Using Vulkan Validation Effectively

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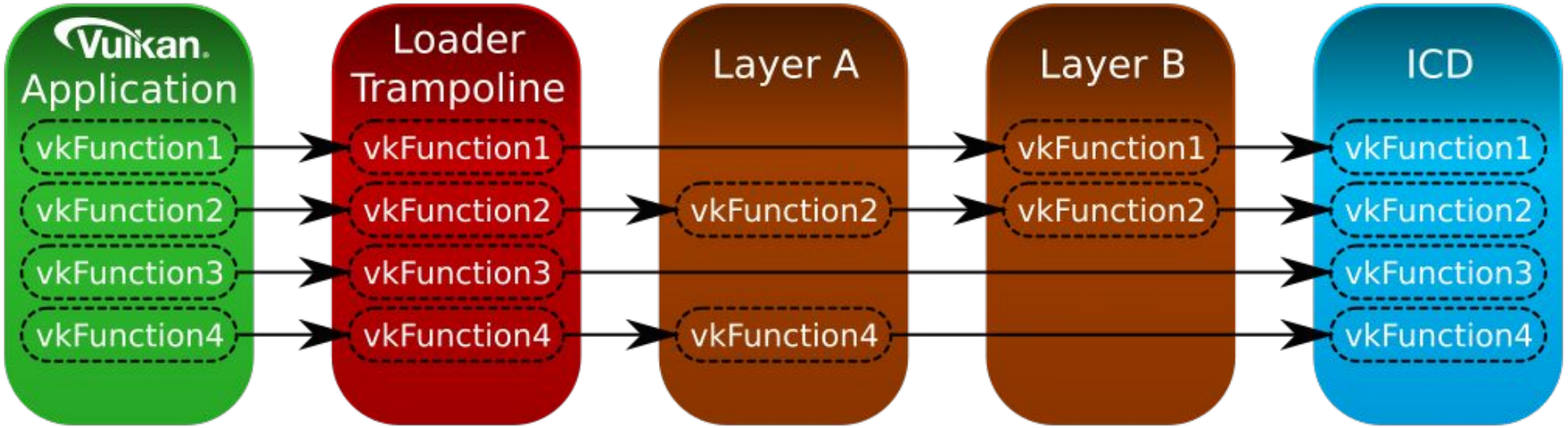
Agenda

- What the validation does and how it benefits developers
- How to interpret and fix validation errors
- Configuration options to improve productivity
- Using the debug utilities extension
- Current limitations of validation
- Recent and upcoming improvements

What is the Vulkan Validation Layer?

- A shared library containing almost all error checking for Vulkan
- OpenGL had many error code checks that drivers had to implement
  - Checks always enabled in drivers -> useless CPU overhead
  - Most checking was the similar in all drivers -> duplicated effort
  - Over time, OpenGL drivers added non-standard ways to disable this error checking in production code.
- Vulkan defined the Loader/Layer Interface to allow:
  - Validation during development only, no CPU overhead in released applications
  - Reuse of common checking code
  - Other types of tooling that wasn't defined during specification development
- *Historical note: At one time there were many separate validation layers, hence the plural name of the Vulkan-ValidationLayers repository.*

Vulkan Loader / Layer Interface



Attend the Vulkan-Loader presentation later today for more details

Types of errors

- Usage - developer is using an API incorrectly
  - `memcpy(NULL, src_buffer, 100);`
  - Will almost always crash, because copying into the NULL address is an error
  - Vulkan Validation is supposed to find errors of this type
- Runtime - unsuccessful interaction between application and its environment
  - `ptr = calloc(1ULL << 31, 8);`
  - Allocating 4Gb *might* succeed or fail, it will depend on the current state of the system
  - Validation can help find some, but not all, of these errors (such as exceeding device limits)
  - If an API call returns a VkResult, you should check it and handle errors.
- Suboptimal usage of the API
  - `ptr = calloc(0, 8);`
  - “If size is zero, the behavior is implementation defined (null pointer may be returned, or some non-null pointer may be returned that may not be used to access storage)” cppreference.com”
  - You cannot store anything into a 0 byte buffer, so why try allocate it?
  - Best Practices validation covers checking such as this

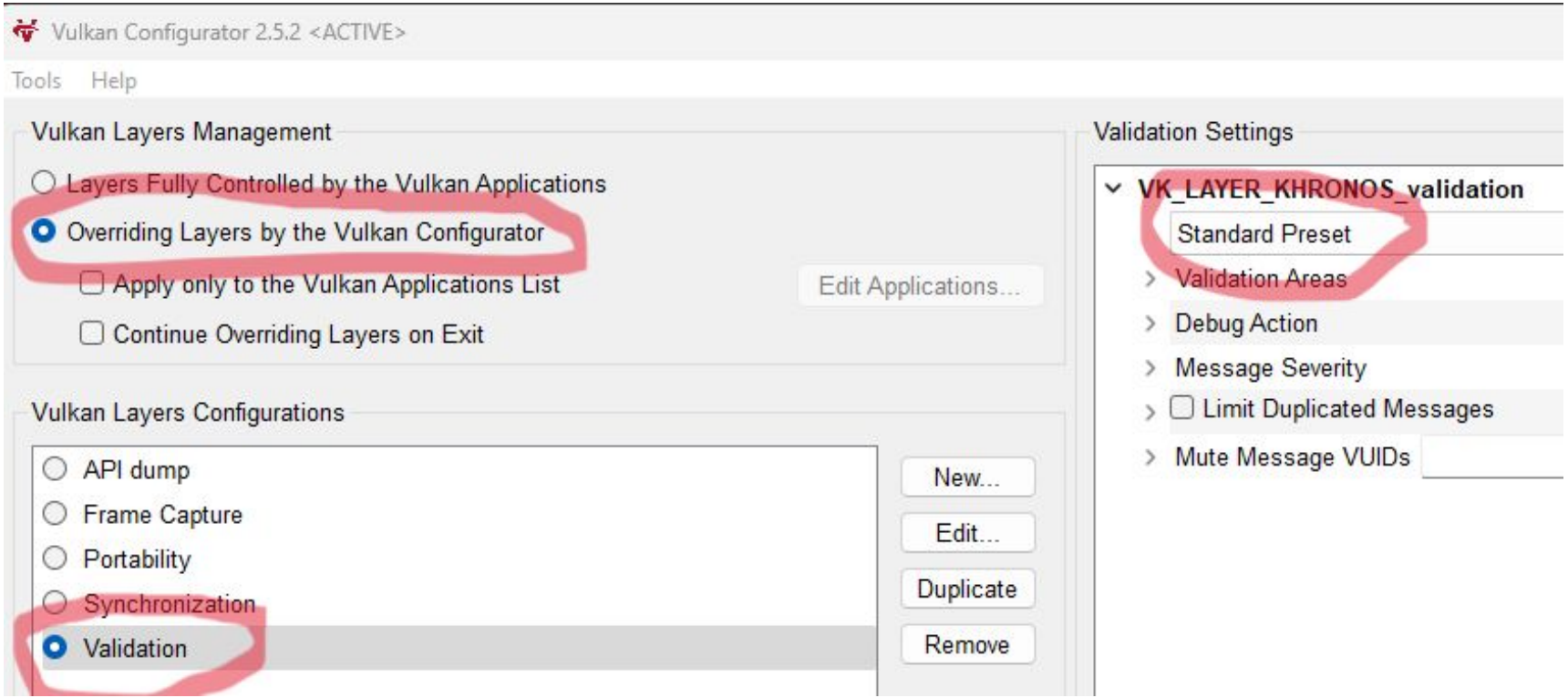
Validation Quick Start

- Install the Vulkan SDK or OS-provided packages
- Run vkconfig (see next slide)
- From a shell:

```
export VK_INSTANCE_LAYERS=VK_LAYER_KHRONOS_validation
./your-application
```

- Note: for non-standard installs you may need to set `VK_LAYER_PATH`
  - It needs to be set to the directory containing `VkLayer_khronos_validation.json`
- You can also enable validation when calling vkCreateInstance()
  - Add the layer name to `VkInstanceCreateInfo::ppEnabledLayerNames`

Validation Quick Start (Vulkan Configurator)



An example error: vkcube –use_staging

I added an error to a portion of the vkcube source:

```
VkBufferImageCopy copy_region = {
    .bufferOffset = 0,
    .bufferRowLength = demo->staging_texture.tex_width*2, // ERROR!
    .bufferImageHeight = demo->staging_texture.tex_height,
    .imageSubresource = {VK_IMAGE_ASPECT_COLOR_BIT, 0, 0, 1},
    .imageOffset = {0, 0, 0},
    .imageExtent = {demo->staging_texture.tex_width, demo->staging_texture.tex_height, 1},
};
vkCmdCopyBufferToImage(demo->cmd, demo->staging_texture.buffer, demo->textures[i].image,
                       VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL, 1, &copy_region)
```

Validation Output: Error Message

```
VUID-vkCmdCopyBufferToImage-pRegions-00171(ERROR / SPEC): msgNum: 1867332608 - Validation Error: [
VUID-vkCmdCopyBufferToImage-pRegions-00171 ] Object 0: handle = 0x56313fd28a00, type =
VK_OBJECT_TYPE_COMMAND_BUFFER; Object 1: handle = 0xd175b40000000013, type = VK_OBJECT_TYPE_BUFFER; |
MessageID = 0x6f4d3c00 | vkCmdCopyBufferToImage: pRegion[0] is trying to copy  523264 bytes plus 0 offset
to/from the VkBuffer (VkBuffer 0xd175b40000000013[]) which exceeds the VkBuffer total size of 262144 bytes.
The Vulkan spec states: srcBuffer must be large enough to contain all buffer locations that are accessed
according to Buffer and Image Addressing, for each element of pRegions
(https://www.khronos.org/registry/vulkan/specs/1.3-extensions/html/vkspec.html#VUID-vkCmdCopyBufferToImage-pR
egions-00171)
    Objects: 2
        [0] 0x56313fd28a00, type: 6, name: NULL
        [1] 0xd175b40000000013, type: 9, name: NULL
```

- `demo->staging_texture.tex_width` is 262144 bytes and the staging buffer was created based on that size.

Validation Output: Valid Usage ID (VUID)

```
VUID-vkCmdCopyBufferToImage-pRegions-00171(ERROR / SPEC): msgNum: 1867332608 - Validation Error: [
VUID-vkCmdCopyBufferToImage-pRegions-00171 ] Object 0: handle = 0x56313fd28a00, type = VK_OBJECT_TYPE_COMMAND_BUFFER;
Object 1: handle = 0xd175b40000000013, type = VK_OBJECT_TYPE_BUFFER; | MessageID = 0x6f4d3c00 | vkCmdCopyBufferToImage:
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(https://www.khronos.org/registry/vulkan/specs/1.3-extensions/html/vkspec.html#VUID-vkCmdCopyBufferToImage-pRegions-00171
)
    Objects: 2
        [0] 0x56313fd28a00, type: 6, name: NULL
        [1] 0xd175b40000000013, type: 9, name: NULL
```

- Almost every error in Vulkan has a Valid usage ID: VUID-*
  - Unique, automatically generated number in the specification text
  - msgNum / MessageID is a hash of the VUID string, used for handling duplicate messages
- Some errors types are not in the specification
  - UNASSIGNED-*: possible error identified by validation developers, should be moved to spec
  - UNASSIGNED-BestPractices-*: best practices warnings
  - SYNC-*: synchonization validation error

Validation Output: Object handles

```
VUID-vkCmdCopyBufferToImage-pRegions-00171(ERROR / SPEC): msgNum: 1867332608 - Validation Error: [
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```

Validation Output: Spec reference

```
VUID-vkCmdCopyBufferToImage-pRegions-00171(ERROR / SPEC): msgNum: 1867332608 - Validation Error: [
VUID-vkCmdCopyBufferToImage-pRegions-00171 ] Object 0: handle = 0x56313fd28a00, type =
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    Objects: 2
        [0] 0x56313fd28a00, type: 6, name: NULL
        [1] 0xd175b40000000013, type: 9, name: NULL
```

- This takes you back to the section of the spec, for more information

Fixing errors

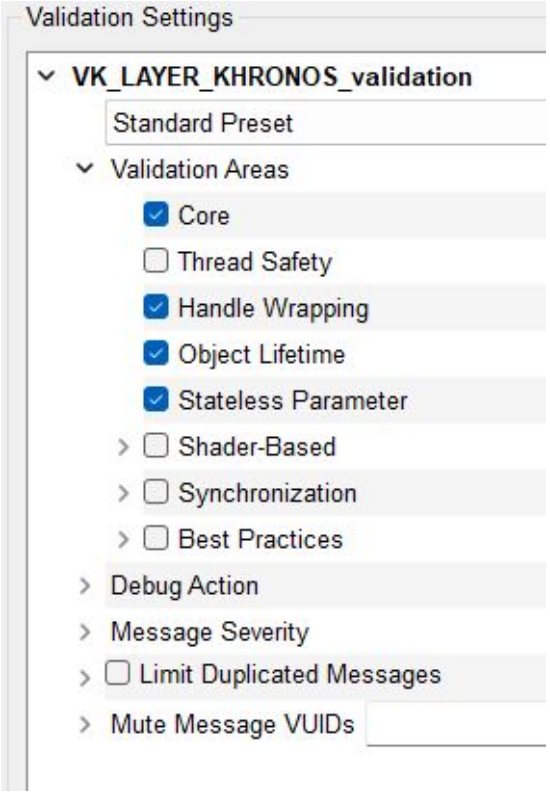
- Fix the first error message first
  - Similar to with C/C++ compiler errors, the first error may cause subsequent errors
- Run in a debugger and use the Break Debug Action
  - Almost all error checking occurs immediately in each Vulkan API call
  - Stack trace will take you to the part of your code causing the error
- Search in the Vulkan-ValidationLayers source for the VUID string to see how it is validated
- Add object names and command buffer labels with the debug utils extension

Configuration options

- Configuring validation is complicated!
  - This section describes some useful settings, not an exhaustive guide
  - See the documentation
- Options:
  - UI: Vulkan Configurator (vkconfig) - **separate presentation later today!**
  - Config file: vk_layer_settings.txt
  - Programatically: VK_EXT_layer_settings
  - Environment variables (not all options supported)

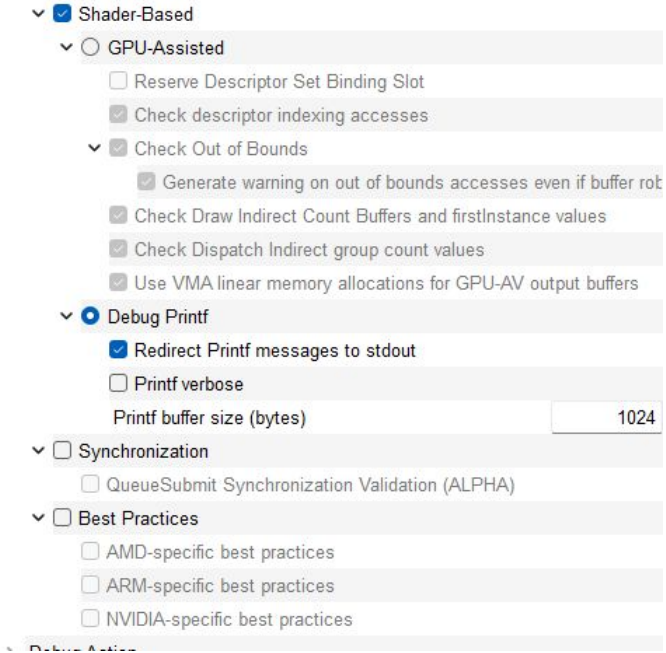
Configuration: Validation areas (1)

- Validation is split up into several areas to reduce performance overhead
- Stateless
  - Checks simple VUIDs that don't require expensive state tracking
  - In Vulkan spec:Valid Usage (Implicit) and a few others
- Core
  - Most VUIDs checked here
- Thread Safety
  - Checks external synchronization requirements
- Handle Wrapping
  - Prevents handle reuse bugs
- Object Lifetime
  - Detects use of destroyed objects



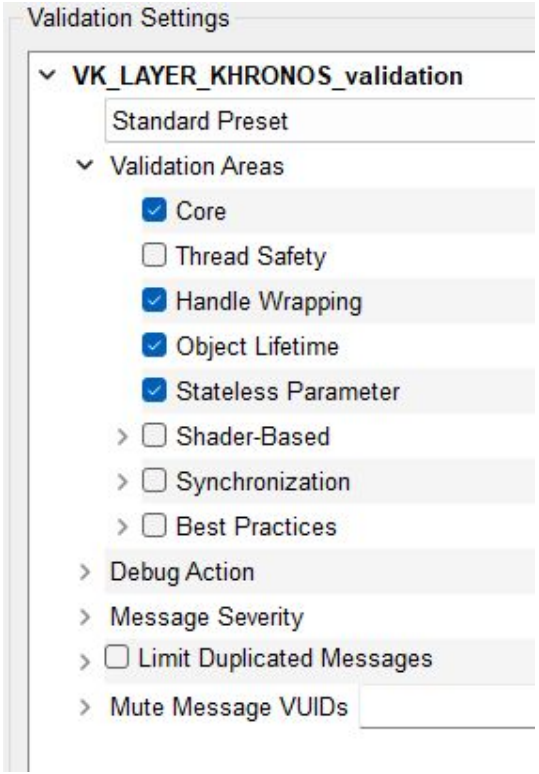
Configuration: Validation areas (2)

- Shader Based: GPU-Assisted
  - AKA: GPU-AV
  - Instruments SPIR-V to detect problems in shaders
  - Descriptor indexing
  - Buffer Device Address
  - Not supported on Mac
- Shader Based: DebugPrintf
  - Adds printf() functionality to shaders
  - Not supported on Mac
- Synchronization
  - Checks for correct Execution and Memory Dependencies
  - vkCmdPipelineBarrier(), VkEvents, etc.
- Best Practices
  - Performance warnings
  - Mixture of common and vendor-specific checks



Configuration: Validation area settings

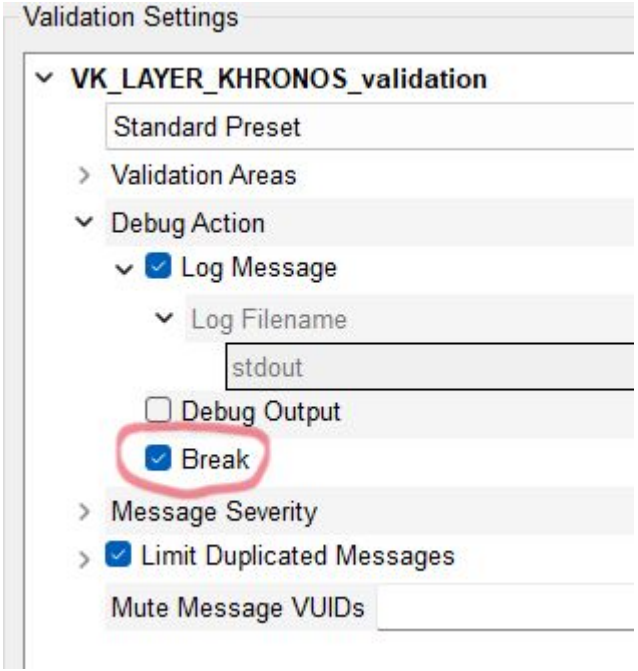
- **Use vkconfig presets**
  - Commonly used and tested configurations
- In vk_layer_settings.txt
  - khronos_validation.enables
  - khronos_validation.disables
- Environment variables
  - VK_LAYER_ENABLES and VK_LAYER_DISABLES
- **Don’t enable all areas at once (it will be slow)**, pick one of
  - Core
  - Shader-Based
  - Synchronization
  - Best Practices
- Fix errors in each area, then run Core / Standard Preset again



Configuration: Break on error

- Will stop program when an error is detected
  - Calls `DebugBreak();` or `raise(SIGTRAP);`

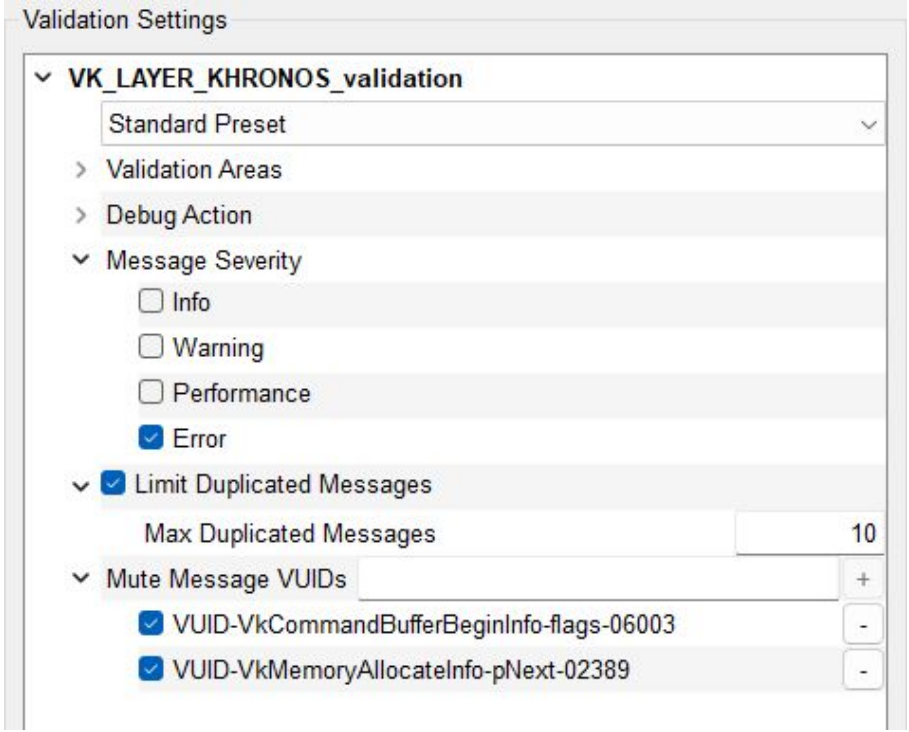
```
# vk_layer_settings.txt
khronos_validation.debug_action = VK_DBG_LAYER_ACTION_BREAK
```



Configuration: Limit repeated messages

- Limit message severity
  - Almost all messages are ‘Error’
  - Except Best Practices, which is ‘Performance’ and ‘Warning’
- Limit times a message is repeated
  - Exact VUID string must match to count as a repeat
  - Env var: VK_LAYER_DUPLICATE_MESSAGE_LIMIT
- Suppress individual error messages entirely
  - Env var: VK_LAYER_MESSAGE_ID_FILTER

```
# vk_layer_settings.txt
khronos_validation.report_flags = error
khronos_validation.enable_message_limit = true
khronos_validation.duplicate_message_limit = 10
khronos_validation.message_id_filter = <comma
separated list>
```



Debug Utilities Extension

- Debug utilities extension VK_EXT_debug_utils
- Implemented by Vulkan-ValidationLayers
- Provides the ability to attach user-defined names to
  - Vulkan Objects
  - Sequences of commands recorded in Command Buffers
  - Queue submissions
- Names show up in validation error messages and are also used by other tools such as RenderDoc
- Allows applications to register their own validation error handling callback

Debug Utilities extension: Object naming

```
typedef struct VkDebugUtilsObjectNameInfoEXT {
    VkStructureType    sType;
    const void*        pNext;
    VkObjectType       objectType;
    uint64_t           objectHandle;
    const char*        pObjectName;
} VkDebugUtilsObjectNameInfoEXT;

VkResult vkSetDebugUtilsObjectNameEXT(
    VkDevice device,
    const VkDebugUtilsObjectNameInfoEXT*);
```

- Allows a name to be attached to any vulkan object
- Can help you identify what part of your code is causing an error.
- Contents of `pObjectName` is copied to internal storage.

```
Objects - 2
      Object[0] - VK_OBJECT_TYPE_COMMAND_BUFFER, Handle 0x5566702c9f60, Name "PrepareCB"
      Object[1] - VK_OBJECT_TYPE_BUFFER, Handle 0x9fde6b0000000014, Name "TexBuffer(lunarg.ppm)"
```

Debug Utilities extension: Command buffer labels

```
typedef struct VkDebugUtilsLabelEXT {
    VkStructureType    sType;
    const void*        pNext;
    const char*        pLabelName;
    float              color[4];
} VkDebugUtilsLabelEXT;

void vkCmdBeginDebugUtilsLabelEXT(
    VkCommandBuffer commandBuffer,
    const VkDebugUtilsLabelEXT* pLabelInfo);
```

- Allows a name to be attached to a sequence of commands in a command buffer
- Stack-like, multiple labels can be present at once
  - `vkCmdBeginDebugUtilsLabelEXT()` pushes
  - `vkCmdEndDebugUtilsLabelEXT()` pops
- The `color` field is used by tools like RenderDoc
- See also `vkQueueBeginDebugUtilsLabelEXT()`
- Not printed by default error handler!

```
Command Buffer Labels - 3
     Label[0] - StagingBufferCopy(0) { 0.000000, 0.000000, 0.000000, 0.000000}
     Label[1] - StagingTexture(0) { 0.000000, 0.000000, 0.000000, 0.000000}
     Label[2] - Prepare { 0.000000, 0.000000, 0.000000, 0.000000}
```

Debug Utilities extension: Custom message callback

- Set up by calling `vkCreateDebugUtilsMessengerEXT()`
  - Your callback receives a complex struct for each error
  - Same mechanism used for default error logging
- Make your own message format
- Add messages to application logging stream
- Send messages to somewhere other than the console
- Trigger failures in your unit test framework
- Filter out unwanted messages (NOT recommended, built-in filtering is faster)

Debug Utils: vkcube code

```
demo_push_cb_label(demo, demo->cmd, NULL, "StagingBufferCopy(%d)", i);
VkBufferImageCopy copy_region = {
    .bufferOffset = 0,
    .bufferRowLength = demo->staging_texture.tex_width*2, // ERROR!
    .bufferImageHeight = demo->staging_texture.tex_height,
    .imageSubresource = {VK_IMAGE_ASPECT_COLOR_BIT, 0, 0, 1},
    .imageOffset = {0, 0, 0},
    .imageExtent = {demo->staging_texture.tex_width,
                    demo->staging_texture.tex_height, 1},
};
vkCmdCopyBufferToImage(demo->cmd, demo->staging_texture.buffer,
                       demo->textures[i].image,
                       VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL, 1, &copy_region);
demo_pop_cb_label(demo, demo->cmd); // "StagingBufferCopy"
```

Debug Utilities extension: vkcube error callback

```
ERROR : VALIDATION - Message Id Number: 1867332608 | Message Id Name:
VUID-vkCmdCopyBufferToImage-pRegions-00171
      Validation Error: [ VUID-vkCmdCopyBufferToImage-pRegions-00171 ] Object 0: handle = 0x562780095ca0,
name = PrepareCB, type = VK_OBJECT_TYPE_COMMAND_BUFFER; Object 1: handle = 0x9fde6b0000000014, name =
TexBuffer(lunarg.ppm), type = VK_OBJECT_TYPE_BUFFER; | MessageID = 0x6f4d3c00 | vkCmdCopyBufferToImage:
pRegion[0] is trying to copy  523264 bytes plus 0 offset to/from the VkBuffer (VkBuffer
0x9fde6b0000000014[TexBuffer(lunarg.ppm)]) which exceeds the VkBuffer total size of 262144 bytes. The Vulkan
spec states: srcBuffer must be large enough to contain all buffer locations that are accessed according to
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(https://www.khronos.org/registry/vulkan/specs/1.3-extensions/html/vkspec.html#VUID-vkCmdCopyBufferToImage-pR
egions-00171)

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            Object[0] - VK_OBJECT_TYPE_COMMAND_BUFFER, Handle 0x562780095ca0, Name "PrepareCB"
            Object[1] - VK_OBJECT_TYPE_BUFFER, Handle 0x9fde6b0000000014, Name "TexBuffer(lunarg.ppm)"

      Command Buffer Labels - 3
            Label[0] - StagingBufferCopy(0) { 0.000000, 0.000000, 0.000000, 0.000000}
            Label[1] - StagingTexture(0) { 0.000000, 0.000000, 0.000000, 0.000000}
            Label[2] - Prepare { 0.000000, 0.000000, 0.000000, 0.000000}
```
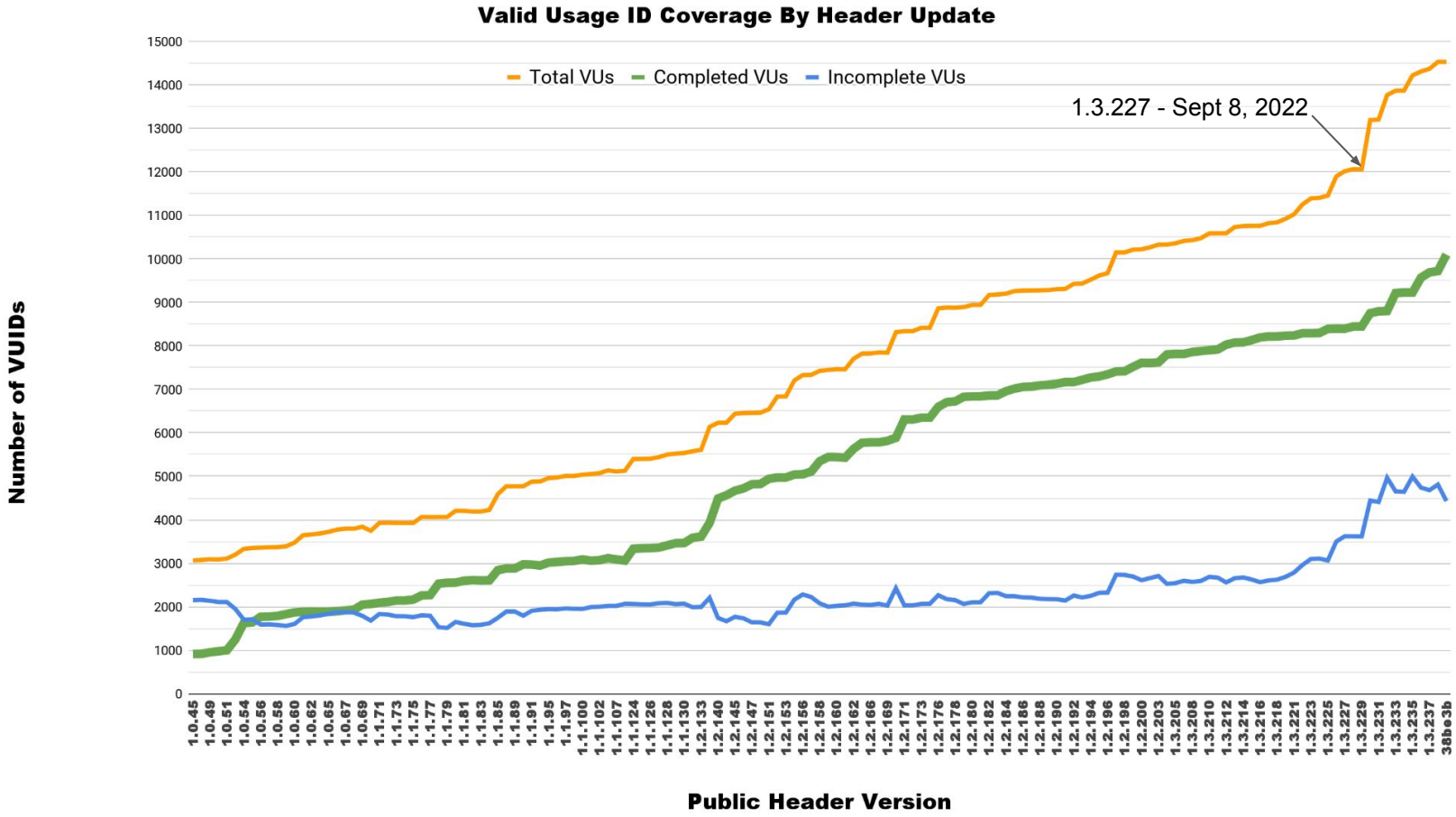

Limitations

- Extensions and VUIDs are constantly added
  - Currently there are 14000+ VUIDs!
- Sometimes validating an extension is more difficult than writing or implementing it.
- Vendor extension validation is entirely up to the vendor
- Triage
  - Try to ensure new KHR or EXT extensions are fully validated
  - Respond to ‘Incomplete’ Issues to implement VUIDs that are needed by the community
  - Please submit an Issue on github if we’re missing something you need!

Limitations: Not all VUIDs checked



Limitations: Extension VUID coverage

EXTENSION	CHECKED	TOTAL	COVERAGE
core	1879	2359	79.65%
VK_VERSION_1_3	1716	2332	73.58%
VK_NV_ray_tracing	953	1555	61.29%
VK_VERSION_1_1	960	1292	74.30%
VK_EXT_mesh_shader	295	1190	24.79%
VK_NV_mesh_shader	491	1178	41.68%
VK_KHR_ray_tracing_pipeline	608	1060	57.36%
VK_VERSION_1_2	740	1004	73.71%
VK_KHR_acceleration_structure	516	912	56.58%
VK_KHR_dynamic_rendering	408	601	67.89%
VK_KHR_synchronization2	473	598	79.10%
VK_KHR_surface	418	547	76.42%
VK_KHR_copy_commands2	345	386	89.38%
VK_EXT_transform_feedback	233	319	73.04%
VK_EXT_extended_dynamic_state	166	316	52.53%

Limitations: Some VUIDs hard to check

- VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT_EXT (aka ‘bindless’)
  - Only descriptors ‘dynamically used’ by a shader must be valid
  - Bindless descriptor sets may contain 1 million+ descriptors
  - But each shader invocation will only use a few of them
  - Descriptor index is calculated in the shader
    - CPU side code doesn’t know which descriptors to validate.
- Validating all descriptors results in large CPU overhead
- Many false positives due to validating unused descriptors
- Need to use GPU-AV to improve validation

Recent Improvements (last 12 months)

- Validation for new extensions
  - Video extensions, VK_EXT_mesh_shader, VK_KHR_descriptor_buffer, VK_KHR_dynamic_rendering, VK_EXT_pipeline_library, and more
  - Big THANK YOU to those who wrote validation for these extensions
- Synchronization validation Phase II
  - Multi-CommandBuffer and multi-Queue checking
- Increased SPIR-V runtime validation
- Improved performance for multithreaded applications
- GPU-AV performance improvements
- Adding UNASSIGNED validation errors to the spec (ongoing)
- Upgrade from C++11 to C++17

Upcoming Improvements

- Better descriptor indexing checking using GPU-AV
  - Improve performance
  - Close gaps in error checking
- Better handling of timeline semaphores and ‘execution-time’ VUIDs
- Shader validation improvements
- Again, please submit an Issue on github if we’re missing something you need!
  - We also accept Pull Requests :)

Questions?

https://www.lunarg.com/news-insights/white-papers/using-vulkan-validation-effectively-feb2023/

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- Survey results are tabulated
- Shared with the Vulkan Working Group
- Actions are assigned
- Results are reported

Survey closes February 27, 2023

https://www.surveymonkey.com/r/PVM92RH