Vulkan®

# DEVELOPER DAY

## Memory management in Vulkan

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UBISOFT

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# Agenda

- Introduction
- Memory Types
- Tips & Tricks
- Libraries
- Conclusions


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# Introduction

# The challenge

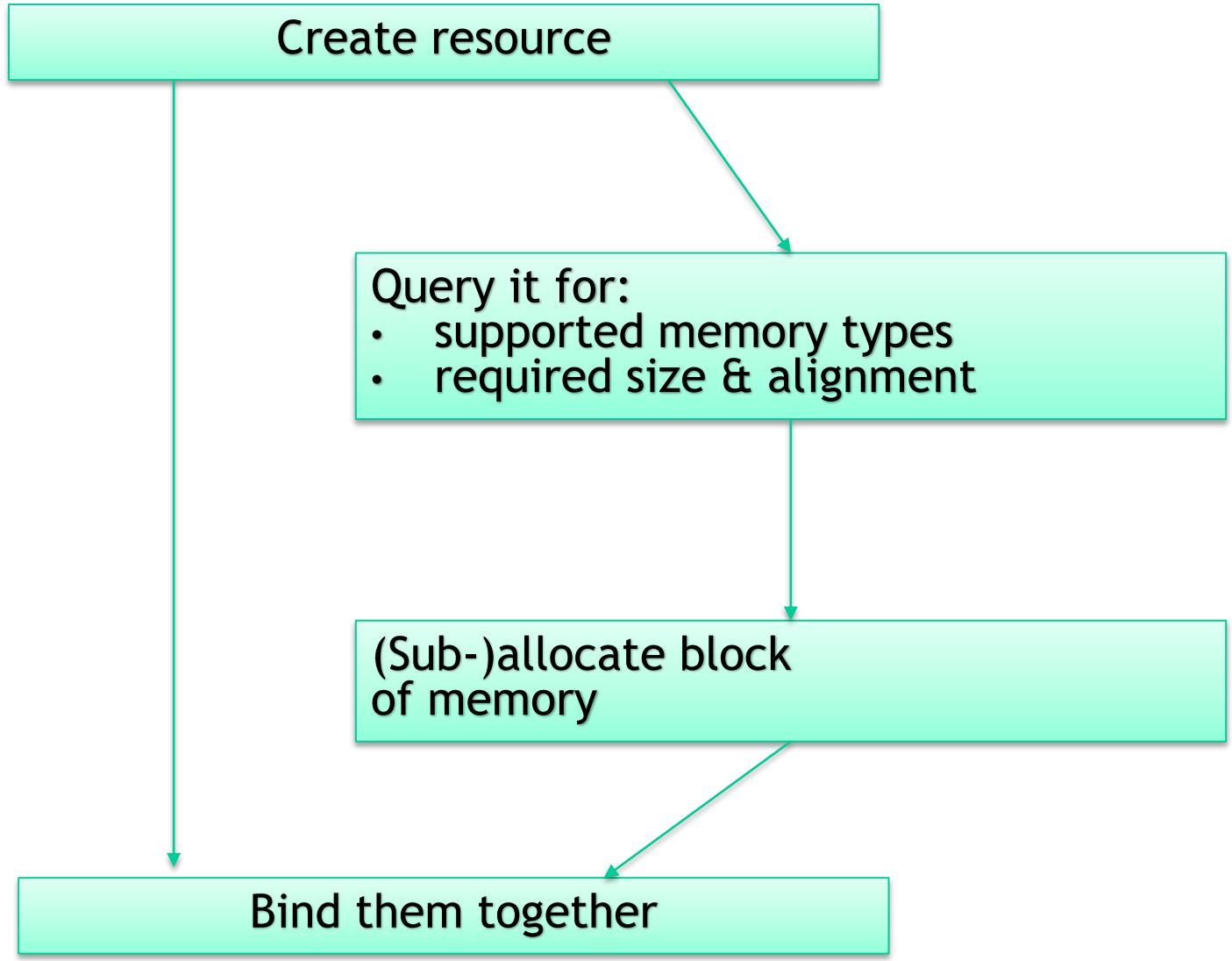
- **Previous generation APIs (OpenGL™, DirectX® 11) manage memory automatically.**
  - You create a resource (e.g. texture, constant buffer), backing memory is allocated automatically.

```
ID3D11Texture2D* pTexture;
pD3D11Device->CreateTexture2D(&desc, nullptr, &pTexture);
```

- **Vulkan™ is lower level, requires explicit memory management.**

# The challenge

- It is now your responsibility to:



# Advantages

Explicit memory management makes it possible to:

- Achieve a smaller memory footprint.
- Better optimize for specific platforms.
- Alias (overlap) transient resources.

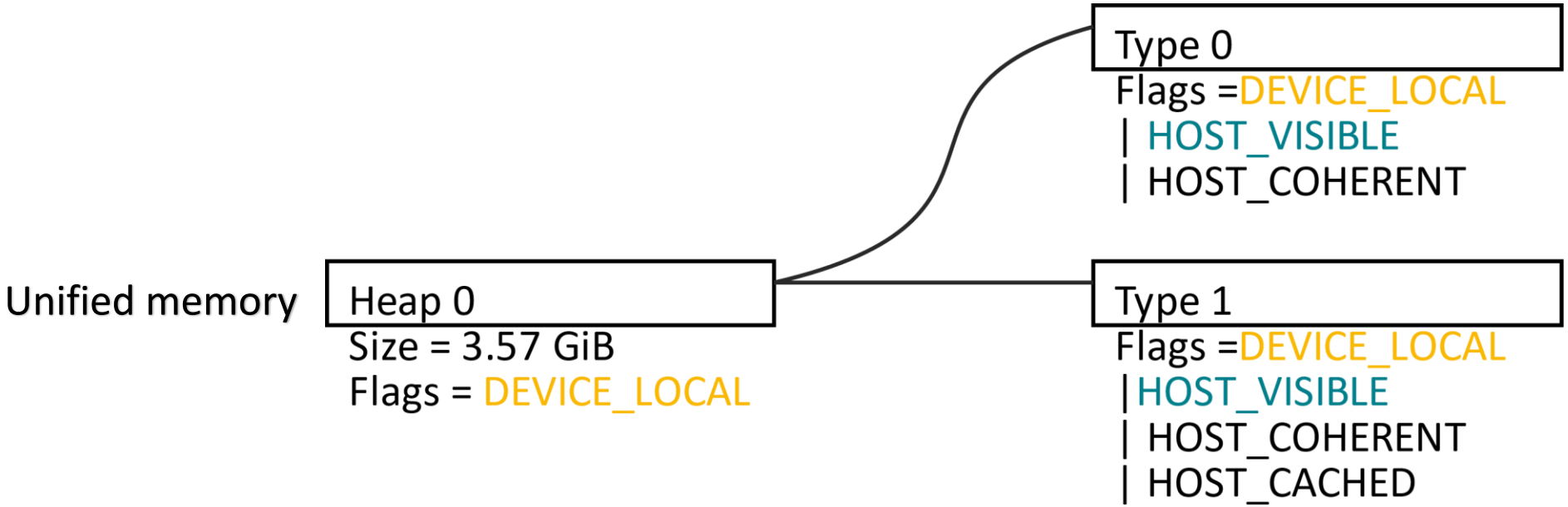
# Memory Types

# Memory Heaps and types

- Heaps: Physical memory (e.g. VRAM, DRAM).
- Types: Describes the properties of the memory and which heap to use.

# Memory types: Intel

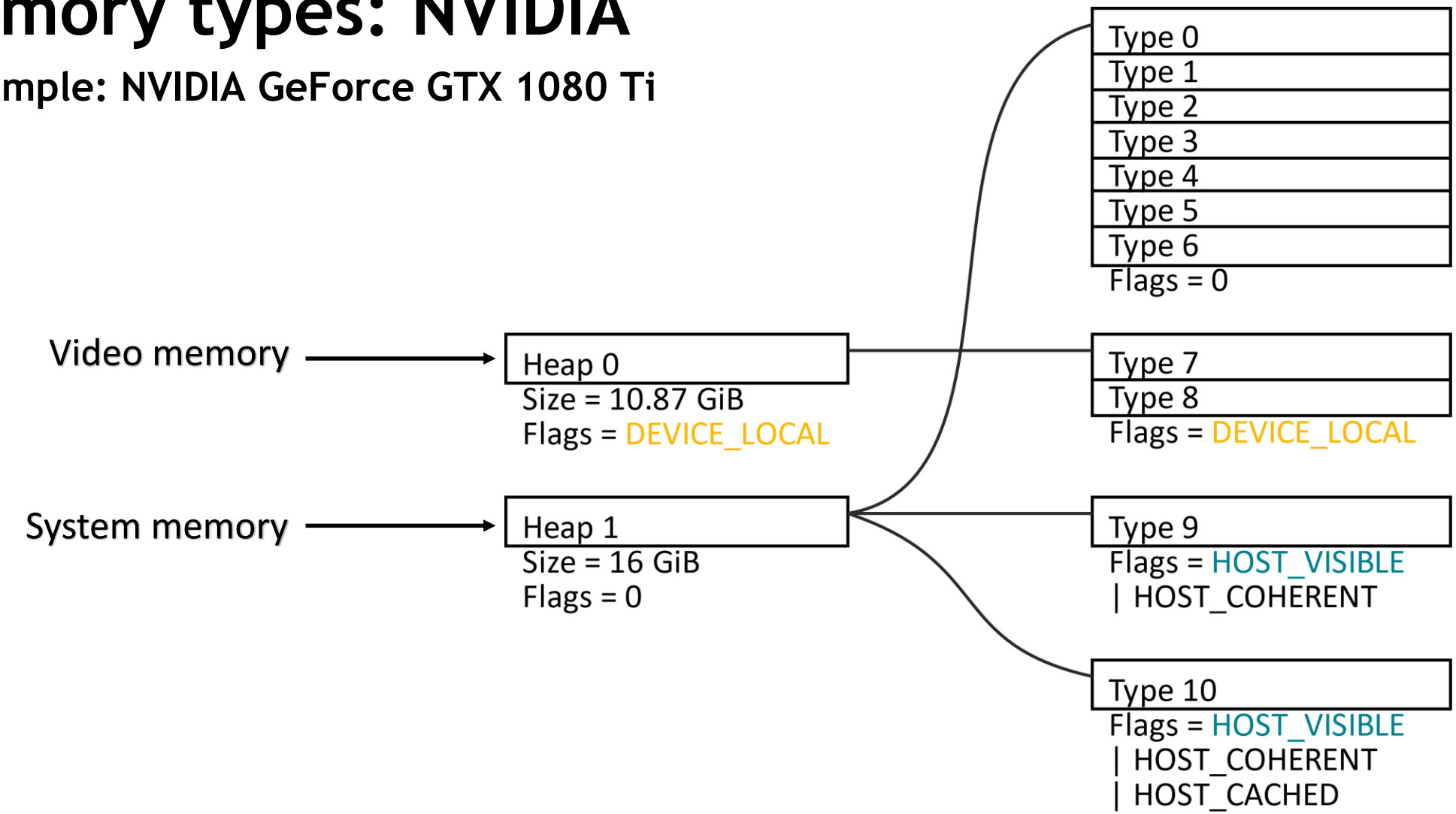
- Example: Intel Iris Plus Graphics 640



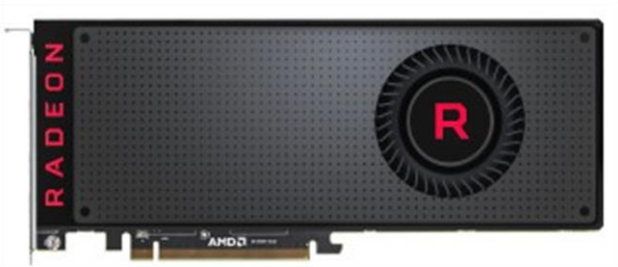
# Memory types: NVIDIA

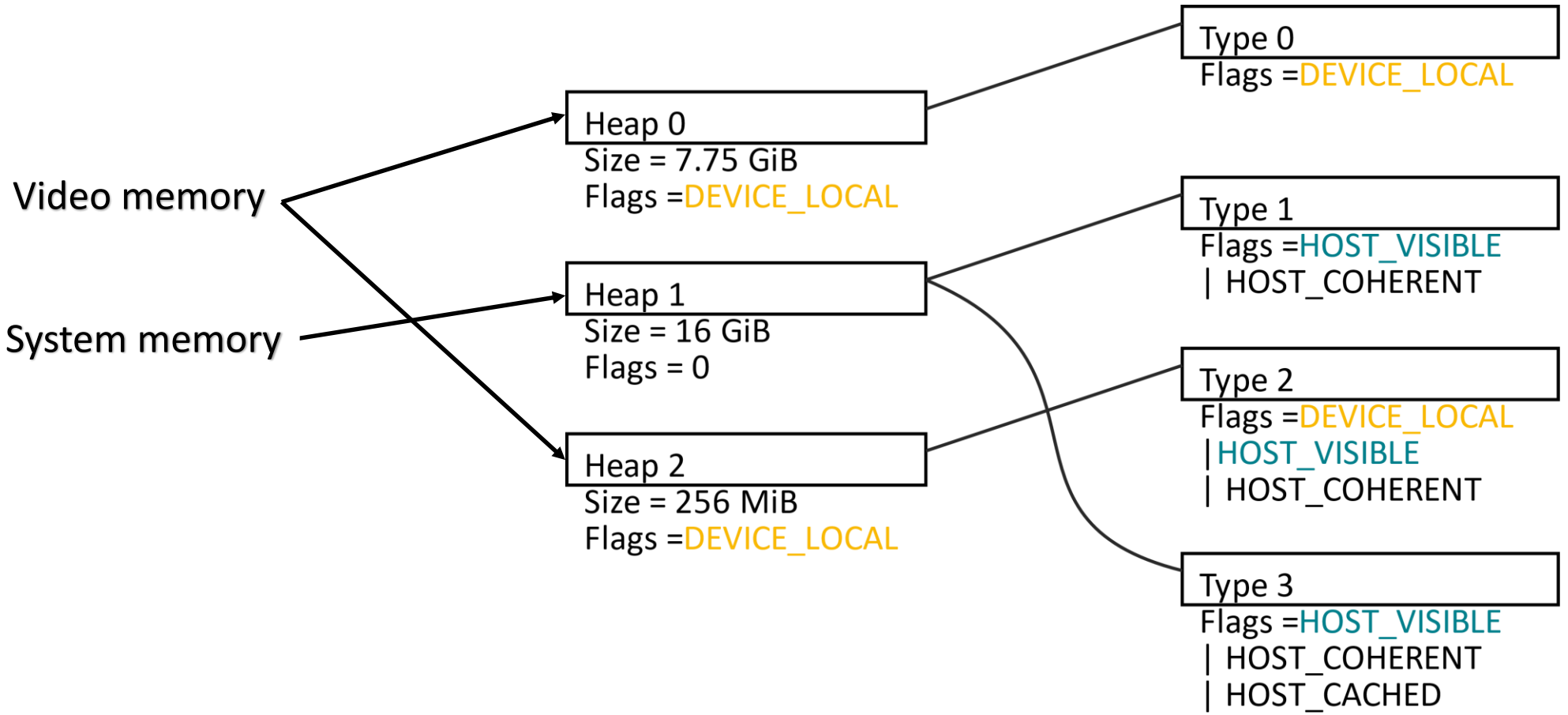
- Example: NVIDIA GeForce GTX 1080 Ti



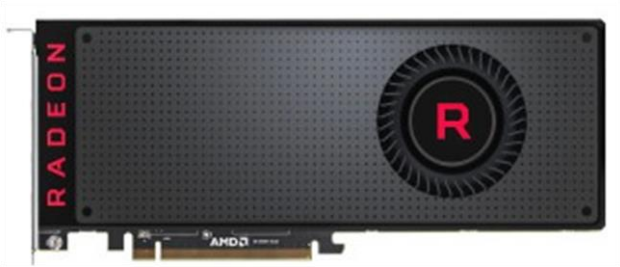
# Memory types: AMD

- Example: AMD Radeon RX Vega 64



# DEVICE_LOCAL

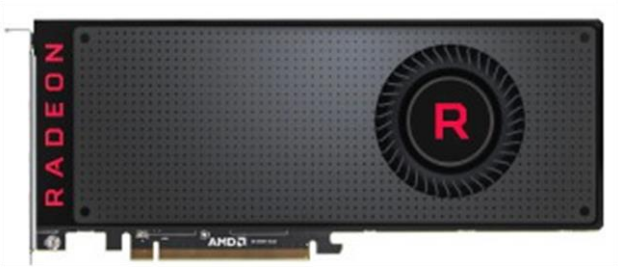



- Video memory. Fast access from GPU.
- No direct access from CPU – mapping not possible.
- Good for resources written and read frequently by GPU.
- Good for resources uploaded once (immutable) or infrequently by CPU, read frequently by GPU.

# HOST_VISIBLE


- System memory. Accessible to CPU – mapping possible.
- Access from GPU possible but slow.
- Across PCIe® bus, reads cached on GPU.
- Good for CPU-side (staging) copy of your resources – used as source of transfer.
- Data written by CPU, read once by GPU (e.g. constant buffer) may work.
  - (always measure!)
- Large data read by GPU – place here as last resort.
- Large data written and read by GPU – shouldn't ever be here.
- Hazard: Uncached. Writes may be write-combined.

# DEVICE_LOCAL + HOST_VISIBLE



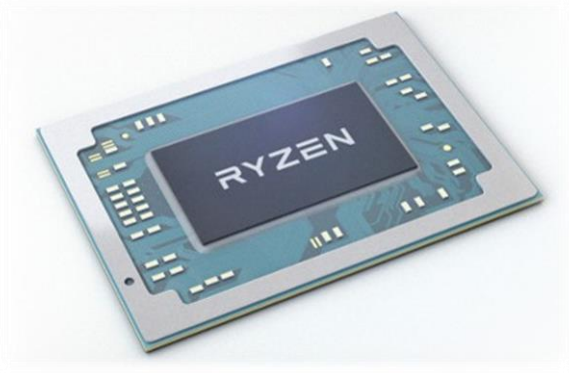

- **Special pool of video memory.**
- **Exposed on AMD only. 256 MiB.**
- **Fast access from GPU.**
- **Direct access by both CPU and GPU.**
  - You don't need to do explicit transfer.
  - Mapping possible.
- **Good for resources updated frequently by CPU (dynamic), read by GPU.**
- **Use as fallback if DEVICE_LOCAL is small and oversubscribed.**
- **Hazard: Driver will use this memory too.**
- **Hazard: Uncached. Writes may be write-combined.**

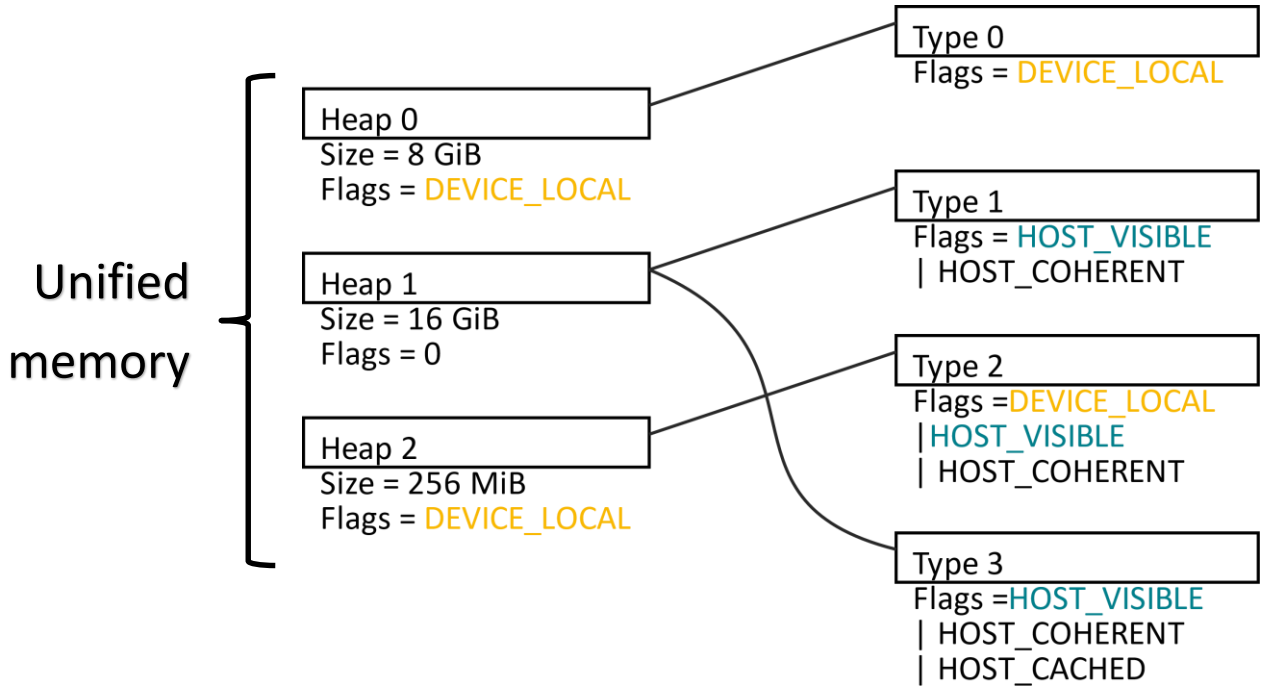
# HOST_VISIBLE + HOST_CACHED


- System memory
- CPU reads and writes cached (write-back).
- GPU access through PCIe.
- GPU reads snoop CPU cache.
- Good for resources written by GPU, read by CPU.
  - Results of computations.
- Direct access by both CPU and GPU.
  - No need to do explicit transfer.
- Use for any resources read or accessed randomly on CPU.

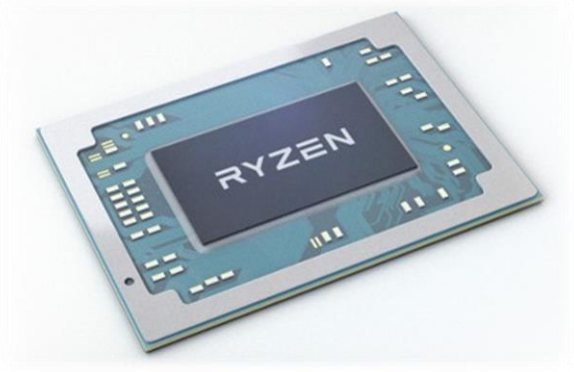
# Memory types: AMD APU

- AMD integrated graphics reports various memory types, like discrete AMD GPUs.
- Reported DEVICE_LOCAL heap can be any size,
  0 B … few GiB.



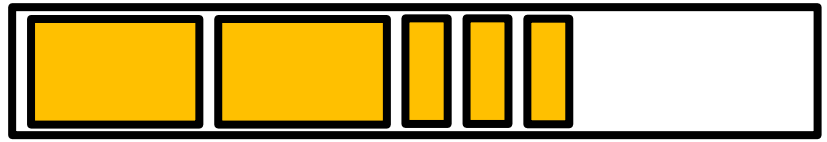
# Memory types: AMD APU




- **Memory is really unified.**
  - DEVICE_LOCAL is still faster.
  - Render and Depth Targets will see the most benefit.
- **If you detect integrated graphics:**
  **VK_PHYSICAL_DEVICE_TYPE_INTEGRATED_GPU:**
  - Count size of all memory heaps together.
  - Put your resources in DEVICE_LOCAL first. If that heap is full then try other heaps.

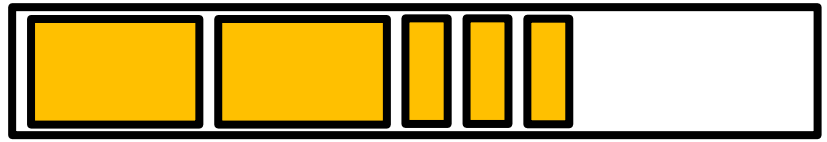
# Tips & Tricks

# Memory blocks



- **In Old API's the resource owns the memory.**
  - Memory is allocated when creating the resource.
  - No control of where that memory is placed.
- **In Vulkan the memory is allocated by itself.**
  - Memory is allocated in blocks.
  - A single block can have many resources.
- **Allows many new optimization techniques**
  - Pool similar resources for tighter packing.
  - Keep object resources together to simplify streaming of that objects required resources.

# Suballocation



- **Don’t allocate a separate memory block for each resource.**
  - Small limit on maximum number of allocations (e.g. 4096).
- **Allocate bigger blocks and sub-allocate ranges for your resources.**
  - 256 MiB is good default block size.
  - For heaps <= 1 GiB use smaller blocks.
    (e.g. heap size / 8).
- **Allocations are slow.**
  - Prefer not to allocate or free memory blocks during gameplay to avoid hitching.
  - If you need to, you can do it on background thread.

# Over-commitment

**What happens when you exceed the maximum amount of physical video memory?**

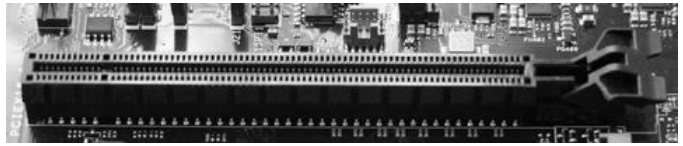
- **It depends on the driver.**
  - Allocation may fail (VK_ERROR_OUT_OF_DEVICE_MEMORY).
  - Allocation may succeed (VK_SUCCESS).
    - Some blocks are silently migrated to system memory.
- **Blocks may be migrated to system memory anyway.**
  - You are not alone – other applications can use video memory.
  - Using blocks migrated to system memory on GPU degrades performance.
- **Don’t use 100% of the heap**
  - Leave room for implicit resources
  - (e.g. 20% of DEVICE_LOCAL,
    33% of DEVICE_LOCAL + HOST_VISIBLE).

# Mapping

```
void* ptr;
```

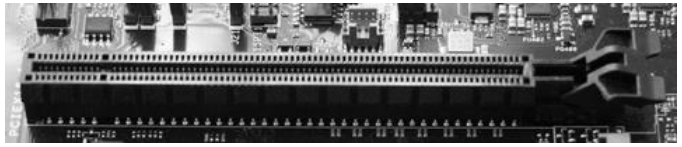
- **No more versioning of resources by the API.**
- **Having entire memory block persistently mapped is generally OK.**
  - You don’t need to unmap before using on GPU.
- **Exceptions:**
  - AMD, Windows® version < 10: Blocks of DEVICE_LOCAL + HOST_VISIBLE memory that stay mapped for the time of any call to Submit or Present are migrated to system memory.
  - Keeping many large memory blocks mapped may impact stability or performance of debugging tools.

# Transfer



- **Transfer queue is designed for efficient transfer via PCIe.**
  - Heavily underutilized queue.
  - Use it in parallel with 3D rendering, even asynchronously to rendering frames.
    - Good for texture streaming.
  - Fastest way to copy across the PCIe bus.
  - Does not use any compute or graphics hardware.
  - Do your transfers long before the data is needed on graphics queue.
- **Transfer queue can be used for defragmenting.**
  - Copy a resource to a new address asynchronously to rendering.
  - When done update next frames descriptor.

# Transfer



- **Some hardware supports more than one queue.**
  - e. g. AMD RX 580 has 2 transfer queues.
  - Can use one queue to defrag while the other one updates frame resources. (constant buffers, etc.)
- **GPU to (the same) GPU copies are much faster on graphics queue.**
  - Use it if graphics queue needs to wait for transfer result anyway.
- **Be careful with granularity.**
  - Always respect queue granularly for copies otherwise you may have corruption, crash, or even deadlock.
  - Don’t need to worry when doing full sub resource copies.

# Aliasing

- You can alias different resources – bind them to the same or overlapping range of memory.
- It saves memory.
- Good for transient resources (e.g. render targets) used only during part of the frame.
- After the memory was used by different resource, treat your resource as uninitialized.
  - …unless you really know what you're doing.

# Resource Creation

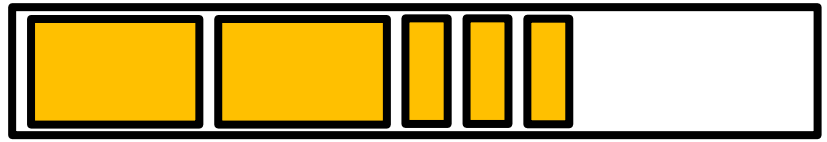
- **Don’t use images with TILING_LINEAR unless you have to.**
  - Use TILING_OPTIMAL.
  - Copy images from/to buffers.
- **Minimize number of USAGE_BITS used during resource creation.**
  - Only fill out what you need.
- **Avoid VK_SHARING_MODE_CONCURRENT on render and depth target textures.**
  - It disables optimizations.
  - Prefer VK_SHARING_MODE_EXCLUSIVE and do explicit queue family ownership transfer barriers.
- **Use VK_KHR_image_format_list for mutable formats.**
  - If you need different formats e.g. to interpret as linear/sRGB, use the VK_KHR_image_format_list extension with the VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT.

# Libraries

# Vulkan Memory Allocator

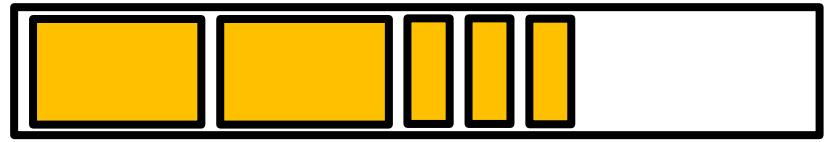
- https://github.com/GPUOpen-LibrariesAndSDKs/VulkanMemoryAllocator
- **Library from AMD.**
  - MIT license
  - easy to integrate – single header
  - interface in C (same style as Vulkan™), implementation in C++
  - well documented
- **Already used in some AAA titles.**
- **Great starting point even if you write your own.**

# Vulkan Memory Allocator



- **Functions 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.**
  - Library keeps track of allocated memory blocks, used and unused ranges inside them,
  - respects alignment and buffer/image granularity.

# Vulkan Memory Allocator



- **Functions that create image/buffer, (sub-)allocate memory for it and bind them together - all in one call.**

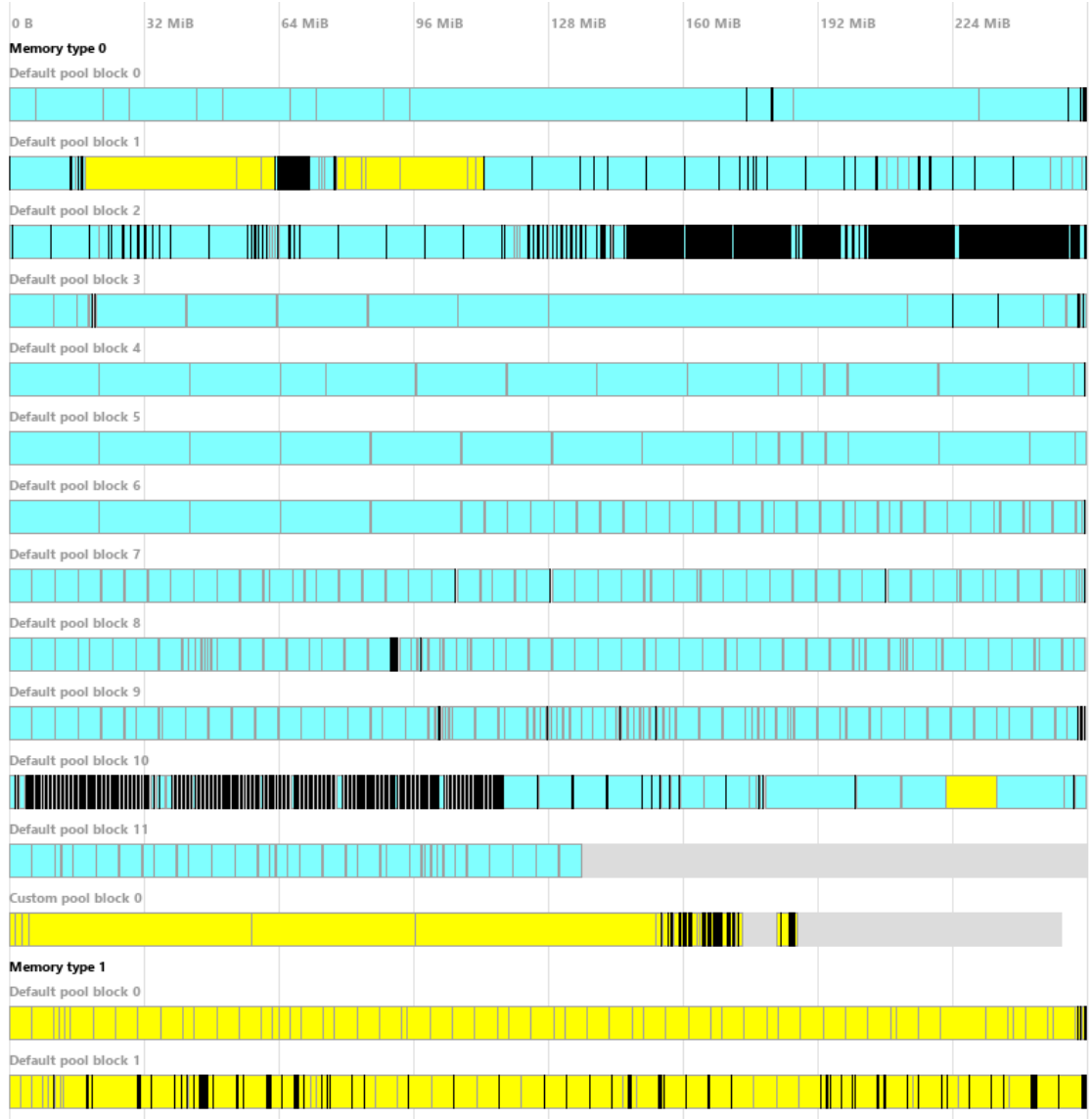
```
VkBufferCreateInfo bufferInfo = { VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO };
bufferInfo.size = 65536;
bufferInfo.usage =
VK_BUFFER_USAGE_VERTEX_BUFFER_BIT | VK_BUFFER_USAGE_TRANSFER_DST_BIT;

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

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

# VmaDumpVis.py

- Auxiliary tool that visualizes JSON dump from Vulkan Memory Allocator.
- Light gray - unused by any allocation.
- Yellow - buffer.
- Aqua - image with TILING_OPTIMAL.
- Green - image with TILING_LINEAR.
- Black - one or more allocations that are too small to visualize.



# Conclusions

- **Vulkan® is lower level, 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.**
- **There are open-source libraries that can help you with this task.**

# References

- Vulkan Memory Allocator (AMD)
  https://github.com/GPUOpen-LibrariesAndSDKs/VulkanMemoryAllocator
- Vulkan Device Memory, Timothy Lottes, GPUOpen
  https://gpuopen.com/vulkan-device-memory/
- Vulkan Memory Management, Chris Hebert, NVIDIA Developer
  https://developer.nvidia.com/vulkan-memory-management
- What's your Vulkan Memory Type?, Mathias Schott & Jeff Bolz, NVIDIA Developer
  https://developer.nvidia.com/what%E2%80%99s-your-vulkan-memory-type
- Vulkan Hardware Database, Sascha Willems
  http://vulkan.gpuinfo.org/

# Thank you

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# Backup

# Cache control

- **Any memory type that doesn't have HOST_COHERENT flag needs manual cache control:**
  - vkInvalidateMappedMemoryRanges before read on CPU
  - vkFlushMappedMemoryRanges after write on CPU
- **In practice, all PC GPU vendors (AMD, Intel, NVIDIA) support HOST_COHERENT on every memory type that is HOST_VISIBLE.**
  - No need to worry about it on current Windows PCs.

# Dedicated allocation

- **Some resources may benefit from having their own, dedicated memory block instead of region suballocated from a bigger block.**
  - Driver may use additional optimizations.
  - VK_KHR_dedicated_allocation
- **Use the get_memory_requirements2 extension to query the driver if it recommends or requires using a dedicated allocation.**
- **Use for:**
  - Render targets, depth-stencil, UAV.
  - Shared resources. (required)
  - Very large buffers and images. (dozens of MiB)
  - Large allocations that may need to be resized (freed and reallocated) at run-time.

# MISC

- **Avoid VK_IMAGE_LAYOUT_GENERAL. Always transition image to appropriate VK_IMAGE_LAYOUT_*_OPTIMAL.**
  - Exception: storage image requires VK_IMAGE_LAYOUT_GENERAL.
- **Memory requirements (e.g. size) can vary for different resources (e.g. images) even when created with same parameters (format, width, height, mip levels etc.)**
  - It really happens in the wild. Be prepared for that. Don’t cache result. Query each resource for requirements.