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KHRONOS GROUP

Vulkan®

Introduction to the Crash Diagnostic Layer

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About me

- At LunarG for the past 4 years
  - Validation and the synchronization2 emulation layer
- Ex Kernel Mode Driver dev
  - Early / mid Android era
  - GPU hangs roll down hill
- Ex Graphics Software Architect
  - “Hey HW team, why can’t we have nice things?”
- Lots of non-GPU embedded experience
  - Can you debug with LEDs?

Overview of Crash Diagnostic Layer

- Provides ‘glue code’ for debugging VK_ERROR_DEVICE_LOST
- New addition to the Vulkan SDK
  - Alpha quality!!!
  - Windows and Linux currently supported
- Works on many devices (that support debug extensions)
- Lightweight (~5% perf hit)

What can CDL do?

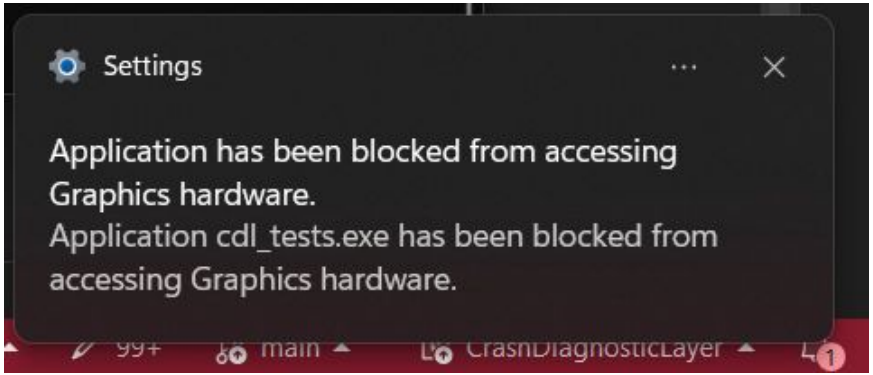
- Track forward progress of queue submission and command buffer processing
- Interpret fault information from the driver
- Manipulate the command stream
  - Add checkpoints, for command buffer forward progress
  - Add pipeline barriers
- Dump state to the filesystem in YAML format
- CANNOT debug within a shader invocation

Extension support

	AMD	ARM	Intel	NVidia	Qualcomm	Samsung
VK_AMD_buffer_marker	✅		✅	✅	✅	✅
VK_AMD_device_coherent_memory	✅					✅
VK_NV_device_diagnostic_checkpoints			✅	✅		
VK_EXT_device_fault	✅	✅			✅	✅
VK_EXT_device_address_binding_report	✅	✅	✅		✅	✅

What happens when a GPU crashes? (user view)

- Error dialog from app, driver, or OS
- Application just vanishes
- Screen goes black momentarily
- Screen goes black forever
- X session gets logged out
- Kernel panic / BSOD
- Device becomes unresponsive and very warm



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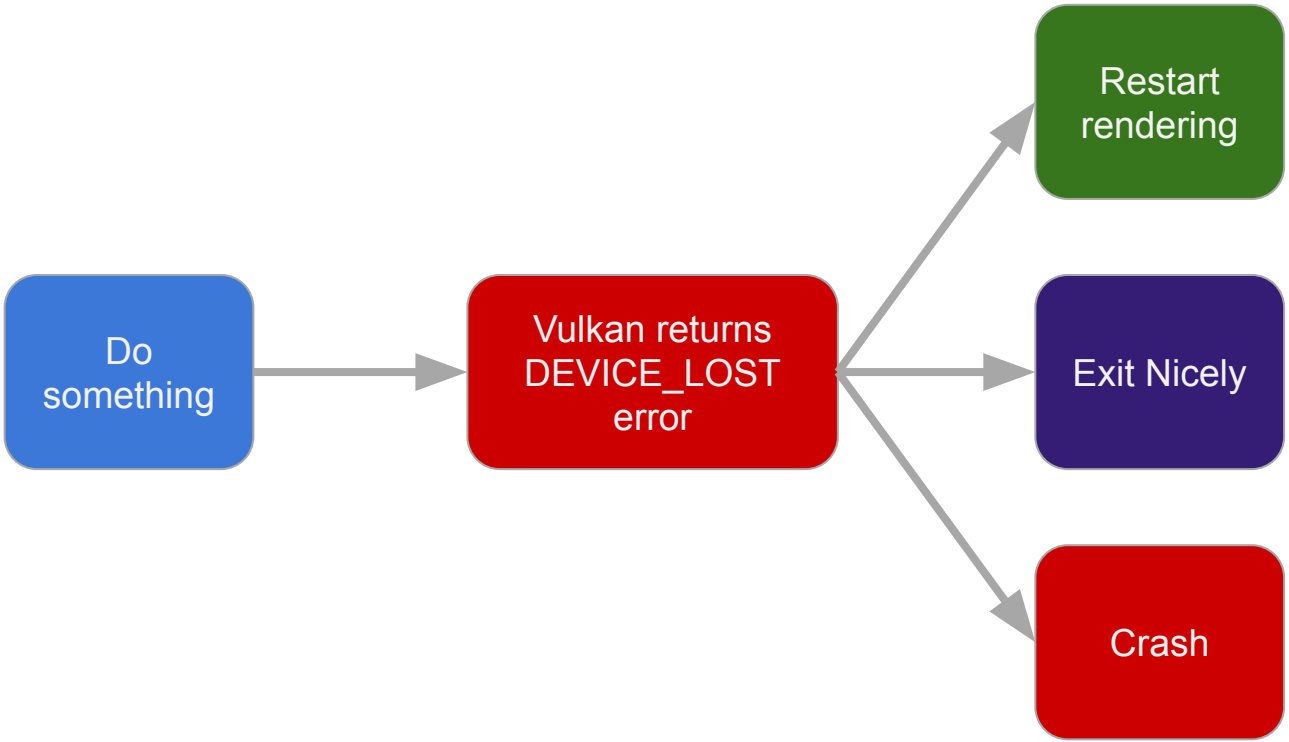
What happens when a GPU crashes? (app view)



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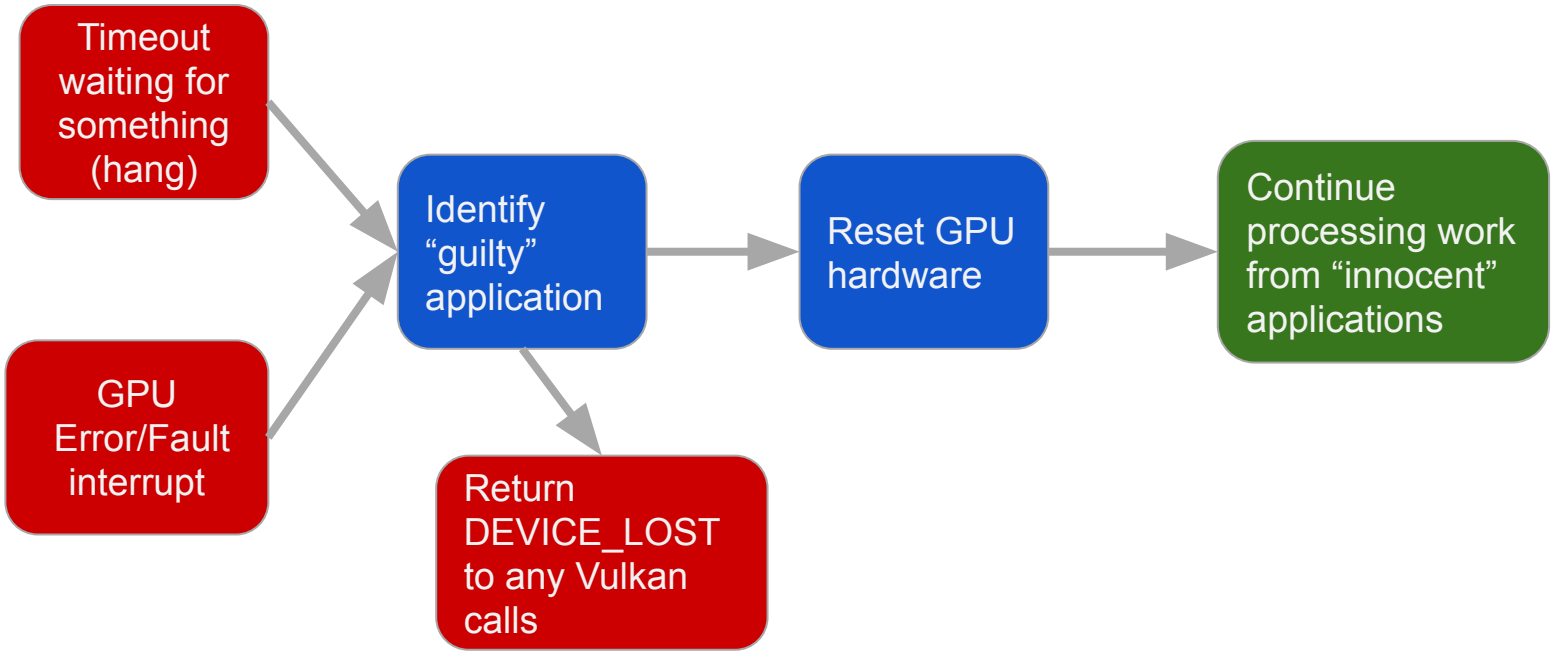
What happens when a GPU crashes? (driver view)



Why is GPU crash debugging so hard?

- Pre-Vulkan graphics APIs didn’t consider crashing possible
  - GPU crash == driver or HW bug! Driver must validate EVERYTHING
  - Full screen games -> No concurrent use of the GPU, no fault recovery features

Why is GPU crash debugging so hard?

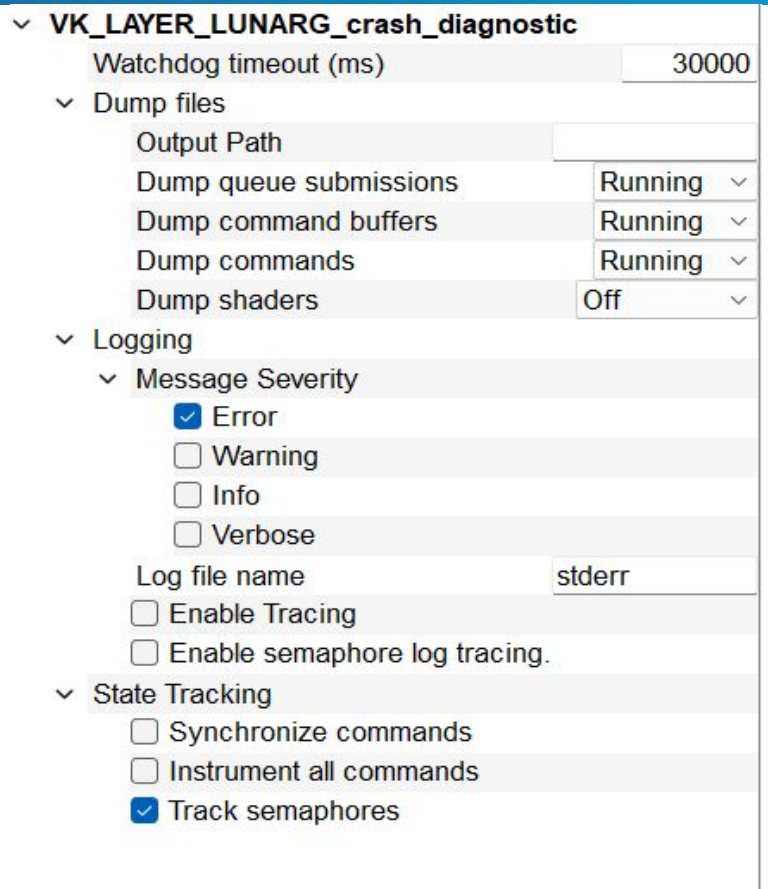
- Massive concurrency
  - How do you single step through 1 million fragment shader invocations?
  - How much state do you save after a crash?
  - Some problems go away when debugging

Why is GPU crash debugging so hard?

- Intellectual property
  - For some GPUs, hardware information is not publicly available
  - Large architecture differences between different GPU designs
  - Debug features aren’t high priority

How to use CDL

- Get the new SDK
- Start vkconfig
- Choose the Crash Diagnostic configuration
- Crash something
- Look at dump files
  - Linux: `~/cdl/…`
  - Windows: `%USERPROFILE%\cdl\...`
- File Issues!



Log message example

```
00:00:00.008 CDL INFO: Version 1.3.289 enabled. Start time tag: 2024-07-03-102527
00:00:00.008 CDL INFO: Begin Watchdog: 30000ms
00:00:00.076 CDL WARNING: No VK_AMD_device_coherent_memory extension, results may not be as accurate as
possible.
00:00:00.076 CDL WARNING: No VK_EXT_device_fault extension, vendor-specific crash dumps will not be
available.
00:00:00.076 CDL WARNING: No VK_EXT_device_address_binding_report extension, DeviceAddress information
will not be available.
00:00:32.236 CDL INFO: Completed sequence number has impossible value: -1 submitted: 4700 VkQueue:
0x00000291204AD320[], VkSemaphore: 0x00000291208C6E70[]
00:00:32.237 CDL INFO: Completed sequence number has impossible value: -1 submitted: 0 VkQueue:
0x00000291206072C0[], VkSemaphore: 0x00000291208C6210[]
00:00:32.237 CDL ERROR: Device error encountered and log being recorded
       Output written to: "C:\\Users\\jgebb\\cdl\\2024-07-03-102527\\cdl_dump.yaml"
```

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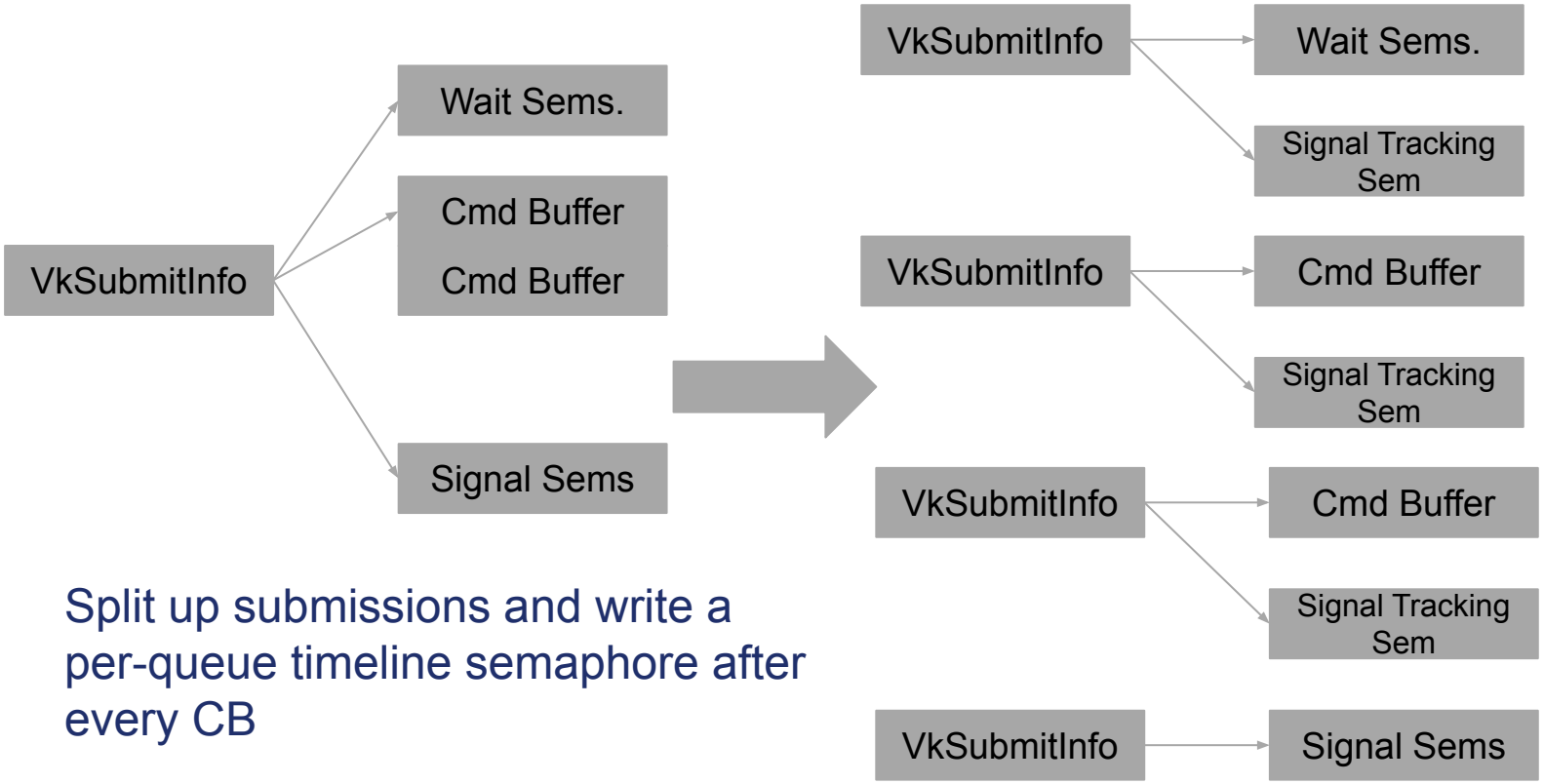
Forward progress

- Evidence that the GPU is still processing work
- In the driver
  - Getting ‘work complete’ interrupts
  - Value of a counter changing in a register or memory counter
  - Lack of fault interrupts
- In an application
  - Various Vulkan wait calls completing
    - But… vkDeviceWaitIdle() and vkQueueWaitIdle() don’t ever time out
  - Timeline semaphore or fence state changing

Watchdog timer

- Monitors application activity and triggers a dump if application appears “stuck”
- Assumption: a non-stuck application will periodically submit new work to the GPU
- Reasons to turn off
  - If using a debugger, the watchdog may fire because the application is stopped
  - Some drivers have their own watchdog timer
  - Non-standard use cases like long running compute jobs

Submission state tracking



Split up submissions and write a per-queue timeline semaphore after every CB

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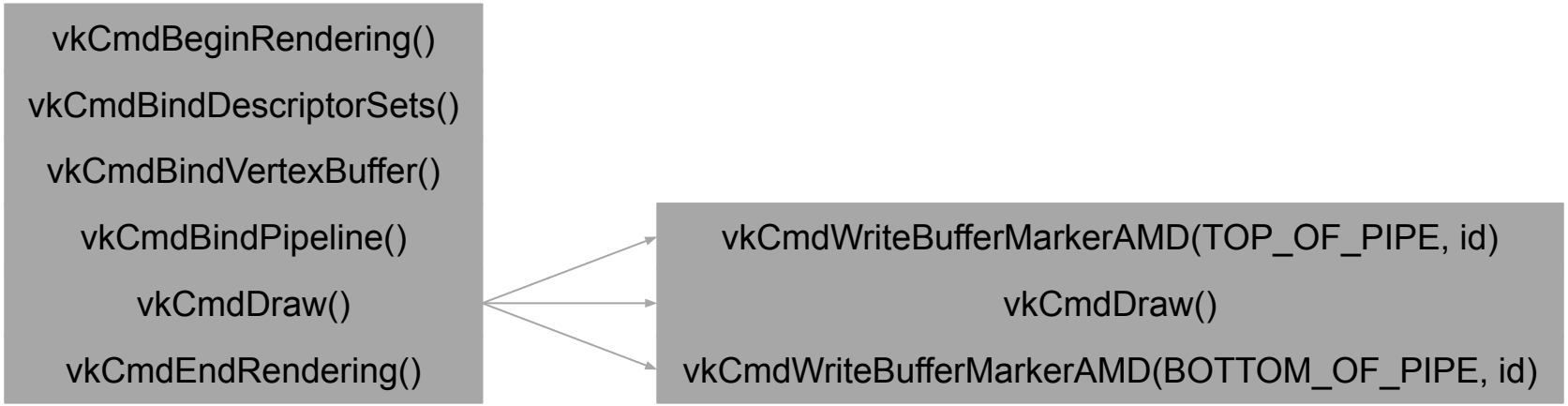
Command Buffer checkpoints

- Reminder: multiple commands can be executing at the same time!
- Counters that track progress within a command buffer
- Write values somewhere after ‘interesting’ commands
- Written at the TOP_OF_PIPE and BOTTOM_OF_PIPE pipeline stages.
  - TOP_OF_PIPE - command has started executing
  - BOTTOM_OF_PIPE - command has finished execution

Command Buffer checkpoints (VK_AMD_buffer_marker)



- Writes arbitrary values to a buffer when the pipeline stage is reached by the command
- Requires `VK_AMD_device_coherent_memory` for accurate reporting during a crash
- But values for completed command buffers are always written

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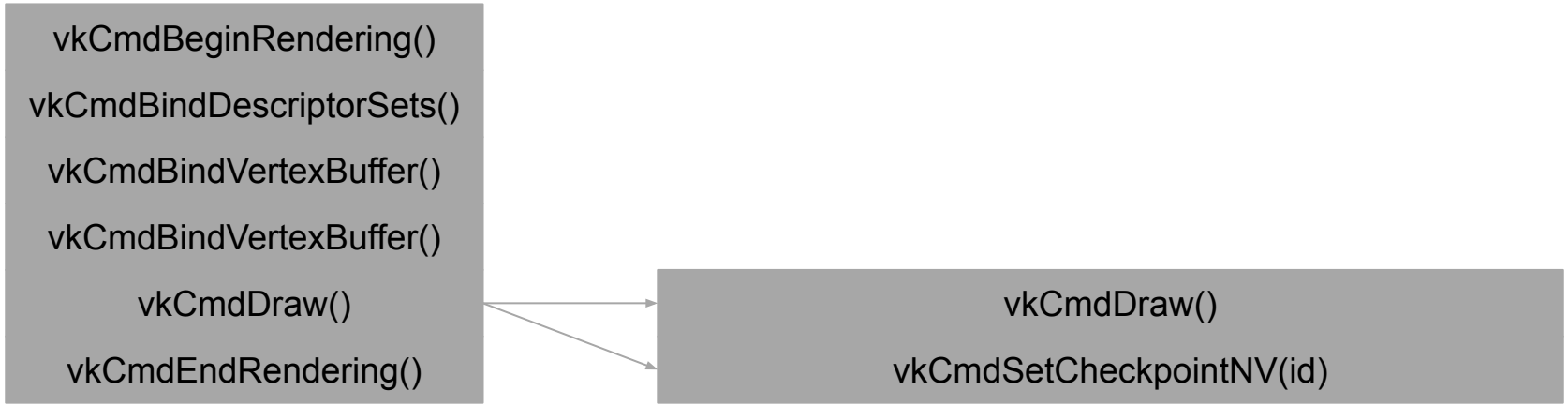
Command Buffer checkpoints (VK_NV_device_diagnostic_checkpoints)



- A single command writes both the TOP_OF_PIPE and BOTTOM_OF_PIPE values
- App can call `vkGetQueueCheckpointDataNV()` to retrieve checkpoint info
- Checkpoints in a crashing CB are usually more accurate
- But checkpoints for completed CBs are not reported

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CDL checkpoint output

```
- # Command:
  id: 17
  checkpointValue: 0x00000012
  name: vkCmdBeginDebugUtilsLabelEXT
  state: COMPLETED
  Labels:
    - Render Mesh
  Parameters: (...)
  message: "'>>>>>>>>>>>>>>> LAST COMPLETE COMMAND <<<<<<<<<<<<<'"

(more commands)

- # Command:
  id: 24
  checkpointValue: 0x00000019
  name: vkCmdDrawIndexed
  state: INCOMPLETE
  labels:
    - Render Mesh
  parameters:
    indexCount: 8511627
    instanceCount: 1
    firstIndex: 0
    vertexOffset: 0
    firstInstance: 0
    internalState:
      pipeline: {}
      descriptorSets: []
    message: "'^^^^^^^^^^^^^^^ LAST STARTED COMMAND ^^^^^^^^^^^^^^'"
```

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GPU faults

- GPU Device Addresses are usually virtual memory
  - Most modern GPUs have some sort of MMU
  - Page faults are generated for invalid memory accesses
- VK_EXT_device_fault
  - Provides details about GPU page faults
  - Faulting address range, type of memory access (read, write, execute)
  - Can provide vendor specific fault information
- VK_EXT_device_address_binding_report
  - Provides notifications about changes to the GPU address space
  - Includes both user-visible objects (eg. buffer, image) and internal driver objects

CDL Device Fault output - buffer overrun

```
DeviceFaultInfo:
   description: GPU fault
   faultAddressRanges:
     - type: Invalid Read
       begin: 0x000000035330A600
       end: 0x000000035330AFFF
       priorAddressRecord:
         begin: 0x00000003531B4D00
         end: 0x000000035330A600
         type: VkDeviceMemory
         handle: 0x000001CDA3359F10[]
         currentlyBound: true
```

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CDL Device Fault output - use after free

```
DeviceFaultInfo:
   description: GPU fault
   faultAddressRanges:
     - type: Invalid Read
       begin: 0x00000003531B4D00
       end: 0x00000003531B4DFF
       matchingAddressRecords:
         begin: 0x00000003531B4D00
         end: 0x000000035330A600
         type: VkDeviceMemory
         handle: 0x000001CDA3359F10[]
         currentlyBound: false
```

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CDL Device Fault - bad address

```
DeviceFaultInfo:
   description: GPU fault
   faultAddressRanges:
     - type: Invalid Read
       begin: 0x00000BADDEADB000
       end: 0x00000BADDEADBFFF
       priorAddressRecord:
         begin: 0x00000003531B4D00
         end: 0x000000035330A600
         type: VkDeviceMemory
         handle: 0x000001CDA3359F10[]
         currentlyBound: true
```

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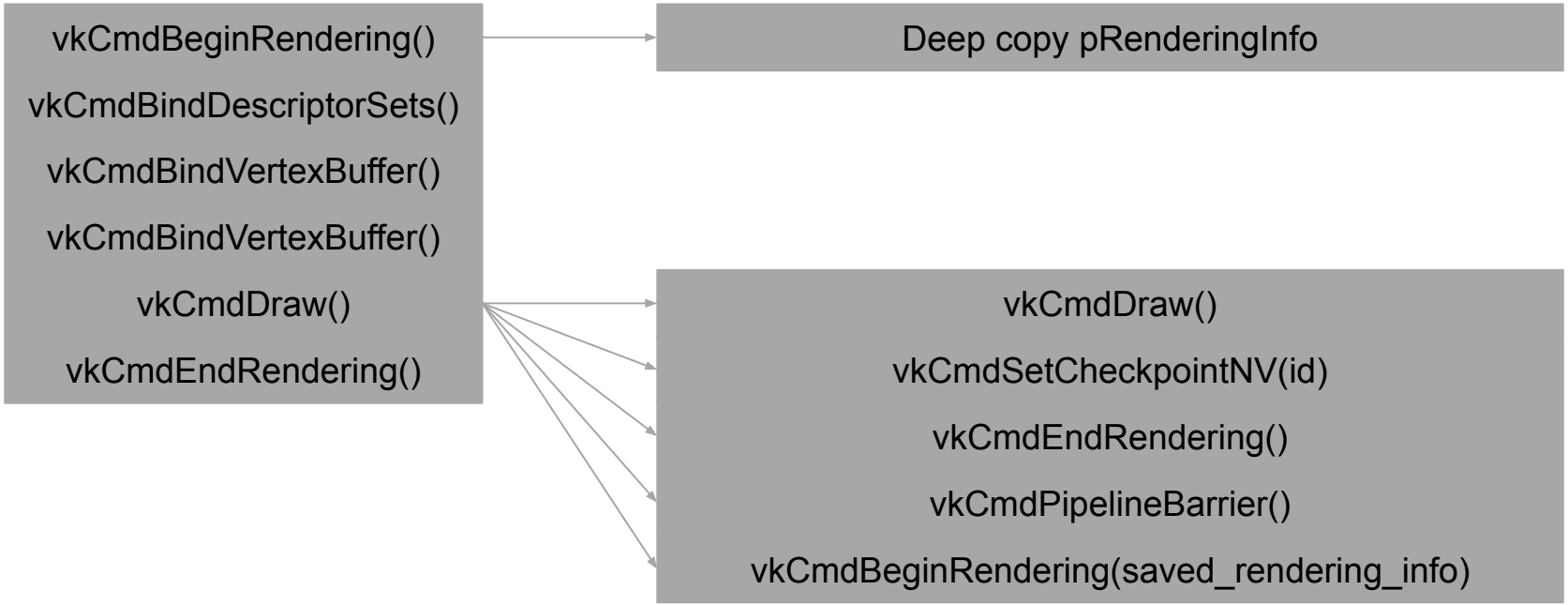
Sync after commands

- Insert a pipeline barrier after each checkpoint
  - `srcStageMask = dstStageMask = ALL_COMMANDS`
  - `srcAccessMask = MEMORY_WRITE, dstAccessMask = MEMORY_READ`
- This limits how many commands can execute in parallel
- In one sample trace, this reduces the number of number of running commands from ~180 to 1
- This will make some GPU crashes stop reproducing, which likely means the application is missing synchronization
- Currently only works with dynamic rendering

Sync after commands



Debug utils

- CDL supports `VK_EXT_debug_utils` and `VK_EXT_debug_marker`
- Object names are printed in the dump file
- Command labels are printed for every command
- Log messages can be sent to `VK_EXT_debug_utils` or `VK_EXT_debug_report` message callbacks

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Thank you!

- Demo at the Khronos Networking Reception
- Included in the 1.3.290 SDK
- Code & Issues at https://github.com/LunarG/CrashDiagnosticLayer
- Thank you to the Google Stadia Graphics Flight Recorder

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