SIGGRAPH 2024
DENVER+ 28 JUL — 1 AUG

KHRONOS GROUP

Vulkan®

Vulkan SDK
Where We Started
Where We are Going

Karen Ghavam
CEO and Engineering Director
LunarG, Inc

Today's Talk

- A Historical Look – Vulkan API and the Vulkan SDK
- Developer Tools – Challenges, Successes, and the Future

A Brief History

LUNARG

A Brief History of Vulkan

KHRONOS GROUP

August 2014 — March 2015 — February 2016

SIGGRAPH in Vancouver

- Khronos call for participation in defining the "glNext" API
  - OpenGL, Direct3D were mature with minor feature updates
  - A need to scrape away the abstractions included in OpenGL and Direct3D
  - Mantle, Direct3D 12, Metal all demonstrated the needs of the future
- Features
  - High-efficiency access to graphics and compute on modern GPUs
  - Abstraction removal – explicit GPU and CPU control over workloads
  - Multithreading-friendly API with reduced overhead
  - Common shader programming intermediate language (SPIR-V)

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A Brief History of Vulkan

First Vulkan POC

- Vulkan ILO Driver (Linux, Intel GPU)
- Valve Source2 Engine
- Key feedback for the Vulkan 1.0 Specification

A Brief History of Vulkan

GDC

- Technical Previews
- Valve Source2 Engine
- Vulkan ILO Driver

A Brief History of Vulkan

KHRONOS GROUP

August 2014 — March 2015 — February 2016

Public Launch

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Vulkan SDK – A Retrospective

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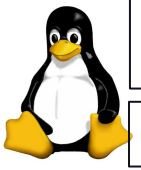
The Vulkan SDK (Today)

	Vulkan Loader	vkconfig	Validation Layer	
SPIR-V Optimizer	SPIR-V Tools	Crash Diagnostic Layer	vulkaninfo	Emulation Layers
shaderc	SPIR-V Validator	Profiles Toolset	GPUInfo	VOLK
DXC	SPIR-V Reflect	apidump	GFX Reconstruct	VKVIA
SPIR-V Cross	glslang	Vulkan-HPP	Screenshot	VMA
MoltenVK	SPIR-V Visualizer	SDL	Monitor	GLM

License Registry

Ubuntu Packages



Tarball

Windows

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The Vulkan SDK (2016)

2016

Vulkan 1.0

Vulkan Loader

SPIR-V Tools

Validation Layer

vulkaninfo

Only SPIR-V assembler and disassembler

apidump

glslang

GLSL to SPIR-V

GLM

Tarball

Windows

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The Vulkan SDK (2017)

Vulkan Loader

Validation Layer

SPIR-V Optimizer

SPIR-V Tools

vulkaninfo

shaderc

SPIR-V Validator

apidump

VKVIA

SPIR-V Cross

glslang

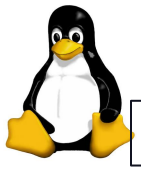
Vulkan-HPP

Screenshot

SDL

Monitor

GLM



Tarball

Windows

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The Vulkan SDK (2018)

2016 2017 2018

Vulkan Loader

vkconfig

Validation Layer

First version of GPU-AV

First version of Best Practices, called the "Assistant Layer"

SPIR-V Optimizer

SPIR-V Tools

vulkaninfo

shaderc

SPIR-V Validator

apidump

VKVIA

Ubuntu Packages

Tarball

SPIR-V Cross

glslang

Vulkan-HPP

Screenshot

Windows

MoltenVK

SDL

Monitor

GLM

Vulkan 1.1

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The Vulkan SDK (2019)

Vulkan Loader

vkconfig

Validation Layer

SPIR-V Optimizer

SPIR-V Tools

vulkaninfo

License Registry

shaderc

SPIR-V Validator

apidump

VKVIA

Ubuntu Packages

SPIR-V Cross

glslang

Vulkan-HPP

Screenshot

Tarball

MoltenVK

SDL

Monitor

GLM

Windows

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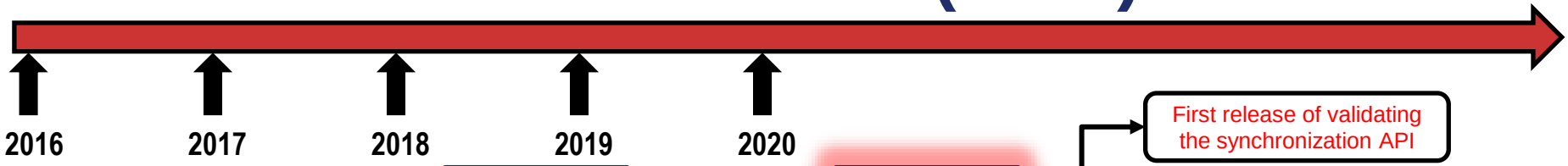
The Vulkan SDK (2020)



Vulkan Loader

vkconfig

Validation Layer

First release of validating the synchronization API

SPIR-V Optimizer

SPIR-V Tools

vulkaninfo

Replaced vktrace / vkreplay API capture and replay

License Registry

shaderc

SPIR-V Validator

Total rewrite – setting the groundwork for the future

DXC

SPIR-V Reflect

apidump

GFX Reconstruct

VKVIA

Ubuntu Packages

SPIR-V Cross

glslang

Vulkan-HPP

Screenshot

Tarball

MoltenVK

SPIR-V Visualizer

SDL

Monitor

GLM

Windows

Vulkan 1.2

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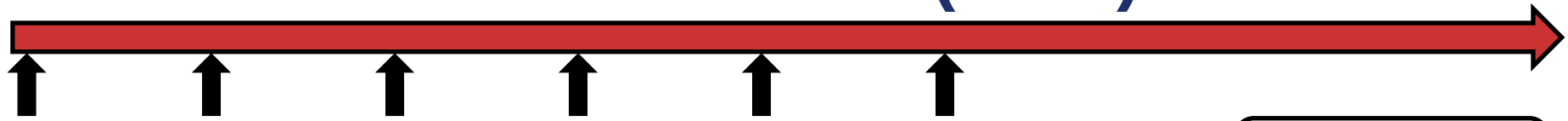
The Vulkan SDK (2021)



License Registry

Vulkan Loader

vkconfig

Validation Layer

Synchronization2 API Validation

SPIR-V Optimizer

SPIR-V Tools

vulkaninfo

Emulation Layers

Synchronization2 emulation

License Registry

shaderc

SPIR-V Validator

DXC

SPIR-V Reflect

apidump

GFX Reconstruct

VKVIA

Ubuntu Packages

SPIR-V Cross

glslang

Vulkan-HPP

Screenshot

Tarball

MoltenVK

SPIR-V Visualizer

SDL

Monitor

GLM

Windows

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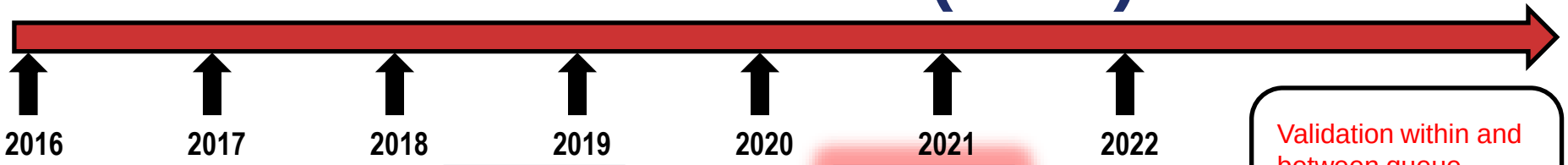
The Vulkan SDK (2022)



Validation within and between queue submissions and across queues

License Registry

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License Registry

Ubuntu Packages

Tarball

Windows

Vulkan 1.3

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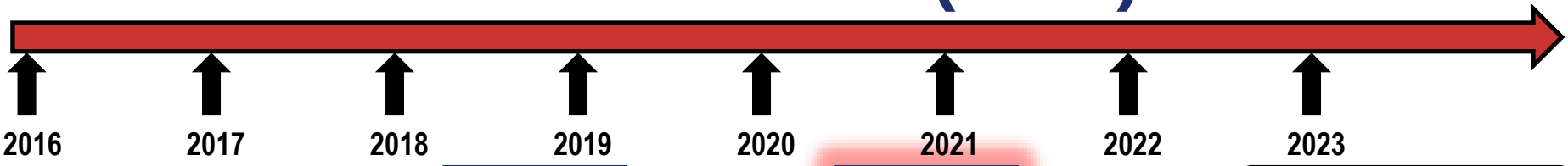
The Vulkan SDK (2023)



License Registry

Vulkan Loader

vkconfig

Validation Layer

VK_EXT_shader_object validation

SPIR-V Optimizer

SPIR-V Tools

vulkaninfo

Emulation Layers

Shader Object Emulation Layer

License Registry

shaderc

SPIR-V Validator

Profiles Toolset

GPUInfo

VOLK

DXC

SPIR-V Reflect

apidump

GFX Reconstruct

VKVIA

SPIR-V Cross

glslang

Vulkan-HPP

Screenshot

VMA

MoltenVK

SPIR-V Visualizer

SDL

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GLM

Ubuntu Packages

Tarball

Windows

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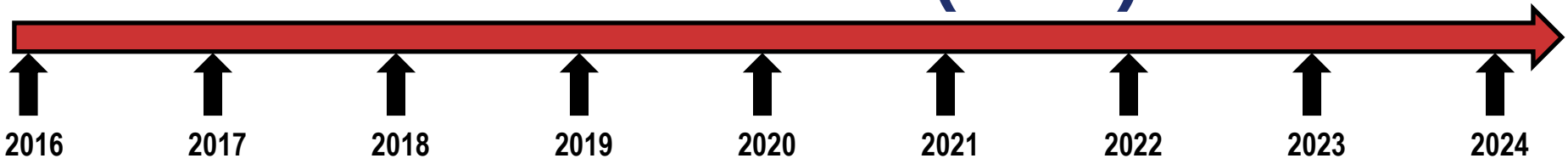
The Vulkan SDK (2024)



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License Registry

Ubuntu Packages

Tarball

Windows

Debug GPU hangs and crashes

NEW!

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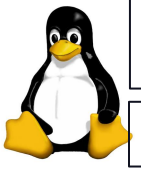
The Vulkan SDK

Windows arm

License Registry

Ubuntu Packages



Tarball

Windows

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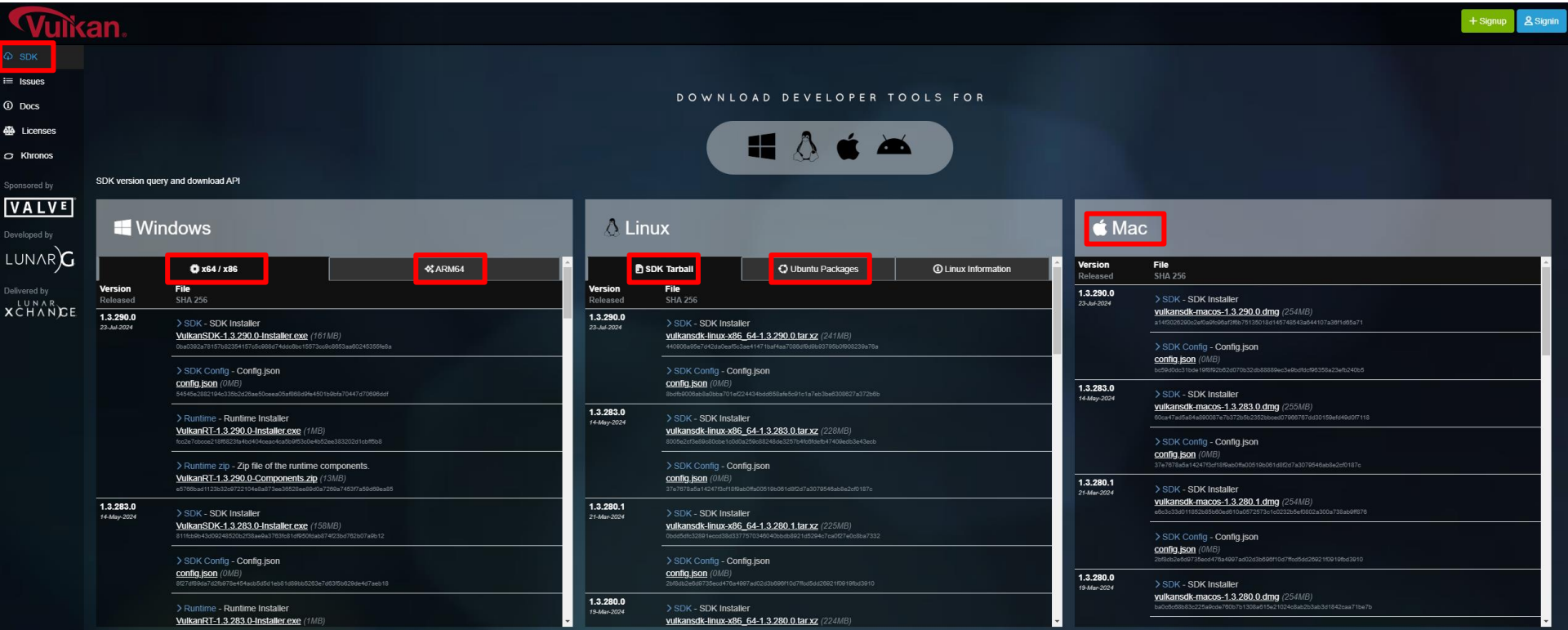
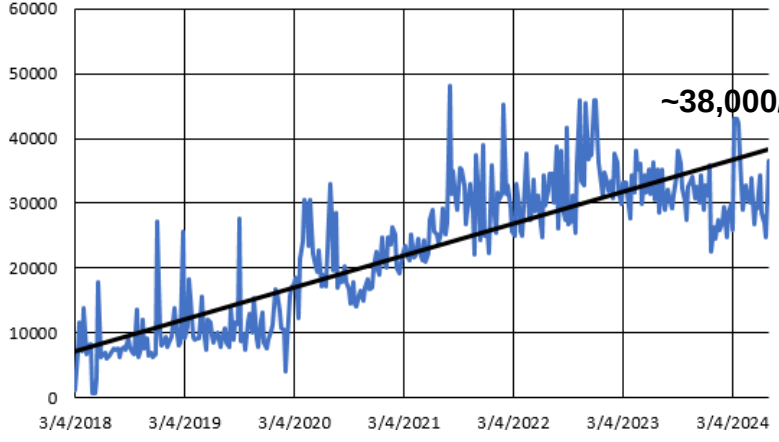
Vulkan SDK Download Page (vulkan.lunarg.com)



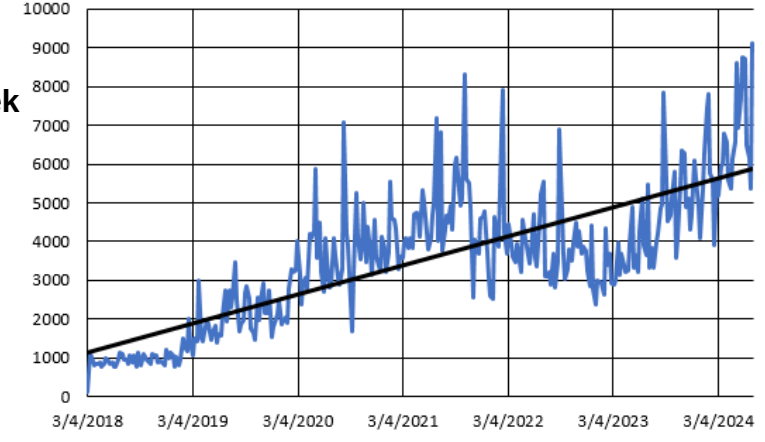
Vulkan SDK Downloads are Healthy

Windows SDK



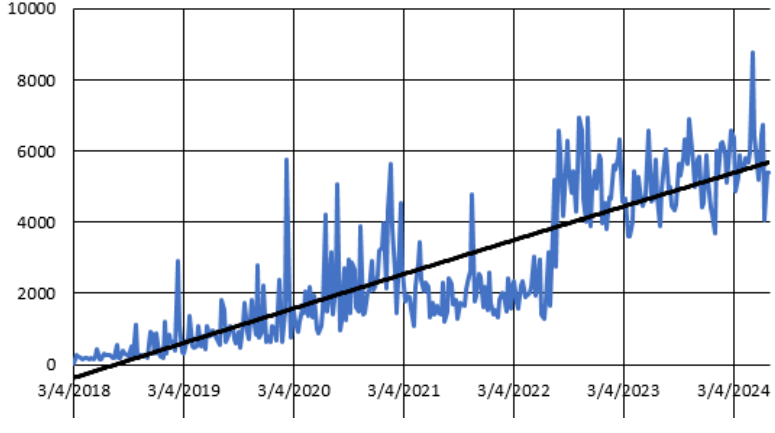
~38,000/week

Linux SDK



~6000/week

Mac SDK



~5800/week

Note: Numbers are for Linux “Tarball” only and don’t include Ubuntu packages also available from LunarG or other linux distros

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How is this funded?

How is this funded?

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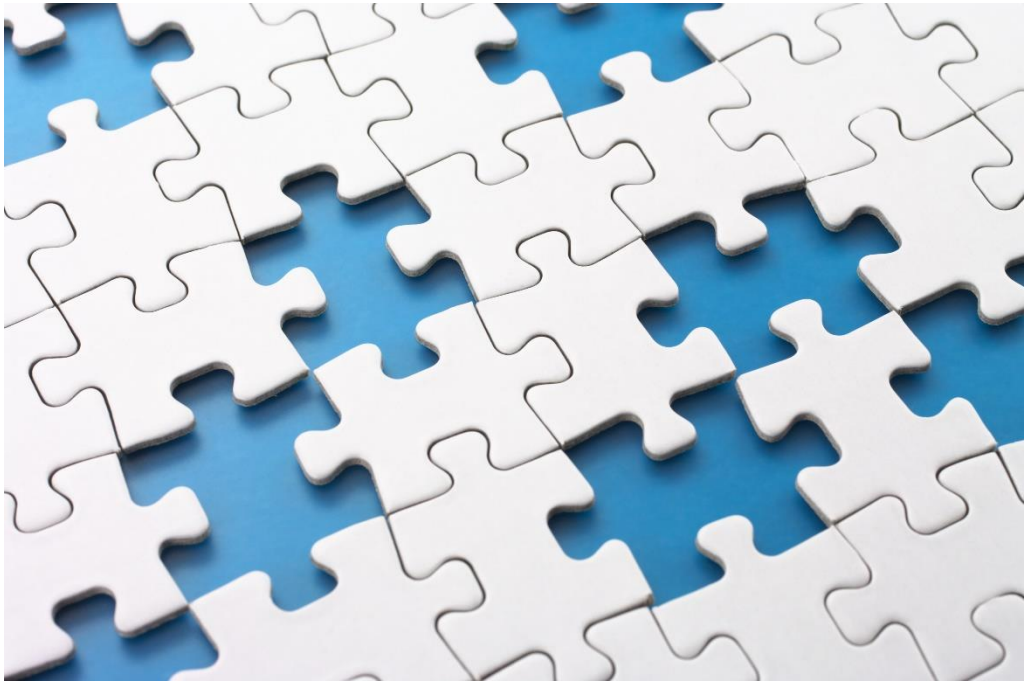
The First Vulkan SDK

- An INCOMPLETE Validation Layer implementation
- The first Vulkan Loader implementation
- Windows and Linux only



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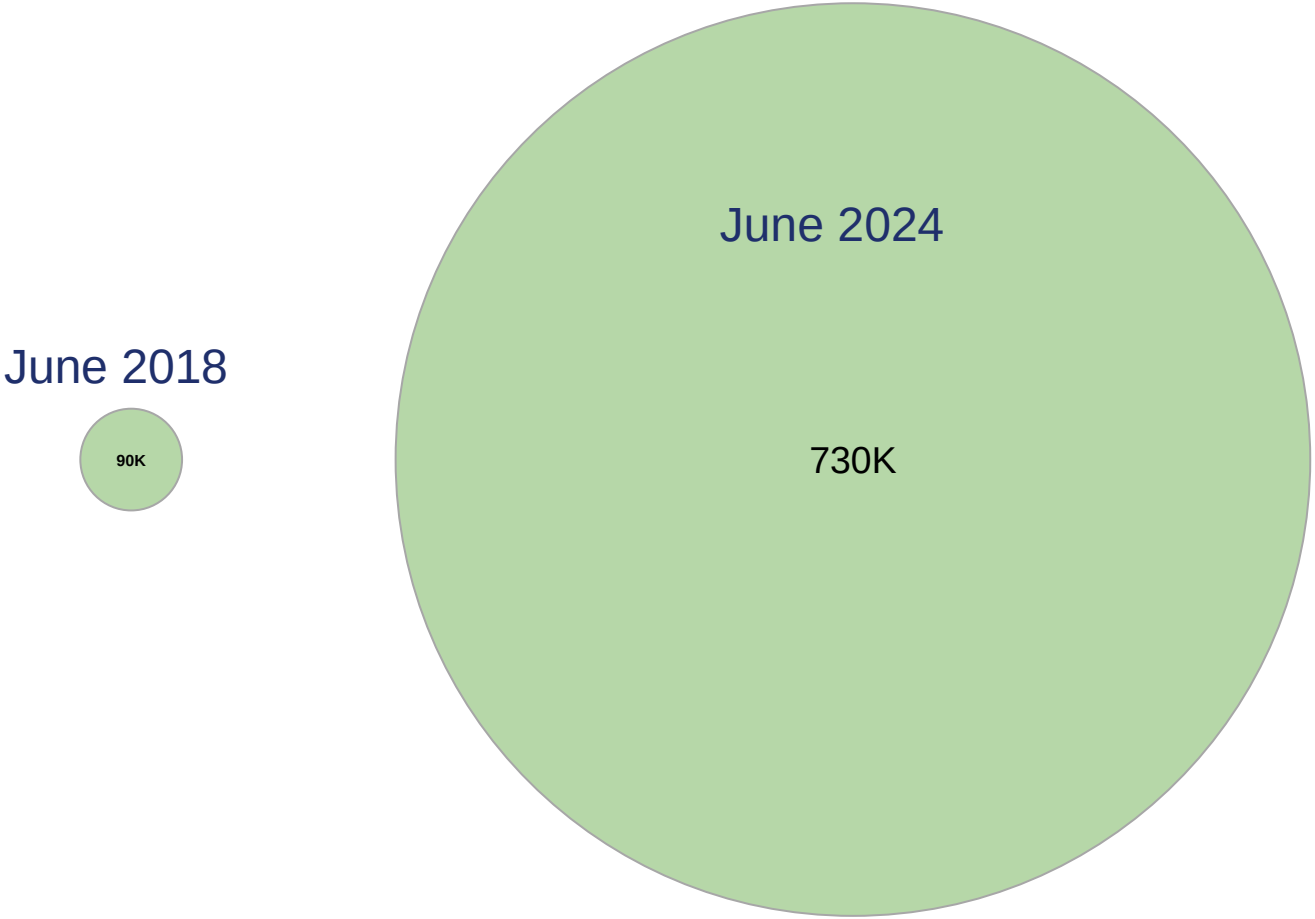
Validation Layer - Then and Now

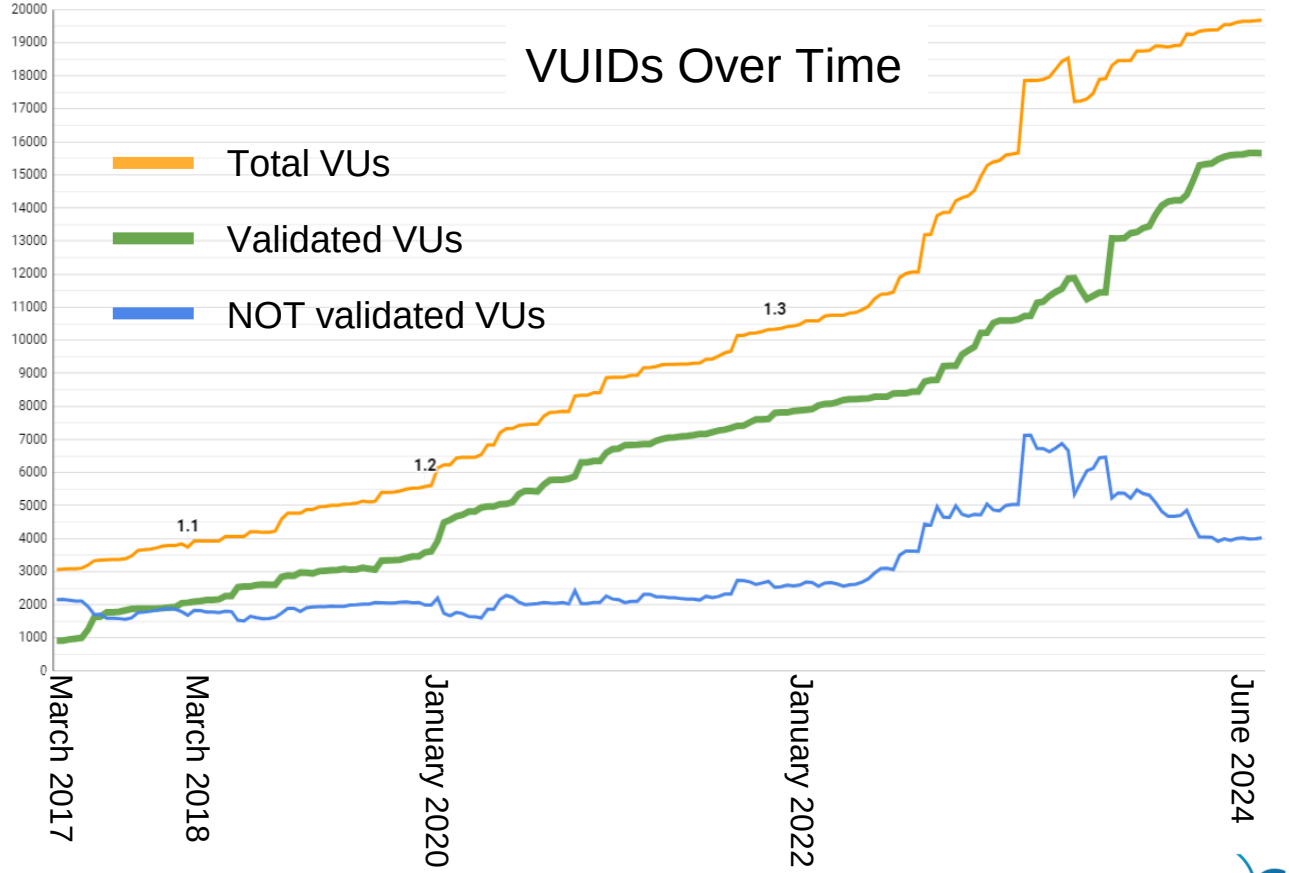
June 2018

Validation Layer - Then and Now



Validation Layer and VUIDs

- VUID - Valid Usage ID
  - Assigned to each API usage
  - How that part of the API must be used
- Validation Layer is validating the VUIDs
  - “Error Checking”



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The Validation Layer - Today

- Healthy open-source project with robust functionality
    - GPU-assisted validation - to support the bindless attributes of the Vulkan API

The Validation Layer - Today

- Healthy open-source project with robust functionality
    - GPU-assisted validation - to support the bindless attributes of the Vulkan API
    - Synchronization Validation - detection of race conditions in otherwise correct Vulkan programs
        - 2019 - Hazard detection within a single buffer
            - 18 man months of effort!
        - 2022 - Hazard detection within and between queue submissions and across queues
            - 24 man months of engineering effort!
        - These two versions enable baseline functionality and does not cover all Vulkan extensions. More to do!

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The Validation Layer - Today

- CI Test Farm
  - SW testing
    - Mock ICD
  - GPU HW
    - Nvidia
    - AMD
    - Intel
    - Android
  - Windows, Linux, Android, macOS

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The Validation Layer

We aren't done yet!
Vulkan API continues to evolve!

Opportunities Presented by the Technology

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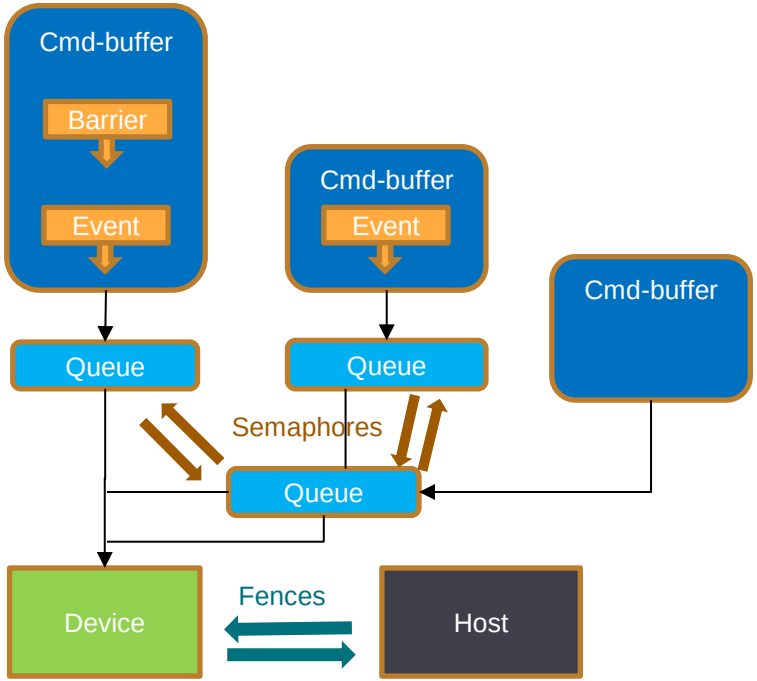
Validation Layer - Vulkan Synchronization

Semaphores
: Main cross-queue synchronization mechanism

Events and Barriers
: Synchronization of commands submitted to a single queue

Fences
: Synchronize work between the device and the host



Validation Layer Improvement Opportunity:

- High Performance Overhead due to required volume of state tracking
- Ongoing improvement opportunity: Performance tuning

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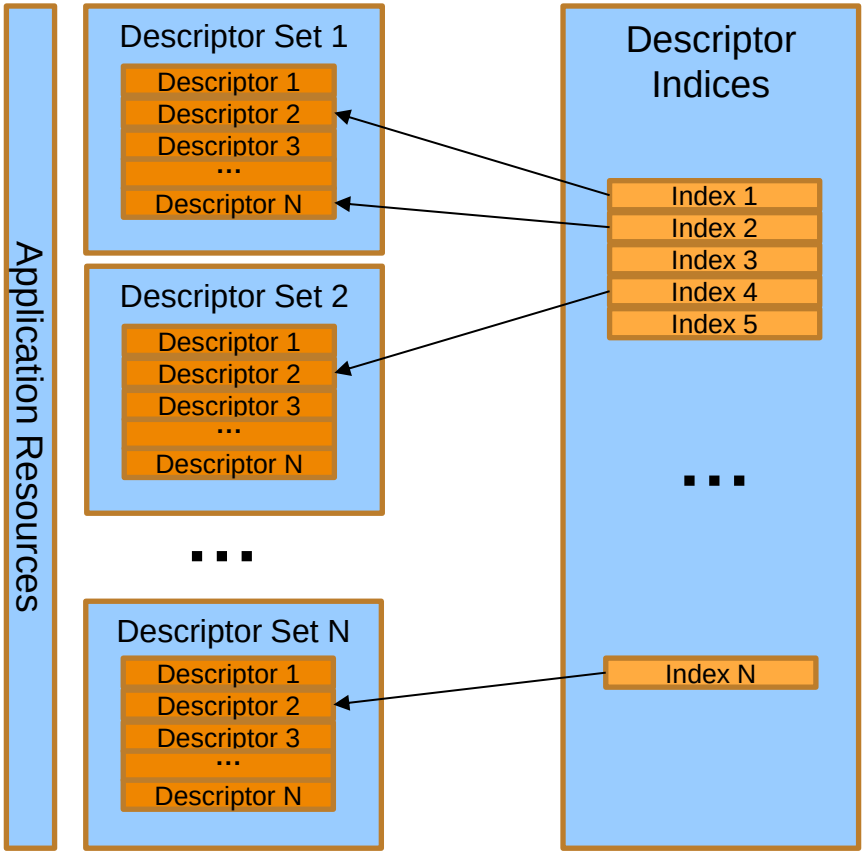
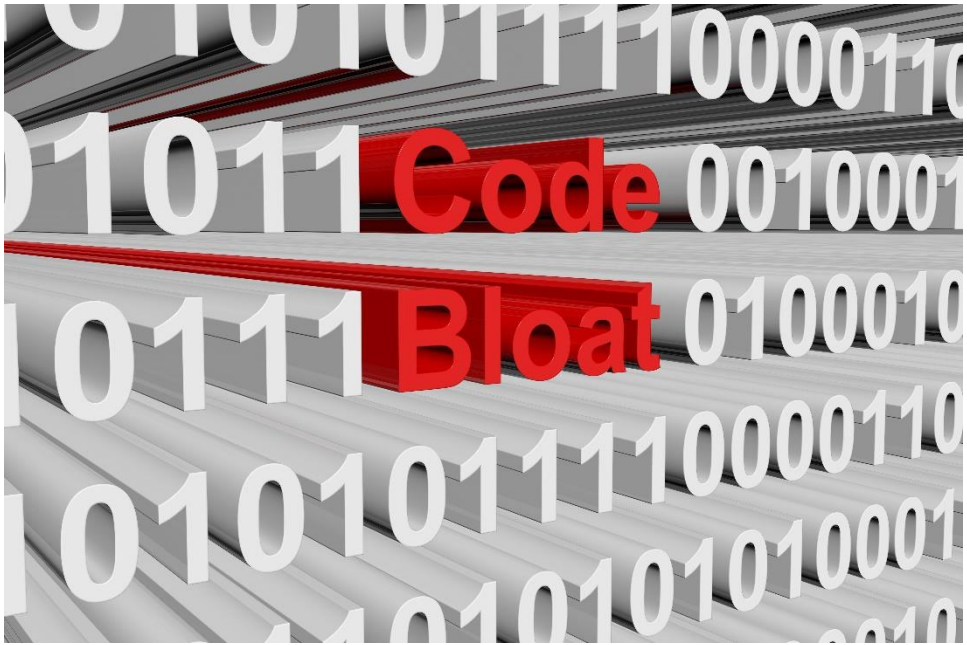
Validation Layer - Descriptor Indexing Validation

- Descriptors invoked from shaders
  - Only used descriptors required to be valid
  - Might only use “10” out of millions
- Initial validation implementation
  - Slowed app from 100+ FPS to a fractional value!
  - All descriptors were being validated, regardless if used!
- Performance Improvement!
  - Using instrumented shaders on the GPU
    - Detect which descriptors are actually used
  - Only validate used descriptors



Validation Layer – GPU-AV Performance



- GPU-AV requires instrumenting shaders
- Shaders become bloated; impacting performance
  - Pipeline compile times
  - Runtime shader execution

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Validation Layer – Latency in Error Reporting

DELIVERY DELAY

- Errors detected well after the Vulkan API call that caused them (aka at vkQueueSubmit time)
- Difficult to provide meaningful error messages
- Opportunity to improve error messages:
  - Storing information for later use without unbearable performance impacts

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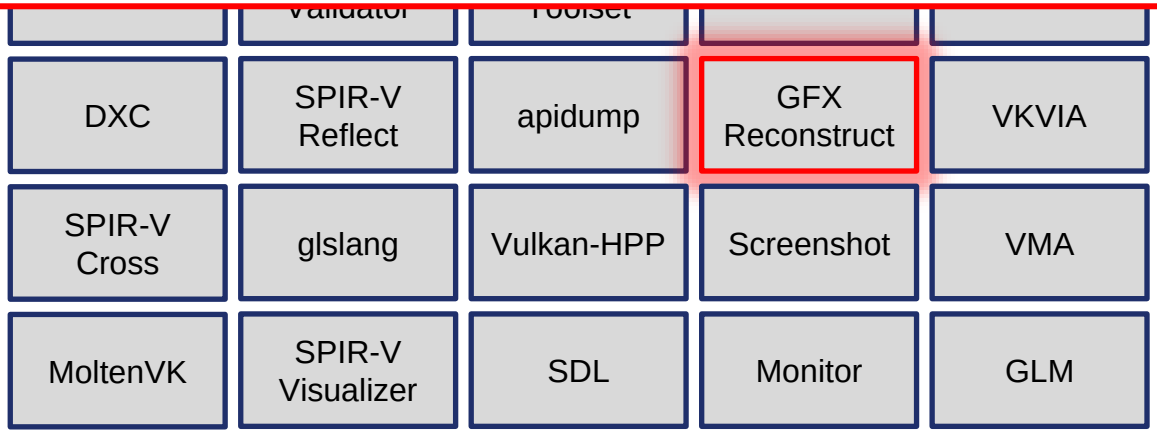
Open-source Vulkan Developer Tools

Included in the Vulkan SDK

GFXReconstruct - API Capture and Replay

- Cross-platform (Windows, Linux, Android, macOS)
- Run Vulkan workloads during GPU development
- Debug Vulkan applications
- Regression testing using real application workloads
- Underlying engine for profiling and debugging tools



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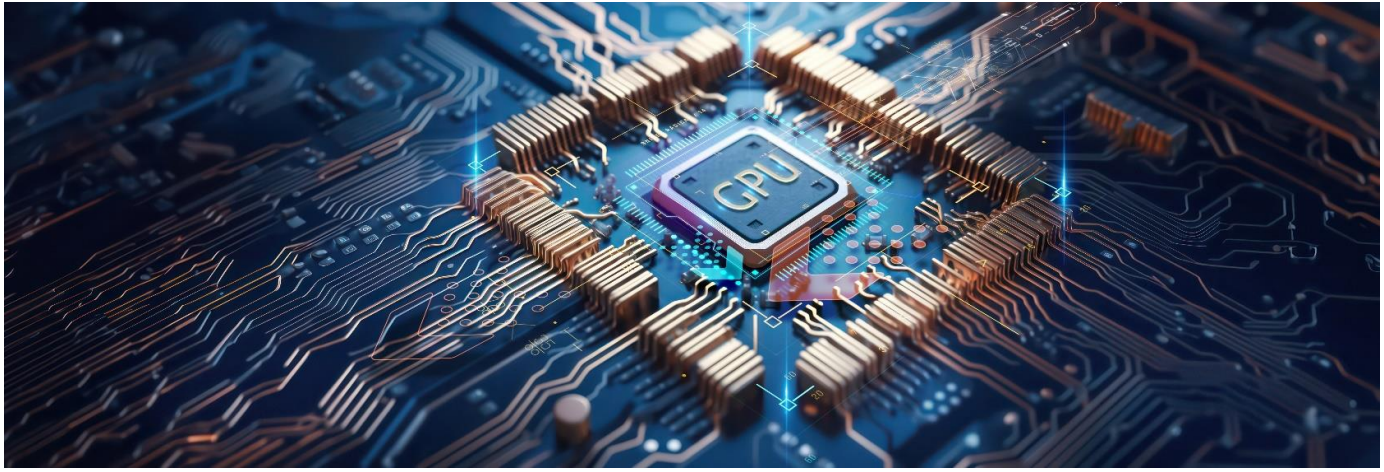
GFXReconstruct - API Explicitness

- Portability Challenge
  - Vulkan API is explicit
  - Hence captures from one GPU can’t be replayed on another GPU
- Conflicting Use Cases
  - Exact API calls needed for analysis
  - Use existing captures on newer/different GPUs
- Opportunity: How to enable some portability of captures
  - Collect additional data?
  - Translation layer?

The GPU-centric Universe

- GPUs - no longer "Graphics Processing Units"
  - Efficient processing of large blocks of data simultaneously
  - Compute - AI and ML
- Less Graphics API usage on the CPU
  - Rendering complexity still increasing via GPU driven rendering
- Many workloads moving to the GPU
  - Maximize utilization of GPU features
  - Reduce CPU interaction



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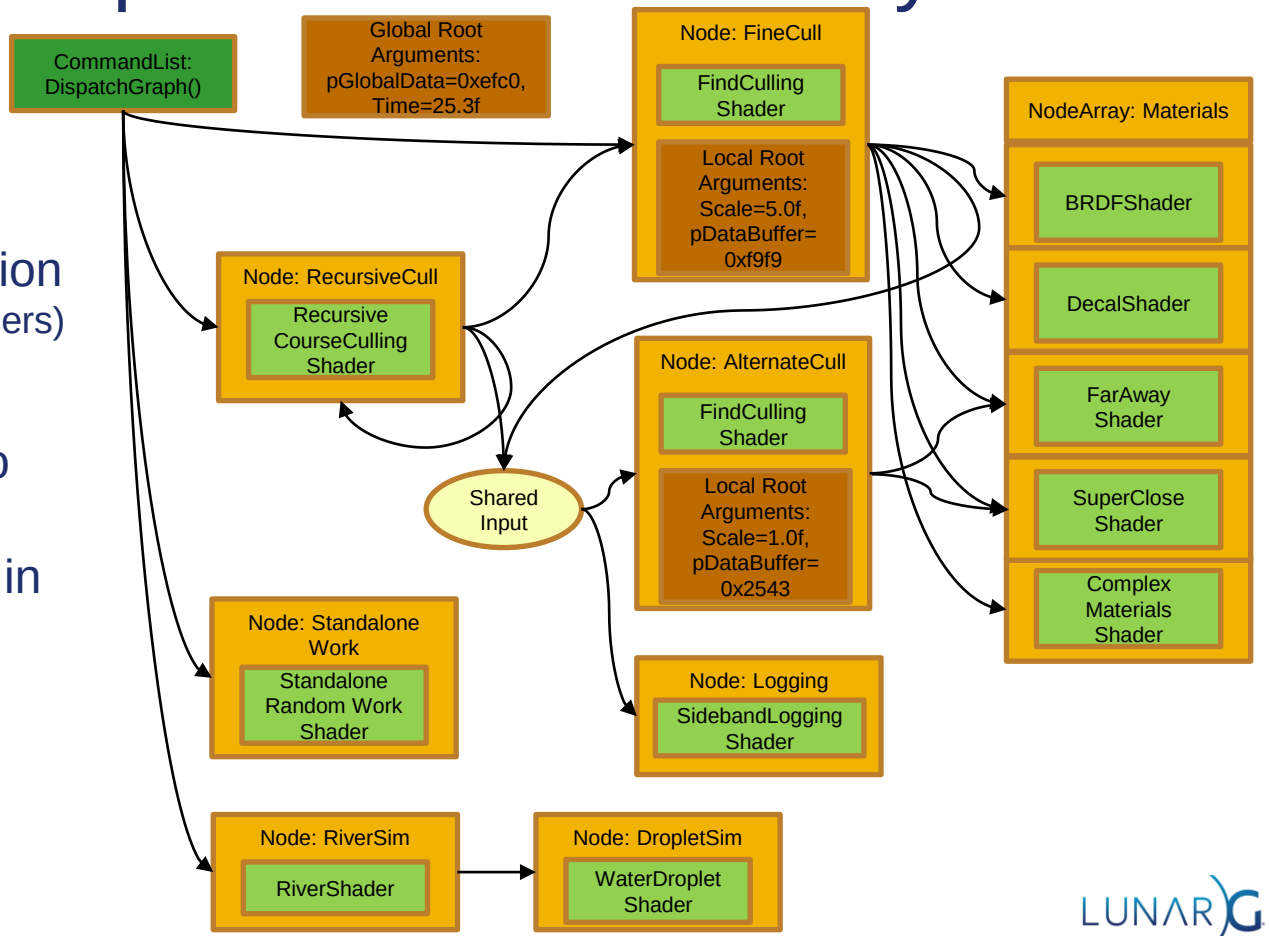
D3D12 Work Graphs – GPU Autonomy

- GPU Autonomy
  - GPU Feeds itself
- Dynamic Work Expansion
  - Shader threads (producers) requesting work to run (consumers)
- Removes round trips to CPU
- Currently not available in Vulkan



Picture from MS D3D12 Work Graphs – DirectX Developer Blog. March 11, 2024

GFXReconstruct - GPU Autonomy

- Information no longer known at a function device call from the CPU side
- Addresses baked into capture content
  - Needs to be a different address during replay

GPU-Centric Universe : Developer Tools Implications

- Debugging on a CPU vs GPU
  - CPUs provide the Instruction Set Architecture (ISA) and ability to step thru code
  - GPUs can be a black box and intrinsically different
    - Imagine stepping through 1 of a million items in a massive parallelism environment!
- Cross-GPU open-source tools are useful today
  - Evolve the tools for the GPU-centric universe
  - Cooperation needed from many parties
    - IHVs
    - Specification definitions
    - Tool writers

An Example API “hook”

- Vulkan “bufferDeviceAddressCaptureReplay”
  - Enable in driver during capture
  - Query memory location upon allocation
  - Can use that same memory allocation during replay
  - Current limitation: Not guaranteed to work from one vendor to another

From the launch of Vulkan to Today…

- There is ONE Industry-standard Vulkan desktop SDK
  - Wide adoption
  - Strong satisfaction
  - Open and free for all developers
  - Cross-platform SDK: Windows-x64/x86, Windows on arm, Linux, Apple platforms
- Valuable developer tools
  - Robust in features and reliability
  - Providing real value to Vulkan application developers

LunarG Purpose Continues!

Evolve the tools for a GPU-centric universe!

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Why Vulkan?

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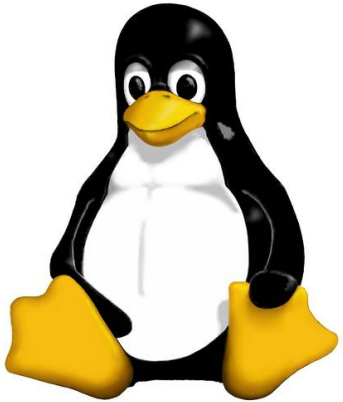
Why Vulkan? Cross-platform support

Same API for Mobile, desktop, (and Apple platforms)



VIA

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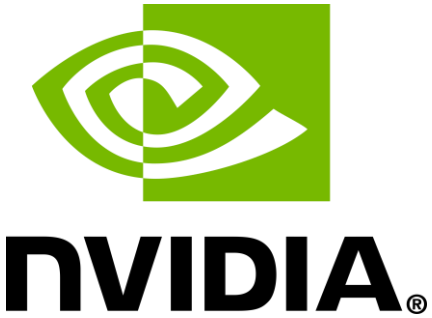
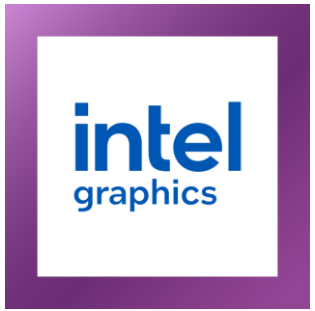
Why Vulkan? Improved Cross-vendor Compatibility

One API usage validator used by all (Vulkan-ValidationLayer)





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Why Vulkan? Improved Performance

- Explicit application control over GPU and CPU workloads
- Multithreading-friendly API
- No more error checking in the Vulkan driver

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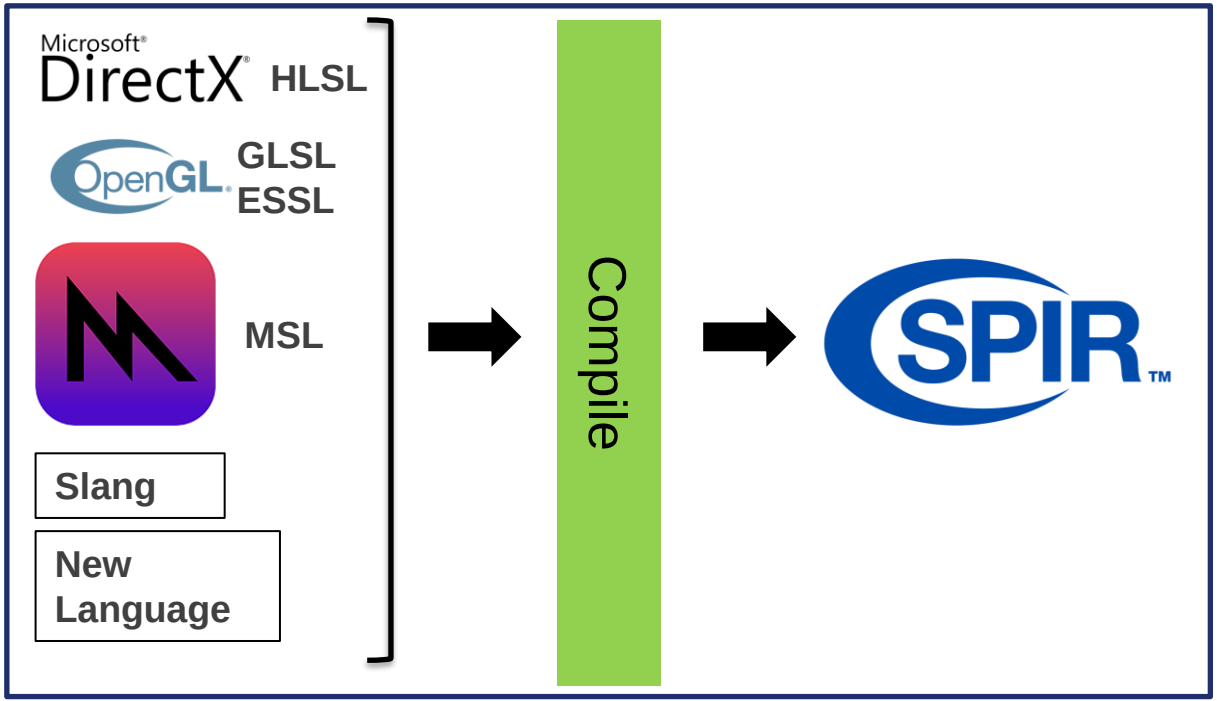
Why Vulkan? Shader Language Flexibility

Standardized Intermediate Language (SPIR-V)

- Eliminates front-end compilers from drivers
  - Reduce driver complexity
- Front-end language flexibility
  - Improve portability



Why Vulkan? Open Standard

Strengthened ecosystem focus

- Embrace and engage with the ISVs
- Open conformance test suite - more rigor
- More control put in the developer's hands

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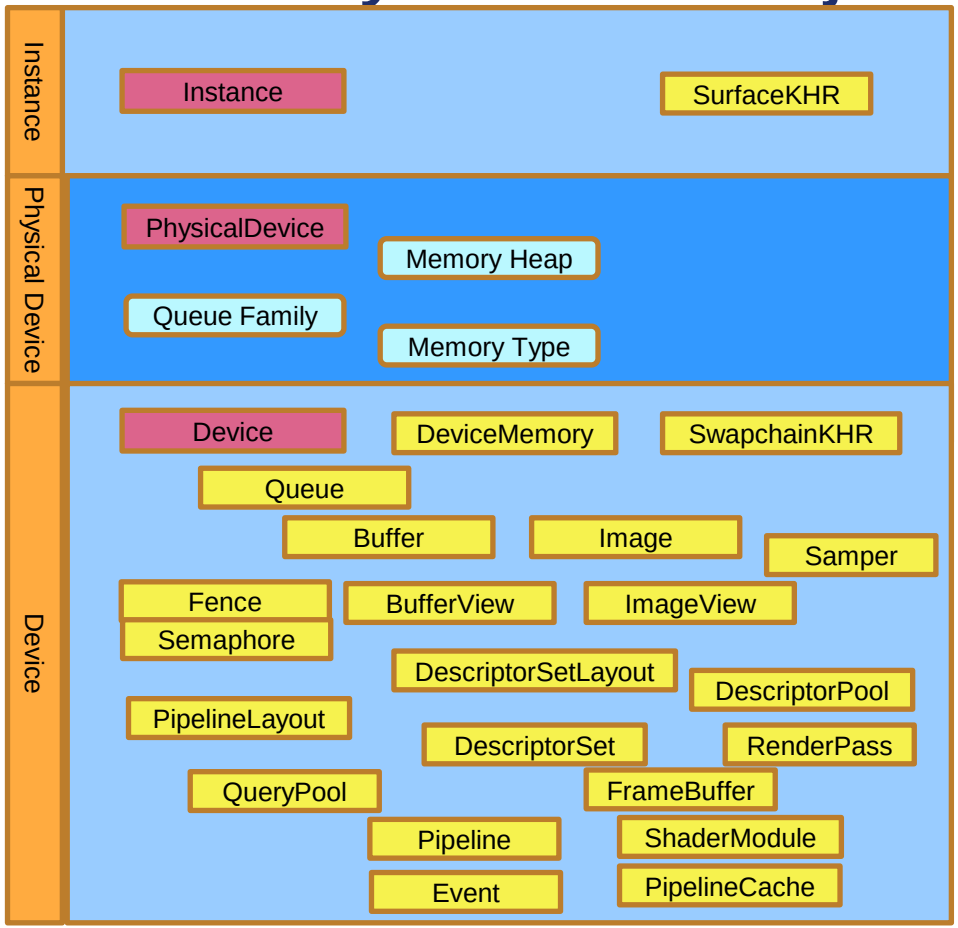
Validation Layer – So Many Vulkan Objects!

- The Sheer Number of Vulkan Objects – complexity
- Different functions and usages
  - Rules for how can they be used
  - Rules for order of creation

→ Complexity in the validation layer



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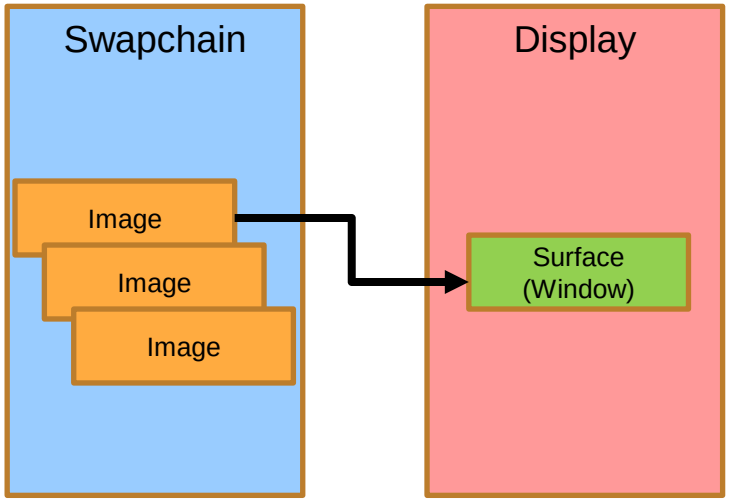
GFXReconstruct - Vulkan Swapchain

- Different swapchain modes present and return images in different order
  - From run to run
- No swapchain presentation mode guarantees return order!
- GFXReconstruct Opportunity: How can we display the correct image during replay?
  - Solution: Implemented a virtual swapchain
  - Same number of images in replay as in capture
  - Use the indices in the same order from capture to replay



Who is LunarG?

- Independent, privately owned software consultancy
- Passionate about 3D graphics & compute technology
- Industry leading, 3D-graphics software experts with decades of experience
  - Vulkan, OpenXR, OpenGL, Direct3D, Metal, …
  - Developer tools, drivers, performance tuning…
- Developers of proprietary and open source drivers, tools, & software solutions
- Founded in 2009 – Headquarters in Fort Collins, CO
- Delivers the Vulkan SDK