VULKAN MEMORY MANAGEMENT

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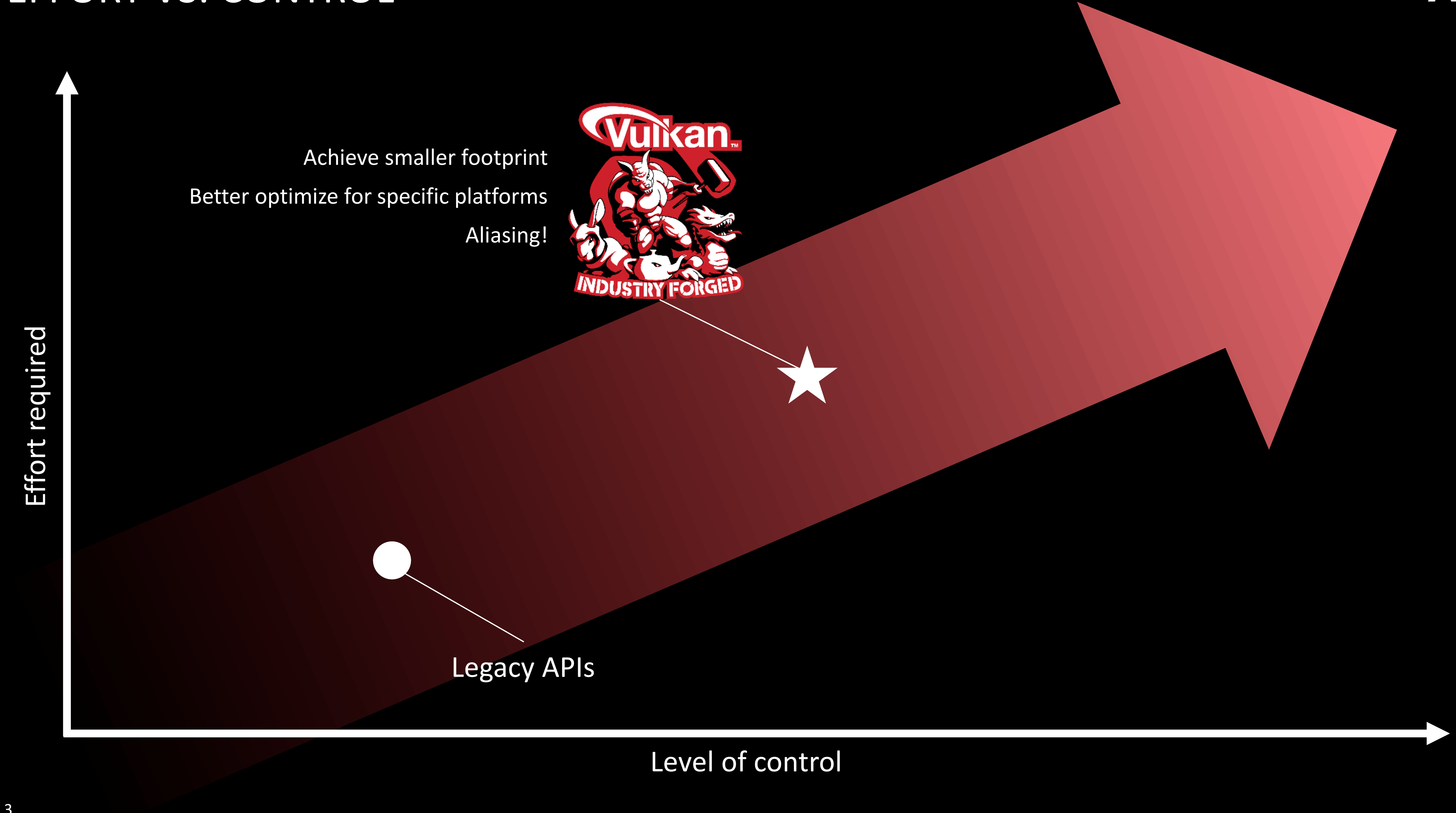
AGENDA

- Heaps & Types
- Tips & Tricks
- The VMA Library
- Conclusion

EFFORT VS. CONTROL



Achieve smaller footprint

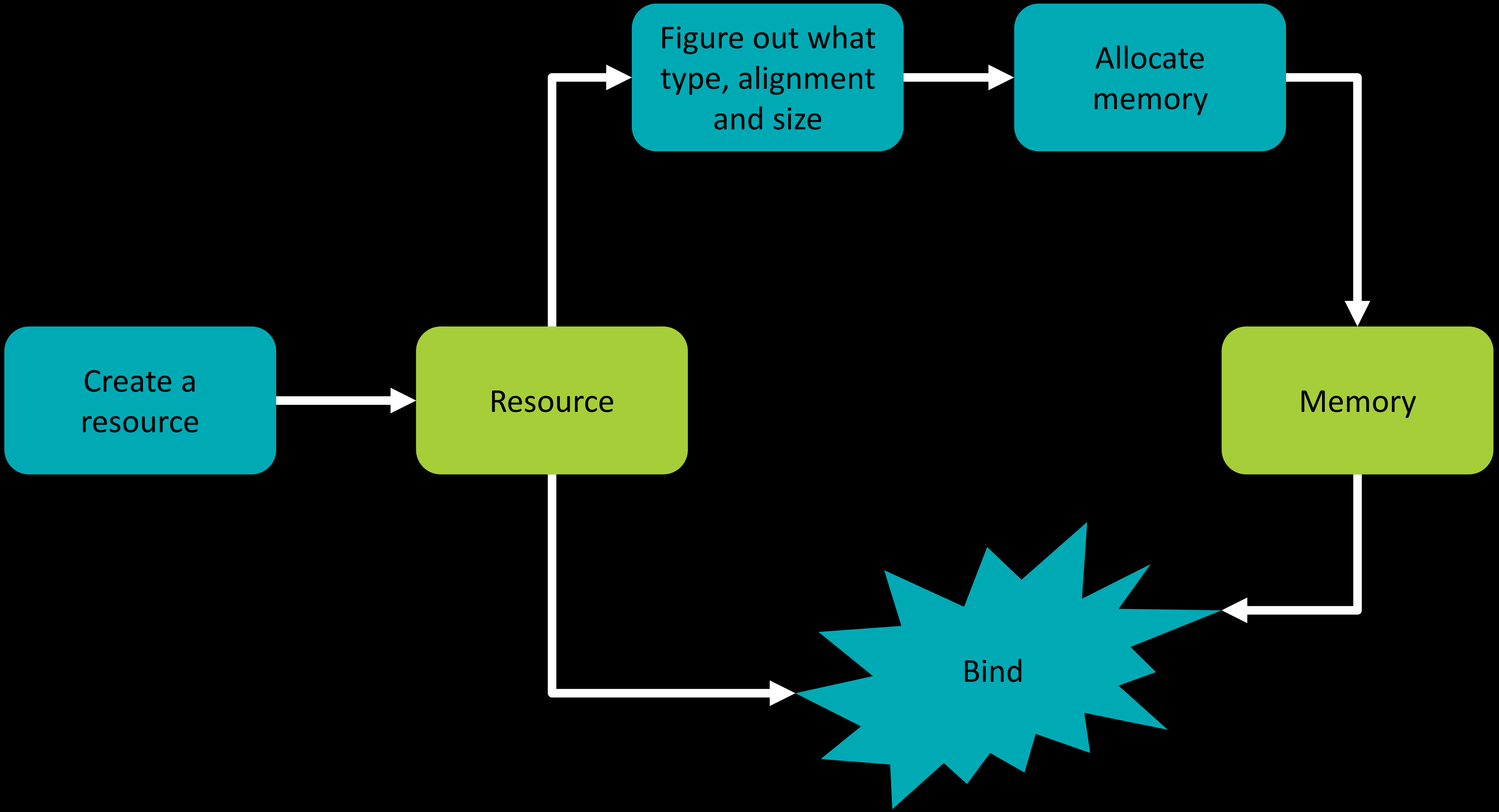
Better optimize for specific platforms

Aliasing!

Legacy APIs

Heaps & Types

YOUR MISSION, JIM…



ALLOCATING SOME MEMORY

```
VkResult vkAllocateMemory(
    VkDevice                        device,
    const VkMemoryAllocateInfo*     pAllocateInfo,
    const VkAllocationCallbacks*    pAllocator,
    VkDeviceMemory*                 pMemory);
```

```
typedef struct VkMemoryAllocateInfo {
    VkStructureType    sType;
    const void*        pNext;
    VkDeviceSize       allocationSize;
    uint32_t           memoryTypeIndex;
} VkMemoryAllocateInfo;
```

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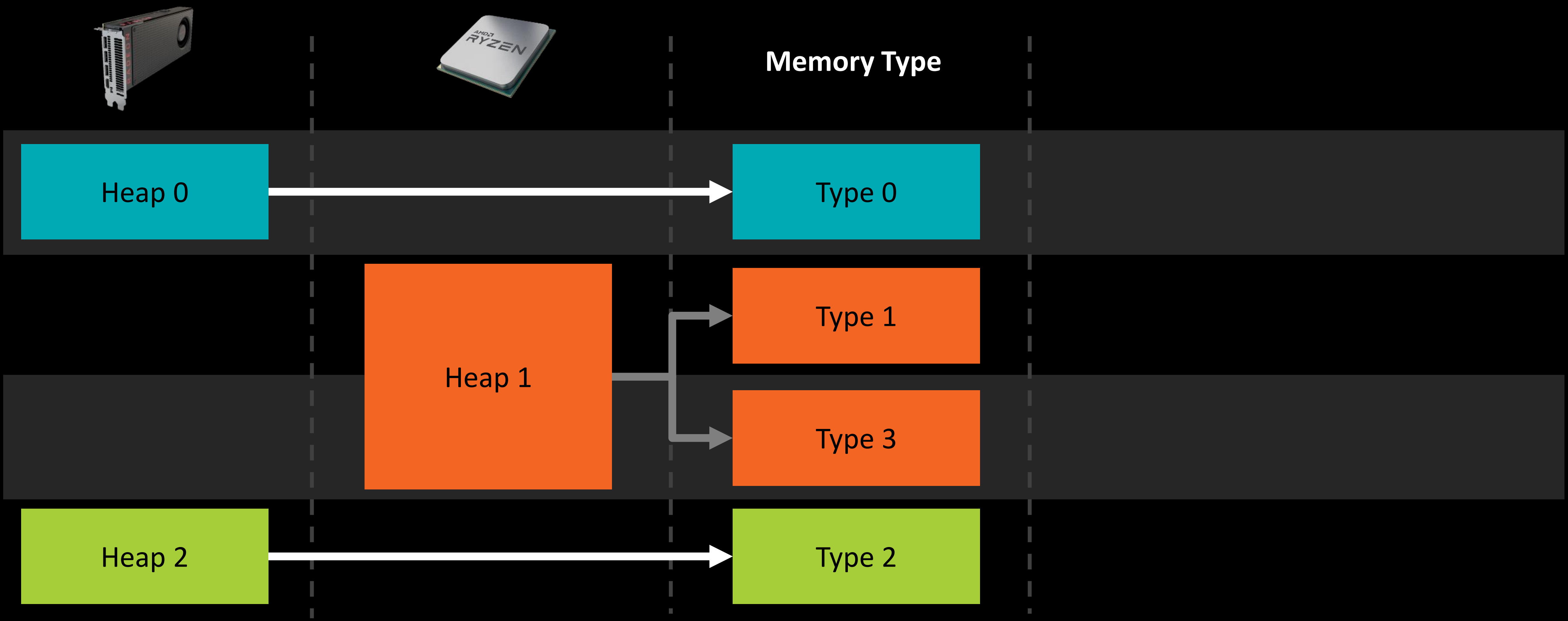
    VkDeviceSize       allocationSize;
    uint32_t           memoryTypeIndex;
} VkMemoryAllocateInfo;
```

```
vkGetPhysicalDeviceMemoryProperties(
    VkPhysicalDevice                    physicalDevice,
    VkPhysicalDeviceMemoryProperties*   pMemoryProperties);
```

```
typedef struct VkPhysicalDeviceMemoryProperties {
    uint32_t        memoryTypeCount;
    VkMemoryType    memoryTypes[VK_MAX_MEMORY_TYPES];
    uint32_t        memoryHeapCount;
    VkMemoryHeap    memoryHeaps[VK_MAX_MEMORY_HEAPS];
} VkPhysicalDeviceMemoryProperties;
```

MEMORY TYPES VS. HEAPS

(AMD RX VEGA 64)



Memory Type

Heap 0

Type 0

Heap 1

Type 1

Type 3

Heap 2

Type 2

MEMORY TYPES CHEAT SHEET

(AMD RX VEGA 64)

Memory Type	🛢	👁	$	🛢	👁	$	R	W	R	W	Size
0	✓	✓	✓	✗	✗	✗	🐇	🐇	✗	✗	Most of VRAM
1	✗	✓	✓	✓	✓	✗	🐢	🐢	🐢	🐇	
2	✓	✓	✓	✗	✓	✗	🐇	🐇	🐢	🐇	Fixed 256MiB
3	✗	✓	✓	✓	✓	✓	🐢	🐢	🐇	🐇	

🛢 - Storage 👁 - Visible $ - Cached

🐇 - Fast 🐢 - Slow

MEMORY TYPES CHEAT SHEET

(AMD RX VEGA 64)

Memory Type	🛢	👁	$	🛢	👁	$	R	W	R	W	Size
0	✓	[illegible]	✓	✗	✗	✗	🐇	🐇	✗	✗	Most of VRAM
1	✗	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	🐢	🐢	🐇	
2	✓	✓	✓	✗	✓	✗	🐇	🐇	🐢	🐇	Fixed 256MiB
3	✗	✓	✓	✓	✓	✓	🐢	🐢	🐇	🐇	

Maps to
VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT in
VkMemoryPropertyFlagBits.

🛢 - Storage 👁 - Visible $ - Cached

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MEMORY TYPES CHEAT SHEET

(AMD RX VEGA 64)

Maps to
VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT and
VK_MEMORY_PROPERTY_CACHED_BIT respectively.

Memory Type	🛢	👁	$	🛢	👁	$	R	W	R	W	Size
0	✓	✓	✓	✗	✗	✗	🐇	🐇	✗	✗	Most of VRAM
1	✗	✓	✓	✓	✓	✗	🐢	🐢	🐢	🐇	
2	✓	✓	✓	✗	✓	✗	🐇	🐇	🐢	🐇	Fixed 256MiB
3	✗	✓	✓	✓	✓	✓	🐢	🐢	🐇	🐇	

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2	✓	✓	✓	✗	✓	✗	🐇	🐇	🐢	🐇	Fixed 256MiB
3	✗	✓	✓	✓	✓	✓	🐢	🐢	🐇	🐇	

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MEMORY TYPES CHEAT SHEET

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1	✗	✓	✓	✓	✓	✗	🐢	🐢	🐢	🐇	
						✗	🐇	🐇	🐢	🐇	Fixed 256MiB
	✗	✓	✓	✓	✓	✓	🐢	🐢	🐇	🐇	

Okay, not *that* bad since we benefit from GPU caches, but certainly worse than just reading from `DEVICE_LOCAL`.

🛢 - Storage 👁 - Visible $ - Cached

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MEMORY TYPES CHEAT SHEET

(AMD RX VEGA 64)

Memory Type	🛢	👁	$	🛢	👁	$				
0	✓	✓	✓	✗	✗	✗				
1	✗	✓	✓	✓	✓	✗	🐢	🐢	🐢	🐇
2	✓	✓	✓	✗	✓	✗	🐇	🐇	🐢	🐇
3	✗	✓	✓	✓	✓	✓				

Fixed 256MiB

On current GPUs & drivers, PC Windows® everything that is HOST_VISIBLE is also marked COHERENT.

On other architectures you may need:
vkInvalidateMappedMemoryRanges before reads
and
vkFlushMappedMemoryRanges after writes.

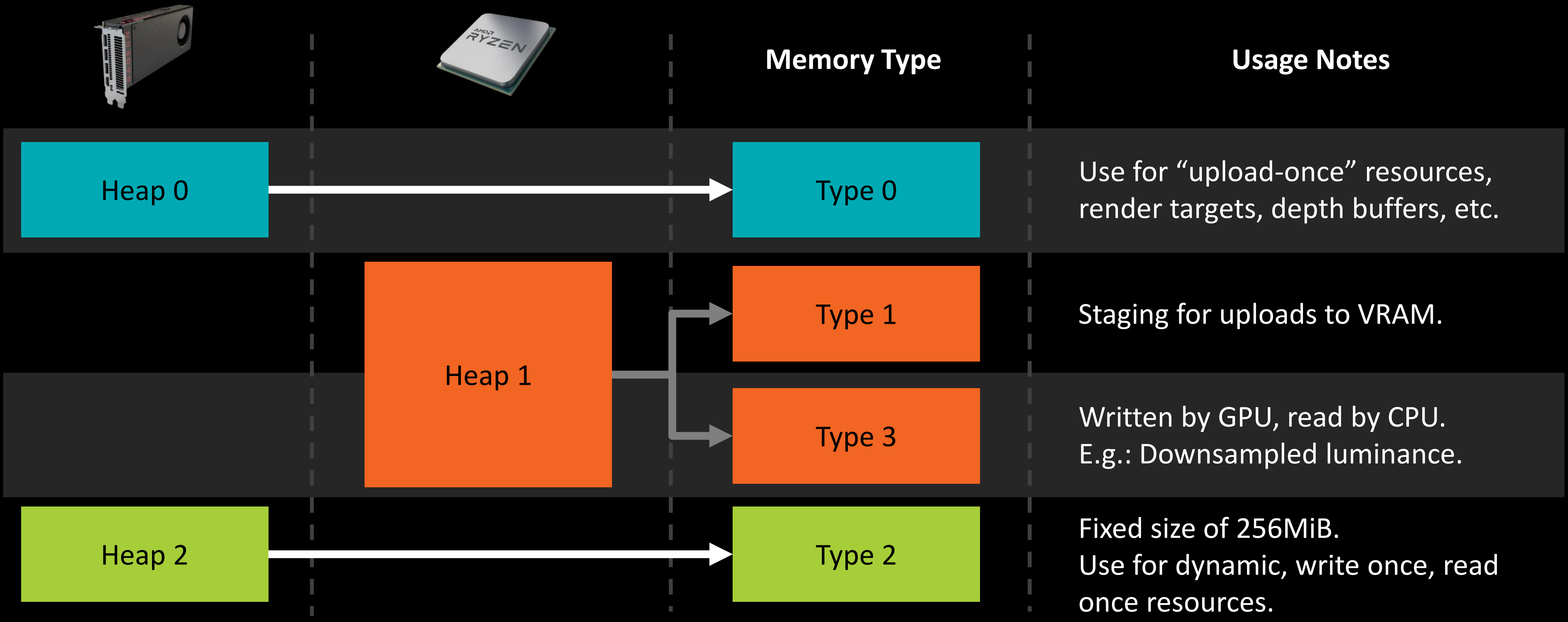
BEWARE: Unmapping **won't** do this for you!

🛢 - Storage 👁 - Visible $ - Cached

🐇 - Fast 🐢 - Slow

MEMORY TYPES VS. HEAPS

(AMD RX VEGA 64)



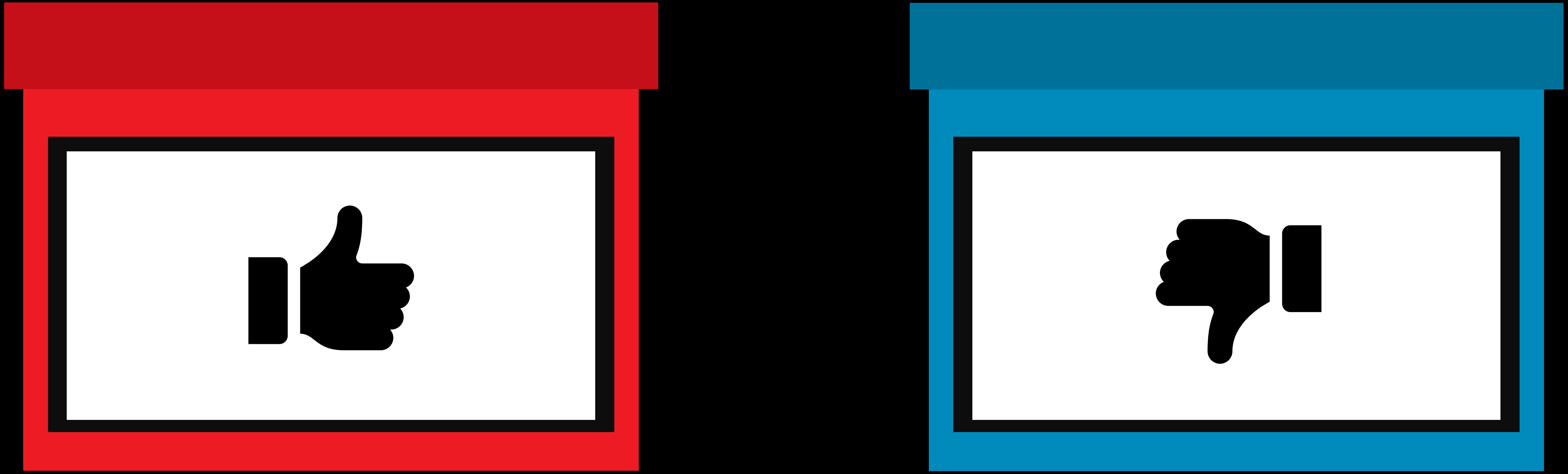
		Memory Type	Usage Notes
Heap 0		Type 0	Use for “upload-once” resources, render targets, depth buffers, etc.
	Heap 1	Type 1	Staging for uploads to VRAM.
		Type 3	Written by GPU, read by CPU. E.g.: Downsampled luminance.
Heap 2		Type 2	Fixed size of 256MiB. Use for dynamic, write once, read once resources.

WARNING!

- Not a good idea to hardcode the memory type indices.
  - Driver may change in future
  - May be different on other/newer hardware
  - Magic numbers
- Query the info using `vkGetPhysicalDeviceMemoryProperties`.
- Map to engine-specific enums.

ALLOCATION STRATEGY

- Would you make a unique allocation from the heap for each structure in a C/C++ program?



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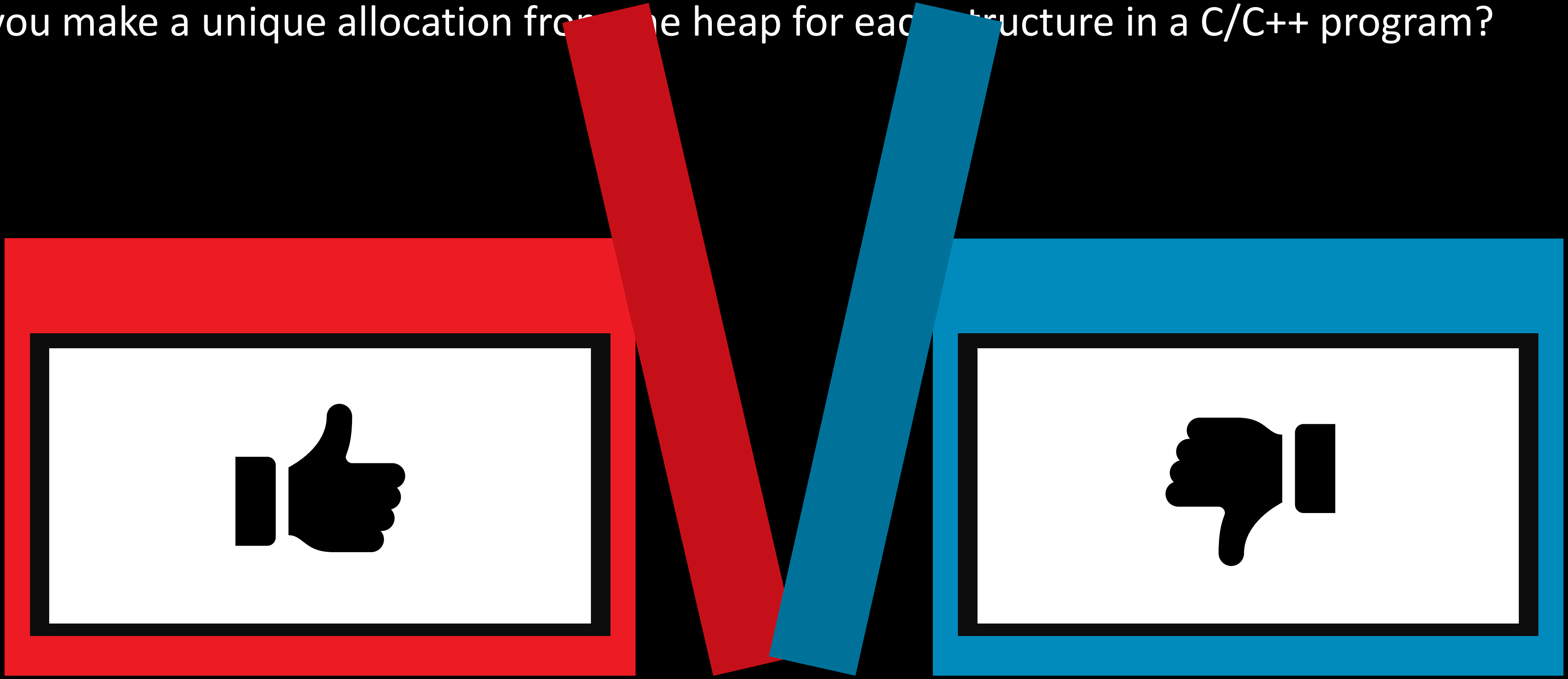
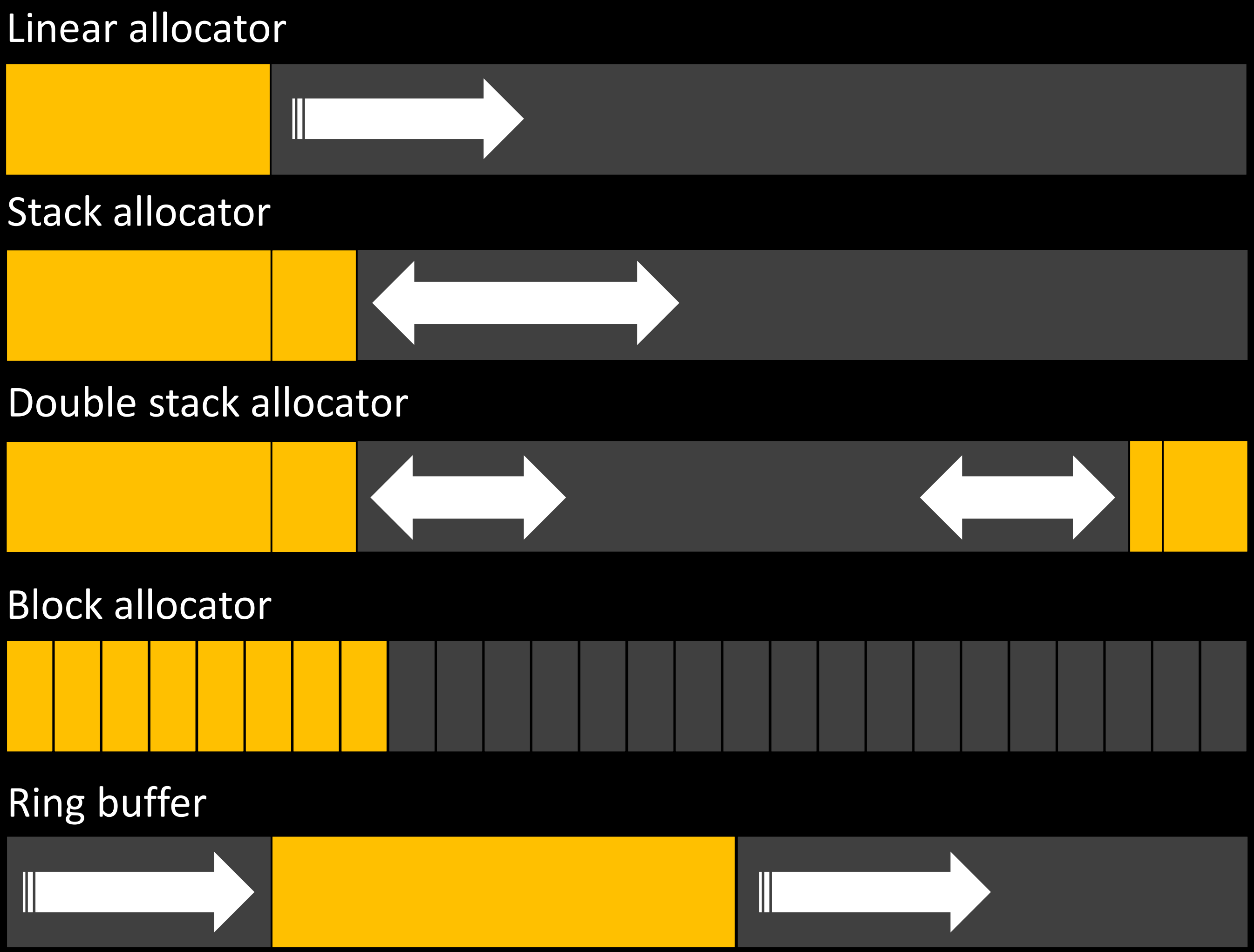


ALLOCATION STRATEGY

- Same idea on GPU for similar reasons:
  - Fragmentation
  - Performance
  - Data locality
  - Personal sanity

- Allocate reasonably large chunks of memory (256MiB).
  - Just 16 allocations fills 4GiB of VRAM.
  - Good balance between flexibility and performance.
    - On Windows®7 Vulkan memory allocations have larger overhead.
- Sub-allocate the memory for resources from these blocks.

ALLOCATION STRATEGY



Linear allocator

Stack allocator

Double stack allocator

Block allocator

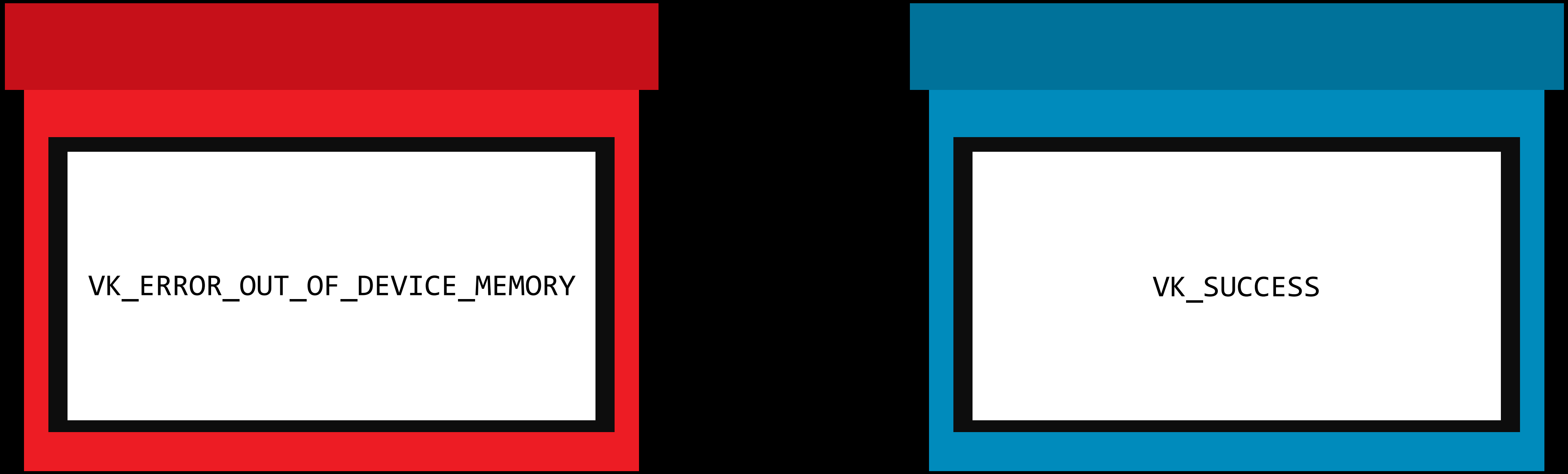
Ring buffer

🟨 - Used memory ⬛ - Free memory

Tips & Tricks

OVER-SUBSCRIPTION

- What happens when you run out of DEVICE_LOCAL memory (VRAM) and try vkAllocateMemory?



VK_ERROR_OUT_OF_DEVICE_MEMORY

VK_SUCCESS

OVER-SUBSCRIPTION

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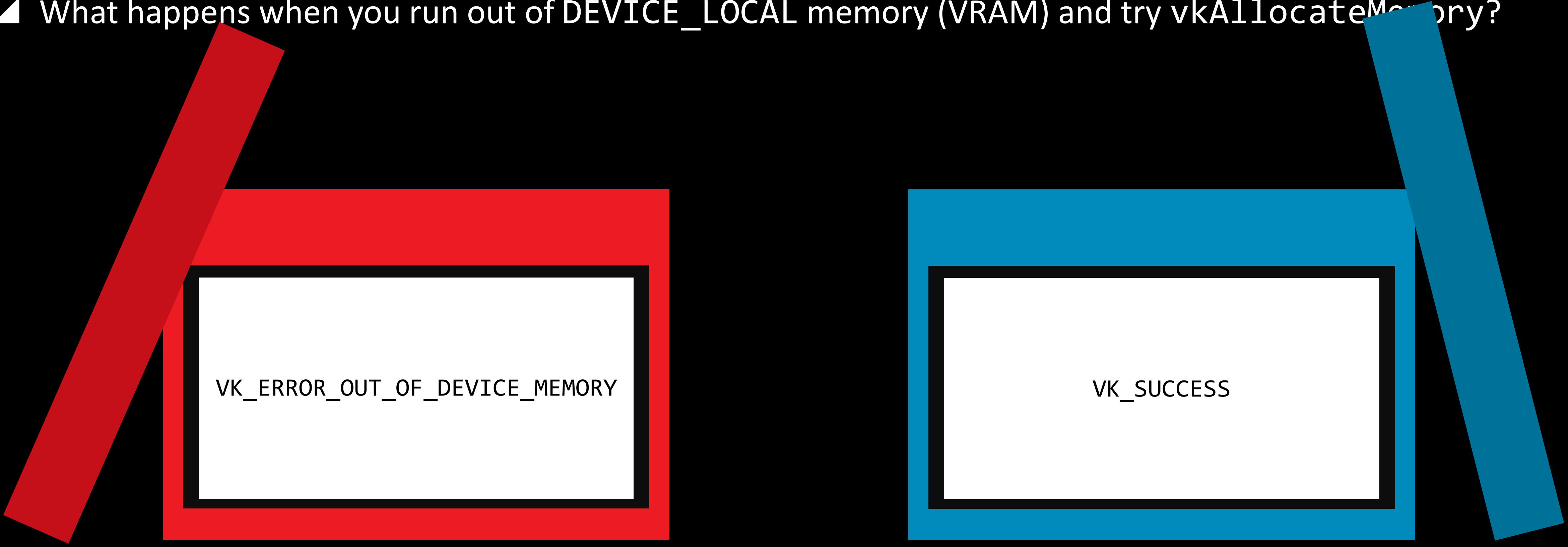


VK_ERROR_OUT_OF_DEVICE_MEMORY

VK_SUCCESS

OVER-SUBSCRIPTION

VK_ERROR_OUT_OF_DEVICE_MEMORY

- Allocation fails.
- Application must handle out-of-memory conditions.
- Out-of-memory potentially changes per driver/hardware.

OVER-SUBSCRIPTION

VK_SUCCESS

- Allocation succeeds.
- Some blocks are silently migrated to system memory.

- Why would you want this?
  - Useful for development purposes - Artists don’t always stick to budgets.
  - Some of your blocks might get paged anyway (you’re not alone on the machine).
  - Application doesn’t have to handle out-of-memory.

- Accessing blocks migrated to system memory can degrade GPU performance.

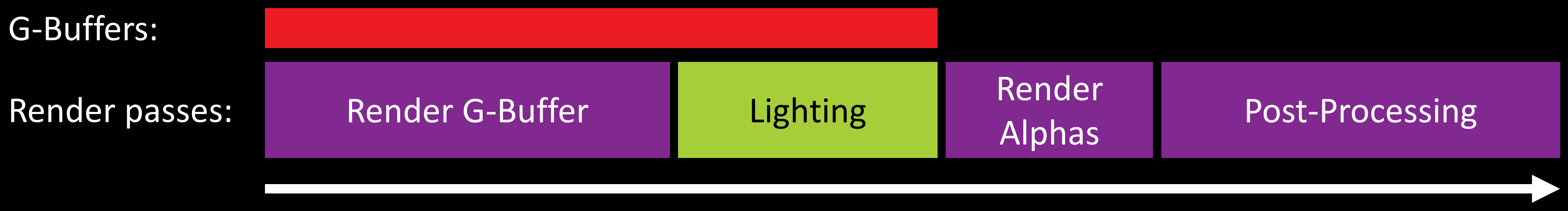
OVER-SUBSCRIPTION

- No way is exposed to control residency manually.
- No way is exposed to query the used/free memory.
- To make things worse, there are other implicit resources which need memory too:
  - Swap chains
  - Command buffers
  - Descriptors
  - Shaders / PSOs
  - Query results
- Use `VkMemoryHeap::size` then apply some “informed adjustments”:

Flags	Hack
DEVICE_LOCAL	VkMemoryHeap::size * 0.8f
DEVICE_LOCAL | HOST_VISIBLE	VkMemoryHeap::size * 0.66f

ALIASING

- As resolutions get larger, render targets follow suit.
- As many resources are transient, aliasing can be a solution to keep render target/UAV memory in check.



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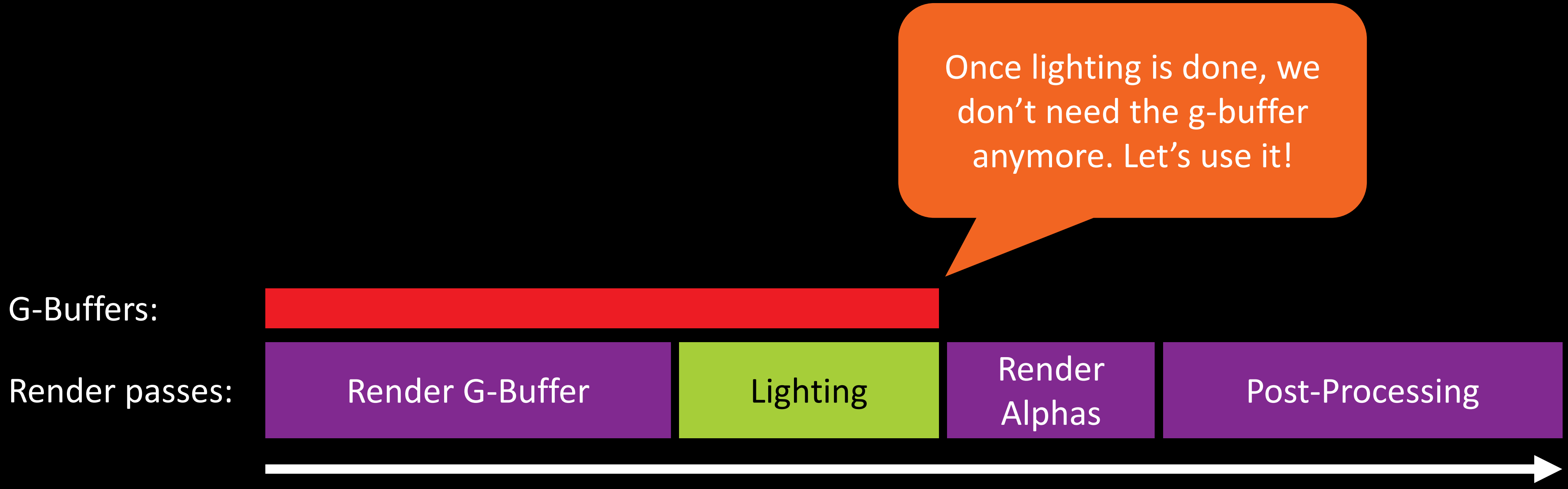

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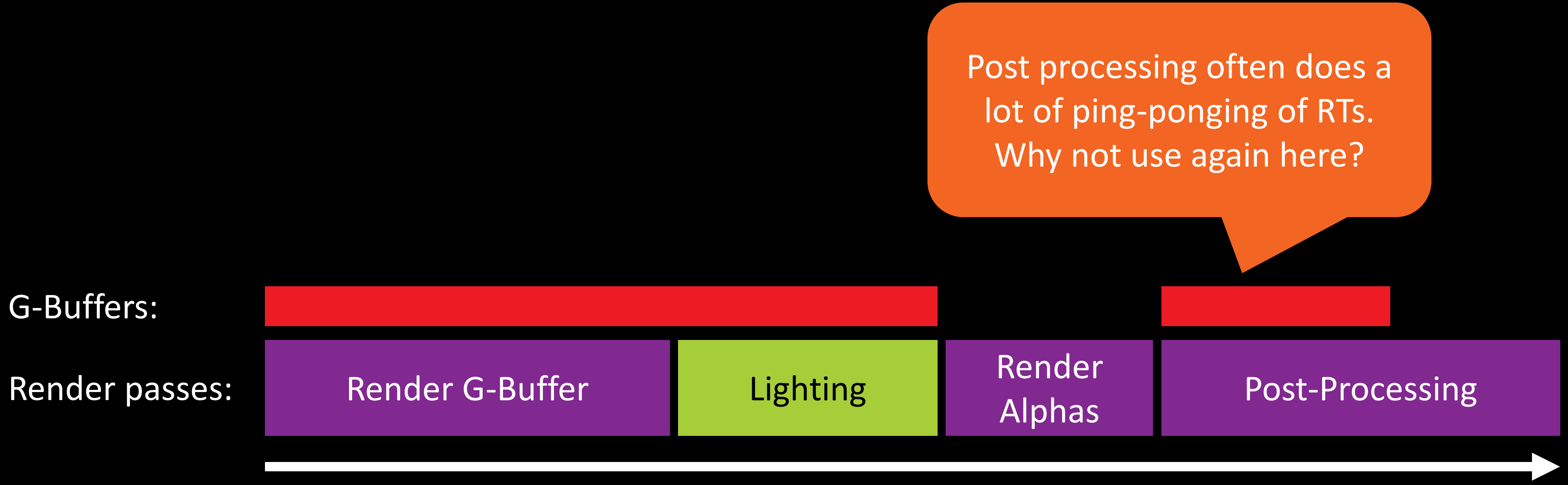
Post processing often does a lot of ping-ponging of RTs. Why not use again here?
G-Buffers:
Render passes:
Render G-Buffer
Lighting
Render Alphas
Post-Processing

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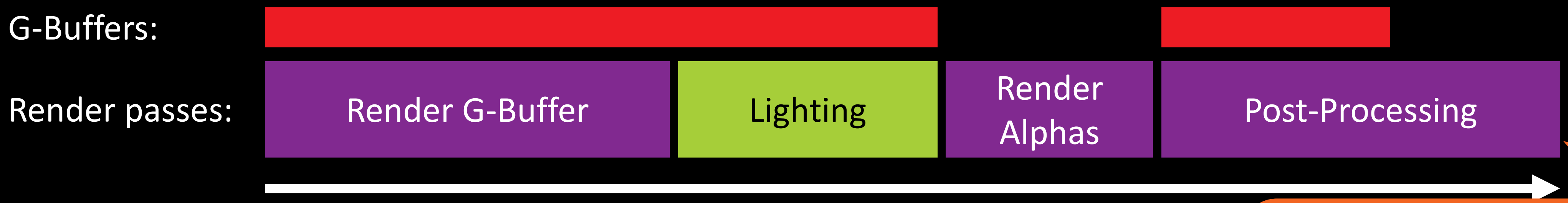
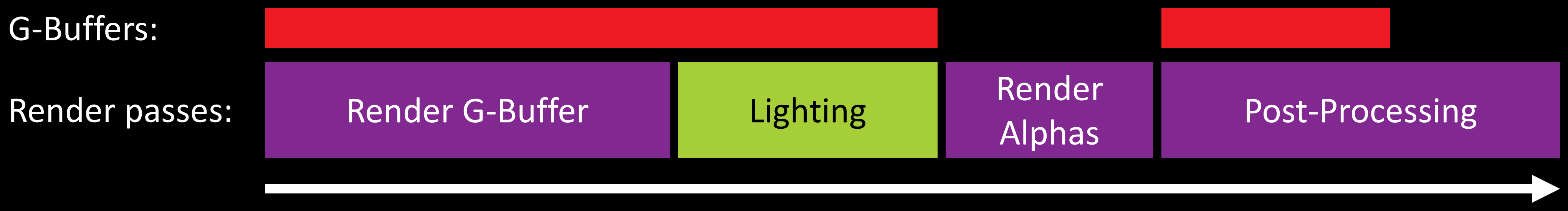


Maybe some compute shader in here needs a nice big UAV for something. No need to allocate, alias with a Render target.

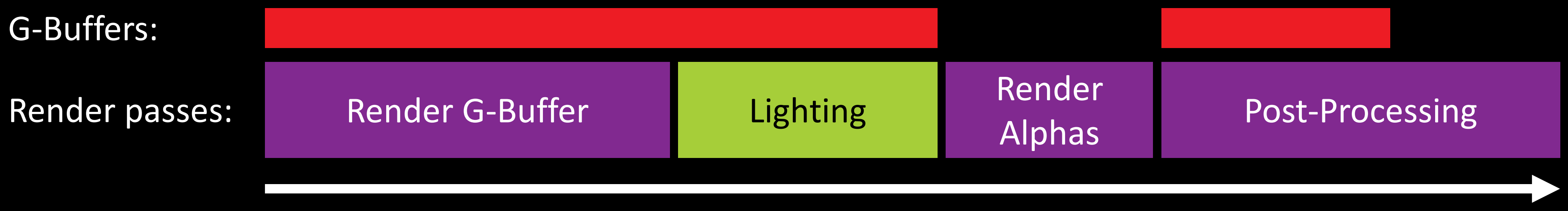
ALIASING

- As resolutions get larger, render targets follow suit.
- As many resources are transient, aliasing can be a solution to keep render target/UAV memory in check.
- For second, third, etc. use of aliased resource best to assume it contains garbage.



ALIASING

- As resolutions get larger, render targets follow suit.
- As many resources are transient, aliasing can be a solution to keep render target/UAV memory in check.
- For second, third, etc. use of aliased resource best to assume it contains garbage.
- >50% memory saved in some titles [ODonnell17].



TRANSFERS

- Which queue should you use to copy a resource from host memory to DEVICE_LOCAL memory?

VK_QUEUE_TRANSFER_BIT

VK_QUEUE_COMPUTE_BIT

TRANSFERS

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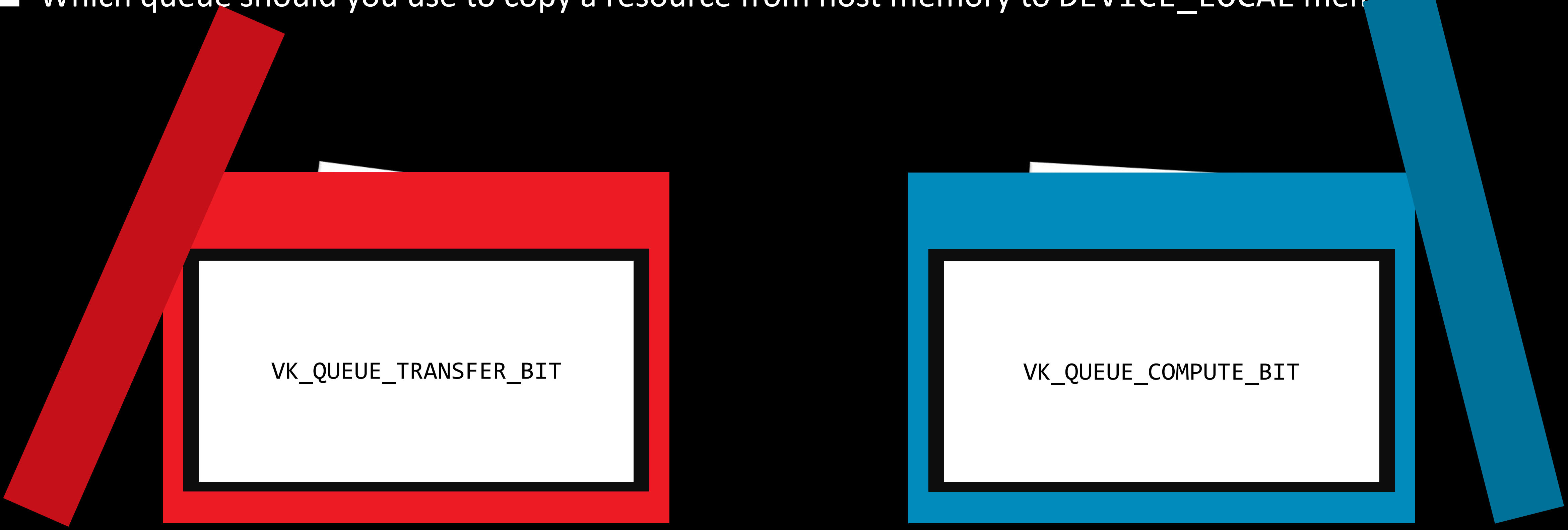


VK_QUEUE_TRANSFER_BIT

VK_QUEUE_COMPUTE_BIT

TRANSFERS

- The transfer queue is great.
  - DMA hardware that you drive asynchronously – doesn’t touch other queues.
  - The fastest way to copy across PCIe bus.
- Kick DMAs off as early as you can, waaaaaay before you need them on graphics/compute queue.
- Some hardware even has 2 transfer queues.
  - E.g. RX 580

TRANSFERS

- What about `DEVICE_LOCAL` to `DEVICE_LOCAL` copies?
  - Choice not as clear cut.
  - Peak transfer rates of Graphics/Compute are probably faster, but it “clogs up” GPU.
  - If you can pipeline the copies, transfer queue can still be a win.

- Use the queue to defrag your allocations.
  - Copy to a new address.
  - Next frame, update descriptor.

- General rules of thumb:
  - Need it now? Graphics/Compute queue.
  - It can wait? Transfer queue.
  - Respect granularity of the queue. Full sub-resource is fine.
  - Measure, measure, measure. Queue semaphores can cost you.

MAPPING

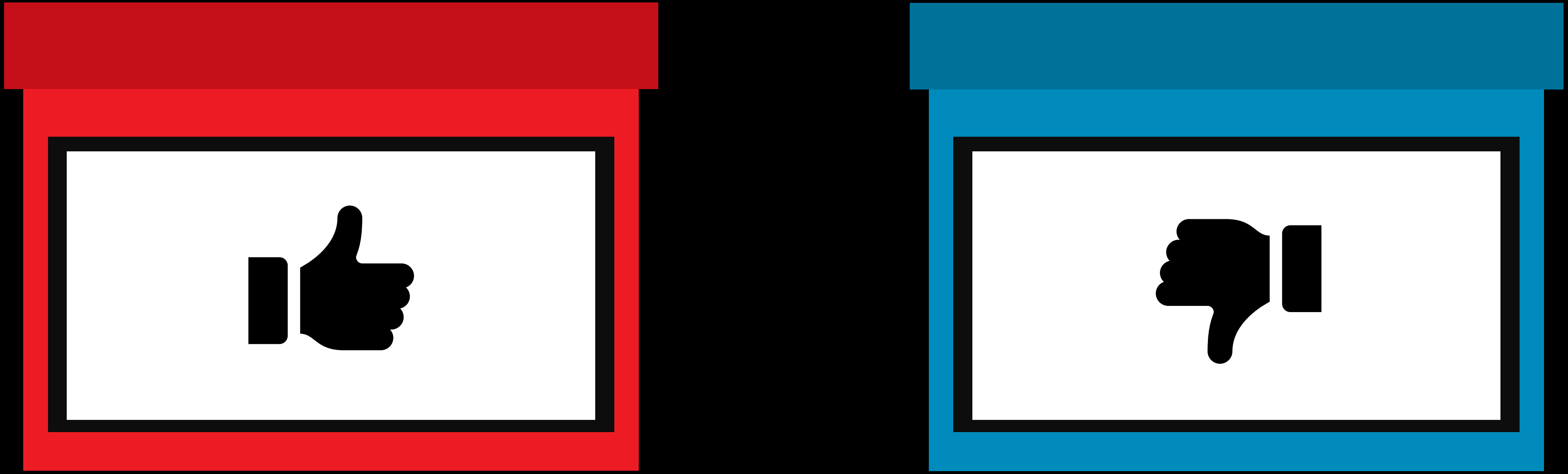
- Having your entire memory block persistently mapped is generally OK.
  - No longer any need to unmap before using stuff on GPU!
- Exceptions:
  - AMD, Windows® version < 10. Blocks of `DEVICE_LOCAL` that are also `HOST_VISIBLE` (type 2) that are still mapped at the time of `Submit` or `Present` will be migrated to system memory.
  - Keeping many large memory blocks mapped may impact stability/performance of debugging tools.

RESOURCE CREATION

- Avoid the following Vulkan ‘lazy-mode’ features:
  - `VK_IMAGE_LAYOUT_GENERAL`
    - Prefer to transition to appropriate `VK_IMAGE_LAYOUT_*_OPTIMAL` state.
  - `VK_SHARING_MODE_CONCURRENT` on render targets or depth buffers
    - It nobbles DCC compression.
    - Go for `VK_SHARING_MODE_EXCLUSIVE` and do explicit queue family ownership barriers.
  - `VK_IMAGE_TILING_LINEAR`
    - `VK_IMAGE_TILING_OPTIMAL` is more… well… optimal.
    - You can always copy to a buffer to de-tile things.
  - Setting too many usage bits on your stuff.
    - Great way to confuse drivers into flushing more caches, and draining the GPU.

RESOURCE SIZES

- Querying the size required for two identical resources always returns the exact same size?



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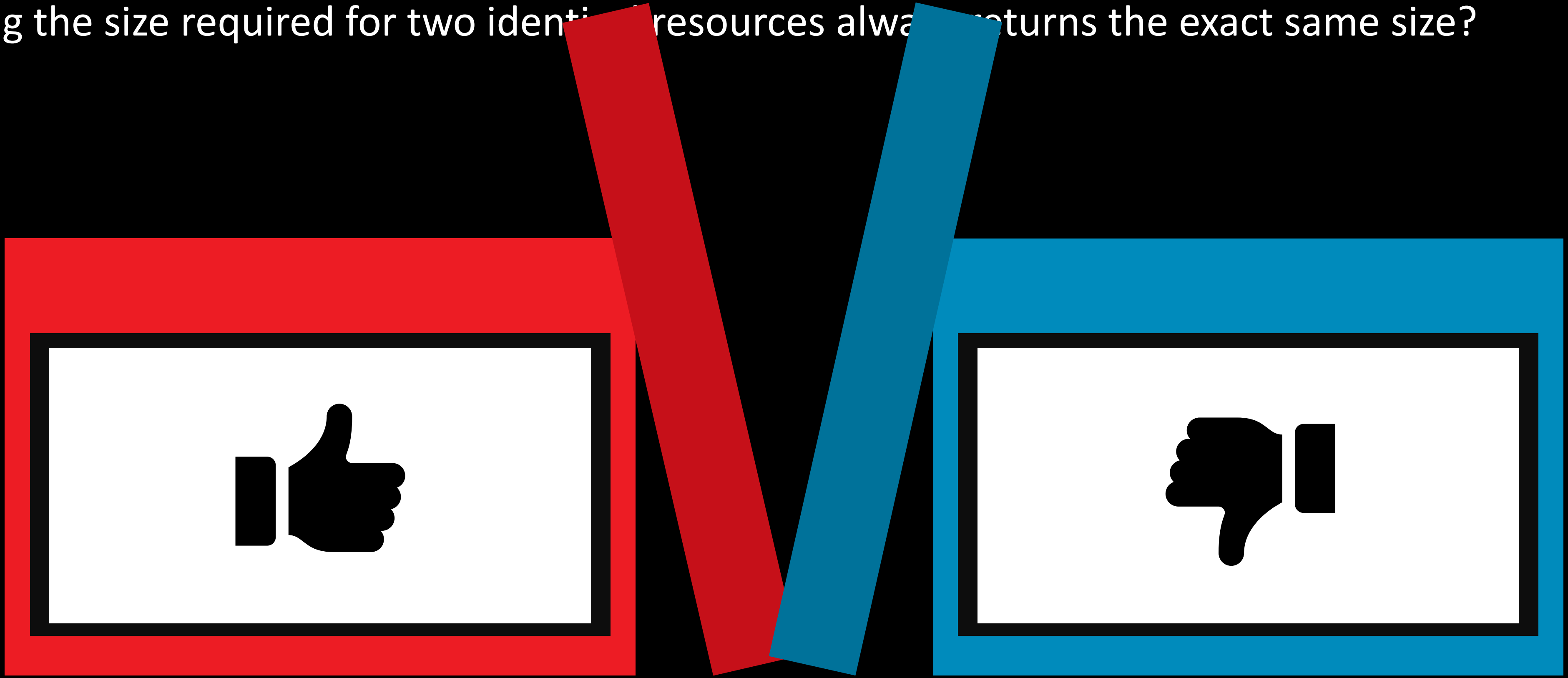


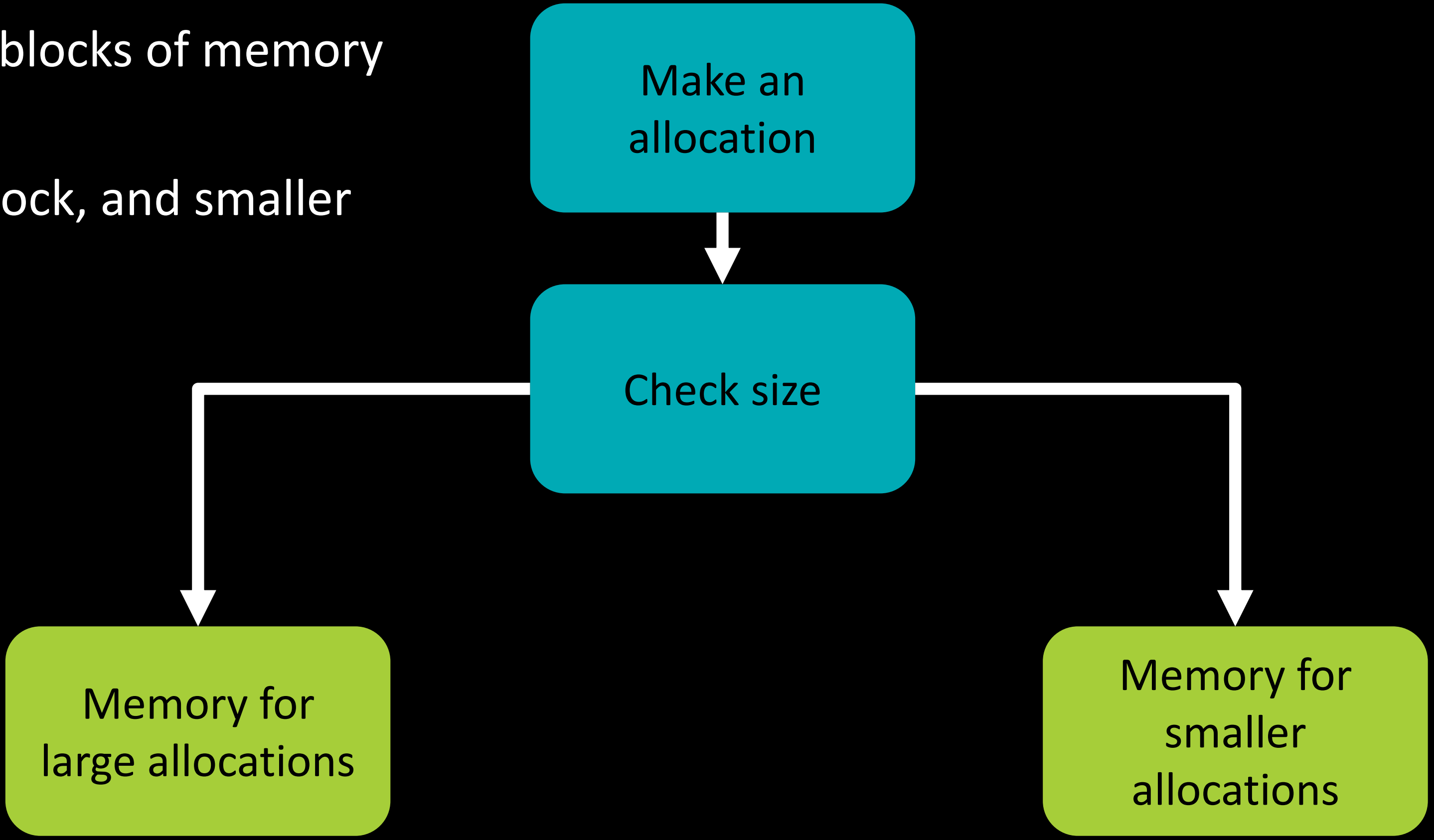
RESOURCE SIZES

- Memory requirements - e.g. size - can vary for different, similar resources.
  - Same format, width, height and mip-levels.
- Not just the preserve of ‘spec wonks’. This *really* happens - don’t cache the results when querying sizes.
- Make sure you query *each* resource for it’s specific requirements.

SMALL BLOCK ALLOCATIONS

DON'T GET FRAGGED!

- Mixing large and small allocations carelessly can be painful.
- Consider routing allocations to different blocks of memory based on their sizes.
- Pool larger allocations together in one block, and smaller allocations together in another one.



The Vulkan Memory Allocator

VULKAN MEMORY ALLOCATOR (VMA)

- Free. Open source. MIT license. Single header.
  - https://github.com/GPUOpen-LibrariesAndSDKs/VulkanMemoryAllocator
- Simple, C99 interface. Same style as Vulkan™.
- Battle tested, already getting some love in the community.

VULKAN MEMORY ALLOCATOR (VMA)

- Function that help to choose the correct and optimal memory type based on intended usage.
- Functions that allocate memory blocks, reserve and return parts of them to the user.
- Allocation tracker, look at used/unused, and fragmentation.
- Respects alignment and buffer/image granularity.

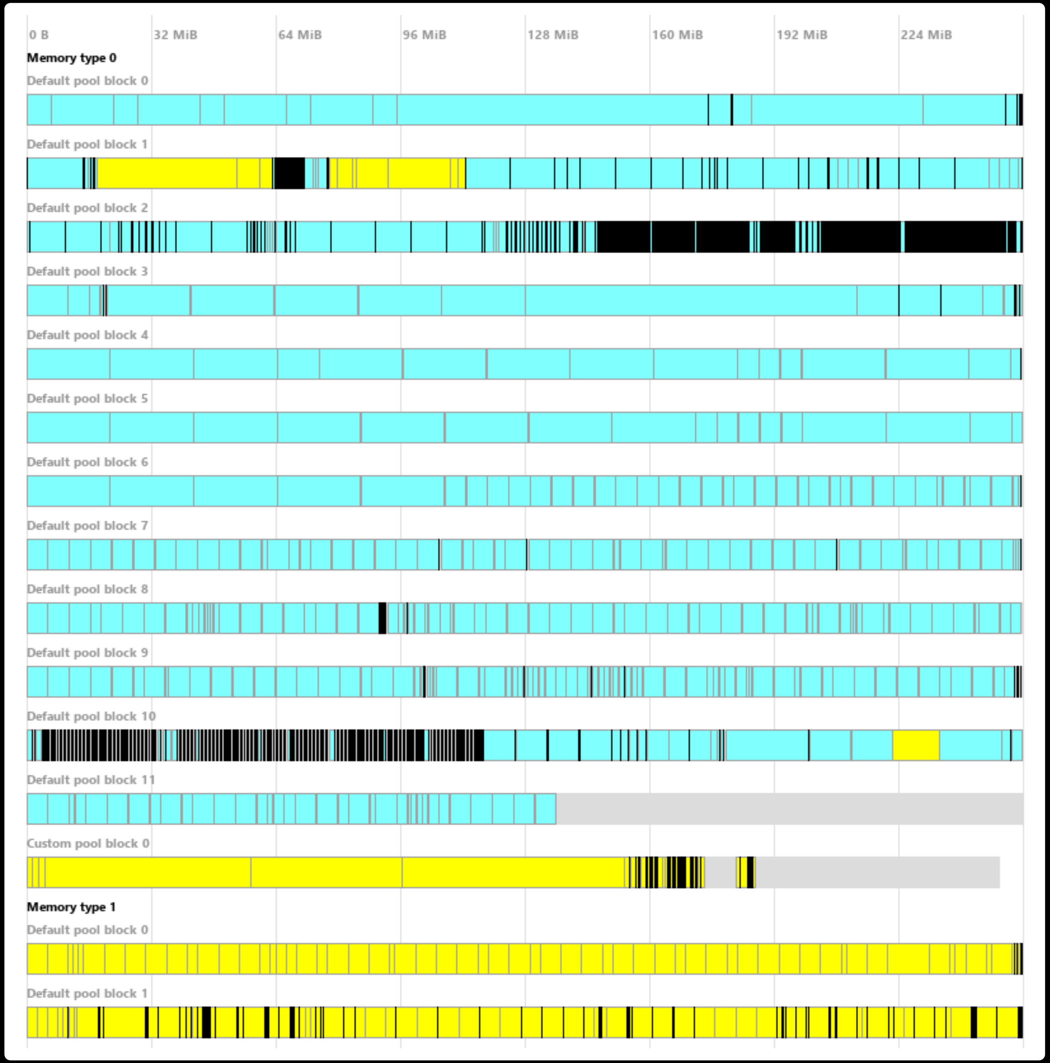
```
VkBufferCreateInfo bufferInfo = { VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO };
bufferInfo.size = 65536;
bufferInfo.usage = VK_BUFFER_USAGE_VERTEX_BUFFER_BIT | VK_BUFFER_USAGE_TRANSFER_DST_BIT;

VmaAllocationCreateInfo allocInfo = {};
allocInfo.usage = VMA_MEMORY_USAGE_GPU_ONLY;

VkBuffer buffer;
VmaAllocation allocation;
vmaCreateBuffer(allocator, &bufferInfo, &allocInfo, &buffer, &allocation, NULL);
```

VULKAN MEMORY ALLOCATOR (VMA)

- Even has some tooling!
- VMA can dump allocator state to JSON.
- Python script generates PNG file which shows the allocator contents.



CONCLUSION

- Vulkan is lower-level and requires explicit memory management.
  - Creating resources is a multi-stage process.
  - Former driver magic is now under your control.
- You need to deal with differences between GPUs.
- By following good practices you can achieve optimal performance on any GPU.
- Vulkan Memory Allocator (VMA) is battle-tested and can really help a lot.

SPECIAL THANKS

- Adam Sawicki
- Dominik Baumeister
- Lou Kramer
- Matthäus G. Chajdas
- Rys Sommefeldt
- Timothy Lottes
- Nicolas Thibieroz
- Alon Or-Bach

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  https://www.gdcvault.com/play/1024612/FrameGraph-Extensible-Rendering-Architecture-in

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