

A night sky with a full moon in the upper right quadrant and a silhouette of a tree in the lower left quadrant. The sky is filled with stars and a blueish tint.

Ensure Correct Vulkan Synchronization by Using Synchronization Validation

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Understanding Vulkan Synchronization

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Slides are available at:

<https://www.lunarg.com/news-insights/white-papers/vulkan-synchronization-siggraph-2021/>

Introduction

- Understanding Vulkan Synchronization
 - Synchronization terminology in the Vulkan spec
 - Some of the new features in VK_KHR_synchronization2 (aka sync2)
- Validating Vulkan Synchronization
 - Theory of operation
 - Demo
 - Interpreting error messages
 - Frequently found errors
- Q & A

Execution Dependencies

- Most Vulkan commands are started in queue submission order but may execute in any order
 - Even commands using the same pipeline stages!
- The programmer must tell Vulkan when 2 commands depend on each other
 - We do this by defining barriers
- *First synchronization scope* is what *happens before* a barrier
 - AKA: **srcStageMask**
- *Second synchronization scope* is what *happens after* a barrier
 - AKA: **dstStageMask**

Memory Dependencies

- GPUs have lots of caches
 - Vulkan defines logical memory access types that correspond to caches that *might* be associated with a pipeline stage
 - Cache maintenance operations are required for different stages to ‘see’ the output of other stages in memory.
- *First access scope*: memory accesses by commands that *happen before* the barrier.
 - AKA: **srcAccessMask**
 - A barrier does a **cache clean (or flush)** on any caches used in the first access scope
- *Second access scope*: memory accesses by commands that *happen after* the barrier.
 - AKA: **dstAccessMask**
 - A barrier does a **cache invalidate** on any caches used in the first access scope

Types of synchronization errors

RAW	Read-after-write	This occurs when a subsequent operation uses the result of a previous operation without waiting for the result to be completed
WAR	Write-after-read	This occurs when a subsequent operation overwrites a memory location read by a previous operation before that operation is complete. (requires only execution dependency)
WAW	Write-after-write	This occurs when a subsequent operation writes to the same set of memory locations (in whole or in part) being written by a previous operation
WRW	Write-racing-write	This occurs when unsynchronized subprocesses/queues perform writes to the same set of memory locations
RRW	Read-racing-write	This occurs when unsynchronized subprocesses/queues perform read and write operations on the same set of memory locations

Hello race condition!

```
vkCmdCopyBuffer(cb, buffer_a, buffer_b, 1, &region); /* a is copy src */  
vkCmdCopyBuffer(cb, buffer_c, buffer_a, 1, &region); /* a is copy dst */
```

Write after read hazard because `buffer_a` is both src and dst in commands with no execution dependency!

```
vkCmdCopyBuffer(cb, buffer_a, buffer_b, 1, &region);  
auto buffer_barrier = lvl_init_struct<VkBufferMemoryBarrier>()  
buffer_barrier.srcAccessMask = VK_ACCESS_TRANSFER_READ_BIT;  
buffer_barrier.dstAccessMask = VK_ACCESS_TRANSFER_WRITE_BIT;  
buffer_barrier.buffer = buffer_a;  
vkCmdPipelineBarrier(cb, VK_PIPELINE_STAGE_TRANSFER_BIT,  
                    VK_PIPELINE_STAGE_TRANSFER_BIT,  
                    0, 0, nullptr, 1, &buffer_barrier, 0, nullptr);  
vkCmdCopyBuffer(cb, buffer_c, buffer_a, 1, &region);
```

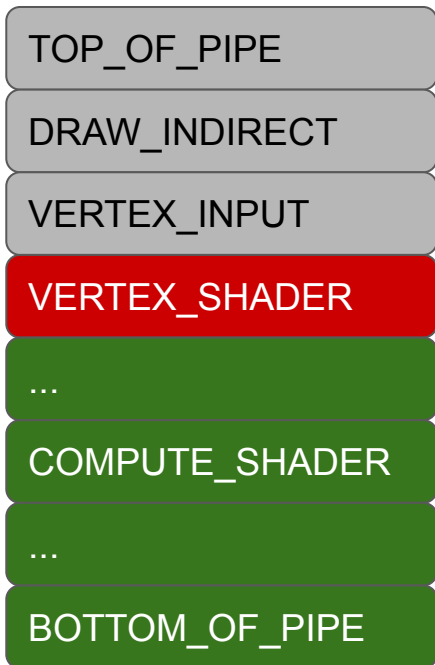
Pipeline Stages and Access Masks

- Pipeline stages bits are ordered
 - Logical ordering defined in vulkan spec
 - In srcStageMask, each stage bit also waits for all earlier stages
 - In dstStageMask, each stage bit also blocks all later stages
 - You can often 'get away' with only setting some of the bits you are synchronizing
- Access mask bits are independent
 - You need to set ALL bits you are synchronizing
 - **BUT**, you must explicitly specify each pipeline stage if you want to use an access mask that requires it. (This is a common source of errors)

Pipeline Stage - details

- Was a 32-bit mask, but all bits are used so sync2 made it 64 bits
 - Several extensions **require** using sync2 or the 'special' stage mask bits
 - All bit values in the 32-bit mask have same meaning in the 64-bit mask
- Valid values are limited by
 - Queue Capabilities
 - Enabled extensions & features
 - Being in a renderpass
- Special values
 - NONE, TOP_OF_PIPE, BOTTOM_OF_PIPE - will be discussed separately
 - ALL_COMMANDS - blocks 'everything', all stages and some event-related commands
 - ALL_GRAPHICS - all active parts of the graphics pipeline
 - In sync2, several stages expand to multiple new stages
 - e.g. TRANSFER stage is equivalent to (COPY | BLIT | CLEAR | RESOLVE)

Pipeline stage ordering example



- In `srcStageMask`:
 - VERTEX_SHADER also waits on all grey stages
- In `dstStageMask`
 - VERTEX_SHADER also blocks all green stages

Pipeline barriers - execution dependency chains

```
Command A  
Barrier1  
Command B  
Barrier2  
Command C  
// A, B, C should  
// execute in order
```

TOP_OF_PIPE

DRAW_INDIRECT

COMPUTE_SHADER

BOTTOM_OF_PIPE

- Used to get sequential execution of multiple commands
- Barrier1.dstMask must be the same as or after Barrier2.srcMask in pipeline stage order

Barrier1.dstMask	Barrier2.srcMask	dependency chain?
DRAW_INDIRECT	DRAW_INDIRECT	Yes
DRAW_INDIRECT	COMPUTE_SHADER	NO
COMPUTE_SHADER	DRAW_INDIRECT	Yes
BOTTOM_OF_PIPE or ALL_COMMANDS	DRAW_INDIRECT	Yes (but might be slow)

Waiting for everything or nothing

- `srcStageMask = ALL_COMMANDS` blocks or waits for all stages
 - This is **wait for idle** on the GPU and will often hurt performance
- `srcStageMask = NONE` or `TOP_OF_PIPE`
 - **Your barrier waits for nothing**
 - Can only form an *execution dependency chain* with the prior barrier with `dstStageMask = ALL_COMMANDS`
- `dstStageMask = NONE` or `BOTTOM_OF_PIPE`
 - **Nothing can wait for your barrier**
 - Use `srcStageMask = ALL_COMMANDS` to form an *execution dependency chain*
- This comes up when interacting with other parts of Vulkan
 - Semaphores & Fences usually are OK
 - Renderpass implicit SubpassDependencies often go poorly (more later)

Access Mask details

- Was a 32-bit mask, but all bits are used so sync2 made it 64 bits
 - Several extensions **require** using sync2 or the 'special' access mask bits
 - All bit values in the 32-bit mask have same meaning in the 64 bit mask
- Valid bits are limited by which bits are set in the corresponding StageMask
 - Eg. PIPELINE_STAGE_TRANSFER allows ACCESS_TRANSFER_READ or WRITE
 - sync2 defines 200+ VUIDs to identify all possible errors
- Special values
 - NONE - no memory access, used to define an execution barrier
 - MEMORY_READ, MEMORY_WRITE - any memory access allowed by StageMask.
 - SHADER_READ- in sync2 expands to (SAMPLER_READ|STORAGE_READ|UNIFORM_READ)
 - SHADER_WRITE - in sync2 expands to STORAGE_WRITE (which is above 2^{32})

Memory Barriers

```
typedef struct VkMemoryBarrier {
    VkStructureType    sType;
    const void*        pNext;
    VkAccessFlags      srcAccessMask;
    VkAccessFlags      dstAccessMask;
} VkMemoryBarrier;

/* sync2 */
typedef struct VkMemoryBarrier2KHR {
    VkStructureType    sType;
    const void*        pNext;
    VkPipelineStageFlags2KHR    srcStageMask;
    VkAccessFlags2KHR  srcAccessMask;
    VkPipelineStageFlags2KHR    dstStageMask;
    VkAccessFlags2KHR  dstAccessMask;
} VkMemoryBarrier2KHR;
```

- A memory barrier synchronizes all memory accessible by the GPU
- You can use to synchronize buffers and images, UNLESS you are doing Image Layout Transition or Queue Family Ownership Transfer
- N barriers can be converted to 1 by or-ing all of their masks together
- Sync2 makes pipeline stages be part of the barrier structures instead of separate parameters to vkCmdPipelineBarrier()

Buffer Barriers - Queue Family Ownership

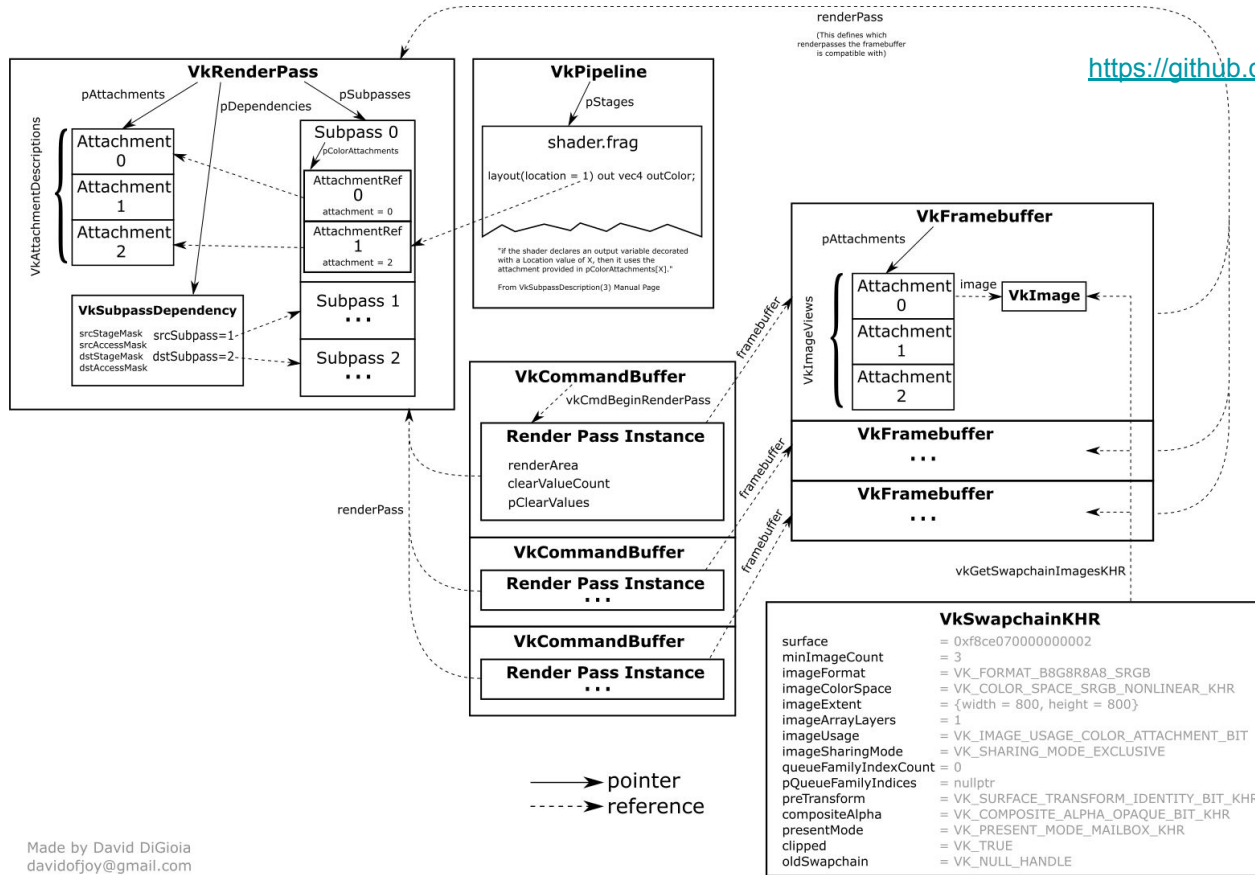
- Like a MemoryBarrier except
 - Adds a VkBuffer handle
 - Adds srcQueueFamilyIndex, dstQueueFamilyIndex for Queue Family Ownership (QFO) Transfer
- Queue Family Ownership Transfer
 - VK_SHARING_MODE_CONCURRENT is usually very slow
 - VK_SHARING_MODE_EXCLUSIVE requires a QFO barrier to switch ownership between one queue family and another
- QFO Barrier
 - Create a Buffer (or Image) Memory Barrier
 - Submit on src queue, only srcAccessMask used.
 - Submit on dst queue, only dstAccessMask used .
 - However, **both** PipelineStageMasks are used by both queues
 - Use NONE pipeline stage for the “other” PipelineStageMask
 - Use a Semaphore to synchronize the 2 queues

Image Memory Barriers

- Like a BufferMemoryBarrier except
 - VkImage handle instead of VkBuffer
 - Adds VkImageLayout oldLayout and newLayout to allow Image Layout Transitions
- Image Layout Transitions
 - Re-arrange memory for efficient use by different pipeline stages
 - *Happens between* 🧠 the first and second execution scopes of the barrier
 - Each subresource of an image can be transitioned independently.
- sync2 adds magic ‘do the right thing’ layouts
 - Avoid the need for providing different layouts for Color, Depth and Stencil Images
 - VK_IMAGE_LAYOUT_READ_ONLY_OPTIMAL_KHR
 - VK_IMAGE_LAYOUT_ATTACHMENT_OPTIMAL_KHR

Renderpass - it is REALLY complicated

<https://github.com/David-DiGioia/vulkan-diagrams>



Made by David DiGioia
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Renderpass - what to watch out for

- Load and store operations often cause synchronization errors
 - `LOAD_OP_DONT_CARE` generates WRITE accesses to your attachments
- Rasterization order synchronizes some operations within a subpass
- Pipeline Barriers in a RenderPass are even trickier
 - You need a Subpass self-Dependency (`srcSubpass == dstSubpass`) that includes all the pipeline stages your barrier(s) will use
 - Set of allowed pipeline stages is limited
- Internal Subpass Dependencies don't affect the outside world
 - (`srcSubpass and dstSubpass != EXTERNAL`)
 - *First and second execution scopes* only include commands in other subpasses
- Implicit External Subpass Dependencies don't do what you want, define them explicitly

Implicit Subpass External Dependencies

```
/* INITIAL implicit subpass */
VkSubpassDependency implicitDependency = {
    .srcSubpass = VK_SUBPASS_EXTERNAL;
    // First subpass attachment is used in
    .dstSubpass = firstSubpass;
    .srcStageMask = NONE;
    .dstStageMask = ALL_COMMANDS;
    .srcAccessMask = 0;
    .dstAccessMask =
VK_ACCESS_INPUT_ATTACHMENT_READ_BIT |
VK_ACCESS_COLOR_ATTACHMENT_READ_BIT |
VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT |
VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT |
VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT;
    .dependencyFlags = 0;
};
/* FINAL implicit subpass is similar,
 * but src and dst are swapped
 */
```

- These are Image Memory Barriers for your attachments
- Inserted by the driver ONLY IF
 - You have initial or final layout transitions.
 - You don't provide your own dependency
- They wait for or block NOTHING
- Use them as a template but change the external side to be useful
 - You probably want an execution dependency chain!
- Maybe use different pipeline stages on internal side instead of ALL_COMMANDS
- Maybe **add** internal side access bits, but you probably want at least the default ones.

Other stuff

- Semaphores and Fences synchronize all GPU execution and memory accesses that were submitted before they signal
 - This is why wait for nothing / block nothing is sometimes ok
- Queries execute completely in submission order
- Many other changes in sync2:
 - `vkQueueSubmit2KHR()` is much nicer than `vkQueueSubmit()`
 - `VkDependencyInfoKHR` reduces typing for pipeline barrier commands
 - Event commands are redesigned

Q & A

Validating Vulkan Synchronization

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Senior Graphics Software Engineer with 30 years Graphics experience across numerous platforms and from kernel drivers to application development.

Slides are available at:

<https://www.lunarg.com/news-insights/white-papers/vulkan-synchronization-siggraph-2021/>

Synchronization Validation

- Detects Hazard From Insufficient Synchronization Operations
 - Hazard -- any access were the access pattern is not well defined
 - Byte Resolution Access/Synchronization Tracking
 - All vkCmd types (transfer, draw, renderpass, compute, resolve, etc)
 - Sync2 support
- Some Limitations
 - Single Command Buffer (current release)
 - Limited aliasing detection (like kinds of resources)
 - No swizzle support
 - Not GPU Assisted (doesn't know shader execution time information)
 - Limited extension support

Hazard Types (common)

- Read-after-write (RAW)
 - Operation uses the result of a previous operation without waiting for the result to be completed.
- Write-after-read (WAR)
 - Operation overwrites a memory location read by a previous operation before operation is complete.
- Write-after-write (WAW)
 - Operation writes to the same set of memory locations being written by a previous operation.

Hazard Types (Vulkan Specific)

- Write-racing-write (WRW)
 - Operations on unsynchronized subpasses/queues perform writes to the same set of memory locations.
- Read-racing-write (RRW)
 - Operations on unsynchronized subpasses/queues perform read and write operations on the same set of memory locations

Synchronization Validation Theory of Operation

- Tracks access history
 - At each byte
 - Operation Type (stage, access)
 - Stores “most recent” only (more below)
- Applies synchronization operations to access history
 - Identifies “safe” subsequent access operations
 - Track dependency chaining
- Validates accesses of each subsequent operation to access history
 - The stage and access for each are compared previous access and synchronization
 - Reports hazards
 - Any hazard reported earlier may mask detection of subsequent hazard with same memory

Using Synchronization Validation

- Clean Validation Run
 - Resolve all outstanding non-synchronization issues.
 - Recommend “best practices” and “GPU Assisted” as well.
- How To Enable
 - vkconfig
 - vk_layer_settings.txt
 - Environment variables
- Running
 - Disable all other validation
 - Chase down issues in debugger.
 - “Debug Action: Break” on Windows
 - Break in vkCreateDebugUtilsMessengerEXT callback

Simple Sync Val Demo

- Using the Vulkan-Samples

Congratulations, It's An Error.

```
[ SYNC-HAZARD-WRITE_AFTER_WRITE ] Object 0: handle =  
0x8483000000000025, type = VK_OBJECT_TYPE_IMAGE; | MessageID =  
0xdf9f5e1 | vkCmdPipelineBarrier: Hazard WRITE_AFTER_WRITE for image  
barrier 0 VkImage 0x8483000000000025[]. Access info (usage:  
SYNC_IMAGE_LAYOUT_TRANSITION, prior_usage:  
SYNC_TRANSFER_TRANSFER_WRITE, write_barriers: 0, command:  
vkCmdCopyBufferToImage, seq_no: 2, reset_no: 1)
```

- Understanding the parts of this error will take a little background knowledge

Think Like Synchronization Validation

- Stage/Access pairs are need to describe the usages of resources
 - Not all pairs are valid, valid pairs expressed as enum SYNC_<STAGE>_<ACCESS>
 - Enum reflects Sync2 expanded pipeline stages
- How does the current operation (draw, transfer, etc.) affect the resource
 - Stage/access of operation for each resource
 - Comparison to earlier command stage/access and sync operations (“..is it safe?”)
 - Include implicit operations (layout transition, load, resolve, store)
- What relation do synch operations have relative to a given resource?
 - Do they apply at all? Also include earlier synch operations (chaining)
 - What subsequent operations are “safed” for that resource
- What are the prior commands that touch a given resource (memory location)?
 - Include implicit operations (layout transition, load, resolve, store)

Synchronization Validation Messages

<command_name>: Hazard <hazard_type>

<command_specific_resource_identifier>

Access info (

usage: <current_stage_access>,

prior_usage: <most_recent_prior_stage_access>,

(read_barriers|write_barriers): <cumulative_barrier_for_prior>,

command: <command_of_prior_usage>,

seq_no: <command_index_of_prior_command>,

reset_no: <times_command_buffer_been_reset>

)

Congratulations, It's An Error. (annotated)

Current command.

vkCmdPipelineBarrier: Hazard WRITE_AFTER_WRITE
for image barrier 0 VkImage 0x8483000000000025[].

Access info (

usage: SYNC_IMAGE_LAYOUT_TRANSITION,
prior_usage: SYNC_TRANSFER_TRANSFER_WRITE,
write_barriers: 0,
command: vkCmdCopyBufferToImage,
seq_no: 2, reset_no: 1).

Congratulations, It's An Error. (annotated)

Current command.

Hazard Type

vkCmdPipelineBarrier: Hazard WRITE_AFTER_WRITE
for image barrier 0 VkImage 0x8483000000000025[].

Access info (

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Congratulations, It's An Error. (annotated)

Current command.

Hazard Type

Command
specific
resource
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vkCmdPipelineBarrier: Hazard WRITE_AFTER_WRITE
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Access info (

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prior_usage: SYNC_TRANSFER_TRANSFER_WRITE,
write_barriers: 0,
command: vkCmdCopyBufferToImage,
seq_no: 2, reset_no: 1).

Congratulations, It's An Error. (annotated)

Current command.

Hazard Type

Command
specific
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vkCmdPipelineBarrier: Hazard WRITE_AFTER_WRITE
for image barrier 0 VkImage 0x8483000000000025[].
Access info (

Current
command
Stage/Access

usage: SYNC_IMAGE_LAYOUT_TRANSITION,
prior_usage: SYNC_TRANSFER_TRANSFER_WRITE,
write_barriers: 0,
command: vkCmdCopyBufferToImage,
seq_no: 2, reset_no: 1).

Congratulations, It's An Error. (annotated)

Current command.

Hazard Type

Command
specific
resource
identifier

vkCmdPipelineBarrier: Hazard WRITE_AFTER_WRITE
for image barrier 0 VkImage 0x8483000000000025[].

Previous
command
Stage/Access

Current
command
Stage/Access

Access info (

usage: SYNC_IMAGE_LAYOUT_TRANSITION,
prior_usage: SYNC_TRANSFER_TRANSFER_WRITE,
write_barriers: 0,
command: vkCmdCopyBufferToImage,
seq_no: 2, reset_no: 1).

Congratulations, It's An Error. (annotated)

Current command.

Hazard Type

Command
specific
resource
identifier

vkCmdPipelineBarrier: Hazard WRITE_AFTER_WRITE
for image barrier 0 VkImage 0x8483000000000025[].

Previous
command
Stage/Access

Current
command
Stage/Access

Access info (

usage: SYNC_IMAGE_LAYOUT_TRANSITION,
prior_usage: SYNC_TRANSFER_TRANSFER_WRITE,
write_barriers: 0,
command: vkCmdCopyBufferToImage,
seq_no: 2, reset_no: 1).

Barriers applied since
previous command

Congratulations, It's An Error. (annotated)

Current command.

Hazard Type

Command
specific
resource
identifier

vkCmdPipelineBarrier: Hazard WRITE_AFTER_WRITE
for image barrier 0 VkImage 0x8483000000000025[].

Previous
command
Stage/Access

Current
command
Stage/Access

Access info (

usage: SYNC_IMAGE_LAYOUT_TRANSITION,
prior_usage: SYNC_TRANSFER_TRANSFER_WRITE,
write_barriers: 0,
command: vkCmdCopyBufferToImage,
seq_no: 2, reset_no: 1).

Barriers applied since
previous command

Previous command

Congratulations, It's An Error. (annotated)

Current command.

Hazard Type

Command specific resource identifier

vkCmdPipelineBarrier: Hazard WRITE_AFTER_WRITE for image barrier 0 VkImage 0x8483000000000025[].

Previous command Stage/Access

Current command Stage/Access

Access info (
usage: SYNC_IMAGE_LAYOUT_TRANSITION,
prior_usage: SYNC_TRANSFER_TRANSFER_WRITE,
write_barriers: 0,
command: vkCmdCopyBufferToImage,
seq_no: 2, reset_no: 1).

Previous command location

Barriers applied since previous command

Previous command

Command Type Specific Error Details

- Copy
 - Source/Destination
 - Region index
- Draw or dispatch
 - Descriptor: binding, type
 - Attachment: index and type
 - Bound buffer: vertex or index
- Image Barriers
 - Transitions: oldLayout, newLayout
 - Image Subresource
- Render pass
 - Transitions: oldLayout, newLayout
 - load/store/resolve: attachment index, type, and operation

Simple Sync Val Demo Part II

- Using the Vulkan-Samples

Frequently Found Issues

- Missing pipeline stage for memory barriers
 - Stages are not logically extended for memory access barriers.
- Invalid stage/access pairs
 - Yields no barrier
- Relying on implicit subpass dependencies with `VK_SUBPASS_EXTERNAL`
 - Implicit Barriers are essential no-ops
- Missing memory dependencies with Image Layout Transitions
 - Transitions are full subresource range *read/write* operations.
- Missing stage/access scopes for load operations
 - Color and depth/stencil are done by different stage/access.

Debugging Strategies

- **Stage/Access Completeness In Barriers**
 - By inspection. Simplest approach.
 - Look at read/write barrier information vs. usage vs. existing barriers
- **Localizing w/ Access info**
 - `prior_usage` and (prior) command data can help identify access which hazard with current
 - `(read|write)_barrier`
- **Hazards vs. Prior Image Layout Transitions**
 - Find the last layout transition (barrier or subpass dependency)
 - Usually a missing `dstStageMask` or `dstAccessMask`
- **Hazards at Image Layout Transitions**
 - Missing `srcStageMask` or `srcAccessMask` for the affected resource

Debugging Strategies (cont'd)

- Hazards between buffer and/or image resource uses
 - Write-target to/from Read-target (pre/post transfer, attachment-to/from-texture)
 - Application needs to track the changing roles of a resource
 - Look for where these role changes happen, and check the synchronization operations
- Method of bisection
 - Insert “big hammer” Barriers/Subpass Dependency
 - Stage: `VK_PIPELINE_STAGE_ALL_COMMANDS_BIT`
(`VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT` inside render pass)
 - Access: `VK_ACCESS_MEMORY_READ_BIT | VK_ACCESS_MEMORY_WRITE_BIT`
 - If error disappears, error source is prior to Barrier, else it is after
 - Move barrier to determine source of hazard
 - Be sure to remove after
- Be sure and check Core/Parameter Validation as you change code

After the presentation

Questions or presentation feedback?

Contact John Zulauf: @jzulauf on the Vulkan KhronosDevs slack channel

- <https://app.slack.com/client/TDMDFS87M/CDTJ9BELF>
- Or sign up for the KhronosDevs slack channel here: <https://www.khronos.org/news/permalink/khronos-developer-slack-5bfc62eb261764.20435008>

Report bugs or make feature requests here:

<https://github.com/KhronosGroup/Vulkan-ValidationLayers>

For more information:

- <https://www.lunarg.com/news-insights/white-papers/guide-to-vulkan-synchronization-validation/>
- <https://www.lunarg.com/news-insights/white-papers/vulkan-synchronization2-validation/>

Vulkan Synchronization -- SIGGRAPH 2021

Slides are available at:

<https://www.lunarg.com/news-insights/white-papers/vulkan-synchronization-siggraph-2021/>

Q & A



Backup

Hello race condition! (sync2)

```
vkCmdCopyBuffer(cb, buffer_a, buffer_b, 1, &region);
```

```
auto buffer_barrier = lvl_init_struct<VkBufferMemoryBarrier2KHR>()  
buffer_barrier.srcStageMask = VK_PIPELINE_STAGE_TRANSFER_BIT;  
buffer_barrier.srcAccessMask = VK_ACCESS_TRANSFER_READ_BIT;  
buffer_barrier.dstStageMask = VK_PIPELINE_STAGE_TRANSFER_BIT;  
buffer_barrier.dstAccessMask = VK_ACCESS_TRANSFER_WRITE_BIT;  
buffer_barrier.buffer = buffer_a;
```

```
auto dep_info = lvl_init_struct<VkDependencyInfoKHR>();  
dep_info.bufferMemoryBarrierCount = 1;  
dep_info.pBufferMemoryBarriers = &buffer_barrier;  
vkCmdPipelineBarrier2KHR(cb, &dep_info);
```

```
vkCmdCopyBuffer(cb, buffer_c, buffer_a, 1, &region);
```

Events

- “Split” pipeline barriers
 - Can allow for more parallelism on the GPU
 - CmdSetEvent() is *first scope* (src)
 - CmdWaitEvents() is the *second scope* (dst)
- Hard to use (and infrequently used)
 - Only partially fixed by synchronization2
- Race conditions between Set, Reset, Wait commands
 - Require semaphore or pipeline barrier using the ALL_COMMANDS to avoid
 - “To fix correctly we need Timeline Events that work like Timeline Semaphores”
- May be signalled by Host
 - Sync2 VK_EVENT_CREATE_DEVICE_ONLY_BIT_KHR disables this

Events - changes sync2

```
void vkCmdSetEvent(  
    VkCommandBuffer commandBuffer,  
    VkEvent event,  
    VkPipelineStageFlags stageMask); /* src stage */
```

```
void vkCmdResetEvent(  
    VkCommandBuffer commandBuffer,  
    VkEvent event,  
    VkPipelineStageFlags stageMask); /* src stage */
```

```
void vkCmdWaitEvents(  
    VkCommandBuffer commandBuffer,  
    uint32_t eventCount,  
    const VkEvent* pEvents,  
    VkPipelineStageFlags srcStageMask,  
    VkPipelineStageFlags dstStageMask,  
    /* barrier lists omitted */);
```

- vkCmdSetEvent() only has enough information to set up execution dependencies.
- Driver cannot schedule work for memory dependencies until vkCmdWaitEvent() is called!

```
void vkCmdSetEvent2KHR(  
    VkCommandBuffer commandBuffer,  
    VkEvent event,  
    const VkDependencyInfoKHR* pDependencyInfo);
```

vkCmdResetEvent2KHR() same as vkCmdResetEvent()

```
void vkCmdWaitEvents2KHR(  
    VkCommandBuffer commandBuffer,  
    uint32_t eventCount,  
    const VkEvent* pEvents,  
    const VkDependencyInfoKHR* pDependencyInfos);
```

- vkCmdSetEvent2KHR() dependency info must match what is passed to vkCmdWaitEvent2KHR()
- each pDependencyInfo[i] has the barriers for pEvents[i]
 - In original function this was unclear