ATTACHMENT`. Calling this function tells the driver to discard the contents of the specified frame buffer attachments, and therefore the driver does not need to store the contents of the frame buffer attachments into system memory. This can save huge amounts of memory bandwidth and improve performance significantly, as by default OpenGL ES will preserve frame buffer attachments.

When developing for PowerVR, it is highly recommended to invalidate depth and stencil buffers at all times. One exception to this rule is when swapping buffers using `eglSwapBuffers`, as the driver automatically discards the backbuffer's depth and stencil buffers. Invalidating buffers usually needs to happen before a frame buffer is sent for processing, such as when switching frame buffer objects. However, in certain cases such as when using `glFenceSync` (which causes a CPU-GPU sync point in the command stream) it is necessary to add extra invalidation to avoid depth load/store to main memory. Ensure no unnecessary depth load/store operations happen by observing PVRTune's "Z load/store" counter.

An application should call `glClear` specifying the buffers to clear - for example `GL_DEPTH_BUFFER_BIT` or `GL_STENCIL_BUFFER_BIT`. Calling this function will tell the driver that it does not need to load the contents of the attachments specified from system memory, again saving a huge amount of memory bandwidth.

Reducing Overhead with Draw*Indirect and MultiDraw*IndirectEXT

Draw*Indirect

A standard OpenGL ES draw call requires passing the parameters of the draw via the function's arguments. With the `Draw*Indirect` calls, it is possible to instead pass in a structure containing the draw parameters. An important benefit of this structure is that it does not have to be populated by the CPU, as the graphics driver and SSBOs can be used to populate it. This enables the application to issue a draw without any CPU-side involvement.

Example use case: Batched Draws

For optimal performance, applications should batch draws by state to reduce the number of API calls. However, a separate draw call needs to be issued for each object in that batch, and draw calls have a CPU overhead it is better to avoid. With `Draw*Indirect`, an SSBO can be populated with the vertex data of all draws that share the same state. With this SSBO, only a single `Draw*Indirect` needs to be made.

Example use case: Particle Systems

Another use case could be a particle system where the developer does not want to allocate a big array for particles up front. Instead, a compute shader could be used to determine how many particles need to be rendered each frame. For complex particle systems, particles could be removed from the render if they are obscured by opaque objects.

MultiDraw*IndirectEXT

These API calls are very similar to `Draw*Indirect`. The key difference is that an array of `Draw*IndirectCommand` structures can be passed into each draw call.

Example use case: Occlusion Culling

In complex 3D navigation systems, draw calls tend to be grouped by map tiles. If a map tile intersects the view frustum, all draw calls within the tile are issued to the graphics core. This can be optimised with occlusion queries to further reduce the number of draw calls that are issued. With `MultiDraw*IndirectEXT` there is a better option than occlusion queries. A compute shader can be used to populate an array of `Draw*IndirectCommand` structures. These can then be used to issue a single draw call for many objects sitting in many different tiles.

Instancing

Instancing is extremely useful for drawing many hundreds or thousands of objects that share the same vertex data but have different world transformations.

Consider the example of drawing many thousands of leaf objects that are very simple in terms of geometry. With the non-instanced approach, the application would need to loop X times calling glDraw* on the same object each time. This is extremely expensive in terms of API overhead, even if the geometry is relatively simple in nature. Every time a draw call is issued, the CPU must spend time instructing the graphics core about how to draw the object. The actual rendering may be extremely fast, but the API overhead completely cripples performance.

In the same scenario described previously but using the instanced approach, the application needs only to call a single API function glDraw*Instanced once. This then allows the application to draw the object X number of times. The instanced function behaves almost identically to glDraw* but takes an extra parameter, primcount, which tells the graphics core how many instances of the object it should render. This approach results in significantly more efficient behaviour.

To achieve optimal performance when implementing instancing, wherever possible use a power of two instance divisor. The result of doing so is a reduction in the number of instructions required to stream the data to the unified shader cores (USCs), effectively eliminating a potential bottleneck.

Uploading Textures into PBOs

PBOs are Pixel Buffer Objects. They were introduced in OpenGL ES 3.0 and enable applications to map GL driver allocated textures into the applications address space. Once mapped, the application can then read from or write to the texture from the CPU.

Optimal texture updates with PBOs

PBOs can be used to reduce the number of memory copies required to transfer data to memory accessible to the graphics core. For example, if a very fast upload of texture data from file was required, a PBO could be created and directly load the contents of the file into this memory. However, if the file was loaded into application memory first and then copied into the PBO, there would be as many memory copies performed as a call to glTexImage2D.

Transfer Queue (TQ) tasks

If glTexStorage has been used to define the texture, transfer tasks for PBO writes will be kicked when glTexImage is called.

Note: The PBO must be unmapped before any GL calls are issued for the texture. Failing to do so will result in an error.

If glTexStorage has not been used, the transfer task will be deferred to the first draw call that uses the modified texture.

If there is already a copy of the texture in graphics memory, the driver will have to TQ copy the mapped region of the texture from twiddled graphics memory to the driver’s PBO buffer.

If the application does not need to preserve the mapped region, it may specify the GL_MAP_INVALIDATE_RANGE_BIT access flag when calling glMapBufferRange.

If the entire texture can be invalidated, then the application can use the `GL_MAP_INVALIDATE_BUFFER_BIT` flag.

Using glTexStorage2D and glTexStorage3D

`glTexStorage2D` and `glTexStorage3D` were introduced in OpenGL ES 3.0. They provide a mechanism to define immutable-format textures. These are textures where the format and dimensions of all levels cannot be altered after their creation. The main benefit of immutable-format textures is that they reduce the amount of validation the driver must perform. Texture format validation is performed up front and only once for all texture levels.

VAOs, UBOs, Transform Feedback Buffers and SSBOs in OpenGL ES

Vertex Array Objects (VAOs)

These encapsulate bound vertex state such as `glVertexAttribPointer`. Binding a VAO applies all the encapsulated state to the global GL state. The ID Zero (‘`0`’) is reserved by GL to represent the default VAO. Always use VAOs when working with SGX or Rogue.

APIs

- OpenGL ES 1.x and 2.0: Extension (`GL_OES_vertex_array_object`), which is discussed in greater detail in the PowerVR Supported Extensions document
- OpenGL ES 3.x: Core

Uploading uniforms (Uniform Buffer Objects)

Instead of uploading uniform data such as `glUniformMatrix4fv` and `glUniform1` from client memory, a Uniform Buffer Object (UBO) allows uniform data to be stored in an OpenGL ES buffer object.

There are different approaches that can be used for supplying uniform data to shaders in OpenGL ES. The most optimal method will vary depending on the use case.

Here are some general guidelines which can be considered when uploading shader uniforms to the graphics core:

- If there are only a small number of uniforms, then setting the uniforms directly – for instance through functions such as `glUniformMatrix4fv` and `glUniform1f` - is usually the most efficient approach. This saves the overhead incurred when using a buffer.
- If there are many uniforms that are changing in bulk, then a UBO is the most efficient method to use. Applications can map and un-map buffers to modify them. There are several slots available to bind UBOs, so an application may use more than one for each draw, such as split static, and dynamic data.
- Consider the case of several uniforms changing in bulk at the same time, and a small number, perhaps one or two uniforms changing at different frequencies. The most efficient method is to split those uniforms out of the UBO, and update them

on their own separately from the rest of the buffer. UBOs come with the general disadvantage of all buffers - if they are modified in any way, then the driver will need to ensure that any previous operations are complete before updating the buffer. Otherwise, the entire buffer must be ghosted (copied).

Use UBOs whenever they are suitable according to the guidelines above when deploying to platforms with Rogue graphics cores. However, UBOs are not recommended when deploying to platforms with SGX graphics cores.

APIs

- OpenGL ES 1.x: Not exposed
- OpenGL ES 2.0: Exposed (`IMG_uniform_buffer_object`)
- OpenGL ES 3.x: Core.

Transform buffer objects

These buffers are used for transform feedback. When these are bound, post-transform vertex data is automatically resolved to the buffer by the graphics hardware. The buffers can be written to/read by the graphics hardware, but cannot be accessed by the CPU. Always use these buffers when working on Rogue, however, they are not available for SGX architectures.

APIs

- OpenGL ES 1.x and 2.0: Not exposed
- OpenGL ES 3.x: Core.

SSBOs – Shader Storage Buffer Objects

SSBOs are similar to UBOs. For example, storage blocks are defined in GLSL, and SSBOs are bound to SSBO binding points.

Unlike UBOs, SSBOs:

- Can be written to by the graphics core.
- Can be used as compute kernel input/output.
- Can be much larger than UBOs - megabytes instead of kilobytes.
- Have variable storage up to the range bound for the given buffer. The actual size of the array, based on the range of the buffer bound, can be queried at runtime in the shader using the length function on the unbounded array variable.

Although SSBOs have similar features to UBOs and transform feedback buffers, the flexibility comes at a cost. SSBO reads may be costlier than UBOs, as data is fetched from system memory like a buffer texture instead of being pre-loaded into shader registers as UBOs would. Unlike transform feedback buffers that are written to automatically when bound, SSBOs need to be written to explicitly in shader code. SSBOs are not available on SGX.

When using PowerVR Rogue graphics cores, favour UBOs and transform feedback buffers where possible, as they take optimal paths through the pipeline. SSBOs are best suited for draw indirect/dispatch compute indirect use cases.

APIs

- OpenGL ES 1.x, 2.0 and 3.0: Not available
- OpenGL ES 3.1+: Core.

Synchronisation

The most efficient method for hardware to schedule tasks is vertex processing executing in parallel to fragment tasks. To achieve this, the application should aim to remove functions which cause synchronisation between the CPU and graphics core wherever possible. In OpenGL ES, this includes synchronisation functions such as `glFlush`, `glReadPixels`, `glFinish`, `eglClientWaitSync`, `glClientWaitSync`, and `glWaitSync`.

- On PowerVR hardware, calling the function `glFlush` flushes (kicks) all outstanding work on render targets and kicks any outstanding tiler work. In practice though when using double-buffering there is no outstanding work.
- On PowerVR hardware, calling the function `glFinish` flushes (kicks) all outstanding work on render targets in a context, as defined by the OpenGL ES specification. `glFinish` might wait for these operations to complete.
- On PowerVR hardware, calling the function `eglClientWaitSync` waits by blocking the calling thread, or until `x` nanoseconds have passed for the specified sync object to be signalled. In other words, it waits for the work to be completed.
- Calling the function `glClientWaitSync` results in similar behaviour to calling the function `eglClientWaitSync`.
- Calling the function `glWaitSync` results in similar behaviour to calling the function `glClientWaitSync`. `glWaitSync`returns immediately so the application can continue processing, but causes the GL server to block until the sync object is signalled.

Multithreading in OpenGL ES

Synchronisation between OpenGL ES threads is done by `eglMakeCurrent`. It performs the following:

- Binds the supplied context to the current rendering thread and the supplied draw/read surfaces.
- If the calling thread already has the current rendering context, then all outstanding operations are flushed and the context is marked as no longer current.
- If the draw and read parameters are set to `EGL_NO_SURFACE` and context is set to `EGL_NO_CONTEXT`, then the current context is released from the calling thread without assigning it to a new one.

Usually the driver must flush all outstanding operations unless the currently bound context is released and then rebound. In this latter case, all outstanding operations have already been kicked. The driver has to wait for operations to finish if the context/surface pairs are broken up and paired up with a different context/surface. For example, surface kept/context changed, or context kept/surface changed. In the case of releasing the current context and surfaces without assigning a new one, the driver must flush all outstanding operations but does not need to wait for them. Therefore, calls to `eglMakeCurrent` should be kept to a minimum.

Using multi-threaded rendering usually has no performance benefits, and sometimes it can lead to worse performance. For example, the worst use case is to frequently bind a single graphics context to different threads using `eglMakeCurrent`. In this case, the API calls have the same cost as a single threaded render as the API call submission is serialised. However, there is the additional overhead of the context switch, which means that performance will be less optimal than a single threaded renderer.

For the best possible performance, rendering threads should be created at start up. A primary thread should be used for all rendering. Additional threads created with a shared context should only be used for shader compilation and buffer data upload. The number of background threads should be kept to a minimum, preferably one thread per-CPU core. Creating threads in excess will lead to unmaintainable, hard to debug code.

Efficient Frame Buffer Down-Sampling with PowerVR

PowerVR hardware provides an efficient fast path for down-sampling frame buffer attachments, which can be extremely useful for certain post-processing techniques such as bloom and screen space reflections. The OpenGL ES function `glFramebufferTexture2DDownsampleIMG` allows an application to attach a buffer to a frame buffer which is at a lower resolution than the frame buffer itself, and have the hardware automatically down sample the attachment.

All PowerVR hardware exposes at least a 2 x 2 downscale. Other down sampling modes may be available depending on the exact hardware, and it is possible for an application to query this information at runtime.

For further information on this extension please refer to the following Khronos extension page *here*.

Pixel Local Storage Extension

Graphics techniques such as deferred lighting are often implemented by attaching multiple colour render targets to a frame buffer object, rendering the required intermediate data, and then sampling from this data as textures. While flexible, this approach even when implemented optimally (see *Using Multiple Render Targets Efficiently*) still consumes a large amount of system memory bandwidth, which comes at a premium on mobile devices.

OpenGL ES 3.x provides the extension `shader_pixel_local_storage(2)` which enables communication between fragment shader invocations which cover the same pixel location. This extension enables applications to store the intermediate per-pixel data on-chip, for example the G-Buffer, in a deferred lighting pass. This memory can be read from and written to by shader invocations at the same pixel location.

The extension enables tile-based renderers such as PowerVR graphics cores to efficiently make use of tile memory. These intermediate buffers are never allocated or written out to system memory, as they only exist in on-chip memory.

This extension is extremely beneficial for mobile and embedded systems and using it correctly will result in a significant reduction in memory bandwidth usage. Most techniques - such as deferred lighting - that write intermediate data out to system memory then sample from it at the same pixel location, can be optimised using this extension.

For further information on this extension please refer to the following Khronos extension page *here*.

7. Vulkan-Specific Optimisations

Vulkan® is a new generation graphics and compute API. It has been built upon components from AMD's Mantle API, which was donated to Khronos® by AMD. Vulkan is a highly efficient, streamlined, and modern API designed to take advantage of current and future device architectures. It works on a wide variety of platforms such as desktop PCs, consoles, mobile devices, and embedded devices.

Vulkan is designed from the ground up to take advantage of modern CPU architecture such as multi-core and multi-threaded systems. Rendering work can be spread over many logical threads - our *Vulkan Gnome Horde demo* in our SDK is a good demonstration of this aspect.

The application does not necessarily need to implement multi-threading to take advantage of Vulkan as the API is very efficient, which results in extremely low CPU overhead. Vulkan requires less work to be carried out by the CPU to instruct the graphics core, which significantly reduces CPU usage. For mobile devices this can reduce thermal output and power consumption.

Vulkan feels more akin to modern object orientated programming languages. The rendering state is packaged into easily manageable independent API objects, rather than one giant global state machine as found in OpenGL ES.

The PowerVR with Vulkan Advantage

Tile-based renderers, such as PowerVR devices, can enjoy several advantages that Vulkan brings to the table.

Explicitly declared dependencies

All dependencies are explicitly declared ahead of time by the application. This means the driver can execute the commands in the most optimal way. This work had to be done on-the-fly in OpenGL ES and would usually never be optimal as the driver has to guess.

More importantly for tile-based renderers, the driver can package the work into tiler and rasterizer tasks which are directly consumable by the underlying hardware.

Fine-grained synchronisation

Applications have much finer control over synchronisation, compared to OpenGL ES, between objects and memory. The driver can build a comprehensive dependency chain, which means only caches that absolutely need to be flushed are, and operations that absolutely need to be completed are waited on. This means the graphics core can be used more efficiently, as work can be scheduled in advance with tiler tasks to get a head start while waiting on a fragment task.

Render passes

The render pass object describes a render from start to finish. It disallows any operations that would cause a mid-frame flush during rasterization, which could stall the graphics hardware. This also means that the graphics core can more effectively use on-chip storage, because the intermediate frame buffer attachments that do not need to be stored are never written back to system memory. This can significantly reduce memory bandwidth and save power.

Explicit render state

The Vulkan driver is aware of the entire render state through pipeline objects ahead of time. Shaders can be better optimised based on input/output and various fixed function states such as blending.

Consider operations such as shader patching, where code must be added to a shader to perform a certain graphical operation, such as alpha blending on PowerVR. These operations can now be done in advance before the shader is compiled, because the entire render state is already known. This can improve the graphics core's efficiency and reduce hitching, as this extra work no longer needs to be carried out at draw time.

Available Memory Types in Vulkan

Vulkan provides several memory types. The specification orders them based on their performance. An application should attempt to use the fastest memory types wherever possible.

The list below contains the memory types and common use cases:

- The memory type `VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT` is recommended when allocating static device buffers (created once at initialisation) used to store data that is exclusively used by the device. This type of memory should be preferred as it will offer the best performance for the application, as it provides the fastest type of memory available.
- The memory type `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT` is recommended when allocating buffers used to upload data to the graphics device. This memory type should always be preferred when implementing staging buffers, which is the optimal method for passing data to the graphics device. The memory allocation should avoid the flags `DEVICE_LOCAL`, `HOST_COHERENT` and `HOST_CACHED` when using this memory type for staging buffers.
- The memory type `VK_MEMORY_PROPERTY_HOST_COHERENT_BIT` is recommended when allocating buffers used to update per frame data, such as uniform buffers. This will provide the optimal memory type available for performing coherent data transfers between the CPU and graphics hardware.

Note: The PowerVR driver does not currently support host cached coherent memory types, but this is subject to change in future driver releases.

Note: All current PowerVR based platforms use Unified Memory Architecture (UMA), meaning that memory types are less critical than on a system employing a Discrete

Memory Architecture (DMA). Buffers may be left mapped without negatively impacting performance.

Recommended frequency of allocation

Vulkan provides the function `vkAllocateMemory` to allocate memory objects. On PowerVR hardware, the function `vkAllocateMemory` should be called as infrequently as possible. Memory allocations should be in the tens of megabytes at a time, and ideally called during initialisation. If the application requires finer-grained allocations, then it should implement its own memory sub-allocation.

Optimising Pipelines

In Vulkan a pipeline object holds all the graphics state information. The following states are described:

- Primitive type
- Depth/stencil test
- Blending
- The shaders to use
- Vertex layout
- Multi-sampling
- Face culling
- Polygon winding.

Pipelines are created from a description of all shader stages and any relevant fixed-function stages. This allows the shaders to be optimised based on their inputs and outputs, and eliminates expensive draw-time state validation/error checking which is done when the object is created. This can increase performance and reduce hitching which removes unpredictability.

Pipeline barriers

On PowerVR hardware, Vulkan pipeline barriers are free if the application does not have to wait for work to be completed, and no data conversion is required.

The most efficient manner for the hardware to schedule tasks is vertex processing executing in parallel to fragment tasks. Therefore, the application should aim to remove unnecessary pipeline dependencies and barriers wherever possible. Smart usage of pipeline barriers can help to avoid pipeline bubbles, where no work can be carried out. An example of this is sub-pass dependencies, where the fragment stage is waiting on the vertex stage to finish.

It may be beneficial to define a dependency by region, which allows for finer control over fence granularity. This is particularly the case if the barriers are being used in fragment stages to fence reads of an input attachment.

Pipeline caching

Pipeline cache objects allow the result of pipeline construction to be reused between pipelines and between runs of an application.

When using the Vulkan API, an application should always use pipeline caching wherever possible, as this means the driver can compile subsequent pipelines much quicker. Ideally, pipelines should be created at initialisation rather than during the main render loop. Using warm-up frames to cache pipeline objects before drawing is not needed, as optimisation is carried out when the pipeline is created, rather than when it is loaded for use.

Derivative pipelines

A pipeline derivative is a child pipeline created from a parent pipeline, where the child and parent are expected to share much commonality. The benefit of derivative pipelines is that they are cheaper to create using the parent as a starting point, and that they are more efficient on either host or device to switch/bind between children of the same parent.

Currently the PowerVR graphics driver does not take advantage of derivative pipelines in Vulkan and therefore applications will see no performance benefits from using them. It is still advised to use Vulkan correctly by using derivative pipelines where applicable, so that the application can take advantage of the feature when future drivers support it.

Using Descriptor Sets on PowerVR

In Vulkan, the base binding unit is a descriptor which represents a single binding, although descriptors are not bound individually. Instead, they are grouped together into descriptor set objects, which are opaque objects that contain storage for a set of descriptors. Each descriptor set has a descriptor set layout which describes the resources, such as buffers and image resources (samplers) that will be bound when drawing. The descriptor set is bound before any drawing commands, just like a vertex buffer or frame buffer.

Multiple descriptor sets

On PowerVR hardware, using multiple Vulkan descriptors for a single draw call has minimal to no impact on performance, due to the driver being able to gather all descriptors on the graphics core. Therefore, a scheme should be chosen that works the best for the particular use case in the application.

Pooled descriptor sets

On PowerVR hardware it is possible to allocate pooled descriptor sets in a fragmentation-less memory pool, depending on the how the descriptor sets and descriptor pool are constructed.

For the driver to perform a fragmentation-less allocate or free, all descriptor sets must be allocated with the same size, and the descriptor pool must have the `VK_DESCRIPTOR_POOL_CREATE_FREE_DESCRIPTOR_SET_BIT` flag set.

Note: If different sized descriptor sets are allocated, the driver will fall back to a non-pooled memory scheme.

Push Constants

Vulkan provides a high speed path to modify constant data in pipelines known as push constants, which are expected to outperform memory-backed resource updates.

On PowerVR, hardware push constants are guaranteed to be placed in fast constant buffers, which are located on-chip.

Push constants also have an efficient allocation mechanism in the command buffer, so an application should use push constants wherever it is appropriate.

Note: Small, statically indexed UBOs may also be placed in constant buffers, but this behaviour is not guaranteed.

Queues and Queue Families on PowerVR

The PowerVR driver exposes a universal graphics queue family (Vulkan graphics, compute, and present) with two queues and a single, separate sparse binding queue. The hardware will aim to parallelise work as much as possible, depending on currently available resources such as overlapping vertex, fragment, and compute. This can be verified by profiling the application with *PVRTune*.

While an application may use a single Vulkan queue, it may be beneficial to use multiple queues. It is harder to accidentally serialise work, which costs performance, across different queues.

Command Buffers

Vulkan command buffers are objects used to record various API commands, such as drawing operations and memory transfer. They can then be submitted to a device queue for execution by the hardware. The advantage of this approach is that all the hard work of setting up the drawing commands can potentially be done in advance, and in multiple threads.

Vulkan provides two levels of command buffers:

- Primary command buffers, which can execute secondary command buffers, and which are submitted to queues.
- Secondary command buffers, which can be executed by primary command buffers, and which are not directly submitted to queues.

Command buffer usage flags

On PowerVR hardware, the command buffer usage flag should be left unset (`0`) unless the application requires specific behaviour.

The following list contains the current usage flags that the API exposes, and their appropriate use cases:

- `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT` – this flag informs the driver that the command buffer will be submitted multiple times. As a result, the driver must perform a copy of the entire buffer after it is submitted to a queue. Applications should only set this flag if absolutely necessary.

Note: This method is faster than manually creating another identical buffer every frame. If the application requires this type of functionally, then the flag should be set on secondary command buffers, and primary command buffers are always rebuilt. The copy of secondary command buffers is made when the secondary command buffer is recorded into the primary command buffer (`vkCmdExecuteCommands`) rather than when the buffer is submitted to a queue (`vkQueueSubmit`).

- `VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT` – this flag must be set if the command buffer is a secondary, and it is executing inside a render-pass.
- `VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT` – currently this flag does not have any effect on how the driver processes the command buffer when submitted. However, it is possible that future drivers may use this flag as a hint about how much time should be spent on compiling the command buffer. Therefore, for maximum portability this should be set if the application intends to submit the command buffer only once.

Transient command buffers

Currently on PowerVR hardware there is no performance benefit gained from using Vulkan transient command buffers, however this is subject to change with future driver updates.

Secondary command buffers

In Vulkan, the use of secondary command buffers may benefit performance significantly. An application may build several secondary command buffers on separate threads preparing commands for the next frame, while the main thread is executing the primary command buffer. Once the secondary command buffers are ready by signalling through some sort of thread synchronisation, the work can be enqueued into the primary command buffer and the process can be repeated.

Using Render Passes and Sub-passes

In Vulkan, a render pass represents a collection of frame buffer attachments, sub-passes, and dependencies between the sub-passes. It also describes how the attachments are used over the course of the sub-passes such as with load and store operations. Render passes group together rendering commands that are all targeted at the same frame buffer into well-defined tasks – they represent the structure of the frame.

Render passes operate in conjunction with frame buffer objects. Frame buffers represent a collection of specific memory attachments that a render pass instance uses.

It is advisable that applications use as few render passes as possible, because changing render targets is a fundamentally expensive operation.

Sub-passes

In Vulkan, a sub-pass represents a phase of rendering that reads and writes a subset of the attachments in a render pass. Rendering commands are recorded into a particular sub-pass of a render pass instance.

Readable attachments are known as input attachments and contain the result of an earlier sub-pass at the same pixel location. An important property of input attachments is that they guarantee that each fragment shader only accesses data produced by shader invocations at the same pixel location.

On PowerVR hardware, make use of sub-passes and sub-pass dependencies wherever appropriate, because the driver will aim to collapse them whenever possible. The sub-pass (attachments) will stay entirely in pixel local storage (on-chip memory) and will never be written out to system memory, significantly reducing transfers to system memory. This makes it a very efficient method for implementing a deferred lighting pipeline.

Load and store ops

Vulkan provides explicit control over load and store operations on frame buffer attachments.

On PowerVR hardware, the most optimal settings are defined below:

- Load operation – should be set to either `VK_ATTACHMENT_LOAD_OP_DONT_CARE` or `VK_ATTACHMENT_LOAD_OP_CLEAR` wherever possible. This is preferred over using the function `vkCmdClearAttachment`. The graphics driver will be informed that it does not need to load the buffers data from system memory, saving enormous amounts of bandwidth
- Store operation – should be set to `VK_ATTACHMENT_STORE_OP_DONT_CARE`, unless the attachment is required for later use, as in preserve the data.

Note: There is a rare situation where the graphics core enters smart parameter mode (SPM) which occurs when the parameter buffer overflows, causing the driver to perform a partial render. In this case, a load/store operation will be performed to preserve the contents of the attachments. This operation must be carried out, so that the state may be restored when rendering resumes.

Transient attachments

Vulkan render pass objects may also contain transient attachments. This type of attachment can be read and written by one or more sub-passes, but is ultimately discarded at the end of the pass. Therefore, the data is never written out to main memory, saving valuable memory bandwidth.

Older PowerVR graphics drivers do not take advantage of Vulkan transient attachments. It is still advised that an application makes use of this feature in Vulkan, as devices with newer drivers will fully support this feature.

Optimal number of attachments

On PowerVR hardware, it is recommended to have fewer than eight input and output frame buffer attachments across an entire render pass.

Attachment order

On PowerVR hardware, the order of input attachments will not adversely affect performance. The driver will re-order the attachments as required, producing the optimal order for the graphics core when the render pass is compiled.

Performing MSAA on PowerVR using Vulkan

To perform MSAA optimally using Vulkan on PowerVR hardware, the application should use a lazily-allocated MSAA frame buffer attachment, which will be used to render the scene to. The store operation flag should be set to `VK_ATTACHMENT_STORE_OP_DONT_CARE` as this tells the driver to discard the contents of this buffer after use to save memory bandwidth - the buffer is not to be preserved. There must also be a second frame buffer attachment, which will be used to resolve multi-sampled image. This attachment should have the store operation flag set to `VK_ATTACHMENT_STORE_OP_STORE`.

This method ensures that the multi-sampled buffer is only allocated by the driver on-chip when required, and the MSAA resolve is performed on-chip and only then written out to system memory.

```
// Multi-sampled frame buffer attachment that is rendered to.
attachments[0].format = swapChain.colorFormat;
attachments[0].samples = VK_SAMPLE_COUNT_2_BIT; // 2x MSAA
attachments[0].loadOp = VK_ATTACHMENT_LOAD_OP_CLEAR;

// No longer required after resolve, this will save memory bandwidth
attachments[0].storeOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
attachments[0].stencilLoadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
attachments[0].stencilStoreOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
attachments[0].initialLayout = VK_IMAGE_LAYOUT_UNDEFINED;
attachments[0].finalLayout = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL;

// The frame buffer attachment where the multi-sampled image will be resolved to.
attachments[1].format = swapChain.colorFormat;
attachments[1].samples = VK_SAMPLE_COUNT_1_BIT;
attachments[1].loadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
attachments[1].storeOp = VK_ATTACHMENT_STORE_OP_STORE; // Store the resolved image
attachments[1].stencilLoadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
attachments[1].stencilStoreOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
attachments[1].initialLayout = VK_IMAGE_LAYOUT_UNDEFINED;
attachments[1].finalLayout = VK_IMAGE_LAYOUT_PRESENT_SRC_KHR;
```

Selecting Appropriate Image Layouts

During image creation, the initial image format does not affect performance in any way. The format `VK_IMAGE_LAYOUT_UNDEFINED` or the format `VK_IMAGE_LAYOUT_PREINITIALIZED` may be used without any impact on application performance.

If the application is using an image as a specific attachment type to a frame buffer such as colour, stencil, or depth, then the final image layout as defined in `VkAttachmentDescription` should be set to the appropriate optimal layout. This depends on the attachment usage, such as `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL` for use as a colour attachment.

8. Contact Details

For further support, visit our forum:

http://forum.imgtec.com

Or file a ticket in our support system:

https://pvrsupport.imgtec.com

For general enquiries, please visit our website:

http://imgtec.com/corporate/contactus.asp