



Mali-G51 Performance Counters

1.2

Reference Guide

Non-Confidential

Copyright © 2022 Arm Limited (or its affiliates).
All rights reserved.

Issue

102619_0102_en



Mali-G51 Performance Counters

Reference Guide

Copyright © 2022 Arm Limited (or its affiliates). All rights reserved.

Release information

Document history

Issue	Date	Confidentiality	Change
1.0	17 February 2022	Non-Confidential	Initial release
1.1	15 July 2022	Non-Confidential	Updated counter guide
1.2	27 October 2022	Non-Confidential	Updated counter guide

Proprietary Notice

This document is protected by copyright and other related rights and the practice or implementation of the information contained in this document may be protected by one or more patents or pending patent applications. No part of this document may be reproduced in any form by any means without the express prior written permission of Arm. No license, express or implied, by estoppel or otherwise to any intellectual property rights is granted by this document unless specifically stated.

Your access to the information in this document is conditional upon your acceptance that you will not use or permit others to use the information for the purposes of determining whether implementations infringe any third party patents.

THIS DOCUMENT IS PROVIDED "AS IS". ARM PROVIDES NO REPRESENTATIONS AND NO WARRANTIES, EXPRESS, IMPLIED OR STATUTORY, INCLUDING, WITHOUT LIMITATION, THE IMPLIED WARRANTIES OF MERCHANTABILITY, SATISFACTORY QUALITY, NON-INFRINGEMENT OR FITNESS FOR A PARTICULAR PURPOSE WITH RESPECT TO THE DOCUMENT. For the avoidance of doubt, Arm makes no representation with respect to, and has undertaken no analysis to identify or understand the scope and content of, patents, copyrights, trade secrets, or other rights.

This document may include technical inaccuracies or typographical errors.

TO THE EXTENT NOT PROHIBITED BY LAW, IN NO EVENT WILL ARM BE LIABLE FOR ANY DAMAGES, INCLUDING WITHOUT LIMITATION ANY DIRECT, INDIRECT, SPECIAL, INCIDENTAL, PUNITIVE, OR CONSEQUENTIAL DAMAGES, HOWEVER CAUSED AND REGARDLESS OF THE THEORY OF LIABILITY, ARISING OUT OF ANY USE OF THIS DOCUMENT, EVEN IF ARM HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

This document consists solely of commercial items. You shall be responsible for ensuring that any use, duplication or disclosure of this document complies fully with any relevant export laws and regulations to assure that this document or any portion thereof is not exported, directly or indirectly, in violation of such export laws. Use of the word “partner” in reference to Arm’s customers is not intended to create or refer to any partnership relationship with any other company. Arm may make changes to this document at any time and without notice.

This document may be translated into other languages for convenience, and you agree that if there is any conflict between the English version of this document and any translation, the terms of the English version of the Agreement shall prevail.

The Arm corporate logo and words marked with ® or ™ are registered trademarks or trademarks of Arm Limited (or its affiliates) in the US and/or elsewhere. All rights reserved. Other brands and names mentioned in this document may be the trademarks of their respective owners. Please follow Arm’s trademark usage guidelines at <https://www.arm.com/company/policies/trademarks>.

Copyright © 2022 Arm Limited (or its affiliates). All rights reserved.

Arm Limited. Company 02557590 registered in England.

110 Fulbourn Road, Cambridge, England CB1 9NJ.

(LES-PRE-20349|version 21.0)

Confidentiality Status

This document is Non-Confidential. The right to use, copy and disclose this document may be subject to license restrictions in accordance with the terms of the agreement entered into by Arm and the party that Arm delivered this document to.

Unrestricted Access is an Arm internal classification.

Product Status

The information in this document is Final, that is for a developed product.

Feedback

Arm® welcomes feedback on this product and its documentation. To provide feedback on the product, create a ticket on <https://support.developer.arm.com>

To provide feedback on the document, fill the following survey: <https://developer.arm.com/documentation-feedback-survey>.

Inclusive language commitment

Arm values inclusive communities. Arm recognizes that we and our industry have used language that can be offensive. Arm strives to lead the industry and create change.

We believe that this document contains no offensive language. To report offensive language in this document, email terms@arm.com.

Contents

1. Mali-G51 performance counters.....	9
2. CPU performance.....	11
2.1 CPU activity.....	11
2.2 CPU cycles.....	11
3. GPU activity.....	12
3.1 GPU usage.....	13
3.1.1 GPU active cycles.....	13
3.1.2 Non-fragment queue active cycles.....	14
3.1.3 Fragment queue active cycles.....	14
3.1.4 Tiler active cycles.....	14
3.1.5 GPU interrupt pending cycles.....	15
3.2 GPU utilization.....	15
3.2.1 Non-fragment queue utilization.....	16
3.2.2 Fragment queue utilization.....	16
3.2.3 Tiler utilization.....	16
3.2.4 Interrupt pending utilization.....	16
3.3 External memory bandwidth.....	17
3.3.1 Output external read bytes.....	17
3.3.2 Output external write bytes.....	18
3.4 External memory stalls.....	18
3.4.1 Output external read stall rate.....	18
3.4.2 Output external write stall rate.....	18
3.5 External memory read latency.....	19
3.5.1 Output external read latency 0-127 cycles.....	19
3.5.2 Output external read latency 128-191 cycles.....	19
3.5.3 Output external read latency 192-255 cycles.....	19
3.5.4 Output external read latency 256-319 cycles.....	19
3.5.5 Output external read latency 320-383 cycles.....	20
3.5.6 Output external read latency 384+ cycles.....	20
4. Content behavior.....	21

4.1 Geometry usage.....	21
4.1.1 Total input primitives.....	21
4.1.2 Culled primitives.....	21
4.1.3 Visible primitives.....	22
4.2 Geometry culling.....	22
4.2.1 Visible primitives rate.....	23
4.2.2 Facing or XY plane test cull rate.....	23
4.2.3 Z plane test cull rate.....	23
4.2.4 Sample test cull rate.....	24
4.3 IDVS shading.....	24
4.3.1 Position shader thread invocations.....	25
4.3.2 Varying shader thread invocations.....	25
4.3.3 Position threads per input primitive.....	25
4.3.4 Varying threads per input primitive.....	26
4.4 Fragment overview.....	26
4.4.1 Pixels.....	27
4.4.2 Cycles per pixel.....	27
4.4.3 Fragments per pixel.....	27
4.5 Fragment depth and stencil testing.....	27
4.5.1 Early ZS tested quad percentage.....	28
4.5.2 Early ZS updated quad percentage.....	28
4.5.3 Early ZS killed quad percentage.....	28
4.5.4 FPK killed quad percentage.....	29
4.5.5 Late ZS tested quad percentage.....	29
4.5.6 Late ZS killed quad percentage.....	29
5. Shader core data path.....	31
5.1 Shader core workload.....	31
5.1.1 Non-fragment warps.....	32
5.1.2 Fragment warps.....	32
5.2 Shader core throughput.....	32
5.2.1 Non-fragment cycles per thread.....	32
5.2.2 Fragment cycles per thread.....	32
5.3 Shader core data path utilization.....	33
5.3.1 Non-fragment utilization.....	33
5.3.2 Fragment utilization.....	33

5.3.3 Fragment FPK buffer utilization.....	33
5.3.4 Execution core utilization.....	34
6. Shader core functional units.....	35
6.1 Functional unit utilization.....	36
6.1.1 Arithmetic unit utilization.....	36
6.1.2 Varying unit utilization.....	36
6.1.3 Texture unit utilization.....	36
6.1.4 Load/store unit utilization.....	37
6.2 Shader program properties.....	37
6.2.1 Diverged instruction issue rate.....	37
6.3 Shader workload properties.....	37
6.3.1 Partial coverage rate.....	38
6.3.2 Unchanged tile kill rate.....	38
7. Shader core varying unit.....	39
7.1 Varying unit usage.....	39
7.1.1 Varying cycles.....	39
7.1.2 16-bit interpolation cycles.....	39
7.1.3 32-bit interpolation cycles.....	39
8. Shader core texture unit.....	40
8.1 Texture unit usage.....	40
8.1.1 Texture filtering cycles.....	40
8.1.2 Texture filtering cycles per instruction.....	40
8.2 Texture unit workload properties.....	41
8.2.1 Texture data fetches from compressed lines.....	41
8.2.2 Texture accesses using trilinear filter percentage.....	41
8.2.3 Texture accesses using mipmapping percentage.....	41
8.3 Texture unit memory usage.....	41
8.3.1 Texture bytes read from L2 per texture cycle.....	42
8.3.2 Texture bytes read from external memory per texture cycle.....	42
9. Shader core load/store unit.....	43
9.1 Load/store unit usage.....	43
9.1.1 Load/store total issues.....	43
9.1.2 Load/store full read issues.....	43

9.1.3 Load/store partial read issues.....	43
9.1.4 Load/store full write issues.....	44
9.1.5 Load/store partial write issues.....	44
9.1.6 Load/store atomic issues.....	44
9.2 Load/store unit memory usage.....	44
9.2.1 Load/store bytes read from L2 per access cycle.....	45
9.2.2 Load/store bytes read from external memory per access cycle.....	45
9.2.3 Load/store bytes written to L2 per access cycle.....	45
10. Shader core memory traffic.....	46
10.1 Read access from L2 cache.....	46
10.1.1 Front-end read bytes from L2 cache.....	46
10.1.2 Load/store read bytes from L2 cache.....	46
10.1.3 Texture read bytes from L2 cache.....	46
10.2 Read access from external memory.....	46
10.2.1 Front-end read bytes from external memory.....	47
10.2.2 Load/store read bytes from external memory.....	47
10.2.3 Texture read bytes from external memory.....	47
10.3 Write access.....	47
10.3.1 Load/store write bytes.....	47
10.3.2 Tile buffer write bytes.....	47
11. GPU configuration.....	48
11.1 GPU configuration counters.....	48
11.1.1 Shader core count.....	48
11.1.2 L2 cache slice count.....	48
11.1.3 External bus beat size.....	48

1. Mali-G51 performance counters

This guide explains the Mali performance counters found in the Arm Streamline profiling template for the Mali-G51 GPU, which is part of the Bifrost architecture family.

The counter template in Streamline follows a step-by-step analysis workflow. Analysis starts with high-level workload triage, measuring the CPU, GPU, and memory bandwidth usage. A detailed analysis of the application rendering workload then reviews how efficiently the available hardware resources are used by the application.

For each counter in the template, this guide documents the meaning of the counter and provides the Streamline variable name or expression associated with it. The Streamline template only shows a subset of the available performance counters. However, it covers the most common types of GPU performance analysis.

This guide contains the following sections:

- **CPU performance:** analyze the overall usage of the CPU by observing the activity on the CPU clusters and cores in the system.
- **GPU activity:** analyze the overall usage of the GPU by observing the activity on the GPU processing queues, and the workload split between non-fragment and fragment processing.
- **Content behavior:** analyze content efficiency by observing the number of vertices being processed, the number of primitives being culled, and the number of pixels being processed.
- **Shader core data path:** analyze the Mali shader core workload scheduling, and data path throughput.
- **Shader core functional units:** analyze the overall usage of the shader core. Observe the effectiveness of fragment depth and stencil testing, the number of threads spawned for shading, and the relative loading of the programmable core processing pipelines.
- **Shader core varying unit:** analyze performance of the varying interpolation unit, and how the unit is being used by the shader programs that are running. Use this data to find optimization opportunities for content identified as varying-bound in the shader core functional units section.
- **Shader core texture unit:** analyze performance of the texture filtering unit, and how the unit is being used by the shader programs that are running. Use this data to find optimization opportunities for content identified as texture-bound in the shader core functional units section.
- **Shader core load/store unit:** analyze performance of the load/store unit, and how the unit is being used by the shader programs that are running. Use this data to find optimization opportunities for content identified as load-store-bound in the shader core functional units section.
- **Shader core memory traffic:** analyze the breakdown of the memory traffic between the shader core and the L2 cache, and the shader core and the external memory system. Use this data to find which type of workload is causing GPU memory accesses, helping you to determine where to apply optimizations.

- **GPU configuration:** these utility counters expose the GPU configuration of the platform, allowing Streamline to create expressions based on the specific configuration of the connected device.

2. CPU performance

High CPU load or poor scheduling of workloads can cause many graphics performance issues. The first part of the analysis template looks at the CPU workloads, allowing you to identify regions where CPU performance impacts the overall application performance.

The default view for the CPU charts shows the activity of each cluster of CPUs. To see individual CPUs, expand the chart group to show individual cores present inside each cluster.

2.1 CPU activity

CPU activity charts show the usage of each processor cluster, displaying the percentage of each time slice that the CPUs in the cluster were running. This percentage allows you to assess how busy the CPUs were. Note that this metric is only a time-based measure and does not factor in the CPU frequency that was used.

For CPU-bound applications, it is common for a single thread to run all the time and become the bottleneck for overall application performance. The thread activity panel below the counter charts shows when each application thread was running. Selecting one or more threads in this view filters the CPU activity and counter charts to show the load attributed to the selected threads.

For scheduling-bound applications, it is common for both CPU and GPU to go idle due to poor synchronization. The CPU goes idle when it is waiting for the GPU to complete work. The GPU goes idle when waiting for the CPU to submit new work. To identify scheduled bound applications in this view, look for activity that is oscillating between the impacted CPU thread and the Mali GPU.

```
$CPUActivityUser.Cluster[0..N]
```

2.2 CPU cycles

The CPU cycle charts show the activity of each processor cluster, presented as the number of processor clock cycles used. Using this data with the CPU activity information can indicate the CPU operating frequency.

```
$CyclesCPUCycles.Cluster[0..N]
```

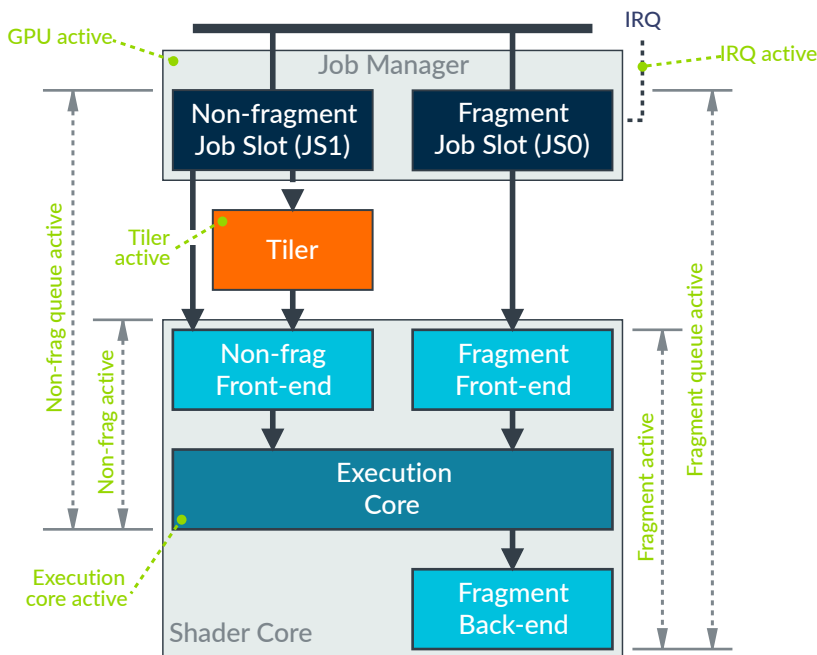
3. GPU activity

The workloads running on this Mali GPU are coordinated by the Job Manager, the hardware unit that is responsible for scheduling workloads onto the GPU. The Job Manager exposes two FIFO work queues to the graphics driver. One queue is used for non-fragment workloads, which include compute shading and vertex shading, and one queue is used for fragment workloads.

These two queues run asynchronously to the CPU and can run in parallel to each other, provided that sufficient non-dependent work is available to run. Keeping the CPU and GPU processing in parallel, and the two queues processing in parallel, is an important goal when optimizing content for Mali GPUs.

The following diagram shows the processing pipeline data paths through the GPU for different kinds of workload. It also shows the performance counters available for each data path or major block in the hierarchy.

Figure 3-1: Bifrost GPU top-level

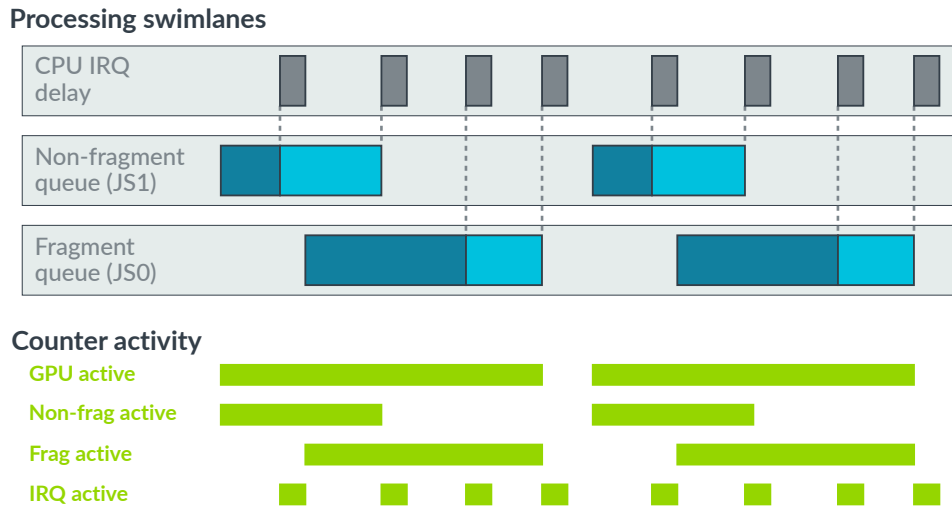


The “active” counters show that a data path or hardware unit processed some workload, but do not necessarily indicate that it was fully utilized. For example, the *Fragment queue active cycles* counter increments every cycle where there is any fragment workload queued to run anywhere in the GPU.

Some counters are common to multiple data paths. For example, both non-fragment and fragment shader programs run on the same unified shader core. If these different workload types are overlapping in the same counter sample, then shader core counter data includes contributions from both.

The following swim lane diagram shows how the top-level GPU counters increment for overlapping render passes.

Figure 3-2: Bifrost GPU top-level timeline



This diagram shows two render passes per frame, shown in different shades of blue. Each render pass consists of a single piece of non-fragment work that must be executed before its fragment shading can start. An interrupt is raised back to the CPU at the end of each piece of work on each queue. The *GPU active cycles* counter increments whenever any queue contains work.

3.1 GPU usage

GPU usage counters monitor the overall load on the GPU by measuring the workload submitted to the Job Manager queues. These counters can indicate the dominant workload type submitted by the application, which is a good target for optimization. They can also indicate the effectiveness of workload scheduling at keeping the hardware queues running in parallel.

3.1.1 GPU active cycles

This counter increments every clock cycle where the GPU has any pending workload present in one of its processing queues. It shows the overall GPU processing load requested by the application.

This counter increments when any workload is present in any processing queue, even if the GPU is stalled waiting for external memory. These cycles are counted as active time even though no progress is being made.

```
$MaliGPUCyclesGPUActive
```

3.1.2 Non-fragment queue active cycles

This counter increments every clock cycle where the GPU has any workload present in the non-fragment queue. This queue is used for vertex shaders, tessellation shaders, geometry shaders, fixed-function tiling, and compute shaders. This counter can not disambiguate between these workloads.

In content achieving good parallelism, which is important for overall efficiency of rendering, the highest queue active cycle counter should be similar to the GPU active counter.

This counter increments when any workload is present in the non-fragment processing queue, even if the GPU is stalled waiting for external memory. These cycles are counted as active time even though no progress is being made.

```
$MaliGPUCyclesNonFragmentQueueActive
```

3.1.3 Fragment queue active cycles

This counter increments every clock cycle where the GPU has any workload present in the fragment queue.

In content achieving good parallelism, which is important for overall efficiency of rendering, the highest queue active cycle counter should be similar to the GPU active counter.

This counter increments when any workload is present in the fragment queue, even if the GPU is stalled waiting for external memory. These cycles are counted as active time even though no progress is being made.

```
$MaliGPUCyclesFragmentQueueActive
```

3.1.4 Tiler active cycles

This counter increments every cycle the tiler has a workload in its processing queue. The tiler is responsible for coordinating geometry processing and providing the fixed-function tiling needed for the Mali tile-based rendering pipeline. It can run in parallel to vertex shading and fragment shading.

A high cycle count here does not necessarily imply a bottleneck, unless the *Non-fragment active cycles* counter in the shader core is comparatively low.

```
$MaliGPUCyclesTilerActive
```

3.1.5 GPU interrupt pending cycles

This counter increments every cycle that the GPU has an interrupt pending and is waiting for the CPU to process it.

Cycles with a pending interrupt do not necessarily indicate lost performance because the GPU can process other queued work in parallel. However, if *GPU interrupt pending cycles* are a high percentage of *GPU active cycles*, an underlying problem might be preventing the CPU from efficiently handling interrupts. This problem is normally a system integration issue, which an application developer cannot work around.

```
$MaliGPUCyclesGPUInterruptActive
```

3.2 GPU utilization

The GPU utilization counters provide an alternative view of the data path activity cycles, normalizing the queue usage against the total GPU active cycle count. These metrics provide a clearer view of breakdown by workload type, and the effectiveness of queue scheduling.

For GPU-bound content that is achieving good parallelism, one of the queues is close to 100% utilization, with the other running in parallel to it. Prioritize the most heavily loaded queue for content optimization, as it is the critical path workload.

If the GPU is always busy, but the queues are running serially for all or part of the frame, application API usage might prevent parallel processing. Serial processing reduces the achievable performance. It can be caused by:

- The application blocking and waiting for GPU activity to complete, for example, by waiting on a query object result which is not yet available. This can cause one or more of the queues to run out of work to process.
- The application using conservative Vulkan pipeline barriers. For example, submitting using a `STAGE_TOP_OF_PIPE` destination when a `STAGE_FRAGMENT_SHADER` destination would have been sufficient.
- The application submitting rendering workloads that have data dependencies across the queues which prevent parallel execution. For example, a fragment-compute-fragment data flow might mean no processing occurs in the fragment queue while the compute shader is running, if no non-dependent work is available.

Mobile systems improve energy efficiency by using Dynamic Voltage and Frequency Scaling (DVFS) to reduce voltage and clock frequency for light workloads. When seeing a workload with high percentage utilization, check the *GPU active cycles* counter to confirm the frequency. If the workload is light, a highly utilized GPU can run at a low clock frequency.

3.2.1 Non-fragment queue utilization

This expression defines the non-fragment queue utilization compared against the GPU active cycles. For GPU bound content, it is expected that the GPU queues process work in parallel. The dominant queue should be close to 100% utilized. If no queue is dominant, but the GPU is close to 100% utilized, then there might be a serialization or dependency problem preventing better overlap across the queues.

```
max(min(($MaliGPUCyclesNonFragmentQueueActive / $MaliGPUCyclesGPUActive) * 100, 100), 0)
```

3.2.2 Fragment queue utilization

This expression defines the fragment queue utilization compared against the GPU active cycles. For GPU bound content, the GPU queues are expected to process work in parallel. Aim to keep the dominant queue close to 100% utilized. If no queue is dominant, but the GPU is close to 100% utilized, then there might be a serialization or dependency problem preventing better queue overlap.

```
max(min(($MaliGPUCyclesFragmentQueueActive / $MaliGPUCyclesGPUActive) * 100, 100), 0)
```

3.2.3 Tiler utilization

This expression defines the tiler utilization compared to the total GPU active cycles.

Note that this metric measures the overall processing time for Index-Driven Vertex Shading (IDVS) workloads, in addition to the fixed-function tiling process. It is not necessarily indicative of the runtime of the fixed-function tiling process itself.

```
max(min(($MaliGPUCyclesTilerActive / $MaliGPUCyclesGPUActive) * 100, 100), 0)
```

3.2.4 Interrupt pending utilization

This expression defines the IRQ pending utilization compared against the GPU active cycles. In a well-functioning system, this expression is ideally less than 2% of the total cycles. If the value is much higher than 2%, a system issue might be preventing the CPU from efficiently handling interrupts.

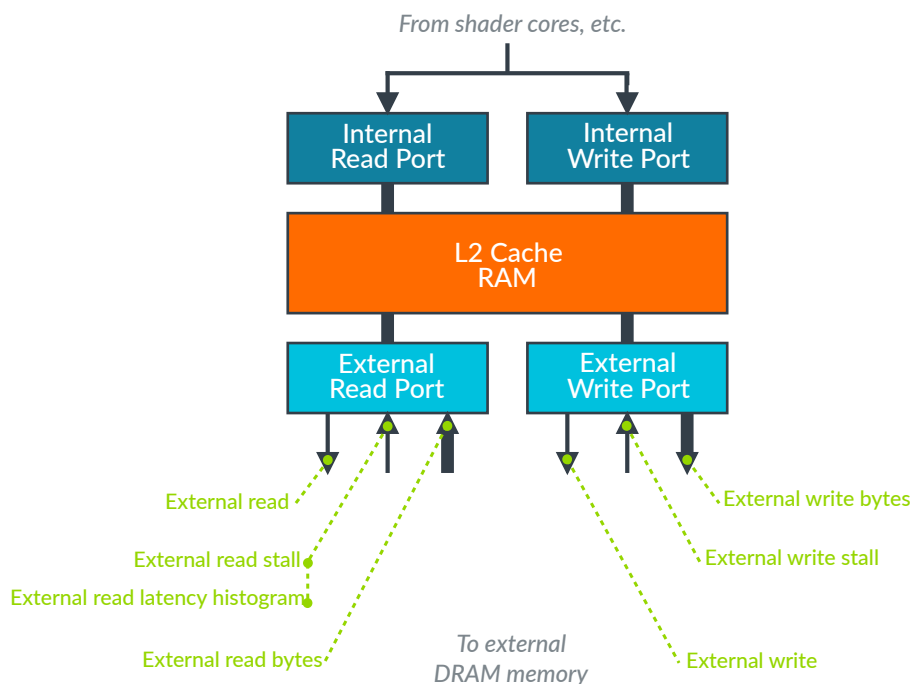
```
max(min(($MaliGPUCyclesGPUInterruptActive / $MaliGPUCyclesGPUActive) * 100, 100), 0)
```


3.3 External memory bandwidth

The external memory bandwidth counters show the total memory bandwidth between the GPU and the downstream memory system. Accessing external DRAM is one of the most energy-intensive operations that the GPU can perform, so reducing memory bandwidth is a key optimization goal.

These performance counters measure the memory accesses that are external to the GPU. If there are layers of system cache between the GPU and external DRAM, these accesses might not be external to the system-on-a-chip.

Figure 3-3: Bifrost GPU memory system



Memory accesses to external DRAM are very power intensive. A good guideline is that external DRAM access costs between 80mW and 100mW per GB/s of bandwidth used. Assuming a typical 650mW power budget for DRAM access, an application can only sustainably use a total of 100MB per frame at 60FPS. Optimizations that help to minimize GPU memory bandwidth are a high priority for mobile application development.

3.3.1 Output external read bytes

This expression defines the total output read bandwidth for the GPU.

```
$MaliExternalBusBeatsReadBeat * ($MaliConstantsBusWidthBits / 8)
```

3.3.2 Output external write bytes

This expression defines the total output write bandwidth for the GPU.

```
$MaliExternalBusBeatsWriteBeat * ($MaliConstantsBusWidthBits / 8)
```

3.4 External memory stalls

The external memory stall rate counters measure the back-pressure seen by the GPU when it is attempting to make external memory accesses.

A high stall rate is indicative of content which is requesting more data than the downstream memory system can provide. To optimize the workload, try to reduce memory bandwidth.

3.4.1 Output external read stall rate

This expression defines the percentage of GPU cycles with a memory stall on an external read transaction.

Stall rates can be reduced by reducing the size of data resources, such as textures or models.

```
max(min(($MaliExternalBusStallsReadStallCycles / ($MaliConstantsL2SliceCount *  
$MaliGPUCyclesGPUActive)) * 100, 100), 0)
```

3.4.2 Output external write stall rate

This expression defines the percentage of GPU cycles with a memory stall on an external write transaction.

Stall rates can be reduced by reducing geometry complexity, or the size of framebuffers in memory.

```
max(min(($MaliExternalBusStallsWriteStallCycles / ($MaliConstantsL2SliceCount *  
$MaliGPUCyclesGPUActive)) * 100, 100), 0)
```

3.5 External memory read latency

The external memory read latency counters present a histogram of access latencies. This metric shows how many GPU cycles it takes to fetch data from the downstream memory system, which is either system cache or external DRAM.

High latency accesses can reduce performance, and are normally an indication that the application is requesting more data than the memory system can provide. To optimize the workload, try to reduce memory bandwidth.

3.5.1 Output external read latency 0-127 cycles

This counter increments for every data beat that is returned between 0 and 127 cycles after the read transaction started. This is considered a fast access response speed.

```
$MaliExternalBusReadLatency0127Cycles
```

3.5.2 Output external read latency 128-191 cycles

This counter increments for every data beat that is returned between 128 and 191 cycles after the read transaction started. This is considered a normal access response speed.

```
$MaliExternalBusReadLatency128191Cycles
```

3.5.3 Output external read latency 192-255 cycles

This counter increments for every data beat that is returned between 192 and 255 cycles after the read transaction started. This is considered a normal access response speed.

```
$MaliExternalBusReadLatency192255Cycles
```

3.5.4 Output external read latency 256-319 cycles

This counter increments for every data beat that is returned between 256 and 319 cycles after the read transaction started. This is considered a slow access response speed.

```
$MaliExternalBusReadLatency256319Cycles
```

3.5.5 Output external read latency 320-383 cycles

This counter increments for every data beat that is returned between 320 and 383 cycles after the read transaction started. This is considered a slow access response speed.

```
$MaliExternalBusReadLatency320383Cycles
```

3.5.6 Output external read latency 384+ cycles

This expression increments for every read beat that is returned at least 384 cycles after the transaction started. This is considered a very slow access response speed.

```
$MaliExternalBusBeatsReadBeat - $MaliExternalBusReadLatency0127Cycles -  
$MaliExternalBusReadLatency128191Cycles - $MaliExternalBusReadLatency192255Cycles -  
$MaliExternalBusReadLatency256319Cycles - $MaliExternalBusReadLatency320383Cycles
```

4. Content behavior

Optimal rendering performance requires both efficient content, and efficient handling of that content by the GPU. The content behavior metrics help you to supply the GPU with efficiently structured content.

Slow rendering performance has three common causes:

- Content which is efficiently written, but doing too much processing given the capabilities of the target device.
- Content which is inefficiently written, with redundancy in the workload submitted for rendering.
- Application API usage which triggers high workload, or causes idle bubbles, due to GPU-specific or driver-specific behaviors.

This section of the Streamline template aims to focus on the first two of these causes. It looks at the size and efficiency of the submitted workload.

4.1 Geometry usage

The vertex stream is the first application input processed by the GPU rendering pipeline. These counters monitor the amount of geometry being processed, and how much is discarded due to culling.

Geometry is one of the most expensive inputs to the GPU, as vertices typically need 32-64 bytes of input data and data access is expensive. To avoid dense geometry appearing on-screen, use simpler meshes when objects are further away from the camera. You can use compressed normal maps as an efficient alternative to high geometric detail.

4.1.1 Total input primitives

This expression defines the total number of input primitives to the rendering process.

```
$MaliPrimitiveCullingFacingAndXYPlaneTestCulledPrimitives  
+ $MaliPrimitiveCullingZPlaneTestCulledPrimitives  
+ $MaliPrimitiveCullingSampleTestCulledPrimitives +  
$MaliPrimitiveCullingVisiblePrimitives
```

4.1.2 Culled primitives

This expression defines the number of primitives that were culled during the rendering process, for any reason.

For 3D content, it is expected that approximately 50% of the primitives are culled due to the facing test. If a significantly higher percentage is culled, then the GPU performance is being lost shading

objects which are not visible. In this scenario, review the efficiency of CPU-side culling techniques and check for overly large batch sizes.

```
$MaliPrimitiveCullingFacingAndXYPlaneTestCulledPrimitives
+ $MaliPrimitiveCullingZPlaneTestCulledPrimitives +
$MaliPrimitiveCullingSampleTestCulledPrimitives
```

4.1.3 Visible primitives

This counter increments for every visible primitive that survives all culling stages.

Visible means only that the primitive is front-facing and inside the visible clip volume. If it is occluded by other primitives closer to the camera, the primitive might produce no visible output.

Application software techniques, such as portal culling, can often be used to efficiently cull occluded objects inside the frustum. This can reduce the amount of redundant vertex processing that the GPU has to do.

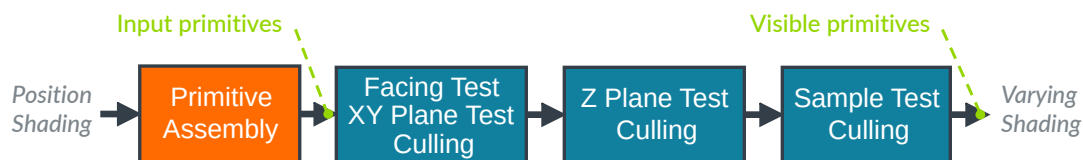
```
$MaliPrimitiveCullingVisiblePrimitives
```

4.2 Geometry culling

The GPU must compute positions of primitives before they can enter the culling stages. Culled geometry can have a significant processing and bandwidth cost, even though it contributes no useful visual output. These counters help to identify the reasons why primitives are culled, allowing you to correctly target optimizations at the area causing problems.

The Mali culling pipeline executes in the order shown in the following diagram. The counters for this pipeline show the percentage of the primitives entering a stage that are culled by it. Because these percentages are relative to the per-stage input, not the total geometry input, they do not add up to 100%.

Figure 4-1: Bifrost GPU culling pipeline



4.2.1 Visible primitives rate

This expression defines the percentage of primitives that are visible after culling.

For 3D content, it is typically expected that 50% of primitives are visible, due to the use of back-face culling. Significantly lower visibility rates can indicate missing optimizations.

```
max(min((($MaliPrimitiveCullingVisiblePrimitives /
($MaliPrimitiveCullingFacingAndXYPlaneTestCulledPrimitives
+ $MaliPrimitiveCullingZPlaneTestCulledPrimitives
+ $MaliPrimitiveCullingSampleTestCulledPrimitives +
$MaliPrimitiveCullingVisiblePrimitives)) * 100, 100), 0)
```

4.2.2 Facing or XY plane test cull rate

This expression defines the percentage of primitives entering the facing and XY plane test that are culled by it. Primitives that are outside of the view frustum in the XY axis, or that are back-facing inside the frustum, are culled by this stage.

It is expected that approximately 50% of primitives are culled at this stage. These triangles are in-frustum, but back-facing. If more than 50% of input primitives are culled due to being out-of-frustum, then there might be opportunity to improve software culling or batching granularity.

```
max(min((($MaliPrimitiveCullingFacingAndXYPlaneTestCulledPrimitives /
($MaliPrimitiveCullingFacingAndXYPlaneTestCulledPrimitives
+ $MaliPrimitiveCullingZPlaneTestCulledPrimitives
+ $MaliPrimitiveCullingSampleTestCulledPrimitives +
$MaliPrimitiveCullingVisiblePrimitives)) * 100, 100), 0)
```

4.2.3 Z plane test cull rate

This expression defines the percentage of primitives entering the Z plane culling test that are culled by it. Primitives that are closer than the frustum near clip plane, or further away than the frustum far clip plane, are culled by this stage.

Seeing a significant proportion of triangles culled at this stage can be indicative of insufficient application software culling.

```
max(min((($MaliPrimitiveCullingZPlaneTestCulledPrimitives /
(($MaliPrimitiveCullingFacingAndXYPlaneTestCulledPrimitives
+ $MaliPrimitiveCullingZPlaneTestCulledPrimitives
+ $MaliPrimitiveCullingSampleTestCulledPrimitives +
$MaliPrimitiveCullingVisiblePrimitives) -
$MaliPrimitiveCullingFacingAndXYPlaneTestCulledPrimitives)) * 100, 100), 0)
```

4.2.4 Sample test cull rate

This expression defines the percentage of primitives entering the sample coverage test that are culled by it. This stage culls primitives that are so small that they hit no rasterizer sample points.

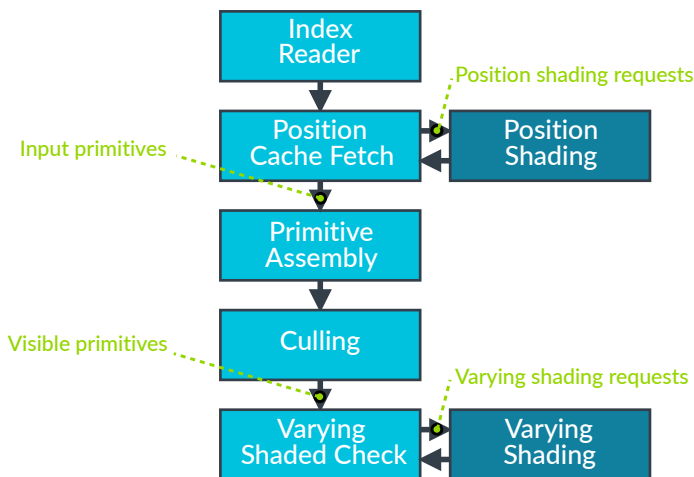
If a significant proportion of primitives are culled at this stage, it is indicative that the application is using geometry meshes that are too complex for their screen coverage. Aim to keep triangle screen area above 10 pixels. Use schemes such as dynamic mesh level-of-detail to select simpler meshes as objects move further away from the camera.

```
max(min((($MaliPrimitiveCullingSampleTestCulledPrimitives /
($MaliPrimitiveCullingFacingAndXYPlaneTestCulledPrimitives
+ $MaliPrimitiveCullingZPlaneTestCulledPrimitives
+ $MaliPrimitiveCullingSampleTestCulledPrimitives +
$MaliPrimitiveCullingVisiblePrimitives) -
$MaliPrimitiveCullingFacingAndXYPlaneTestCulledPrimitives -
$MaliPrimitiveCullingZPlaneTestCulledPrimitives)) * 100, 100), 0)
```

4.3 IDVS shading

This GPU uses an optimized Index-Driven Vertex Shading (IDVS) processing pipeline. In this pipeline, the vertex position is computed before culling. The remaining varyings for any visible vertices are computed after culling. To determine mesh encoding efficiency, use the performance counters to measure the average number of position threads and varying threads per primitive.

Figure 4-2: Bifrost GPU tiling pipeline



This pipeline uses a post-transform vertex cache, which contains the positions of recently shaded vertices, to avoid reshading vertices that are common to multiple primitives. Poor temporal locality of index reuse can result in a vertex being shaded multiple times, because it is evicted from the cache before it is reused.

This pipeline submits shading requests in groups of 4 contiguous index values. Unused index locations might be shaded if they are near used index locations. Reduce redundant shading by ensuring that every index between the minimum and maximum index is used.

4.3.1 Position shader thread invocations

This expression defines the number of position shader thread invocations.

```
$MaliTilerShadingRequestsPositionShadingRequests * 4
```

4.3.2 Varying shader thread invocations

This expression defines the number of varying shader thread invocations.

```
$MaliTilerShadingRequestsVaryingShadingRequests * 4
```

Normalized versions of these counters show the amount of shading per primitive, which gives a direct measure of mesh encoding efficiency.

4.3.3 Position threads per input primitive

This expression defines the number of position shader threads per input primitive. Minimize this number by reusing vertices for nearby primitives, improving temporal locality of index reuse, and avoiding unused values in the active index range.

Efficient meshes with a good vertex reuse have average less than 1.5 vertices shaded per triangle, as vertex computation is shared by multiple primitives.

Inefficient meshes with no vertex reuse shade at least 3 vertices per triangle. They can require more if indices are reshaded or if redundant indices are shaded.

```
( $MaliTilerShadingRequestsPositionShadingRequests * 4 ) /  
( $MaliPrimitiveCullingFacingAndXYPlaneTestCulledPrimitives  
+ $MaliPrimitiveCullingZPlaneTestCulledPrimitives  
+ $MaliPrimitiveCullingSampleTestCulledPrimitives +  
$MaliPrimitiveCullingVisiblePrimitives )
```

4.3.4 Varying threads per input primitive

This expression defines the number of varying shader invocations per visible primitive. Minimize this number by reusing vertices for nearby primitives, improving temporal locality of index reuse, and avoiding unused values in the active index range.

Efficient meshes with a good vertex reuse have average less than 1.5 vertices shaded per triangle, as vertex computation is shared by multiple primitives.

Inefficient meshes with no vertex reuse shade at least 3 vertices per visible triangle. They can require more if indices are reshaded or if redundant indices are shaded.

```
($MaliTilerShadingRequestsVaryingShadingRequests * 4) /
$MaliPrimitiveCullingVisiblePrimitives
```

4.4 Fragment overview

Fragment overview counters look at the requested pixel processing workload. These counters can show the total number of output pixels shaded, the average number of cycles spent per pixel, and the average overdraw factor.

It is a useful exercise to set a cycle budget for an application, measured in terms of cycles per pixel. Compute the maximum cycle budget using this equation:

```
shaderCyclesPerSecond = MaliCoreCount MaliFrequency
pixelsPerSecond = Screen_Resolution * Target_FPS

// Maximum cycle budget assuming perfect execution
maxBudget = shaderCyclesPerSecond / pixelsPerSecond

// Real-world cycle budget assuming 85% utilization
realBudget = 0.85 * maxBudget
```

Setting a cycle budget helps manage expectations of what is possible. For example, consider a mass-market device with a 3 core Mali GPU running at 500MHz. At 1080p60 this device has a cycle budget of just 10 cycles per pixel. This budget must cover all processing costs, including vertex shading and fragment shading. If you want to achieve the best graphics fidelity, you must ensure you spend each cycle wisely.

4.4.1 Pixels

This expression defines the total number of pixels that are shaded by the GPU, including on-screen and off-screen render passes.

This measure can be a slight overestimate because it assumes all pixels in each active 32x32 pixel region are shaded. If the rendered region does not align with 32 pixel aligned boundaries, then this metric includes pixels that are not actually fragment shaded.

```
$MaliGPUTasksFragmentTasks * 1024
```

4.4.2 Cycles per pixel

This expression defines the average number of GPU cycles being spent per pixel rendered, including any vertex shading cost.

It can be a useful exercise to set a cycle budget for each render pass in your game, based on your target resolution and frame rate. Rendering 1080p at 60 FPS is possible in a mass-market device, but the number of cycles per pixel you have to work with can be small. Those cycles must be used wisely to achieve a 60 FPS performance target.

```
$MaliGPUCyclesGPUActive / ($MaliGPUTasksFragmentTasks * 1024)
```

4.4.3 Fragments per pixel

This expression computes the number of fragments shaded per output pixel.

GPU processing cost per pixel accumulates with the layer count. High overdraw can build up to a significant processing cost, especially when rendering to a high-resolution framebuffer. Minimize overdraw by rendering opaque objects front-to-back and minimizing use of blended transparent layers.

```
($MaliCoreWarpsFragmentWarps * 4 * $MaliConstantsShaderCoreCount) /  
($MaliGPUTasksFragmentTasks * 1024)
```

4.5 Fragment depth and stencil testing

It is important that as many fragments as possible are early ZS (depth and stencil) tested before shading. Removing redundant work at this stage is more efficient than testing and killing fragments

later using late ZS. These counters monitor the number of early and late test and kill operations performed.

To maximize the efficiency of early ZS testing, we recommend drawing opaque objects starting with those closest to camera and then working further away. Render transparent objects from back-to-front in a second pass.

4.5.1 Early ZS tested quad percentage

This expression defines the percentage of rasterized quads that were subjected to early depth and stencil testing.

You achieve the best early test rates by ensuring depth testing is enabled, and avoiding fragment shaders that write their depth value.

```
max(min(($MaliCoreQuadsEarlyZSTestedQuads / $MaliCoreQuadsRasterizedFineQuads) *  
100, 100), 0)
```

4.5.2 Early ZS updated quad percentage

This expression defines the percentage of rasterized quads that update the framebuffer during early depth and stencil testing.

You achieve the best early update rates by enabling depth testing, and avoiding draw calls with modifiable coverage or shader depth writes.

```
max(min(($MaliCoreQuadsEarlyZSUpdatedQuads / $MaliCoreQuadsRasterizedFineQuads) *  
100, 100), 0)
```

4.5.3 Early ZS killed quad percentage

This expression defines the percentage of rasterized quads that are killed by early depth and stencil testing.

Quads killed at this stage are killed before shading, so a high percentage here is not generally a performance problem. However, it can indicate an opportunity to use software culling techniques such as a portal culling to avoid sending occluded draw calls to the CPU.

```
max(min(($MaliCoreQuadsEarlyZSKilledQuads / $MaliCoreQuadsRasterizedFineQuads) *  
100, 100), 0)
```

4.5.4 FPK killed quad percentage

This expression defines the percentage of rasterized quads that are killed by the Forward Pixel Kill (FPK) hidden surface removal scheme.

Quads killed at this stage are killed before shading, so a high percentage here is not generally a performance problem. However, it can indicate an opportunity to use software culling techniques such as a portal culling to avoid sending occluded draw calls to the CPU.

```
max(min(((MaliCoreQuadsRasterizedFineQuads - MaliCoreQuadsEarlyZSKilledQuads -
MaliCoreWarpsFragmentWarps) / MaliCoreQuadsRasterizedFineQuads) * 100, 100), 0)
```

4.5.5 Late ZS tested quad percentage

This expression defines the percentage of rasterized quads that are tested by late depth and stencil testing.

A high percentage of fragments performing a late ZS update can cause slow performance, even if fragments are not killed. This occurs because younger fragments cannot complete early ZS until all older fragments at the same coordinate have completed their late ZS operations.

Shaders with mutable coverage, mutable depth, or side-effects on shared resources in memory, use late ZS testing.

The driver also generates late ZS updates to preload a depth or stencil attachment at the start of a render pass. This is needed if the render pass does not start from a cleared depth value.

```
max(min(MaliCoreQuadsLateZSTestedQuads / MaliCoreQuadsRasterizedFineQuads) * 100,
100), 0)
```

4.5.6 Late ZS killed quad percentage

This expression defines the percentage of rasterized quads that are killed by late depth and stencil testing. Quads killed by late ZS testing execute at least some of their fragment program before being killed. A significant number of quads being killed at late ZS testing indicates a potential overhead. Aim to minimize the number of quads using and being killed by late ZS testing.

Shaders with mutable coverage, mutable depth, or side-effects on shared resources in memory, use late ZS testing.

The driver also generates late ZS updates to preload a depth or stencil attachment at the start of a render pass. This is needed if the render pass does not start from a cleared depth value. These

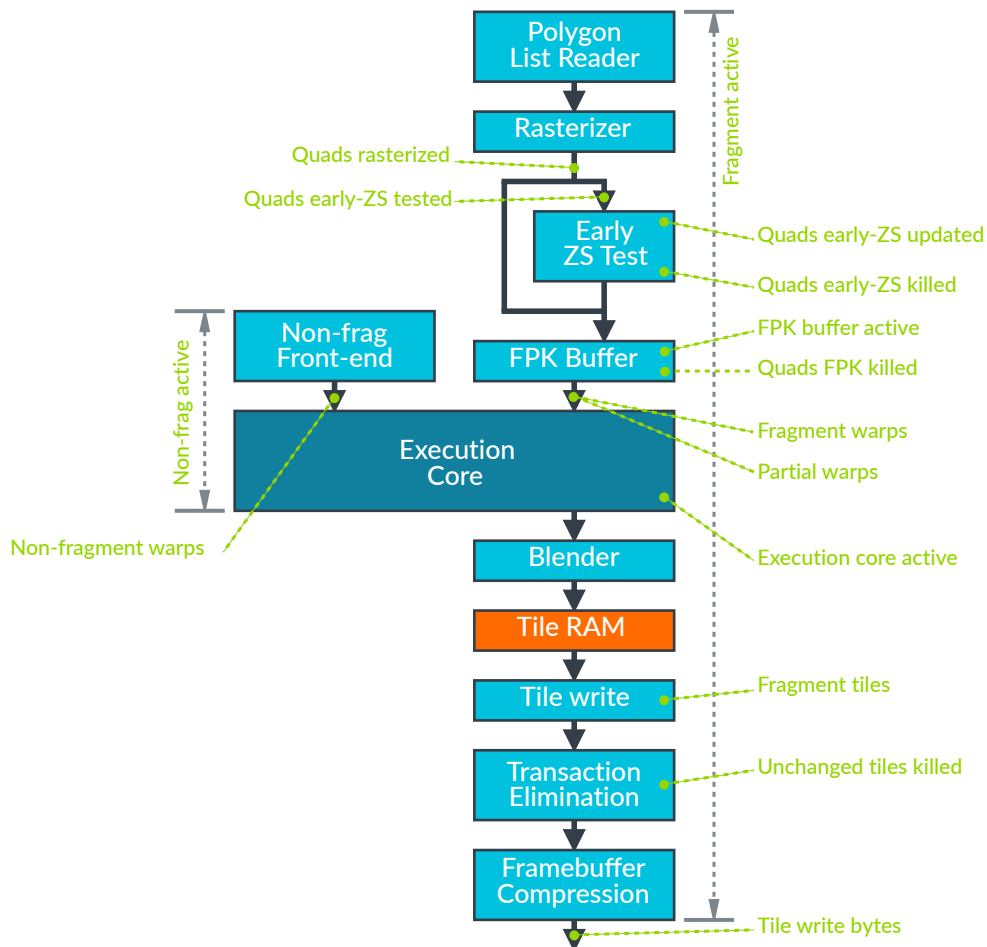
fragments show as a late ZS kill, as no shader execution is needed once the depth or stencil value has been set.

```
max(min(($MaliCoreQuadsLateZSKilledQuads / $MaliCoreQuadsRasterizedFineQuads) * 100,  
100), 0)
```

5. Shader core data path

Each shader core has two parallel data paths for issuing threads to the core, one for non-fragment workloads and one for fragment workloads. These counters track the thread issue for each path, and their relative scheduling.

Figure 5-1: Bifrost GPU shader core



5.1 Shader core workload

The warp counters count the number of shader warps issued for the two workload types. Each warp contains 4 threads.

5.1.1 Non-fragment warps

This counter increments for every created non-fragment warp. For this GPU, a warp contains 4 threads.

For compute shaders, to ensure full utilization of the warp capacity any compute work groups should be a multiple of warp size.

```
$MaliCoreWarpsNonFragmentWarps
```

5.1.2 Fragment warps

This counter increments for every created fragment warp. For this GPU, a warp contains 4 threads.

Fragment warps are populated with fragment quads, where each quad corresponds to a 2x2 fragment region from a single triangle. Threads in a quad which correspond to a sample point outside of the triangle still consumes shader resource, which makes small triangles disproportionately expensive.

```
$MaliCoreWarpsFragmentWarps
```

5.2 Shader core throughput

The throughput metrics show the average number of cycles it takes to get a single thread shaded by the shader core. Note that these metrics show average throughput, not average cost, so include the impact of processing latency, memory latency, and any resource sharing inside the shader core.

5.2.1 Non-fragment cycles per thread

This expression defines the average number of shader core cycles per non-fragment thread.

Note that this measurement captures the average throughput, which might not be a direct measure of processing cost for content that is sensitive to memory access latency. In addition, there is some interference caused by non-fragment and fragment workloads running concurrently on the same hardware. This expression is therefore indicative of cost, but does not reflect precise costing.

```
$MaliCoreCyclesNonFragmentActive / ($MaliCoreWarpsNonFragmentWarps * 4)
```

5.2.2 Fragment cycles per thread

This expression defines the average number of shader core cycles per fragment thread. Note that this measurement captures the average throughput, which might not be a direct measure of

processing cost for content which is sensitive to memory access latency. In addition, there is some interference caused by different workload types running concurrently on the same hardware. This expression is therefore indicative of cost, but does not reflect precise costing.

```
$MaliCoreCyclesFragmentActive / ($MaliCoreWarpsFragmentWarps * 4)
```

5.3 Shader core data path utilization

The data path utilization counters show the total activity level of the major data paths in the shader core. Identifying the dominant workload type helps to target optimizations. Identifying lack of parallelism can confirm that there are scheduling problems.

5.3.1 Non-fragment utilization

This expression defines the percentage utilization of the shader core non-fragment path. This counter measures any cycle where a non-fragment workload is active in either the non-fragment shader core front-end, or in the programmable core itself.

```
max(min(($MaliCoreCyclesNonFragmentActive / $MaliGPUCyclesGPUActive) * 100, 100), 0)
```

5.3.2 Fragment utilization

This expression defines the percentage utilization of the shader core fragment path. This counter measures any cycle where a fragment workload is active in either the fragment shader core front-end, or in the programmable core itself.

```
max(min(($MaliCoreCyclesFragmentActive / $MaliGPUCyclesGPUActive) * 100, 100), 0)
```

5.3.3 Fragment FPK buffer utilization

This expression defines the percentage of cycles where the Forward Pixel Kill (FPK) quad buffer contains at least one fragment quad. This buffer is located after early ZS but before the execution core.

During fragment shading this counter should be close to 100%. This indicates that the fragment front-end is able to keep up with the shader core shading rate. This counter commonly drops below 100% for three reasons:

- The running workload has many empty tiles with no geometry to render. This is common in shadow maps, for any screen region with no shadow casters.
- The application consists of simple shaders but a high percentage of microtriangles. This causes the shader core to complete fragments faster than they are rasterized, so the quad buffer starts to drain.

- The application consists of layers which stall at early ZS due to a dependency on an earlier fragment layer which is still in flight. This prevents new fragments entering the quad buffer, so the quad buffer starts to drain.

```
max(min(($MaliCoreCyclesFragmentFPKBAActive / $MaliCoreCyclesFragmentActive) * 100, 100), 0)
```

5.3.4 Execution core utilization

This expression defines the percentage utilization of the programmable execution core, monitoring any cycle where the shader core contains at least one warp. A low utilization here indicates lost performance, because there are spare shader core cycles that are unused.

In some use cases an idle core is unavoidable. For example, a clear color tile that contains no shaded geometry, or a shadow map that is resolved entirely using early ZS depth updates.

Improve execution core utilization by parallel processing of the non-fragment and fragment queues, running overlapping workloads from multiple render passes. Also aim to keep the FPK buffer utilization as high as possible, ensuring constant forward-pressure on fragment shading.

```
max(min(($MaliCoreCyclesExecutionCoreActive / $MaliGPUCyclesGPUActive) * 100, 100), 0)
```

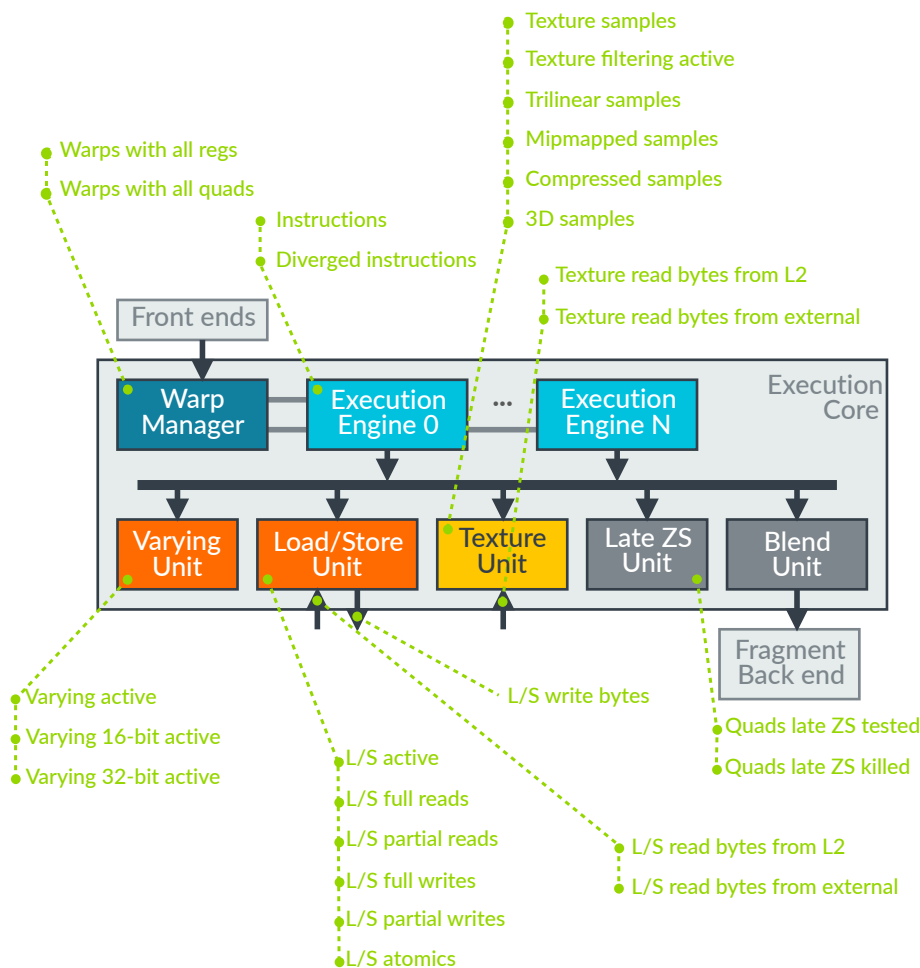
6. Shader core functional units

A shader core consists of multiple parallel processing units that provide both programmable and fixed-function operations. Performance counters can track utilization and workload type for all the major processing units, allowing developers to find both bottlenecks and content inefficiencies to optimize.

For shader-bound content, the functional unit with the highest loading is likely to be the bottleneck. To improve performance you can reduce the number of operations of that type in the shader. Alternatively, reduce the precision of the operations to use 16-bit types so that multiple operations can be performed in parallel.

For thermally bound content, reducing the critical path load gives the biggest gain as allows use of a lower operating frequency. However, reducing load on any functional unit helps improve energy efficiency.

Figure 6-1: Bifrost GPU execution core



6.1 Functional unit utilization

Functional unit utilization counters provide normalized views of the functional unit activity inside the shader core. The functional units run in parallel. To improve performance, target the most heavily utilized functional unit for optimization. Although it might not help performance, reducing the load of any unit improves energy efficiency.

6.1.1 Arithmetic unit utilization

This expression defines the percentage utilization of the arithmetic unit in the execution engine.

The most effective technique for reducing arithmetic load is reducing the complexity of your shader programs. Increasing shader usage of 16-bit (mediump) variables can also help.

```
max(min(($MaliCoreInstructionsExecutedInstructions /  
$MaliCoreCyclesExecutionCoreActive) * 100, 100), 0)
```

6.1.2 Varying unit utilization

This expression defines the percentage utilization of the varying unit.

The most effective technique for reducing varying load is reducing the number of interpolated values read by the fragment shading. Increasing shader usage of 16-bit (mediump) input variables also helps, as they can be interpolated as twice the speed of 32-bit variables.

```
max(min(($MaliCoreVaryingIssues32BitInterpolationSlots  
+ $MaliCoreVaryingIssues16BitInterpolationSlots) /  
$MaliCoreCyclesExecutionCoreActive) * 100, 100), 0)
```

6.1.3 Texture unit utilization

This expression defines the percentage utilization of the texturing unit.

The most effective technique for reducing texturing unit load is reducing the number of texture samples read by the fragment shader. Using simpler texture filters can reduce filtering cost. Using 32bpp color formats, and the ASTC decode mode extensions can reduce data access cost.

```
max(min(($MaliCoreTextureCyclesTexturingActive / $MaliCoreCyclesExecutionCoreActive)  
* 100, 100), 0)
```

6.1.4 Load/store unit utilization

This expression defines the percentage utilization of the load/store unit. The load/store unit is used for general-purpose memory accesses. This includes vertex attribute access, buffer access, work group shared memory access, and stack access. This unit also implements imageLoad/Store and atomic access functionality.

For traditional graphics content the most significant contributor to load/store usage is vertex data. Arm recommends simplifying mesh complexity, using fewer triangles, fewer vertices, and fewer bytes per vertex.

Shaders that spill to stack are also expensive, as any spilling is multiplied by the large number of parallel threads that are running. You can use the Mali Offline Compiler to check your shaders for spilling.

```
max(min((($MaliCoreLoadStoreCyclesFullReadCycles +
  $MaliCoreLoadStoreCyclesPartialReadCycles + $MaliCoreLoadStoreCyclesFullWriteCycles
  + $MaliCoreLoadStoreCyclesPartialWriteCycles +
  $MaliCoreLoadStoreCyclesAtomicAccessCycles) / $MaliCoreCyclesExecutionCoreActive) *
  100, 100), 0)
```

6.2 Shader program properties

Shader program property counters track multiple properties related to the running shader program instruction execution. They are used to identify shader execution behaviors that are sources of program inefficiency.

6.2.1 Diverged instruction issue rate

This expression defines the percentage of instructions that have control flow divergence across the warp.

Control flow divergence can reduce performance, because only some lanes of the warp are active while diverged. Minimize divergence by using warp-uniform branch decisions for conditional checks and loop limits.

```
max(min(($MaliCoreInstructionsDivergedInstructions /
  $MaliCoreInstructionsExecutedInstructions) * 100, 100), 0)
```

6.3 Shader workload properties

Shader workload property counters track multiple properties of the running workload that can impact efficiency. These can be used to identify sources of inefficiency that are not related to the shader program code itself.

6.3.1 Partial coverage rate

This expression defines the percentage of warps quads that contain fragment samples with no coverage. A high percentage can indicate that the content has a high density of small triangles, which are expensive to process. To avoid this, use mesh level-of-detail algorithms to select simpler meshes as objects move further from the camera.

```
max(min(($MaliCoreWarpsPartialFragmentWarps / $MaliCoreWarpsFragmentWarps) * 100, 100), 0)
```

6.3.2 Unchanged tile kill rate

This expression defines the percentage of tiles that are killed by the transaction elimination CRC check because the content of a tile matches the content already stored in memory.

A high percentage of tile writes being killed indicates that a significant part of the framebuffer is static from frame to frame. Consider using scissor rectangles to reduce the area that is redrawn. To help manage the partial frame updates for window surfaces consider using the EGL extensions such as:

- EGL_KHR_partial_update
- EGL_EXT_swap_buffers_with_damage

```
max(min(($MaliCoreTilesUnchangedTilesKilled / $MaliCoreTilesTiles) * 100, 100), 0)
```

7. Shader core varying unit

The varying unit counters monitor the varying interpolation in fragment shaders. If the shader core utilization counters show that this unit is a bottleneck, these counters can indicate optimization opportunities.

The interpolator has one or more 32-bit data paths per thread. Each data path can interpolate a scalar 32-bit value or a vec2 16-bit value in a single cycle. We recommend using 16-bit (`mediump`) varying inputs to fragment shaders whenever possible. We also recommend packing 16-bit values into vec2 or vec4 values. For example, a single vec4 interpolates faster than a separate vec3 and scalar float pair.

7.1 Varying unit usage

These counters show the usage of the varying interpolation unit, and the breakdown by data type size.

7.1.1 Varying cycles

This expression defines the total number of cycles where the varying interpolator is active.

```
$MaliCoreVaryingIssues32BitInterpolationSlots +  
$MaliCoreVaryingIssues16BitInterpolationSlots
```

7.1.2 16-bit interpolation cycles

This counter increments for every 16-bit interpolation cycle processed by the varying unit.

```
$MaliCoreVaryingIssues16BitInterpolationSlots
```

7.1.3 32-bit interpolation cycles

This counter increments for every 32-bit interpolation cycle processed by the varying unit. 32-bit interpolation is half the performance of 16-bit interpolation, so if content is varying bound consider reducing precision of varying inputs to fragment shaders.

```
$MaliCoreVaryingIssues32BitInterpolationSlots
```

8. Shader core texture unit

The texture unit counters show use of all texture sampling and filtering in shaders. If the shader core utilization counters show that this unit is a bottleneck, these counters can indicate optimization opportunities.

8.1 Texture unit usage

These counters show the usage of the texturing unit, and the average number of cycles per instruction. The performance of the texture unit in the shader core varies for different GPUs in the Bifrost family. For Mali-G51 the maximum performance (bilinear filtered samples) is 0.5 cycles per sample.

8.1.1 Texture filtering cycles

This counter increments for every texture filtering issue cycle. This GPU can do 2 2D bilinear texture samples per clock. More complex filtering operations are composed of multiple 2D bilinear samples, and takes proportionally more filtering time to complete. The costs per sampled quad are:

- 2D bilinear filtering takes two cycles.
- 2D trilinear filtering takes four cycles.
- 3D bilinear filtering takes four cycles.
- 3D trilinear filtering takes eight cycles.

Anisotropic filtering makes multiple filtered subsamples which are combined to make the final output sample color. For a filter with MAX_ANISOTROPY of N, up to N times the cycles of the base filter are required.

```
$MaliCoreTextureCyclesTexturingActive
```

8.1.2 Texture filtering cycles per instruction

This expression defines the average number of texture filtering cycles per instruction. For texture-limited content that has a CPI higher than the optimal throughout of this core (2 samples per cycle), consider using simpler texture filters. See *Texture filtering cycles* for details of the expected performance for different types of operation.

```
$MaliCoreTextureCyclesTexturingActive / ($MaliCoreTextureQuadsTextureRequests * 4)
```


8.2 Texture unit workload properties

These counters show the content behavior in the texture unit, in terms of the number of accesses using texture compression, mipmapping, or trilinear filtering probes.

8.2.1 Texture data fetches from compressed lines

This expression defines the percentage of texture line fetches that are from textures using API block compression, such as ASTC or ETC2.

Texture compression significantly reduces memory bandwidth consumption, so aim to maximize this percentage by compressing all offline-authored texture assets. However, note that this counter does not include texture data fetches from framebuffers compressed with AFBC lossless compression.

```
max(min(($MaliCoreTextureLineFetchesCompressedLineFetches /  
$MaliCoreTextureLineFetchesLineFetches) * 100, 100), 0)
```

8.2.2 Texture accesses using trilinear filter percentage

This expression defines the percentage of texture operations using trilinear filtering. Trilinear samples are twice the cost of simple bilinear samples.

```
max(min(($MaliCoreTextureQuadsTrilinearFilteredIssues /  
$MaliCoreTextureQuadsTextureRequests) * 100, 100), 0)
```

8.2.3 Texture accesses using mipmapping percentage

This expression defines the percentage of texture operations accessing mipmapped textures.

Mipmapping significantly improves image quality and memory bandwidth in 3D scenes with variable object view distance. Aim to enable mipmapping for all offline-authored texture assets in 3D content.

```
max(min(($MaliCoreTextureQuadsMipmappedTextureIssues /  
$MaliCoreTextureQuadsTextureIssues) * 100, 100), 0)
```

8.3 Texture unit memory usage

These counters show the average number of bytes read from the L2 cache or external memory per texture sample. If you are fetching more bytes per access than the size of the texture format, you

might be thrashing the cache. Consider using a narrower texture format data type, compression, and mipmaps.

8.3.1 Texture bytes read from L2 per texture cycle

This expression defines the average number of bytes read from the L2 memory system by the texture unit per filtering cycle. This metric indicates how effectively textures are being cached in the L1 texture cache.

If more bytes are being requested per access than you would expect for the format you are using, review your texture settings. We recommend:

- Enabling mipmaps for offline generated textures.
- Using ASTC or ETC compression for offline generated textures.
- Replacing runtime generated framebuffer and texture formats with a narrower format.
- Reducing use of imageLoad/Store in OpenGL ES and Vulkan, as they prevent use of framebuffer compression.
- Reducing any use of negative LOD bias used for texture sharpening.
- Reducing the MAX_ANISOTROPY level for anisotropic filtering.

```
($MaliCoreL2ReadsTextureL2ReadBeats * 16) / $MaliCoreTextureCyclesTexturingActive
```

8.3.2 Texture bytes read from external memory per texture cycle

This expression defines the average number of bytes read from the external memory system by the texture unit per filtering cycle. This metric indicates how effectively textures are being cached in the L2 cache.

If more bytes are being requested per access than you would expect for the format you are using, review your texture settings. We recommend:

- Enabling mipmaps for offline generated textures.
- Using ASTC or ETC compression for offline generated textures.
- Replacing runtime generated framebuffer and texture formats with a narrower format.
- Reducing use of imageLoad/Store in OpenGL ES and Vulkan, as they prevent use of framebuffer compression.
- Reducing any use of negative LOD bias used for texture sharpening.
- Reducing the MAX_ANISOTROPY level for anisotropic filtering.

```
($MaliCoreExternalReadsTextureExternalReadBeats * 16) /  
$MaliCoreTextureCyclesTexturingActive
```

9. Shader core load/store unit

The load/store unit counters show the use of the general-purpose L1 data cache. This unit is used for all shader data accesses except texturing and framebuffer write-back. This includes buffer, image, shared storage, and stack access.

9.1 Load/store unit usage

The unit usage counters show the content behavior in the load/store unit. They show the number of reads and writes being made, and whether those loads use the full width of the available data path.

Make effective use of the load/store unit by making full-width accesses. We recommend shaders use vector memory accesses, and ensure threads in the same warp access overlapping or sequential addresses inside a single 64 byte range.

9.1.1 Load/store total issues

This expression defines the total number of load/store cache access cycles. This counter ignores secondary effects such as cache misses, so provides the minimum possible cycle usage.

```
$MaliCoreLoadStoreCyclesFullReadCycles + $MaliCoreLoadStoreCyclesPartialReadCycles +  
$MaliCoreLoadStoreCyclesFullWriteCycles +  
$MaliCoreLoadStoreCyclesPartialWriteCycles +  
$MaliCoreLoadStoreCyclesAtomicAccessCycles
```

9.1.2 Load/store full read issues

This counter increments for every full-width load/store cache read.

```
$MaliCoreLoadStoreCyclesFullReadCycles
```

9.1.3 Load/store partial read issues

This counter increments for every partial-width load/store cache read. Partial data accesses do not make full use of the load/store cache capability. Merging short accesses together to make fewer larger requests improves efficiency. To do this in shader code:

- Use vector data loads.
- Avoid padding in strided data accesses.

- Write compute shaders so that adjacent threads in a warp access adjacent addresses in memory.

```
$MaliCoreLoadStoreCyclesPartialReadCycles
```

9.1.4 Load/store full write issues

This counter increments for every full-width load/store cache write.

```
$MaliCoreLoadStoreCyclesFullWriteCycles
```

9.1.5 Load/store partial write issues

This counter increments for every partial-width load/store cache write. Partial data accesses do not make full use of the load/store cache capability. Merging short accesses together to make fewer larger requests improves efficiency. To do this in shader code:

- Use vector data loads.
- Avoid padding in strided data accesses.
- Write compute shaders so that adjacent threads in a warp access adjacent addresses in memory.

```
$MaliCoreLoadStoreCyclesPartialWriteCycles
```

9.1.6 Load/store atomic issues

This counter increments for every load/store atomic access. Atomic memory accesses are typically multicycle operations per thread in the warp, so they are exceptionally expensive. Minimize the use of atomics in performance critical code.

```
$MaliCoreLoadStoreCyclesAtomicAccessCycles
```

9.2 Load/store unit memory usage

The memory usage counters show the average number of bytes read or written to the L2 cache per load/store read or write. Use these metrics to see how effectively your workloads are using the L1 and L2 data caches.

9.2.1 Load/store bytes read from L2 per access cycle

This expression defines the average number of bytes read from the L2 memory system by the load/store unit per read cycle. This metric gives some idea how effectively data is being cached in the L1 load/store cache.

Review your access patterns if more bytes are being requested per access than you would expect for the data format you are using.

```
($MaliCoreL2ReadsLoadStoreL2ReadBeats * 16) /  
($MaliCoreLoadStoreCyclesFullReadCycles +  
$MaliCoreLoadStoreCyclesPartialReadCycles)
```

9.2.2 Load/store bytes read from external memory per access cycle

This expression defines the average number of bytes read from the external memory system by the load/store unit per read cycle. This metric indicates how effectively data is being cached in the L2 cache. If a high number of bytes are being requested per access for the buffer formats you are using, review your data types and access patterns.

```
($MaliCoreExternalReadsLoadStoreExternalReadBeats  
* 16) / ($MaliCoreLoadStoreCyclesFullReadCycles +  
$MaliCoreLoadStoreCyclesPartialReadCycles)
```

9.2.3 Load/store bytes written to L2 per access cycle

This expression defines the average number of bytes written to the L2 memory system by the load/store unit per write cycle.

```
(( $MaliCoreWritesLoadStoreWriteBackWriteBeats +  
$MaliCoreWritesLoadStoreOtherWriteBeats) * 16) /  
($MaliCoreLoadStoreCyclesFullWriteCycles +  
$MaliCoreLoadStoreCyclesPartialWriteCycles)
```

10. Shader core memory traffic

The shader core memory traffic counters show the total amount of memory access a shader core makes to the L2 cache and external memory system. Use the data breakdown to identify the unit making the accesses, and target that unit for optimization.

10.1 Read access from L2 cache

The L2 memory read counters show the shader core memory read traffic that is fetched from the GPU L2 cache.

10.1.1 Front-end read bytes from L2 cache

This expression defines the total number of bytes read from the L2 memory system by the fragment front-end unit.

```
$MaliCoreL2ReadsFragmentL2ReadBeats * 16
```

10.1.2 Load/store read bytes from L2 cache

This expression defines the total number of bytes read from the L2 memory system by the load/store unit.

```
$MaliCoreL2ReadsLoadStoreL2ReadBeats * 16
```

10.1.3 Texture read bytes from L2 cache

This expression defines the total number of bytes read from the L2 memory system by the texture unit.

```
$MaliCoreL2ReadsTextureL2ReadBeats * 16
```

10.2 Read access from external memory

The external memory read counters show the shader core memory read traffic that misses in the GPU cache and that is fetched from the external memory system. This data is either fetched from a layer of system cache external to the GPU, or from the main system DRAM.

10.2.1 Front-end read bytes from external memory

This expression defines the total number of bytes read from the external memory system by the fragment front-end unit.

```
$MaliCoreExternalReadsFragmentExternalReadBeats * 16
```

10.2.2 Load/store read bytes from external memory

This expression defines the total number of bytes read from the external memory system by the load/store unit.

```
$MaliCoreExternalReadsLoadStoreExternalReadBeats * 16
```

10.2.3 Texture read bytes from external memory

This expression defines the total number of bytes read from the external memory system by the texture unit.

```
$MaliCoreExternalReadsTextureExternalReadBeats * 16
```

10.3 Write access

The memory write counters show the shader core memory traffic that is written into the memory system. These writes can be buffered by the GPU L2, or sent to external memory.

10.3.1 Load/store write bytes

This expression defines the total number of bytes written to the L2 memory system by the load/store unit.

```
($MaliCoreWritesLoadStoreWriteBackWriteBeats +  
$MaliCoreWritesLoadStoreOtherWriteBeats) * 16
```

10.3.2 Tile buffer write bytes

This expression defines the total number of bytes written to the L2 memory system by the tile buffer write-back unit.

```
$MaliCoreWritesTileBufferWriteBeats * 16
```

11. GPU configuration

The GPU configuration counters show the hardware product configuration in the target device. For example, showing the number of shader cores present in the design.

11.1 GPU configuration counters

The configuration counters are virtual counters that you can use to scale performance results and create alternative data visualizations. For example, multiplying the per shader core workload counter series by `$MaliConstantsShaderCoreCount` would give a GPU-wide total.

11.1.1 Shader core count

This configuration constant defines the number of shader cores in the design.

```
$MaliConstantsShaderCoreCount
```

11.1.2 L2 cache slice count

This configuration constant defines the number of L2 cache slices in the design.

```
$MaliConstantsL2SliceCount
```

11.1.3 External bus beat size

This configuration constant defines the number of bytes transferred per external bus beat.

```
($MaliConstantsBusWidthBits / 8)
```