D3D12 and Vulkan: Lessons learned

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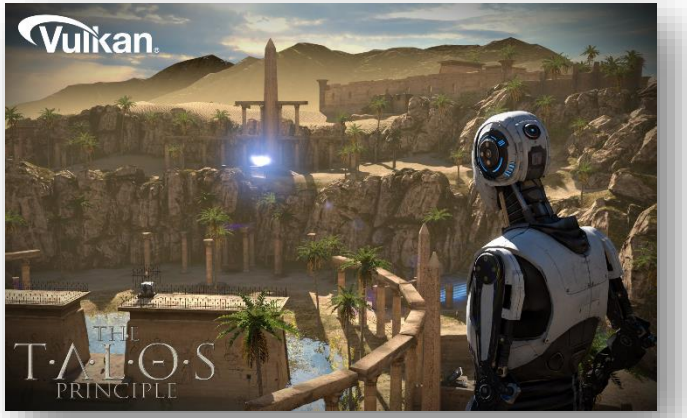
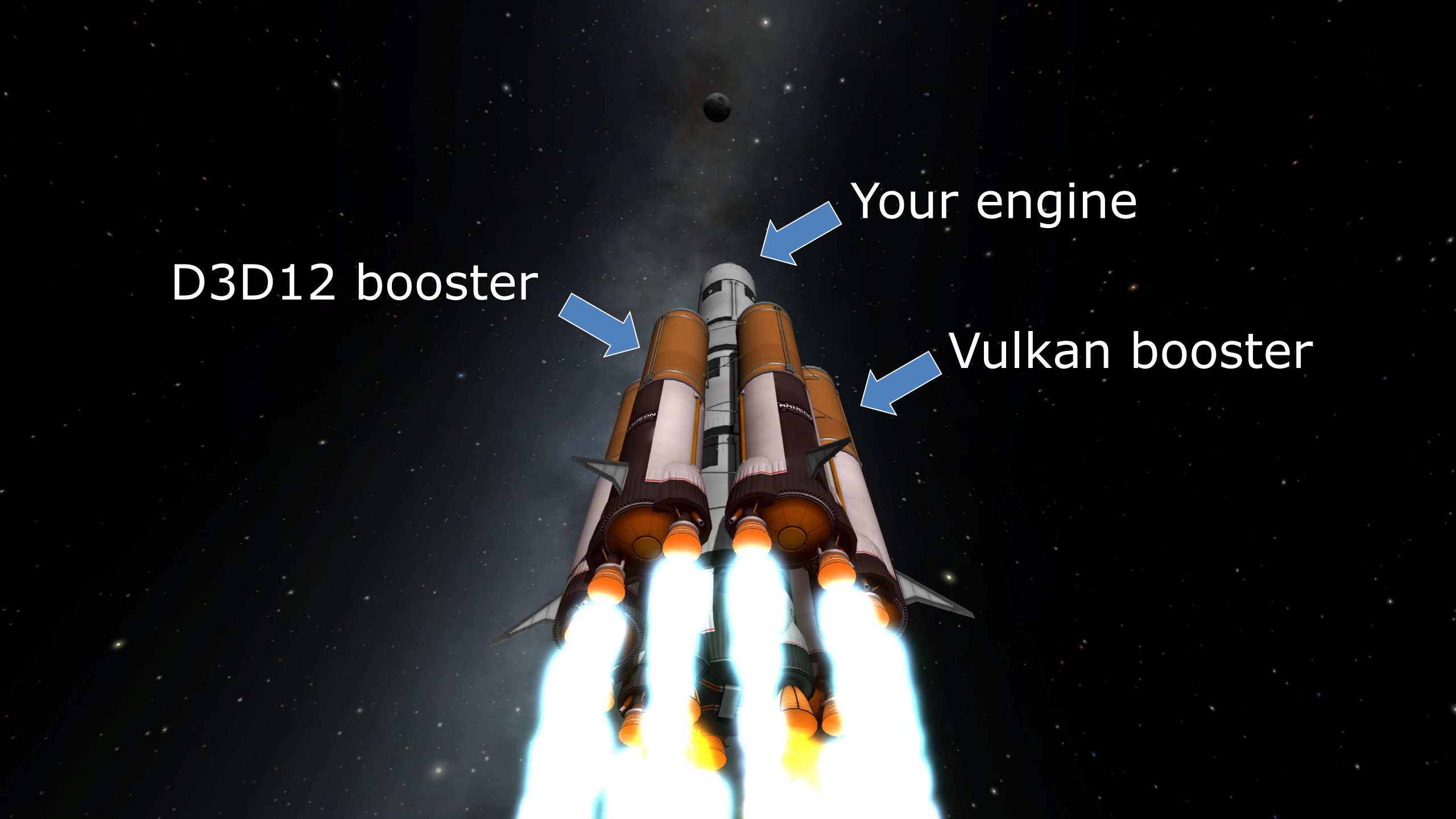
Overview

The **age of D3D12 & Vulkan** has begun!

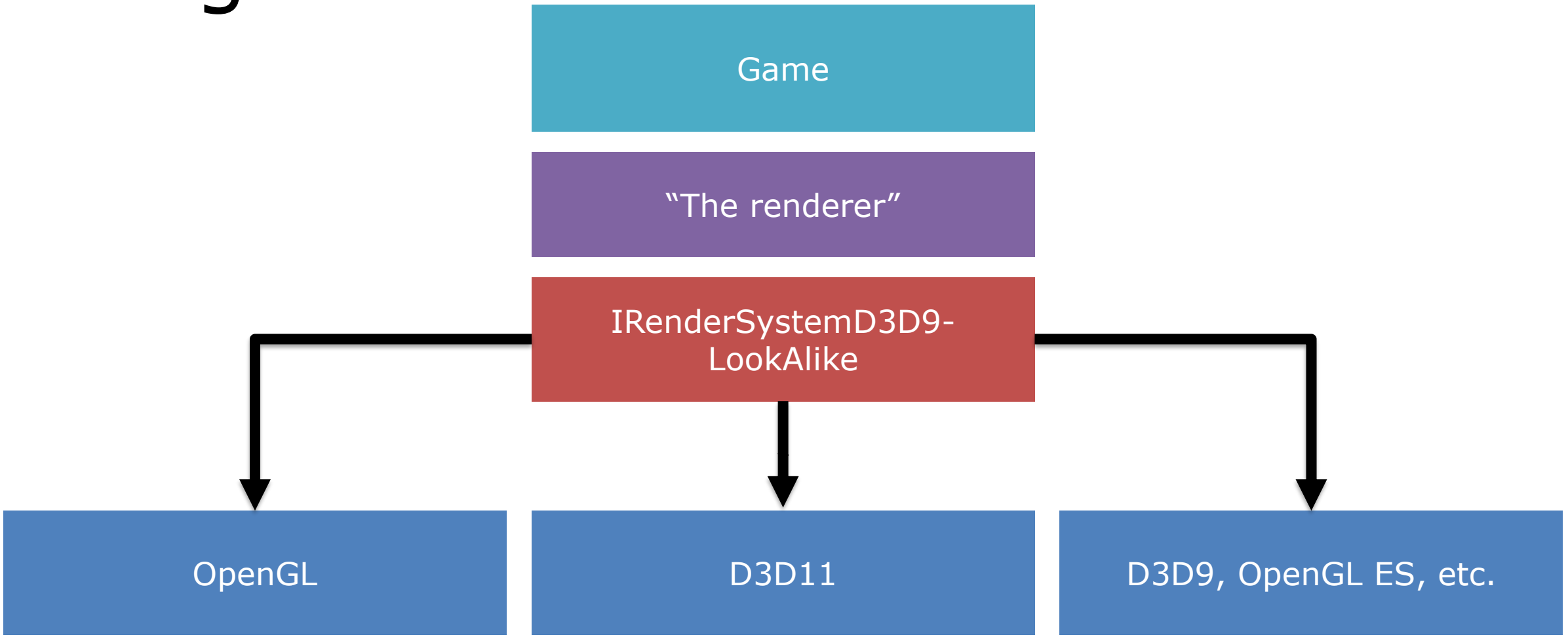


Caveat emptor

- D3D11 drivers are really well optimized
  - Use your knowledge to outsmart & outperform the D3D11 driver
  - D3D12 was not invented to write a legacy API driver on top
- Other issues

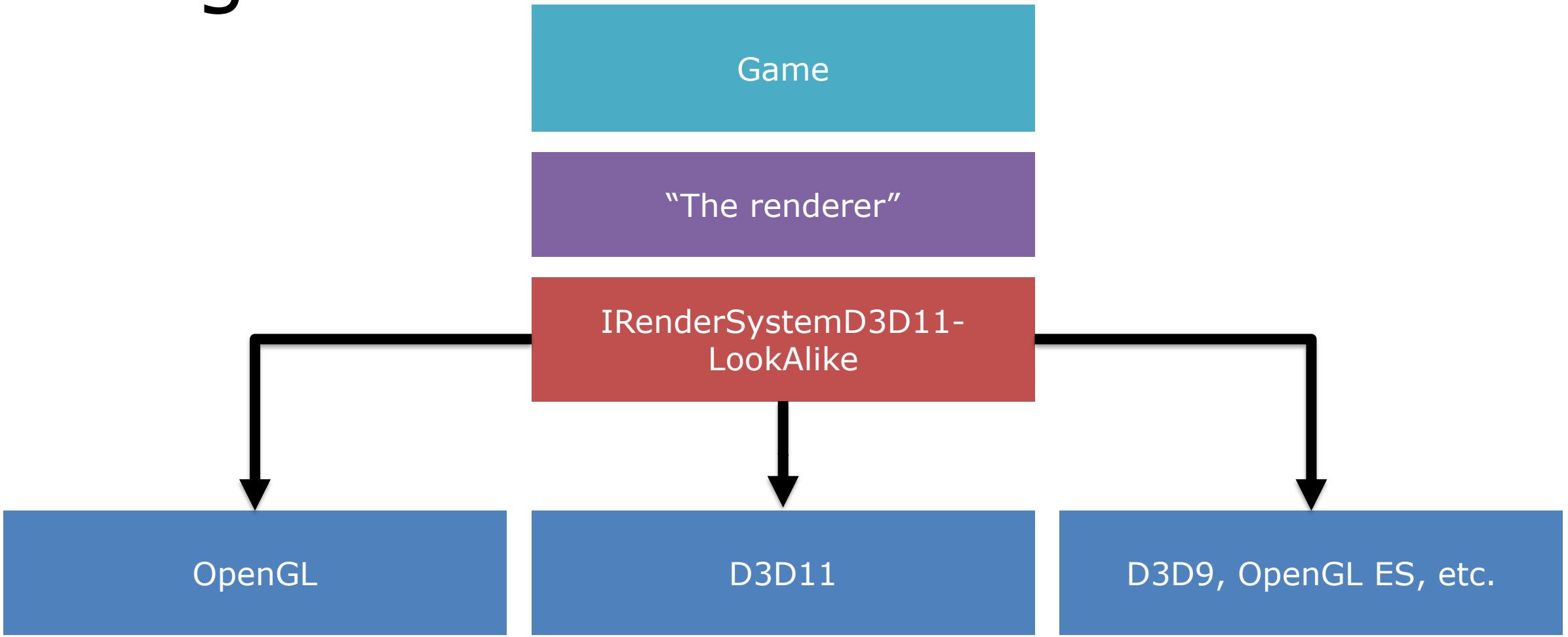

Your engine
D3D12 booster
Vulkan booster

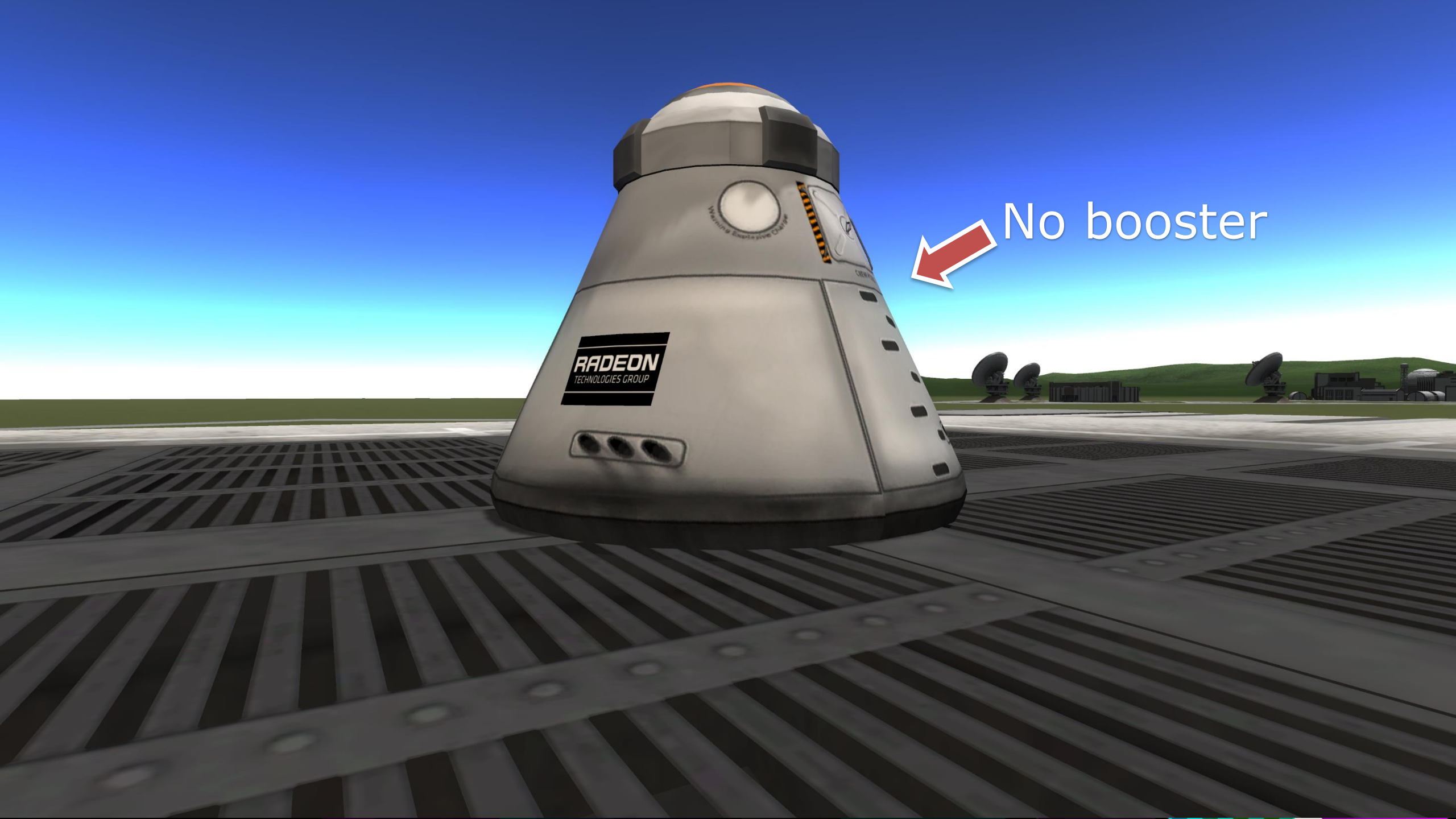
Stage 0


Game
"The renderer"
IRenderSystemD3D9-LookAlike
OpenGL
D3D11
D3D9, OpenGL ES, etc.

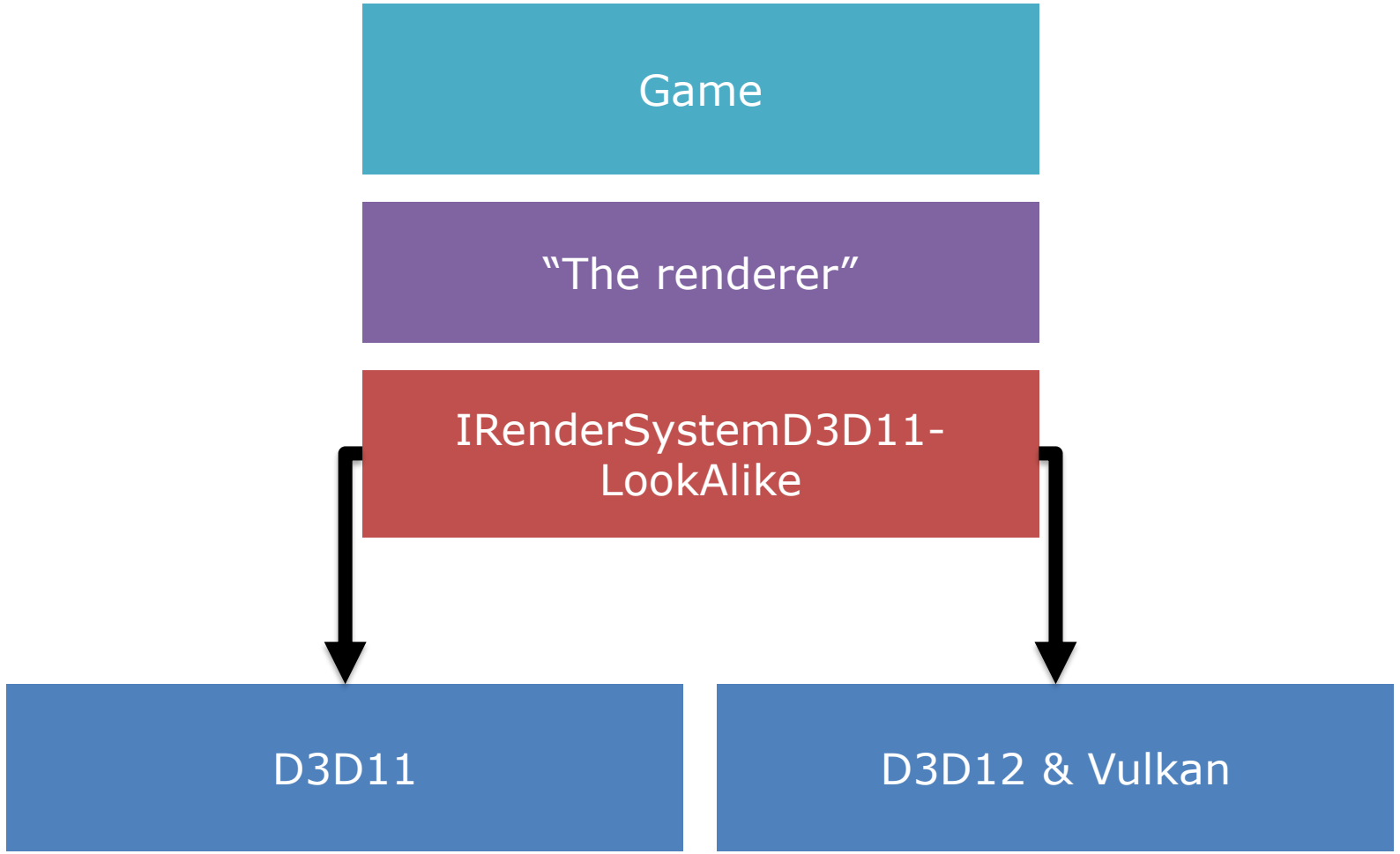

RADEON
KSC
WARNING
No booster

Stage 0.5


Game
"The renderer"
IRenderSystemD3D11-LookAlike
OpenGL
D3D11
D3D9, OpenGL ES, etc.

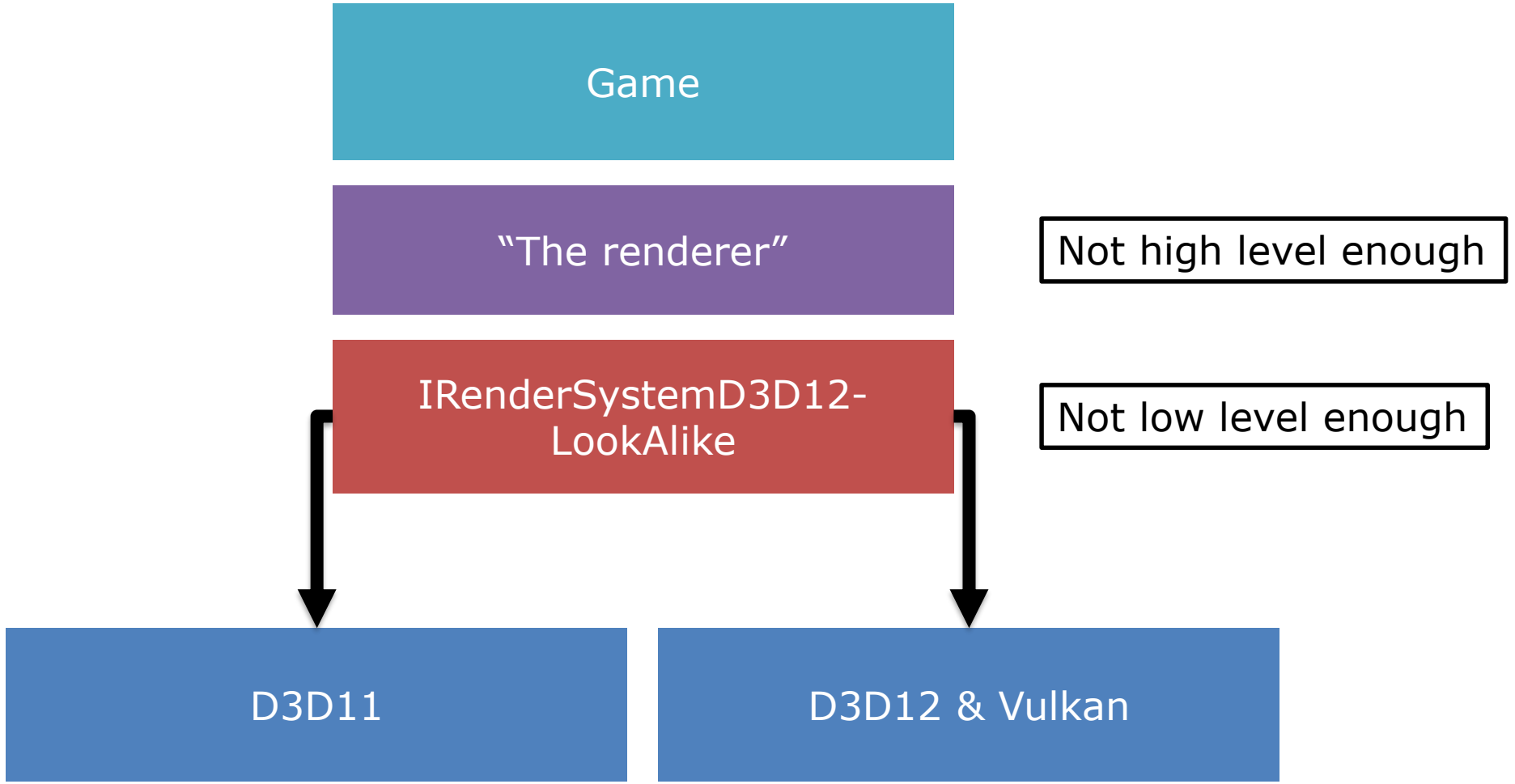

No booster
RADEON
TECHNOLOGIES GROUP

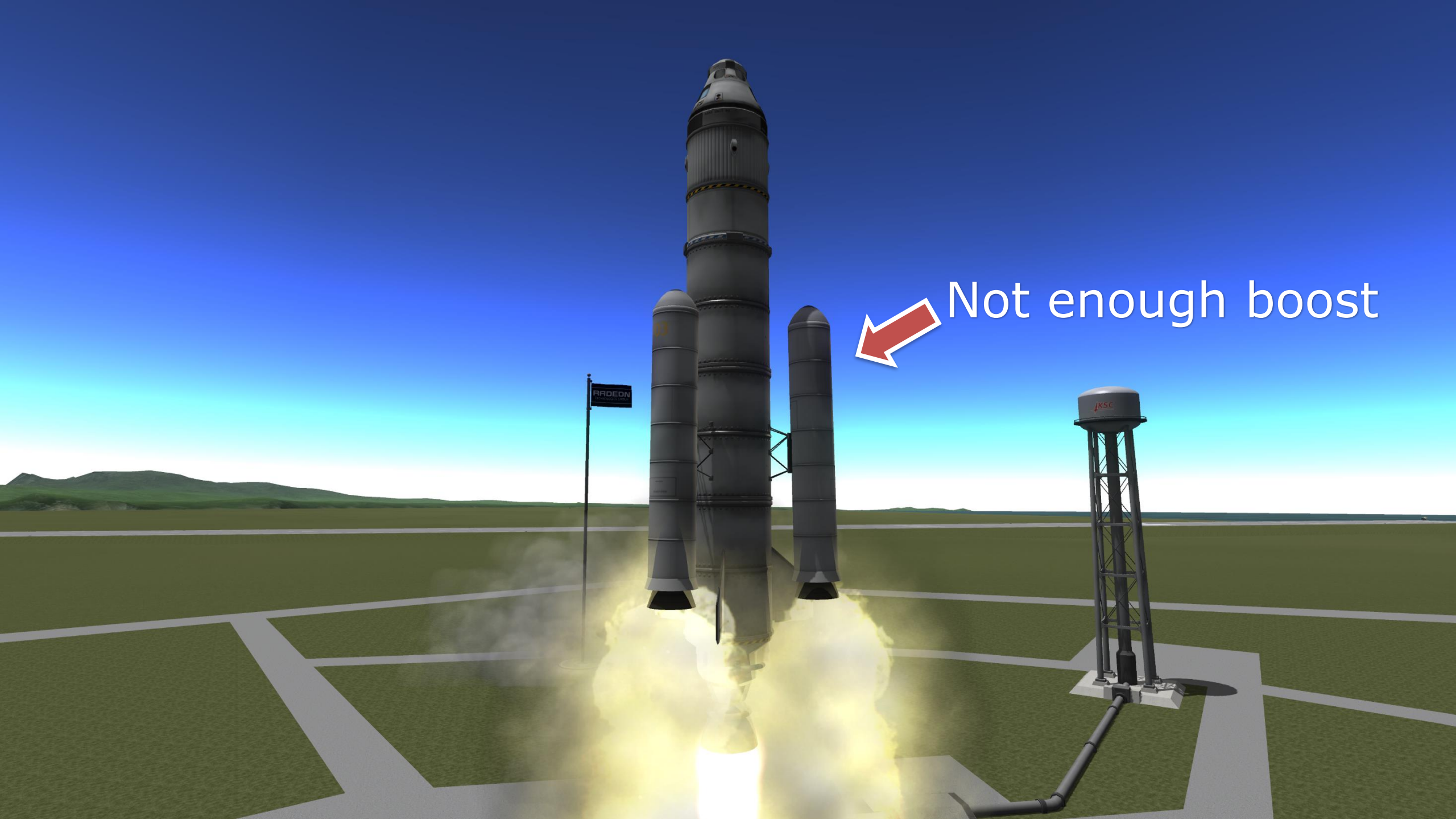
Stage 1


Game
"The renderer"
IRenderSystemD3D11-LookAlike
D3D11
D3D12 & Vulkan

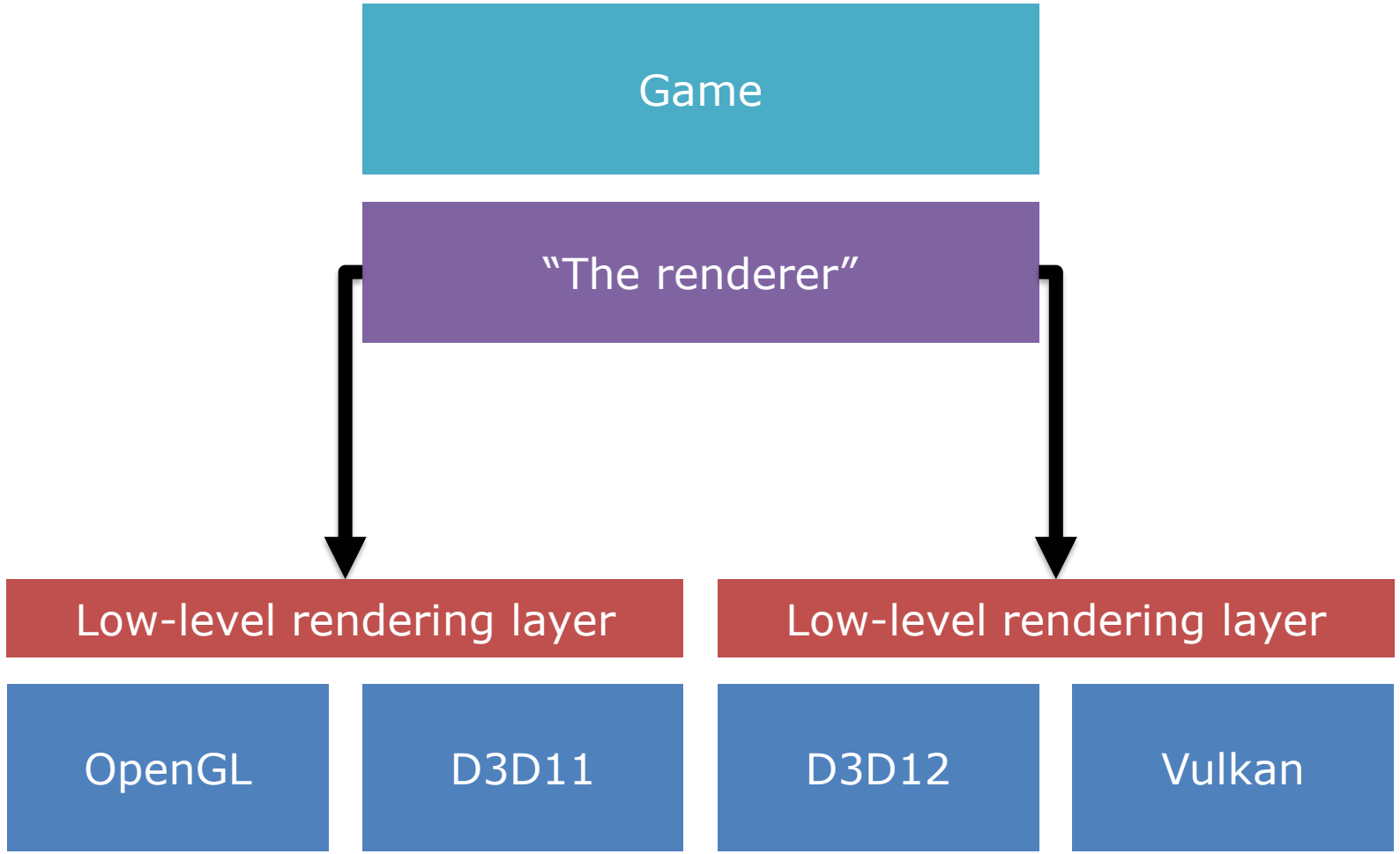

No booster

Stage 2


Game
"The renderer"
Not high level enough
IRenderSystemD3D12-LookAlike
Not low level enough
D3D11
D3D12 & Vulkan


Not enough boost
RADEON
KSC

Stage 3


Game
"The renderer"
Low-level rendering layer
Low-level rendering layer
OpenGL
D3D11
D3D12
Vulkan


Weeeeh!

State of the nation

- Engines are transitioning to support Vulkan and D3D12
  - D3D11 support still required
  - Most are midway between Stage 1 and 2
- Lots of thought needed to get the best out of all APIs
  - Multi-queue support requires additional work
  - Needs to scale down to D3D11
- Targeting D3D12/Vulkan and running on D3D11 is the recommended way

Design for the future

- I'll point out common design issues
- Get your engine ready
- Turn your knowledge into better performance

Design first!


Resource Barriers

Barrier control

- Barriers are a new concept in D3D12/Vulkan
- Sad truth: **Everyone** gets them wrong
- Two failure cases:
  - Too many or too broad: **Bad performance**
  - Missing barriers: **Corruptions**
- D3D11 driver does this under the hood – and quite well

What's a barrier, anyway?

Render target to **texture**

- Probably a decompression is needed (& cache flush)
- What will happen changes between vendors and GPU generations – can be a no-op, can be a wait for idle, can be a full cache flush

What's a barrier, anyway?

UAV to **resource**

- If done badly, it will cost – flush or wait for idle
- If done correctly, those transitions can be free

Missing barriers

- Format problems – GPU/driver specific corruption
- Synchronization problems – time-dependent corruption

Subresources

Subresources

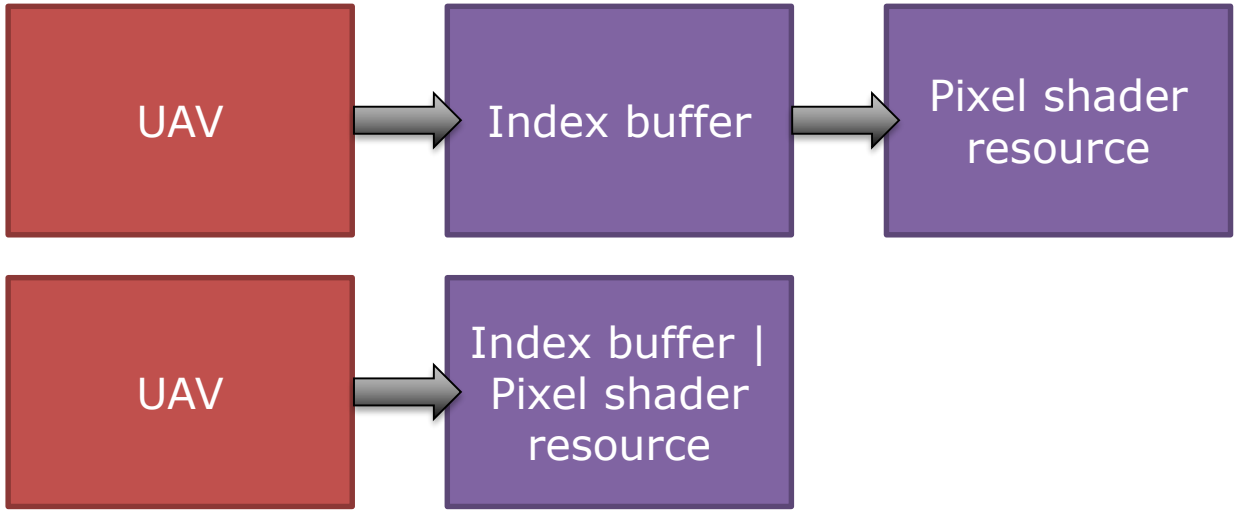
- Need to be tracked individually
  - Downsampling
  - Shadow map atlas
- If you transition all subresources, use `D3D12_RESOURCE_BARRIER_ALL_SUBRESOURCES` instead of going one-by-one

Placed resources & initial states

- Render targets created as placed resources etc. **must** be cleared before use
- Go into **clear state directly**, don’t start with some random state and transition

Unnecessary transitions

- Transitioning to wrong type
  - Not common but still occasionally happens
  - Make sure to check with validation layer
- Read-read transitions
  - Moving between two read states, i.e. from index buffer to shader resource
  - Moving to **union of all future states** requires only one barrier

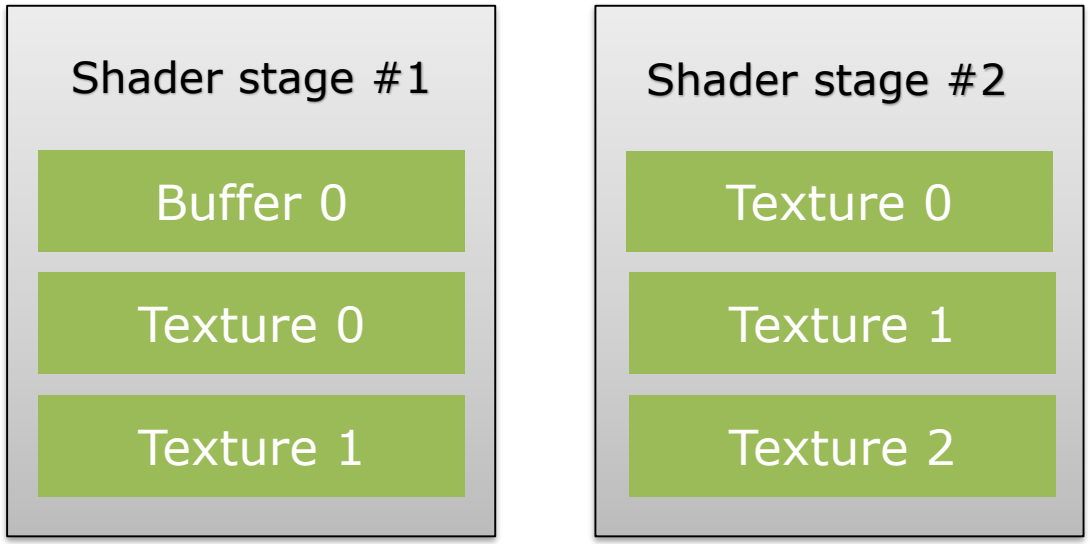


Costly transitions

- `COMMON` is for copies/present, not a general "catch all" state
- Usually you want shader access
  - In D3D12: `PS_RESOURCE | NON_PS_RESOURCE`
  - In Vulkan: `VK_ACCESS_SHADER_READ_BIT`

Barrier control – Worst case #1

- Worst-case barrier system – too many barriers
  - Material system going wrong
  - For maximum damage, do it per stage



Barrier control – Worst case #1

- "Late binding", or fixing up resources per draw
- ```
  for (auto& stage : stages) {
      for (auto& resource : resources) {
          if (resource.state & STATE_READ == 0) {
              ResourceBarrier (1, &resource.Barrier (STATE_READ));
          }
      }
  }
  ```
- Let's take a look what happens here!
  ```

Barrier control – Worst case #1

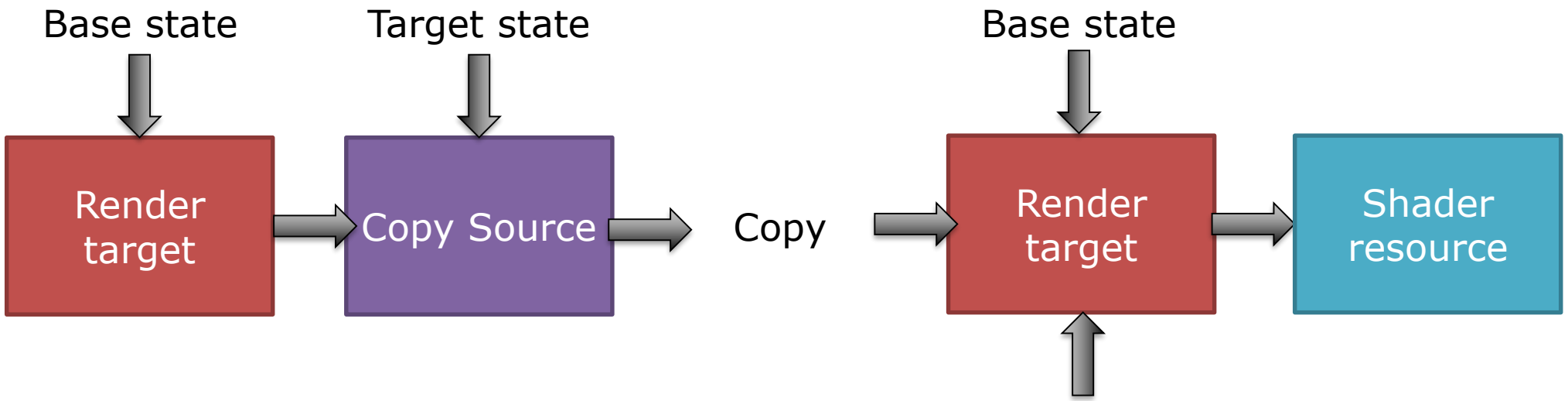
- Ideal flow

- Per material/stage anti-pattern
  - One barrier per stage per resource
  - Barriers scattered all over the command list

- In the worst case, multiple wait-for-idle back-to-back

Barrier control – Worst case #2

- "Base state" or redundant transitioning
- Transition to target state followed by restore



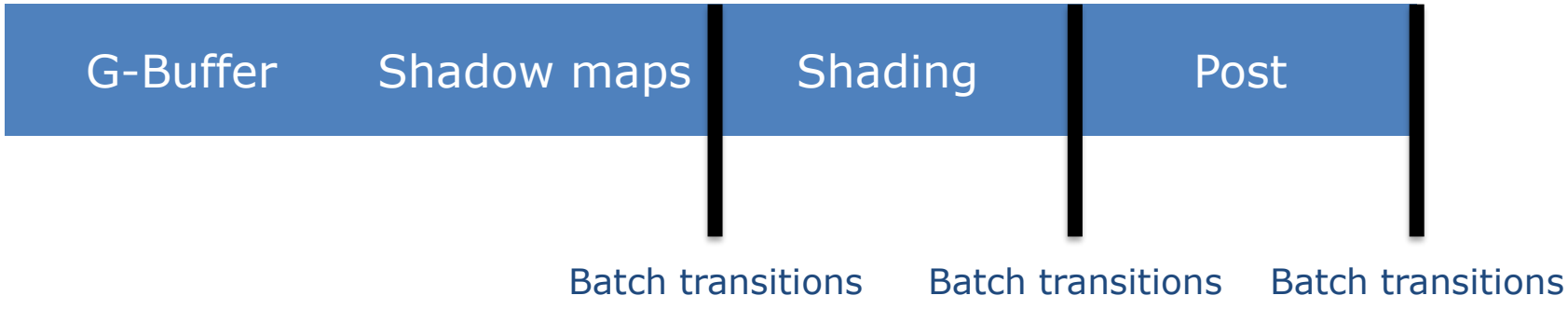
Funny barriers

- `ResourceBarrier (0, nullptr)`
  - Nothing changed, thank you!
  - Indicates your state tracking is doing the wrong thing
- Previous state equal to next state
  - Happens more than you believe – just say no
- Always remember – driver **assumes you're doing the optimal thing**, doesn't go through **any** heuristic itself!

Get ready for the future

- You should **not** have to track all resource state
- 99% of your resources are immutable – read-only. Trust me ☺
- Find "transitions" points – when do passes end?
  - Batch barriers here
  - Only transition what you need

Design first!



Barrier debugging tips

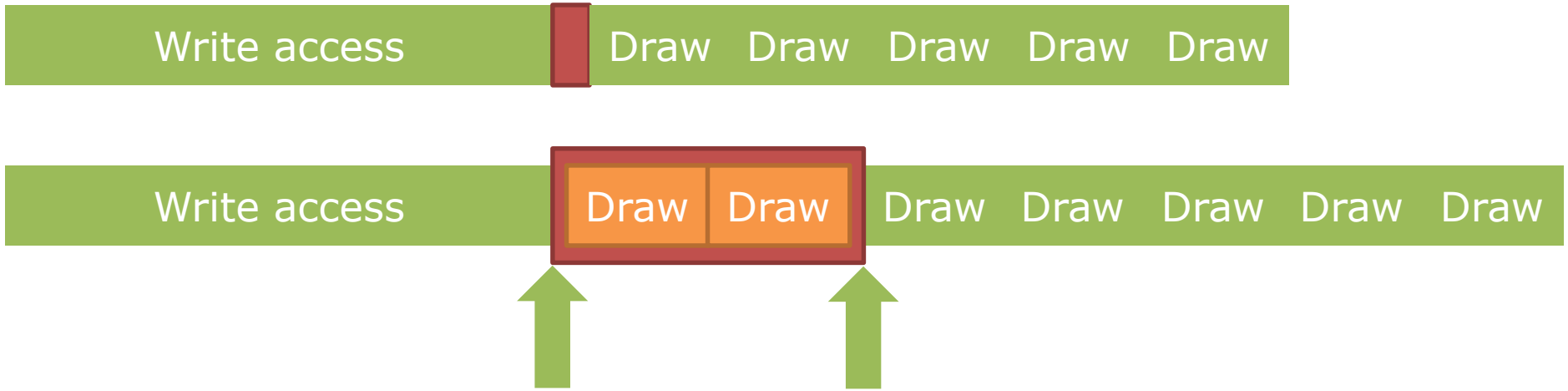
- Have a write/read bit
- Log all transitions
  - Grep & spreadsheets are your friends
  - Check for # transitions, transition type, etc.
- Number of transitions should be in the order of number of writable resources
  - Again, log and grep are your friends
  - If it’s over 9000, something is fishy!

Barrier debugging tips

- Have a barrier-everything mode
  - Same as the “worst-case” mode described previously
  - For **debugging** only
- Ensure your resources are in a known state at least once per frame
  - For example, at frame end/start
  - Transition everything into a known state – that resolves problems like TAA or shadow atlas breakage

Going forward

- Even better, eventually



  - Give driver time to handle the transition
  - “Split barrier” in D3D12
  - `vkCmdSetEvent + vkCmdWaitEvents`

Summary: Barriers

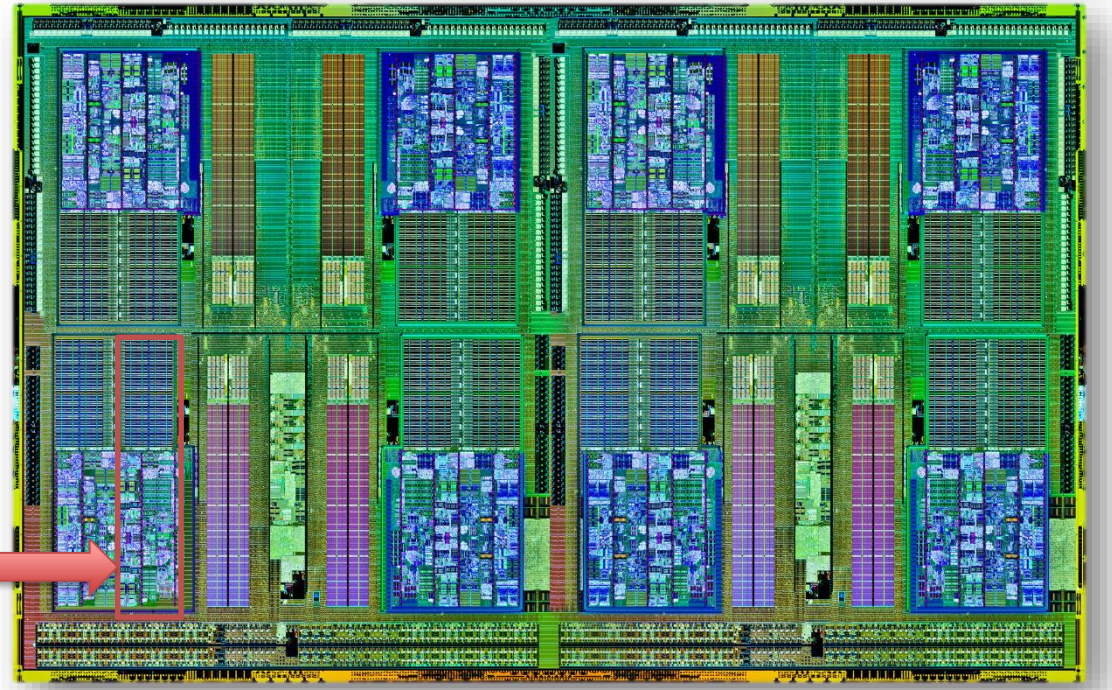
- Make sure to transition all the resources that need it (but not more)
- Go into the most specific state you can
- Remember you can combine various states


Launch control

Launch control

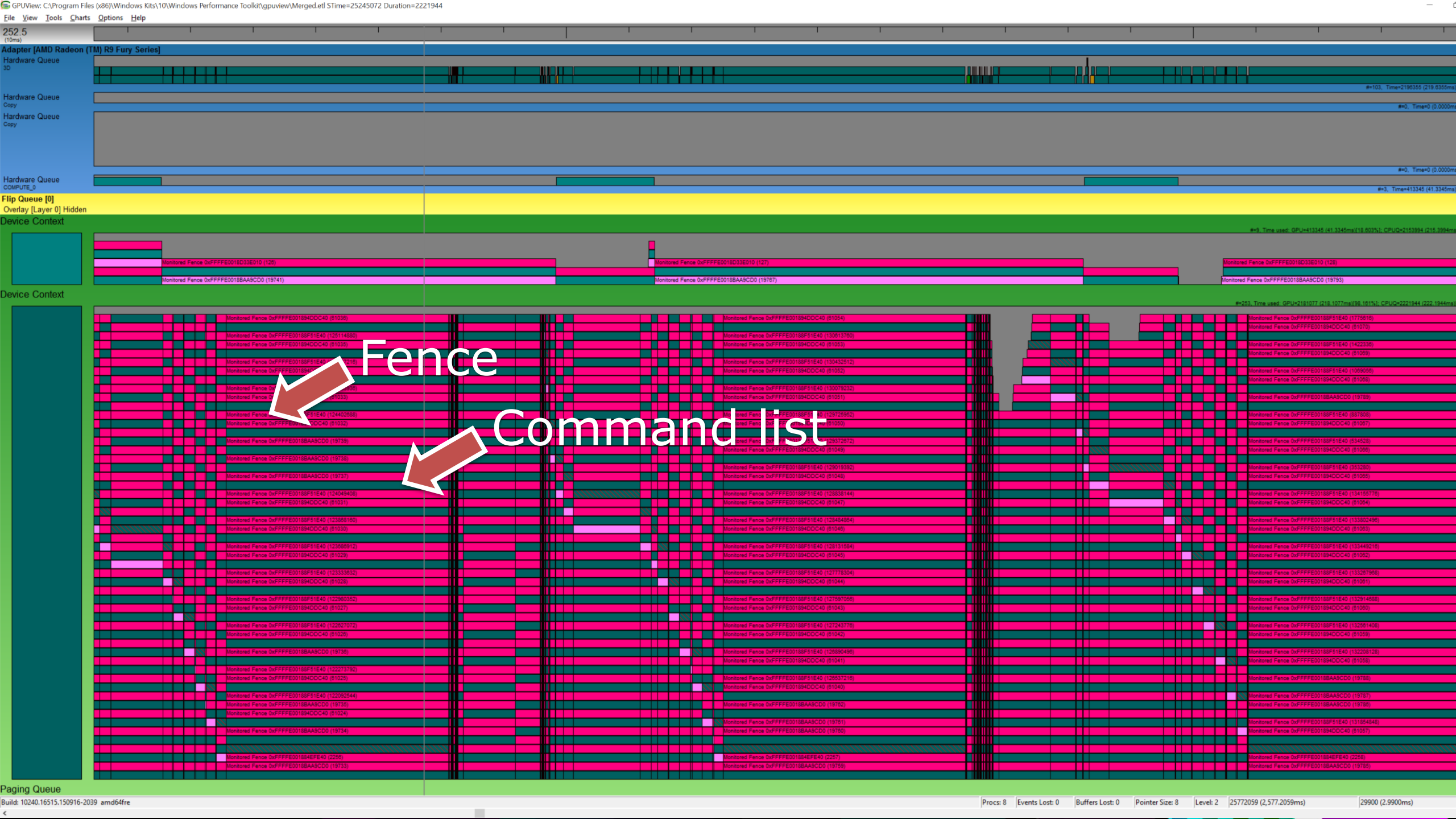
- How to feed the GPU
  - Submitting command lists, first and foremost
  - Per-frame resource updates & tracking second

CPU threading



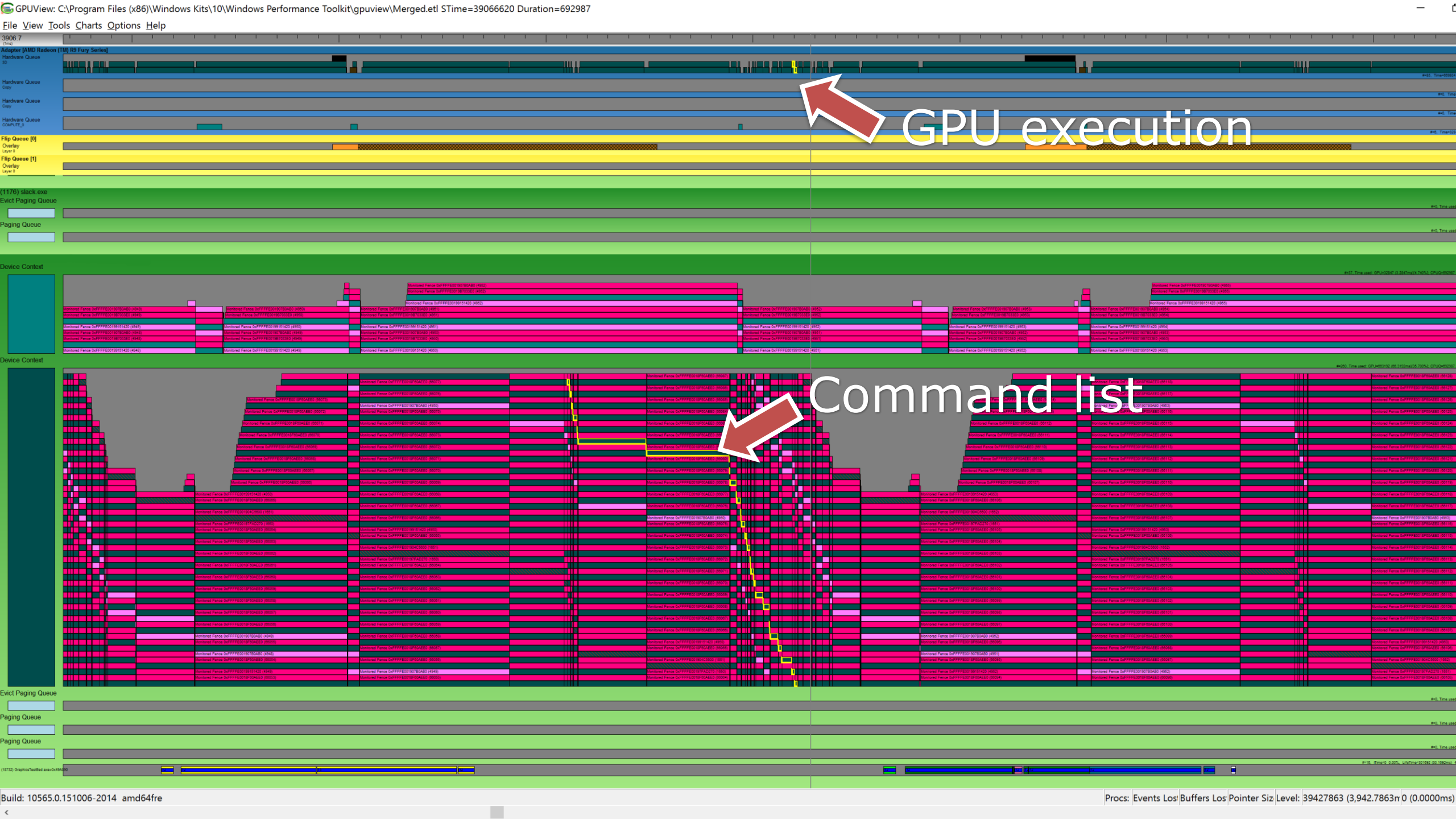
CPU threading

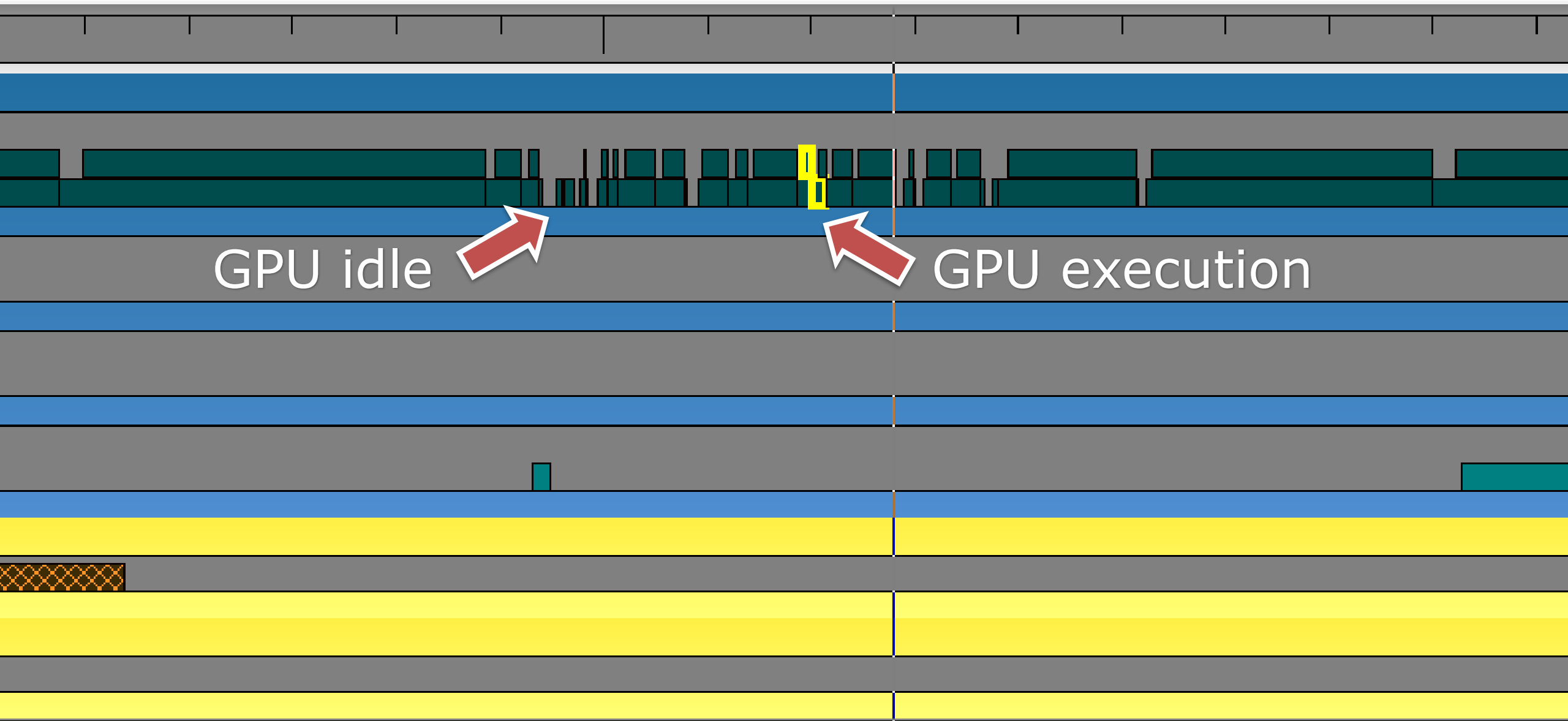
- Don’t limit parallelism by assigning cores manually
- Use a task/job system
  - Uses all cores automatically
  - Requires extra care for efficient work submission and resource syncronization


GPUView: C:\Program Files (x86)\Windows Kits\10\Windows Performance Toolkit\gpuview\Merged.etl STime=25245072 Duration=2221944
File View Tools Charts Options Help
252.5
(10ms)
Adapter [AMD Radeon (TM) R9 Fury Series]
Hardware Queue
3D
Hardware Queue
Copy
Hardware Queue
Copy
Hardware Queue
COMPUTE_0
Flip Queue [0]
Overlay [Layer 0] Hidden
Device Context
Device Context
Fence
Command list
Paging Queue
Build: 10240.16515.150916-2039 amd64fre
Procs: 8
Events Lost: 0
Buffers Lost: 0
Pointer Size: 8
Level: 2
25772059 (2,577.2059ms)
29900 (2.9900ms)

What happened?

- Thread pool gone wild ☺
  - CPU tasks submitted work at the end
  - Task boundary became CPU/GPU sync point
- Take control over the command lists after the tasks have finished

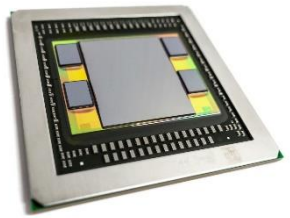

GPUView: C:\Program Files (x86)\Windows Kits\10\Windows Performance Toolkit\gpuview\Merged.etl STime=39066620 Duration=692987
File View Tools Charts Options Help
3906.7
Adapter [AMD Radeon (TM) R9 Fury Series]
Hardware Queue
Hardware Queue
Hardware Queue
Hardware Queue
Flip Queue [0]
Overlay
Flip Queue [1]
Overlay
(1176) slack.exe
Evict Paging Queue
Paging Queue
Device Context
Device Context
Evict Paging Queue
Paging Queue
Paging Queue
GPU execution
Command list
Build: 10565.0.151006-2014 amd64fre
Procs: Events Los Buffers Los Pointer Siz Level: 39427863 (3,942.7863n 0 (0.0000ms)

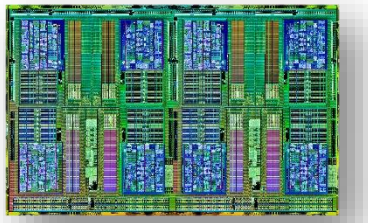

GPU idle
GPU execution

What happened?

- Each fence is basically a wait-for-**idle** on the GPU (more or less)
- Better:
  - Protect **per-frame** resources
  - Unlikely you can start working on a command list “mid-frame” anyway
  - Protect many resources with a single fence
- Make sure your job system can do this
- Batch up submissions as much as possible
- Submit early to **keep the GPU busy at all times**

Ideal submission



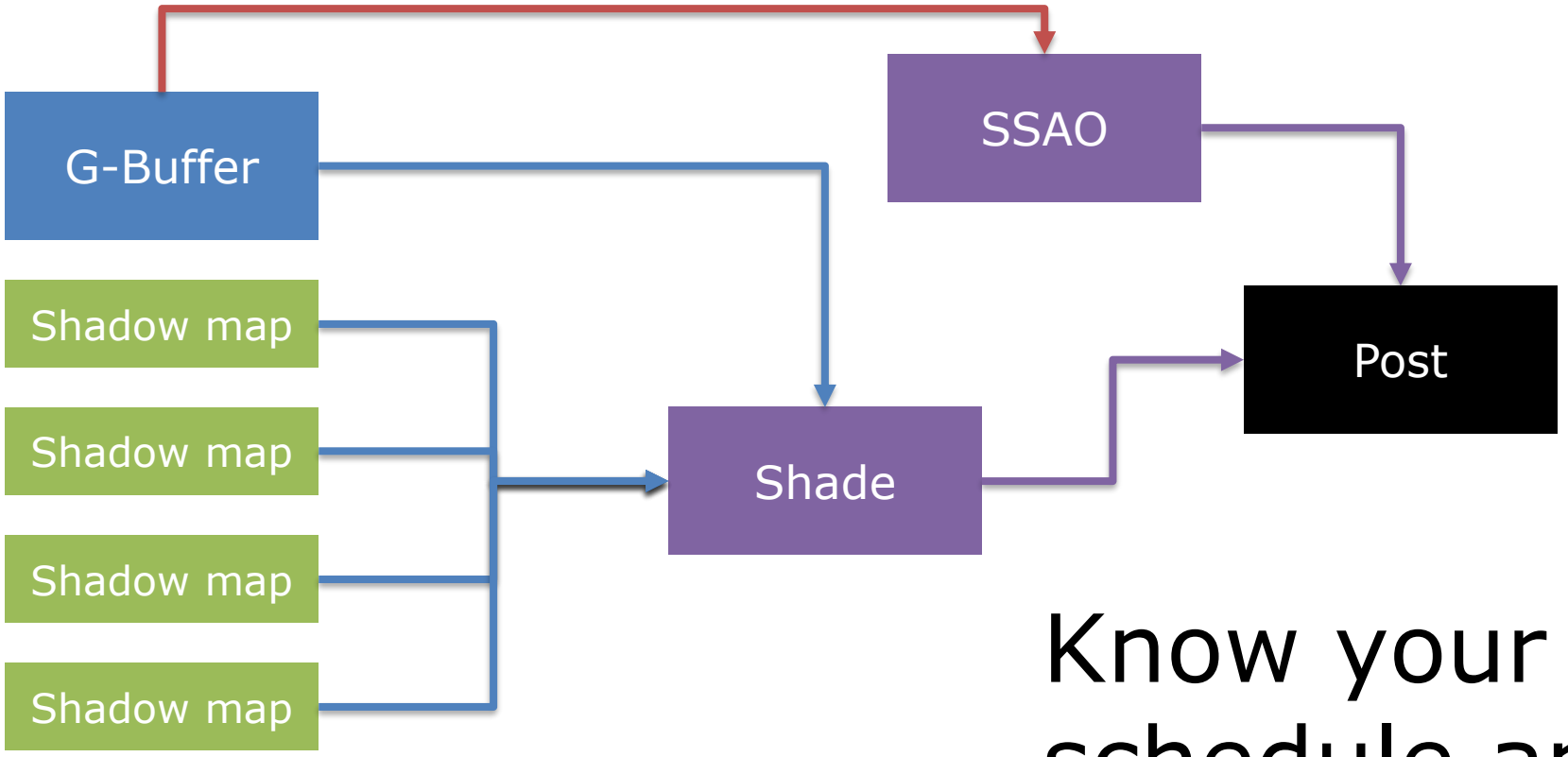


CL = Command list

Command allocators

- Command allocators are defined to be “grow only”
  - Record 100 draw calls on fresh allocator will allocate memory
  - Resetting and recording the same draw calls again will **not** allocate memory again
  - Try to reuse command allocators for similar workloads
- Recycling allocators will grow them to the worst-case size
- In total, number of allocators should be roughly
  # threads × # frames buffered × # GPUs
  - We’ve seen 20.000 allocators being allocated – lots of memory waste
- Make sure to reuse allocators/command lists and don’t recreate per frame

Designing for Multithreading



Design first!

Know your workload and schedule appropriately

Also: Renderpasses

- Build a high-level graph of your frame
- Tell the renderer about it via Vulkan's render-passes and subpasses
- Allows the driver to pick an optimal schedule

Also: Renderpasses

- Allows you to express “don’t care” nicely
- Much more about this can be found in the “**Vulkan Fast Paths**” talk

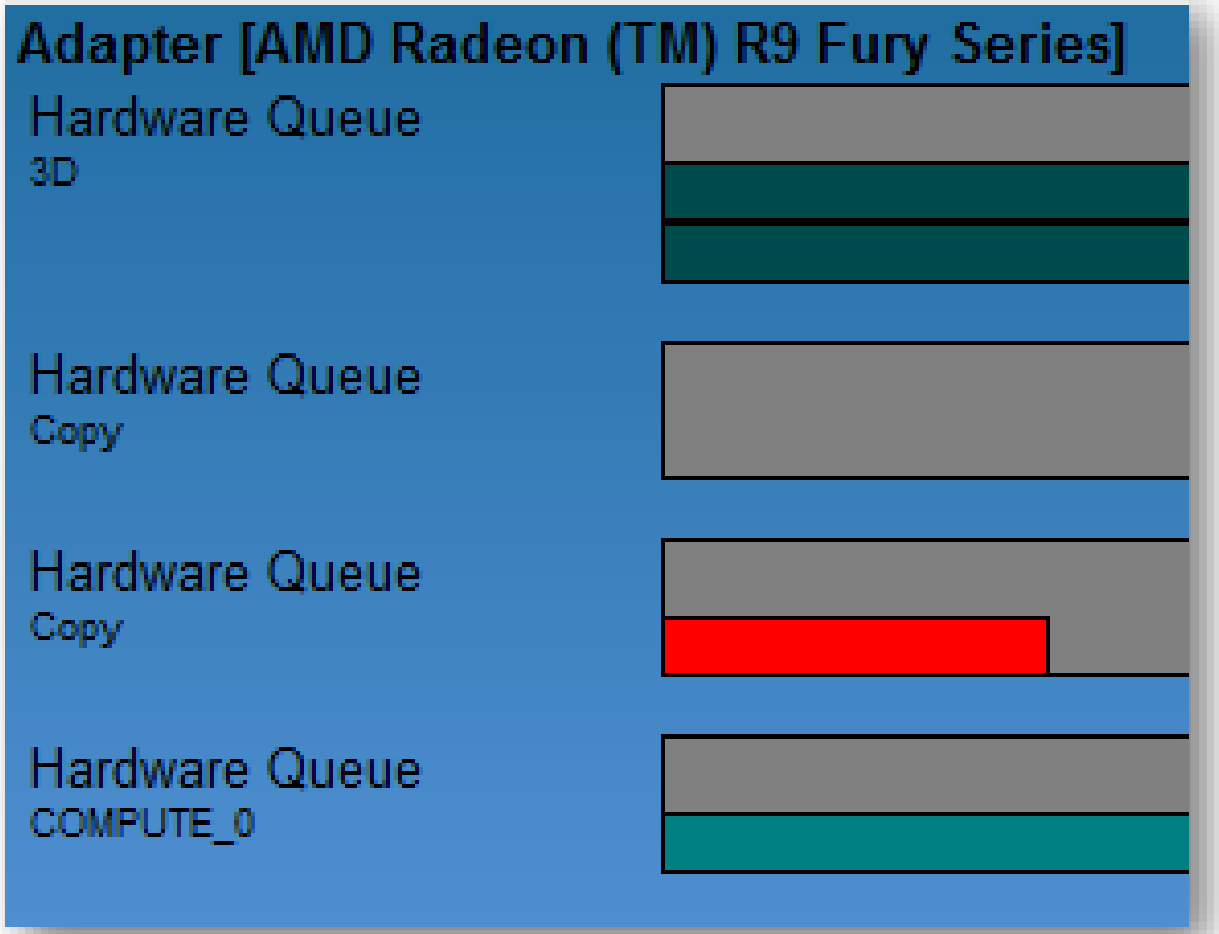
Debugging hints

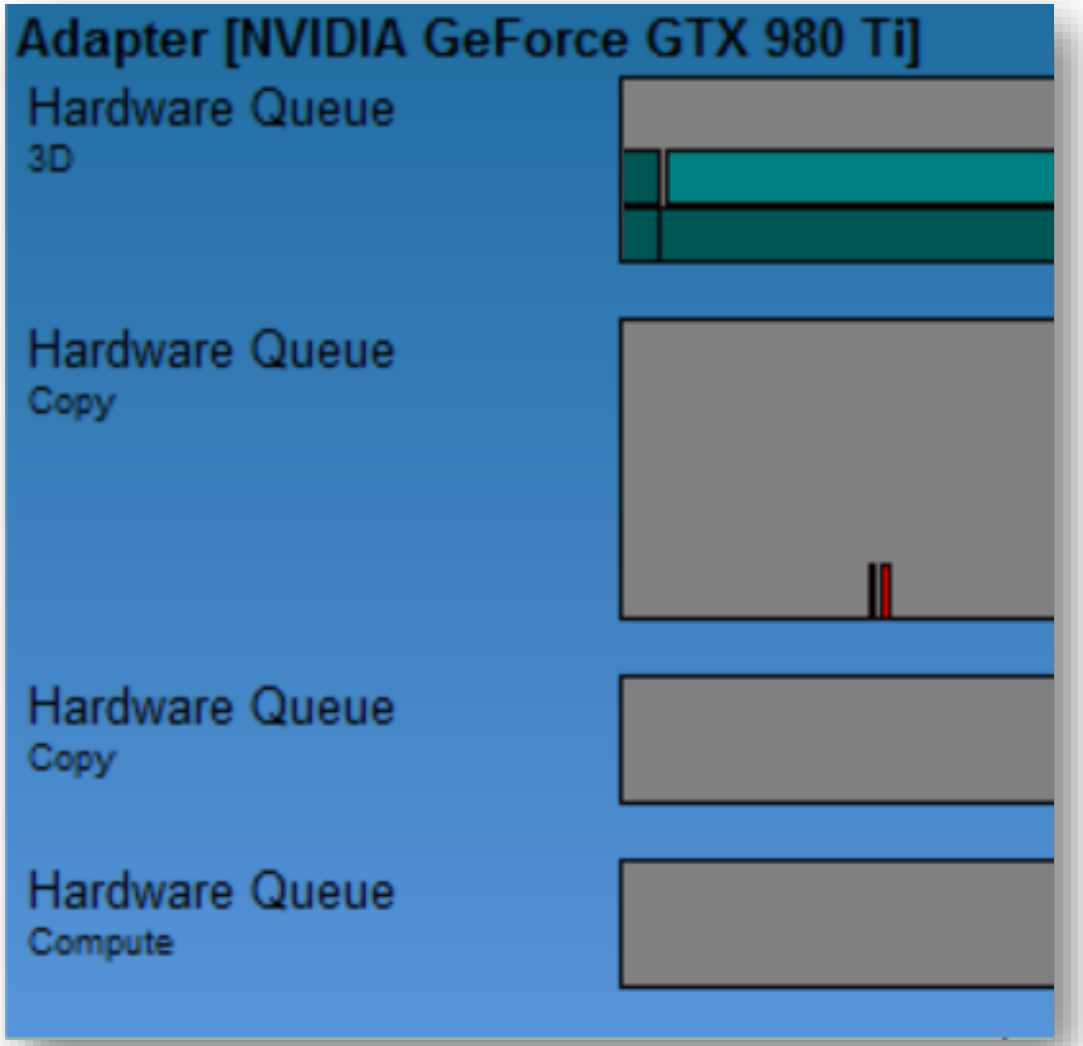
- Have an option to submit all command lists in one submission
  - Helps with timing issues
  - If not possible, you have in-frame GPU/CPU synchronization ☹
- Have an option to wait for any command list
  - Helps with upload/resource synchronization
  - Some resource gets corrupted? Flush the GPU before updating it

Summary: Submission

- Track resources at a per-frame granularity
- Know your frame structure
- Threading is essential to get good CPU usage

Multi-queue


Adapter [AMD Radeon (TM) R9 Fury Series]
Hardware Queue
3D
Hardware Queue
Copy
Hardware Queue
Copy
Hardware Queue
COMPUTE_0


Adapter [NVIDIA GeForce GTX 980 Ti]
Hardware Queue
3D
Hardware Queue
Copy
Hardware Queue
Copy
Hardware Queue
Compute

Multi-Queue

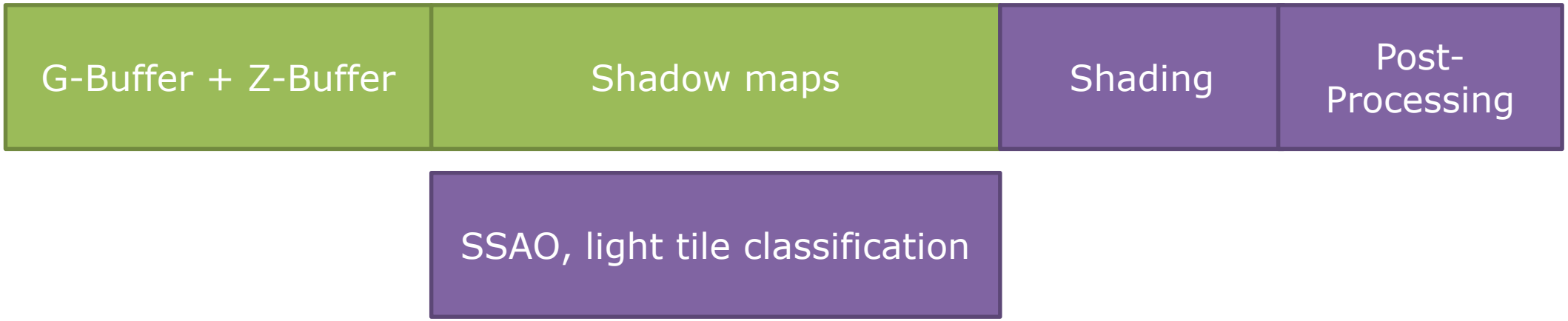
- D3D12 and Vulkan expose multiple queue types: Copy, graphics, compute
  - On Vulkan, check the queue capabilities and how many are present
  - On D3D12, one of every kind is guaranteed to be available – but no scheduling guarantees are given
- Compute queue is getting a lot of good use
- Copy queue is not used much – could use more love

Graphics and Compute

- We see great results from async compute so far
- Run compute load while graphics queue is idle
- We typically see one compute command list running in parallel with one fence for sync
  - That’s fine
  - The more compute the better ☺

Async compute

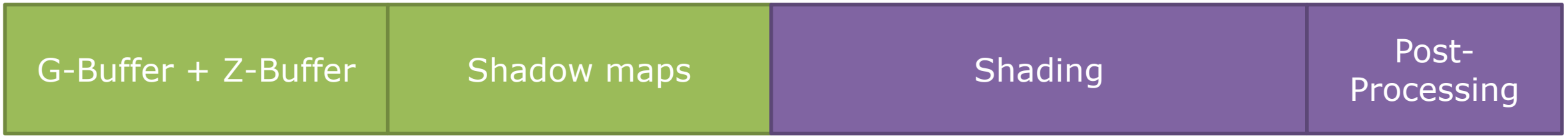
- Pit of success



Different bottlenecks – maximized GPU usage with async

Async compute

- Pit of no success

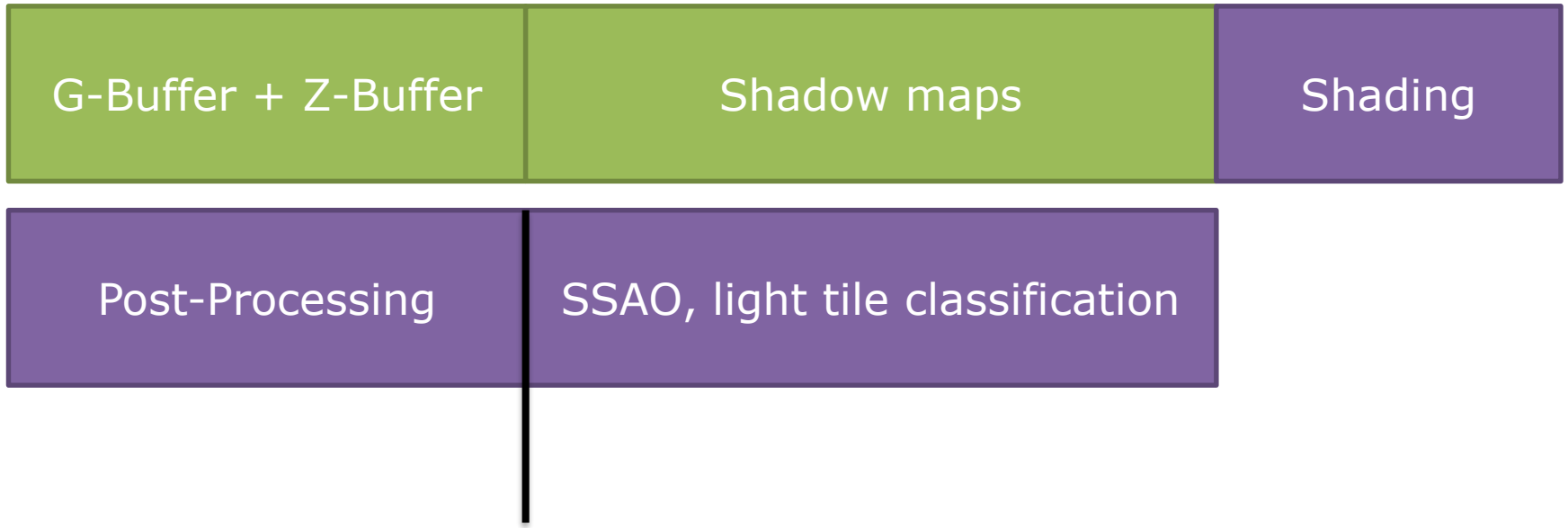


Resource competition – can be worse than running sequentially

Async compute

- Pit of even more success

Design first!



Copy to the rescue?

- Copy queue is low-latency, low-speed, but it’s separate hardware
  - Copy queue is optimized for transfer over PCIe, not for GPU local copies
  - For PCIe, it is the **fastest way** to transfer data
  - Avoid waiting on copy queue from graphics/compute
  - Ideal use of copy queue is streaming data over a few frames
- Haven't seen much use so far
  - Talk to us why?
  - For copying between adapters, copy queue is also best – consider shared swapchain though

Summary: Multi-queue

- Use the compute queue to fill up the GPU
- Use copy queue to saturate PCIe
- Know your frame structure to find the best location to schedule async work

Other issues

Resources

- On average, things work just fine
  - Uploads rarely a problem, but remember to look at the copy queue
  - On-GPU management mostly ok
  - Packing sometimes not as tight as it could be, check alignment!
- For "high-frequency" resources like frame buffers, prefer `CreateCommittedResource` in D3D12
- Lots of issues with residency and budget
  - Time travel back to yesterday and watch Dave Oldcorn's & Stephan Hodes' talk "**Right on Queue - Advanced DirectX12 programming**" [*If time travel is not invented until the talk replace with presentation URL*]
  - It's an ugly topic – too much to cover here. Talk to me afterwards!

Debug runtime & Validation layers

- D3D12 and Vulkan have validation layers
- The driver **does not validate** for performance reasons
- We assume your application is **perfect**
- During development, make sure to pass validation warning/error free
  - If your app doesn't support validation, add support for that now!
  - **Any undefined behavior will bite you**, especially with Vulkan – much wider hardware variety
- Please don't play spec lawyer yourself – if something is unclear or in doubt, contact IHV partner to clarify
  - Spec and validation layers are constantly evolving
  - Various corner cases haven't been fully understood yet

Mysteries that need more R&D

- `ExecuteIndirect`
  - Haven’t seen serious problems with this yet
  - Mostly used for draw auto and dispatch indirect – we expect more crazy use down the line
  - See “**Optimizing the Graphics Pipeline With Compute**” on Friday
- Bundles
  - Not enough game experience yet
  - Unclear how to get performance out of it – we’re still gathering data
- mGPU
  - Not enough game experience yet but in general seems to be “easy” enough
  - Copies through system memory should go on copy queue
  - Shared swapchain is good – but needs Windows 10 1511

Closing remarks

- Vulkan and D3D12 deliver on their promises
  - Require additional thought
  - Just trying to reimplement D3D11 does not provide a benefit!
  - Engines require re-thinking to take advantage of the explicit APIs going forward
- Many driver issues are now app issues
  - Synchronization (barriers!)
  - Memory management (uploads, residency)
  - This means you have the power to fix most issues!

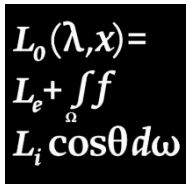
Who's awesome? You're Awesome!

@jasperbekkers

@baldurk

@gwihlidal

@maverikou



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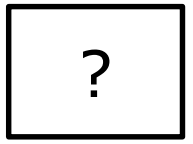
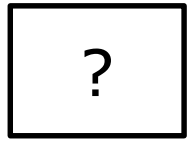


Dean Sekulić



Markus Rogowsky

@dankbaker

Raymund Fülöp

Thanks to Kerbal Space Program to let me use screenshots! Go Jebediah!

AMD