codeplay

Enable AI & HPC to be Open, Safe and Accessible to All

ComputeAorta

A Toolkit for Implementing Heterogeneous Programming Models

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Codeplay - Enabling AI to be Open, Safe and Accessible to all

Products

Acoran
Integrates all the industry standard technologies needed to support a very wide range of AI and HPC

ComputeCpp™
C++ platform via the SYCL™ open standard, enabling vision & machine learning e.g. TensorFlow™

ComputeAorta™
The heart of Codeplay's compute technology enabling OpenCL™, SPIR-V™, HSA™ and Vulkan™

Addressable Markets

High Performance Compute (HPC)
Automotive ADAS, IoT, Cloud Compute
Smartphones & Tablets
Medical & Industrial

Technologies: Artificial Intelligence
Vision Processing
Machine Learning
Big Data Compute

Company

Leaders in enabling high-performance software solutions for new AI processing systems

Enabling the toughest processors with tools and middleware based on open standards

Established 2002 in Scotland with ~80 employees

Customers

Broadcom, Renesas, Qualcomm, Imagination, CEVA, arm, intel, Synopsys

Stacking Heterogeneous Standards

DSLs
- Tensorflow, Eigen, SYCL-BLAS, SYCL-DNN, OpenCV

Compute Cpp
- SYCL 1.2.1 implementation

Compute Aorta
- Enables OpenCL 1.2 and Vulkan 1.x Compute

Mux
- Abstraction layer to implement ComputeAorta on customer hardware

Introduction

- ComputeAorta's role in the stack is:
  - To expose the full performance potential of heterogenous hardware
  - To provide standards-compliant interfaces for users of the hardware

- Requires a design that scales with minimum effort:
  - When supporting new heterogeneous programming standards
  - When supporting new customer hardware devices
  - Without comprising on performance at any stage

- This talk is about our solutions to these requirements via:
  - The intermediate abstraction layer "Mux"
  - The toolkit of components we provide to customer teams

How is ComputeAorta delivered?

Generic ComputeAorta

- Implementations of runtime APIs
- Software implementation of builtin functions
- Device agnostic optimizations
- Testing infrastructure

Customized ComputeAorta

- Generally by a project team within Codeplay
- Mux API Implementation for target hardware
- Writing device specific code/tests
- Optimizing for performance

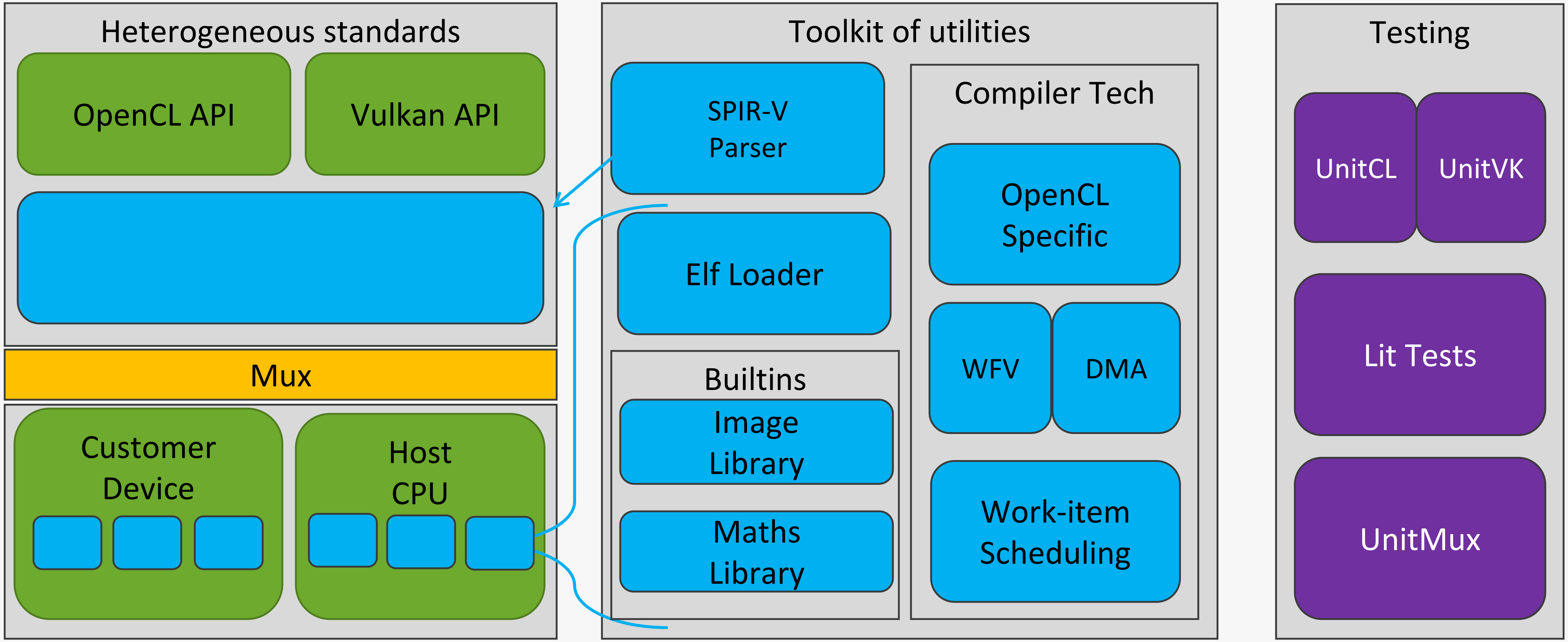
Customer technology

- Compiler backend
- Hardware driver
- Simulator
- Any of these may be created by Codeplay

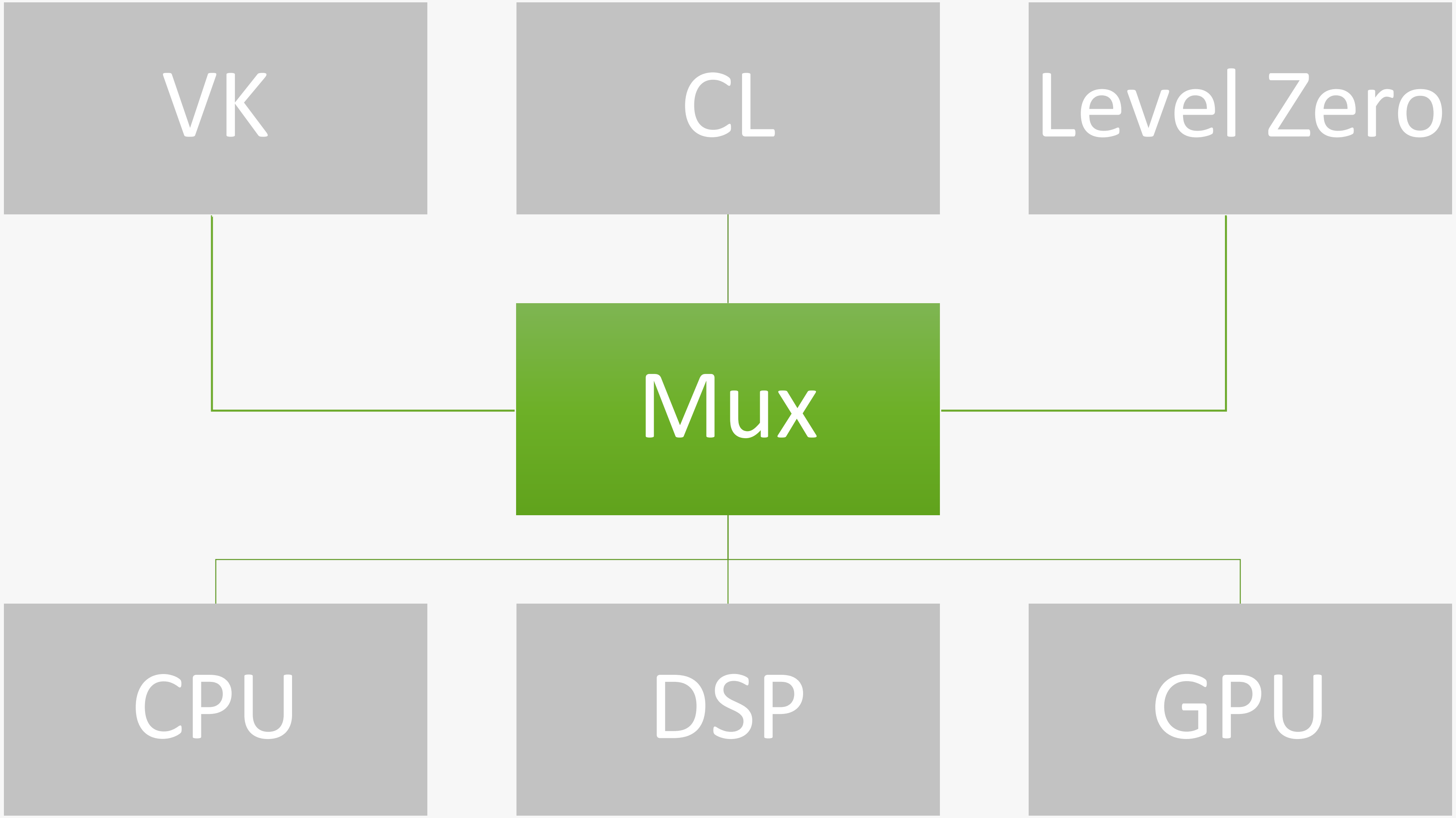
Requirements for delivery

- Absolutely no customer specific functionality in generic code.
  - ComputeAorta delivers source to multiple customers.
- Need to provide well-defined and documented interfaces between generic and custom code.
  - Expect customer teams to not modify generic ComputeAorta source.
  - But customer projects may need to extend behavior, so hooks required.
- Large amount of testing must be delivered.
  - Customer teams have confidence in correctness, so they can focus on performance.
  - Tests on external APIs are implementation independent and refactor agnostic.
  - Mux API has generic tests to validate customer specific implementation.
- ComputeAorta does modify Clang and LLVM directly.
  - Different customers use different versions, with their own modifications.

ComputeAorta™

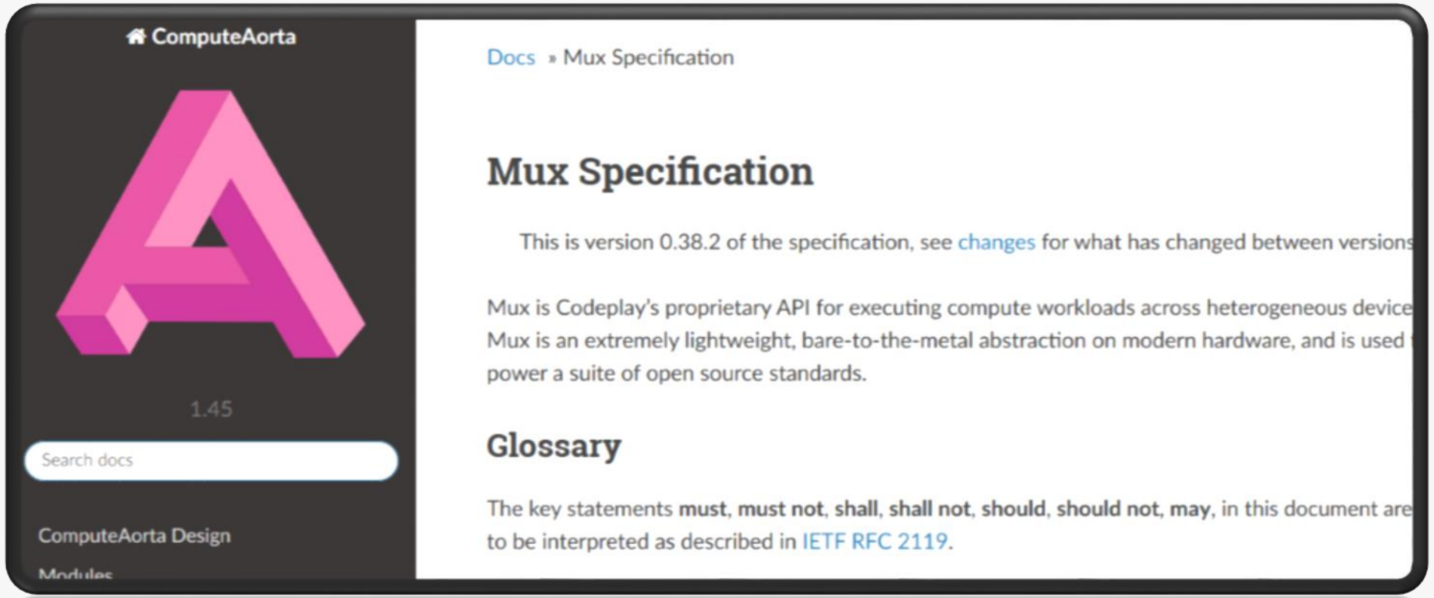


ComputeAorta™



Mux is a Specification

- A specification like the OpenCL or Vulkan specifications
- Multiplexes from API to hardware device targets
- Build heterogeneous standards on top of the interface
- Implement the interface however best suits the hardware
- API is lower-level than OpenCL, similar level to Vulkan



Why a C specification?

- Well defined interface between teams as well as code
  - Separation of Intellectual Property

- Why not define a C++ interface with abstract classes?
  - Easier for humans to reason about a written specification
  - Most types in Mux are opaque, customer teams can implement them as required

- Compared to POCL-like approach, gives each customer implementation complete flexibility
  - Use hardware driver code and intrinsics
  - Optimal work-item/work-group scheduling
  - Device debugger integration

Why not use an existing standard?

- Many aspects of the Vulkan API are attractive
  - Mux was strongly influenced by Vulkan as it provides precise control to the developer
  - But a current stage we would have to extend it a lot to use as a base API

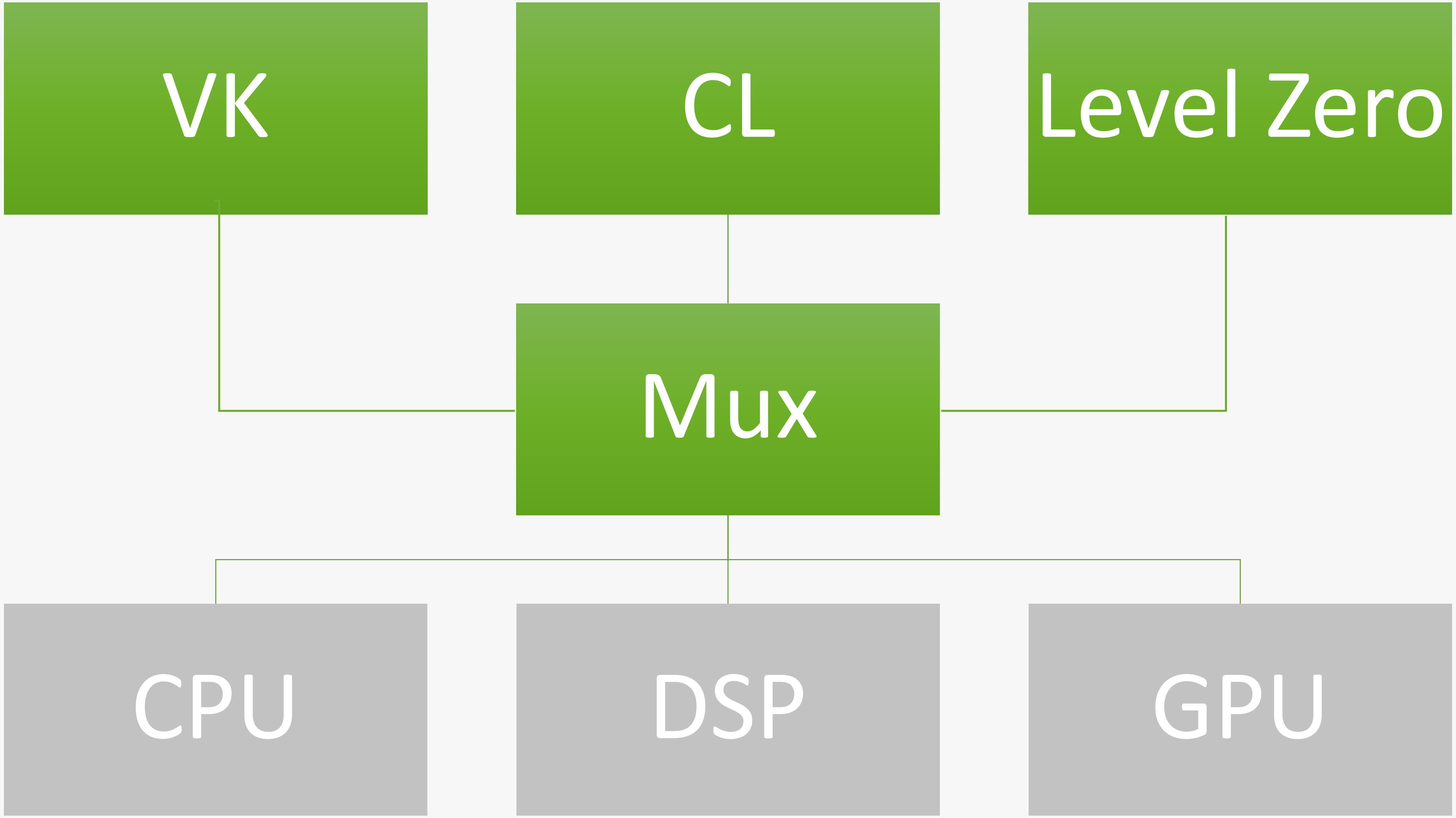
- Full control over API entry points we want
  - Important to minimize work as this is done per customer project
  - Avoid stubbing out of undesired features or having to meet conformance

- Don’t need to preserve backwards compatibility
  - But do need to justify changes to customer teams
  - Quicker to iterate on based on what customers need now

Performance Philosophy

- Make it possible for programmers to write code that achieves near to 100% of absolute performance on customer hardware
  - Compiler optimizations if they will work on many cases
  - Extensions for specialist cases
- Customers are interested in performance even in early stages as "will it be fast enough" is the highest risk part of a project
  - Pre-written optimizations allows demonstrations of what will be possible
- Software emulate features if required
  - Describe the consequences in the optimization guide
  - In the future, OpenCL's deployment flexibility should provide other paths for this, but being able to run software out-of-the-box is very useful

Building on top of Mux



Kernel Languages

- Vanilla upstream Clang front-end
  - Used for OpenCL-C clCreateProgramWithSource
  - Get new language extensions and support for any new kernel languages
  - Can contribute bug-fixes back upstream

- SPIR-V consumption
  - Enables Vulkan, Level Zero
  - OpenCL 1.2 cl_khr_il_program extension or core feature in 2.1+
  - Vital for SYCL and other technologies further up the stack

- Offline compiler
  - Device programs can be compiled offline to a binary format, then loaded at runtime using our dependency-less ELF loader module
  - ComputeAorta supports building a compiler-less driver with reduced C++ dependencies, where programs can only be created from loaded binaries

Customer Extensions

A Mux target can provide API extensions to expose target-specific features. There are two types of extensions which a target can expose:

- Runtime extensions - Modify the behaviour of the runtime API
- Compiler extensions - Modify the behaviour of the OpenCL-C/SPIR/SPIR-V compiler

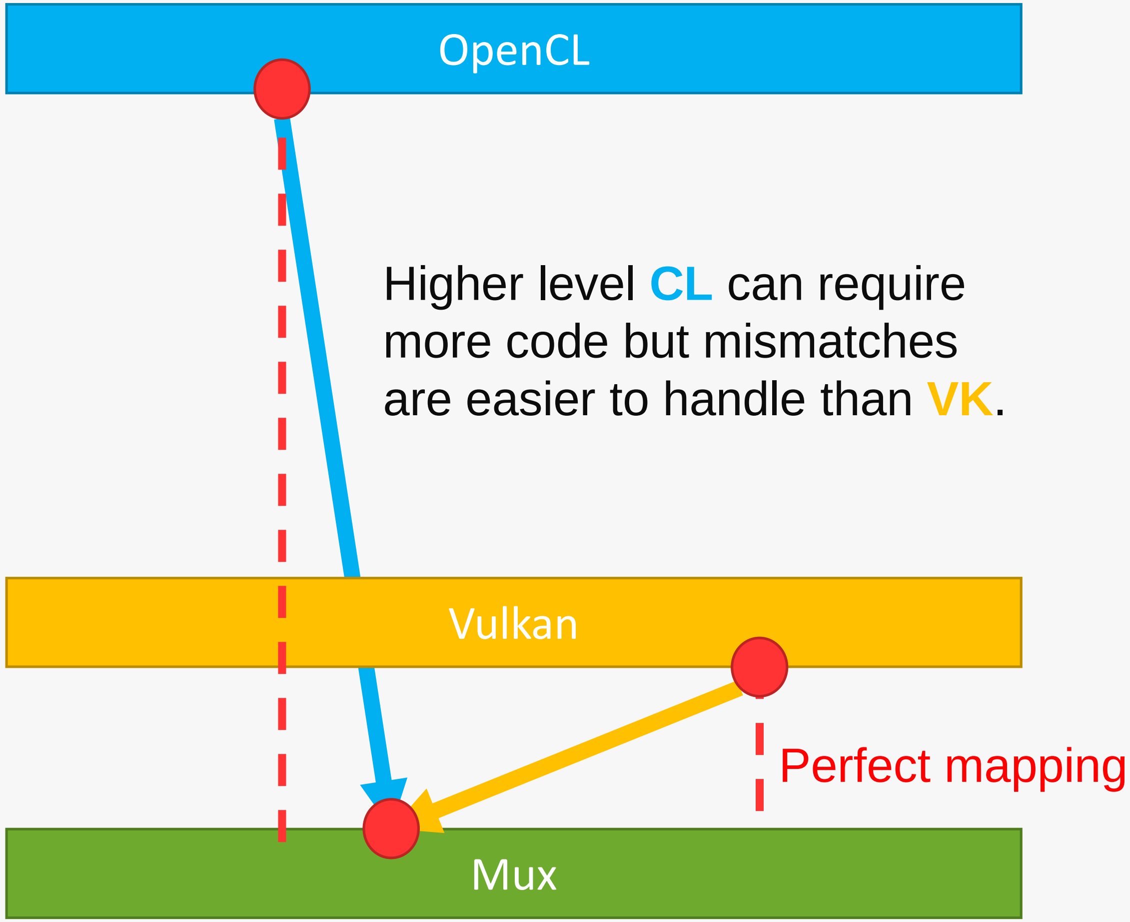
Registered through CMake hooks we provide rather than Mux API

VK On OpenCL Builtins

- Maths library functions matching OpenCL precision requirement used for VK.
  - Overly accurate for GLSL SPIR-V extended instructions
  - Exact for OpenCL SPIR-V extended instructions

- VK uses mangled OpenCL work-item builtins for SPIR-V compute builtins
  - *GlobalInvocationId* maps to CL *get_global_id()*
  - *LocalInvocationIndex* implemented using CL *get_local_id()*

Abstraction Distance



Maps well: Mux descriptor type for specifying data for a given kernel parameter is an exact mapping to Vulkan. CL can use it to implement *clSetKernelArgs* efficiently but requires more code.

Maps awkwardly: Mux semaphore type for synchronisation can be used for OpenCL events, but Vulkan synchronisation is more fine-grained, and Level Zero events are even more complex.

Take the most constrained model in the case of subtly difference behaviours.

- OpenCL queues execute commands in-order by default
- Vulkan queues execute commands in arbitrary order
- Mux commands are thus executed as if in-order

Synchronization Primitives

VkFence

- One way coordination from device to host

VkSempahore

- Device only synchronization

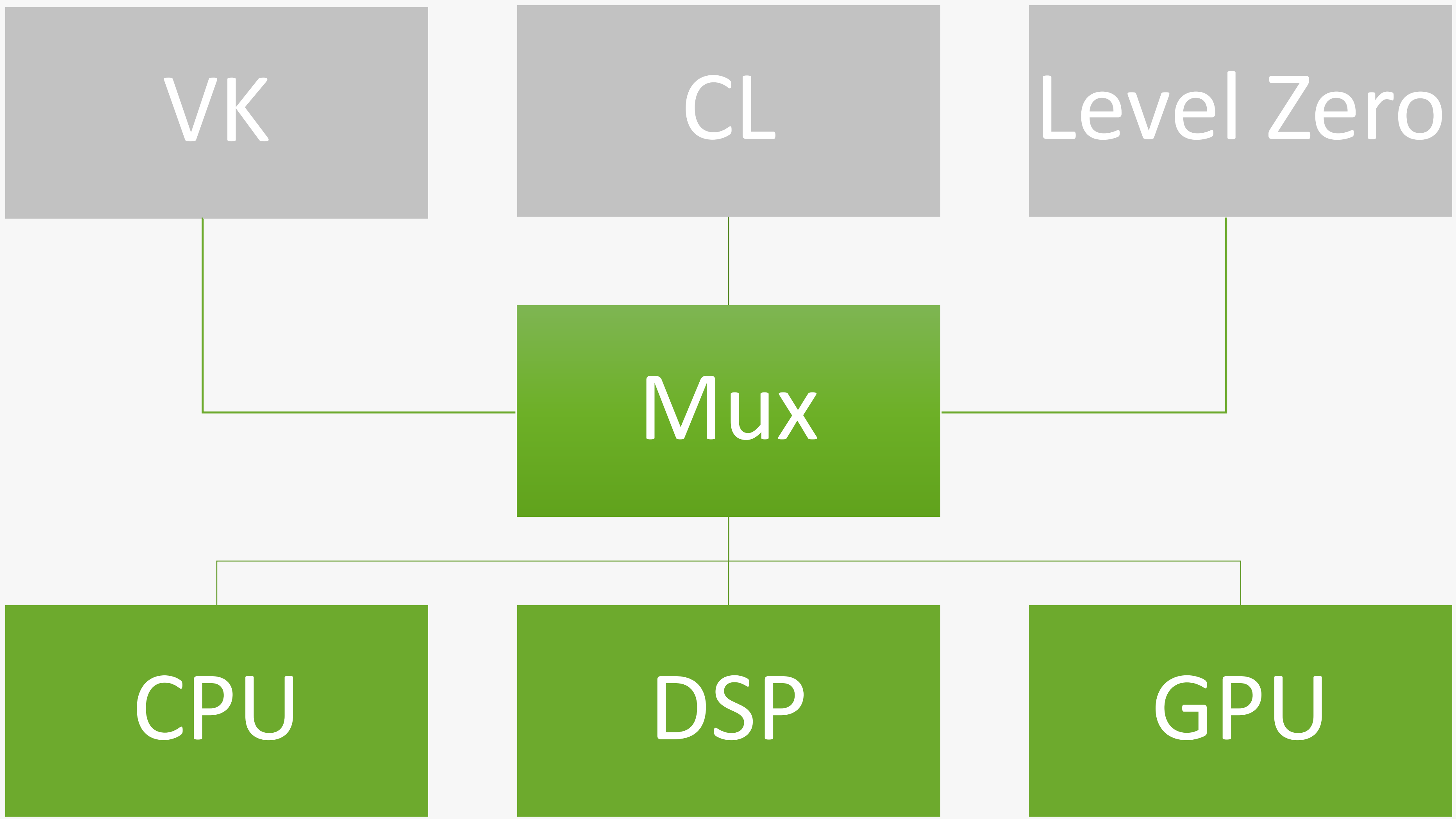
VkEvent

- Bi-directional synchronization between device and host

Mux Semaphore

- One way coordination from device to host
- Device side synchronization

Implementing Mux



“Host” Reference CPU Implementation

- Kernel and host code run under same process
- CPU can be desktop CPU or housekeeping CPU on heterogenous device
- Cross compile then run natively or on emulator

✓ Guide to customer teams on implementing Mux

✓ Test toolkit components

✓ Track performance

✓ Easy to debug

Command Batching

Problem On embedded devices building a command stream accounts for a significant expenditure of resources.

APIs ideally provide a way to reuse command streams

- ✓ Vulkan exposes command buffers
- ✓ Level Zero exposes command lists
- OpenCL has currently has no mechanism to achieve this
- ✓ Mux exposes command groups

Batching OpenCL Commands

Solution Build up Mux command groups by pushing OpenCL enqueue calls until a blocking event or flush, incurring a dispatch.

CL concept of **pending dispatches**, where additional commands can be pushed when a wait list contains compatible cl_events. A pending dispatch tracks:

- Mux command group
- Associated wait & signal Mux semaphores
- Associated wait & signal cl_events
- Callbacks to invoke upon completion

Analysis of OpenCL wait list

No wait events	Push command to the current command group or the last pending dispatch
Wait events associated with a single pending dispatch	Push command to the associated command group
Wait events associated with multiple pending dispatches	Get an unused command group
Wait events with no associated pending dispatches (already dispatched)	Get an unused command group

Toolkit Modules

- Whole Function Vectorizer
- STL alternative containers
- Maths Library
- ELF Loader
- SPIRV to LLVM IR translator

Maths Library

C++ Maths Library

Clang

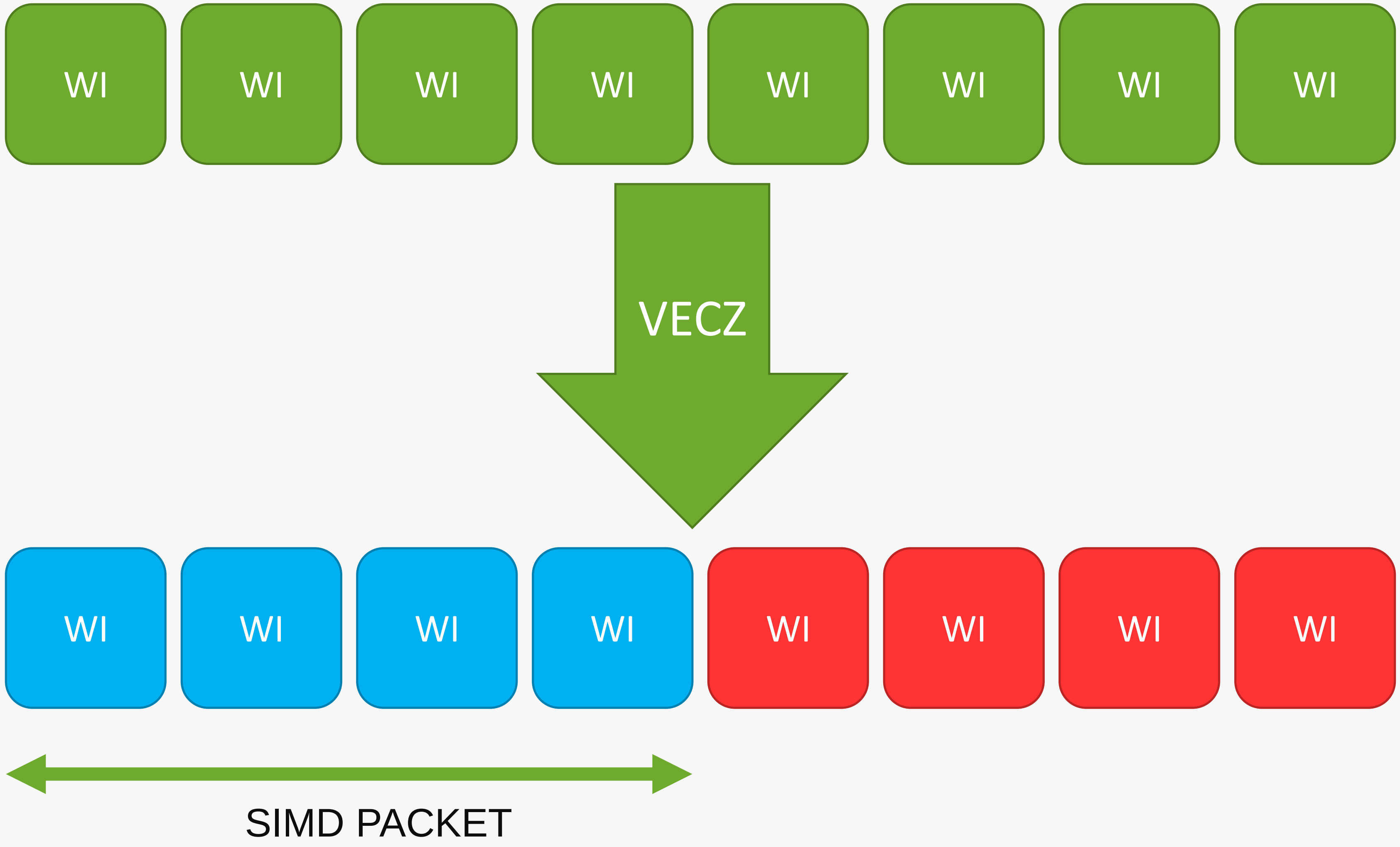
.bc Bitcode

Embed in binary

Shared Library

Load from .data section at runtime

VECZ – SPMD Vectorizer



VECZ – SPMD Vectorizer

- Computing multiple work-items in parallel does not depend on special patterns like loops which not all kernels contain

- Configurable by customer team for hardware traits
  - Vector width for SIMD packets
  - Optimizations, e.g. Branch On Superword Condition Code
  - Always enable, or enabled based on heuristic cost model

- See 2015 LLVM developers meeting talk "Creating an SPMD Vectorizer for OpenCL with LLVM"

Testing

Jenkins
- Automation
- Continuous integration
- Most testing runs on every branch before merge.
- Long-running tests run nightly.

OpenCL CTS
- Khronos official
- Very strict on math precision
- Not strict on compiler accuracy
- No negative testing (i.e. doesn't check for valid errors)

UnitCL
- Developed by Codeplay
- Checks error handling
- Primary regression test suite for ComputeAorta.

UnitMux
- Like UnitCL, but for the Mux specification.
- ComputeAorta-specific
- Checks Mux implementations against the Mux specification.

Lit
- Highly targeted compiler tests.
- Used to ensure that compiler passes have desired effect.
- Used heavily to test that debug info is preserved.

Vulkan CTS
- Khronos official

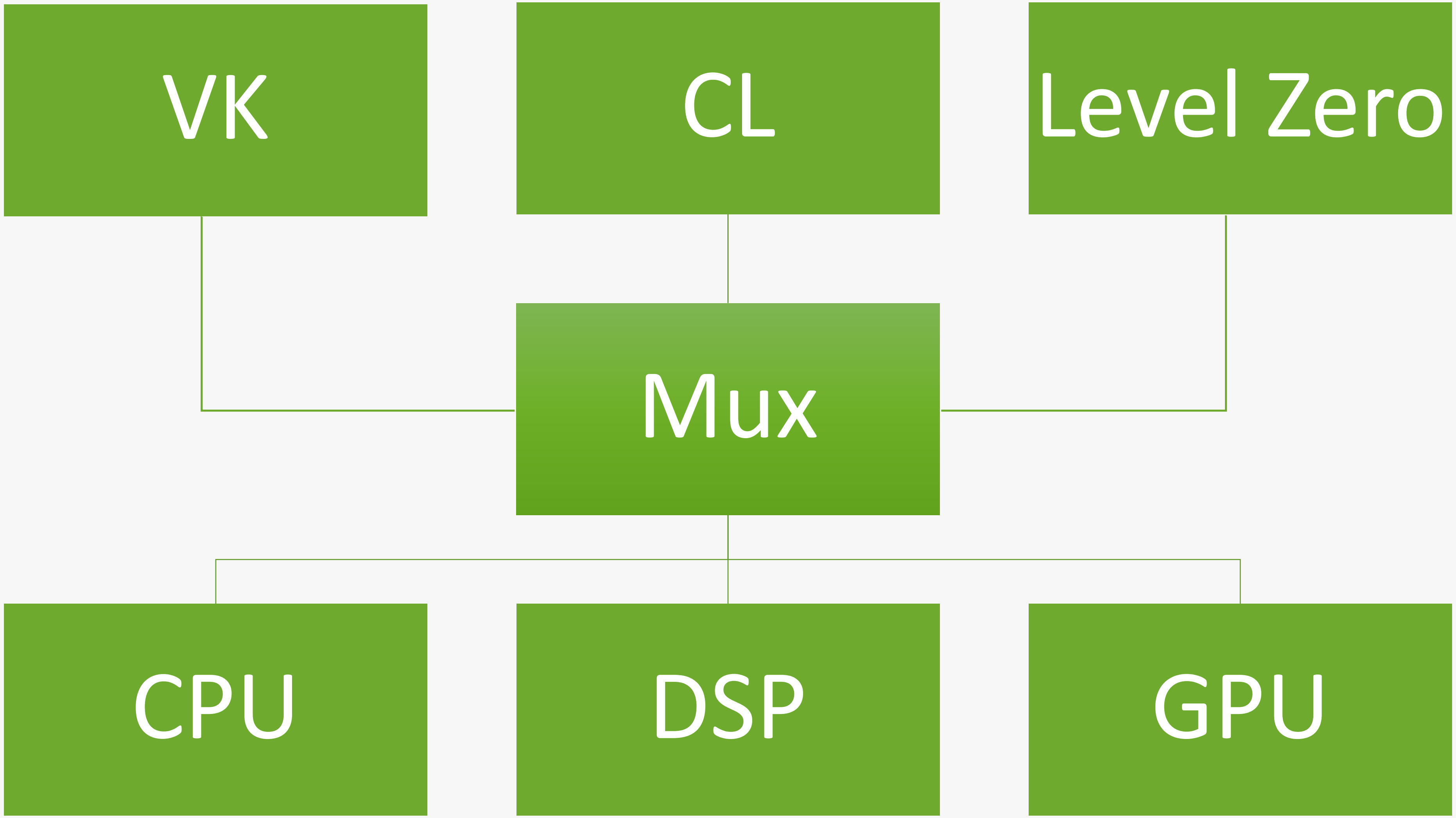
UnitVK
- Like UnitCL, but for the Vulkan specification.
- Covers SPIR-V extensively.

Fuzzing
- CLSmith etc.
- Tests the compiler very thoroughly
- Open source
- Creates random compiler tests

Ecosystem

Arrayfire	Babelstream	Boost-compute	clBLAS	CLBlast	clGPU	clFFT
clRNG	Cloverleaf	clSPARSE	ComputeApps	ComputeCpp SDK	Eigen	Glow
Halide	opencl-book-samples	OpenCV	SYCL-DNN	piglit	Polybench	pyOpenCL
SYCL-BLAS	SYCL-DNN	Tensorflow	TVM	VexCL	ViennaCL	

Conclusion



Conclusion

- Supporting multiple heterogeneous standards on a variety of devices requires making use of reusable components where possible, and allowing custom ones where it is not.

- Hard to predict in advance which parts will need to be customized, as exposing heterogeneous hardware capabilities is complicated. So follow an approach that allows flexibility.

- We do this primarily through the Mux API, allowing us to:
  - ✓Minimize effort to implement a heterogeneous API on a new device
  - ✓Enable high-performance programs on customer hardware
  - ✓Scale to supporting new standards

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