Heterogeneous Modern C++ with SYCL 2020

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NEVIN LIBER, TOM DEAKIN

Cppcon
The C++ Conference
2021
October 24-29

Distinguished Engineer

- Chair of SYCL Heterogeneous Programming Language
- ISO C++ Directions Group past Chair
- Past CEO OpenMP
- ISOCPP.org Director, VP
  http://isocpp.org/wiki/faq/wg21#michael-wong
- michael@codeplay.com
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- Head of Delegation for C++ Standard for Canada
- Chair of Programming Languages for Standards Council of Canada
  Chair of WG21 SG19 Machine Learning
  Chair of WG21 SG14 Games Dev/Low Latency/Financial Trading/Embedded
- Editor: C++ SG5 Transactional Memory Technical Specification
- Editor: C++ SG1 Concurrency Technical Specification
- MISRA C++ and AUTOSAR
- Chair of Standards Council Canada TC22/SC32 Electrical and electronic components (SOTIF)
- Chair of UL4600 Object Tracking
- RISC-V Datacenter/Cloud Computing Chair
- http://wongmichael.com/about
- C++11 book in Chinese: https://www.amazon.cn/dp/B00ETOV2OQ

Michael Wong

Argonne and Oak Ridge National Laboratories Award Codeplay® Software to Further Strengthen SYCL™ Support Extending the Open Standard Software for AMD GPUs

17 June 2021

LEMONT, IL, and OAK RIDGE, TN, and EDINBURGH, UK, June 17, 2021 - Argonne National Laboratory (ANL) in collaboration with Oak Ridge National Laboratory (ORNL), has awarded Codeplay a contract implementing the oneAPI DPC++ compiler, an implementation of the SYCL open standard software, to support AMD GPU-based high-performance compute (HPC) supercomputers

NSITEXE, Kyoto Microcomputer and Codeplay Software are bringing open standards programming to RISC-V Vector processor for HPC and AI systems

29 October 2020

NSI-TEXE | KMC | codeplay

Implementing OpenCL™ and SYCL™ for the popular RISC-V processors will make it easier to port existing HPC and AI software for embedded systems

NERSC, ALCF, Codeplay Partner on SYCL for Next-generation Supercomputers

02 February 2021

The **National Energy Research Scientific Computing Center** (NERSC) at **Lawrence Berkeley National Laboratory** (Berkeley Lab), in collaboration with the **Argonne Leadership Computing Facility** (ALCF) at Argonne National Laboratory, has signed a contract with **Codeplay Software** to enhance the LLVM SYCL™ GPU compiler capabilities for NVIDIA® A100 GPUs.

We build GPU compilers for some of the most powerful supercomputers in the world

Argonne NATIONAL LABORATORY | 75 1946–2021

Nevin ":-)" Liber

nliber@anl.gov

- Advanced Leadership Computing Facility (ALCF)
  - Computer Scientist
  - Kokkos (SYCL/DPC++ backend)
  - Vice Chair WG21 Library Evolution Working Group Incubator (LEWGI / SG18)
  - SYCL Committee Representative
  - oneAPI, oneMKL Technical Advisory Board Representative
- C++ developer for over three decades
- C++ Committee member for over a decade
  - Former host WG21 (C++) & WG14 (C) meetings

This presentation was supported by the Exascale Computing Project (17-SC-20-SC), a collaborative effort of two U.S. Department of Energy organizations (Office of Science and the National Nuclear Security Administration) responsible for the planning and preparation of a capable exascale ecosystem, including software, applications, hardware, advanced system engineering, and early testbed platforms, in support of the nation's exascale computing imperative. Additionally, this presentation used resources of the Argonne Leadership Computing Facility, which is a DOE Office of Science User Facility supported under Contract DE-AC02-06CH11357.

codeplay

Gordon Brown

Principal Product Owner, oneAPI & Automotive

Currently leading team developing HIP & CUDA backends for DPC++
Background in C++ programming models for heterogeneous systems
Worked on ComputeCpp (SYCL) since its inception
Contributor to the Khronos SYCL standard for 8 years
Contributor to C++ executors and heterogeneity or 5 years

University of BRISTOL

Dr Tom Deakin

Senior Research Associate / Lecturer (fixed term)

High Performance Computing Research Group

Chair Khronos SYCL Advisory Panel

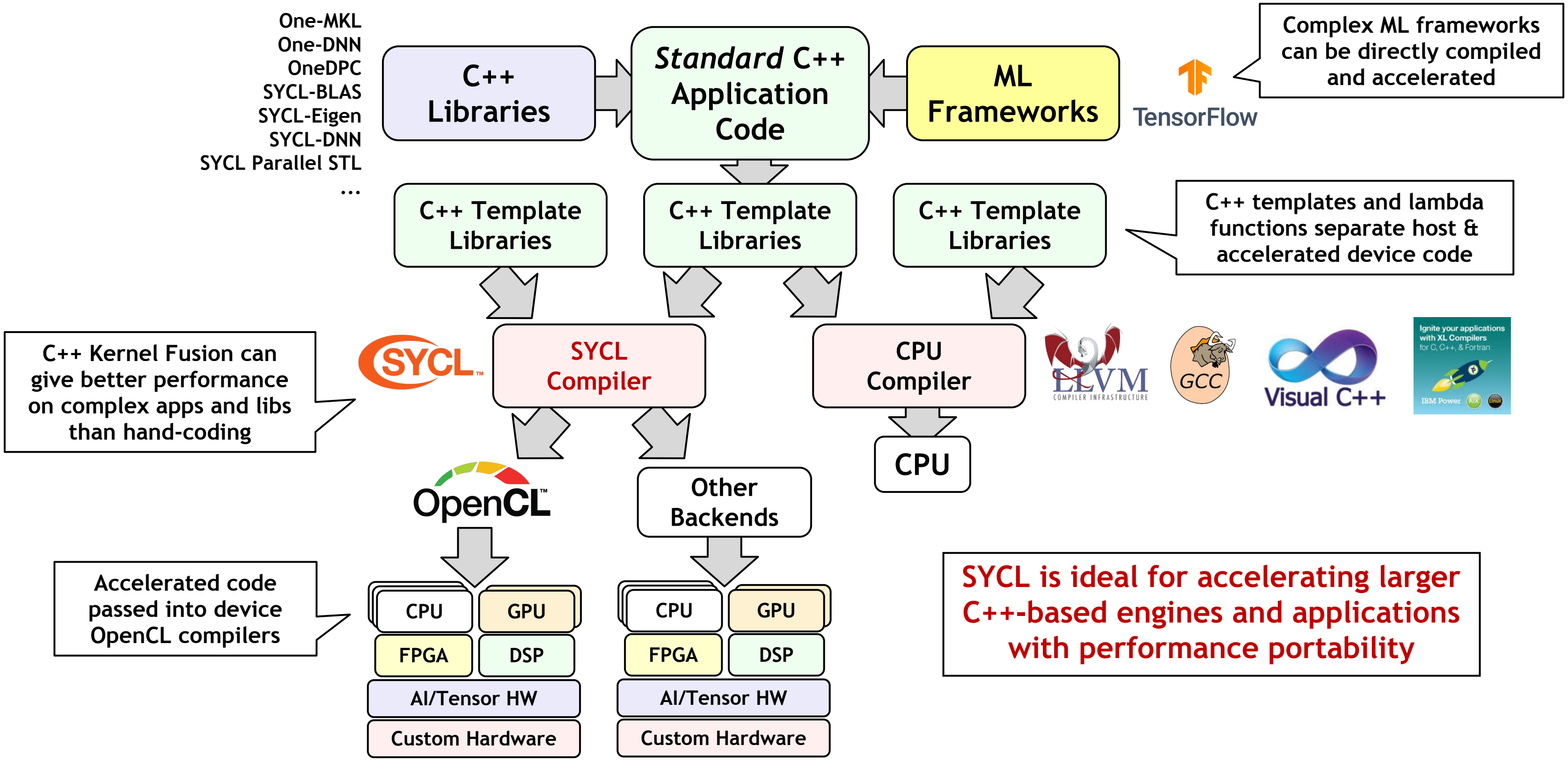
Khronos SYCL Outreach Officer

hpc.tomdeakin.com

Agenda

1. SYCL, oneAPI, and ecosystem
2. SYCL 2020 features
   - Moving with the Times and Any Backend
   - Memory Spaces and Dimensions
   - Reductions and Group Algorithms
3. SYCL futures

SYCL Single Source C++ Parallel Programming



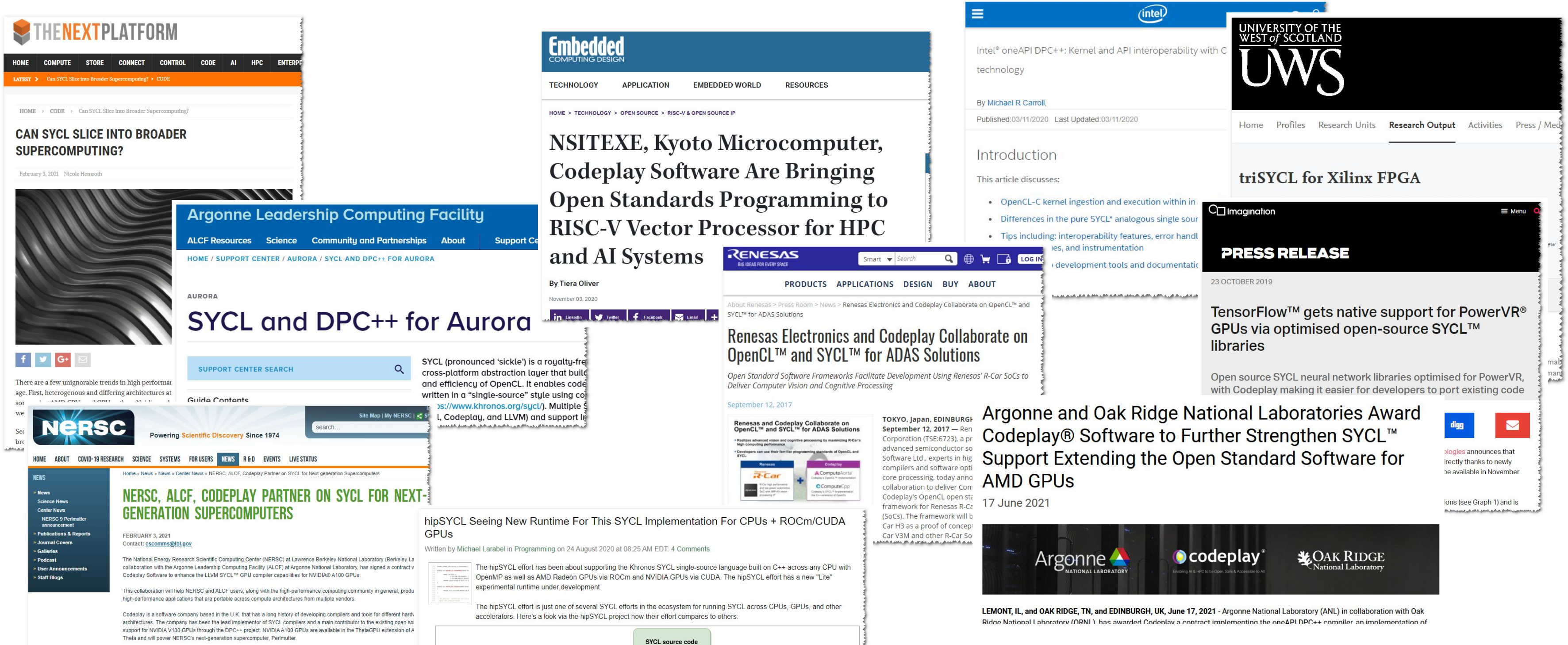
SYCL 2020 is here!

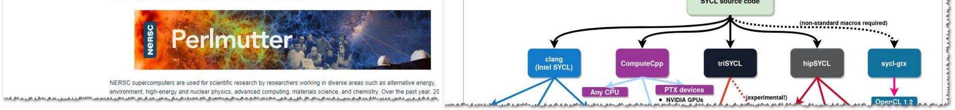
Open Standard for Single Source C++ Parallel Heterogeneous Programming

SYCL 2020 is released after 3 years of intense work
Significant adoption in Embedded, Desktop and HPC markets
Improved programmability, smaller code size, faster performance
Based on C++17, backwards compatible with SYCL 1.2.1
Simplify porting of standard C++ applications to SYCL
Closer alignment and integration with ISO C++
Multiple Backend acceleration and API independent

SYCL 2020 increases expressiveness and simplicity
for modern C++ heterogeneous programming

SYCL 2020 Industry Momentum





SYCL support growing from Embedded Systems through Desktops to Supercomputers

https://www.alcf.anl.gov/support-center/aurora/sycl-and-dpc-aurora
https://www.embeddedcomputing.com/technology/open-source/risc-v-open-source-ip/nsitexe-kyoto-microcomputer-and-codeplay-software-are-bringing-open-standards-programming-to-risc-v-vector-processor-for-hpc-and-ai-systems
https://www.nextplatform.com/2021/02/03/can-sycl-slice-into-broader-supercomputing/
https://www.phoronix.com/scan.php?page=news_item&px=hipSYCL-New-Lite-Runtime
https://software.intel.com/content/www/us/en/develop/articles/interoperability-dpcpp-sycl-opencl.html
https://www.renesas.com/br/en/about/press-room/renesas-electronics-and-codeplay-collaborate-opencl-and-sycl-adas-solutions
https://www.nersc.gov/news-publications/nersc-news/nersc-center-news/2021/nersc-alcf-codeplay-partner-on-sycl-for-next-generation-supercomputers/
https://research-portal.uws.ac.uk/en/publications/trisycl-for-xilinx-fpga
https://www.imaginationtech.com/news/press-release/tensorflow-gets-native-support-for-powervr-gpus-via-optimised-open-source-sycl-libraries/

SYCL 2020 Major Features

- Unified Shared Memory (USM)
    - Code with pointers can work naturally without buffers or accessors
    - Simplifies porting from most code (e.g. CUDA, C++)
- Parallel Reductions
    - Added built-in reduction operation to avoid boilerplate code and achieve maximum performance on hardware with built-in reduction operation acceleration.
- Work group and subgroup algorithms
    - Efficient parallel operations between work items
- Class template argument deduction (CTAD) and template deduction guides
    - Simplified class template instantiation
- Simplified use of Accessors with a built-in reduction operation
    - Reduces boilerplate code and streamlines the use of C++ software design patterns
- Expanded interoperability
    - Efficient acceleration by diverse backend acceleration APIs
- SYCL atomic operations are now more closely aligned to standard C++ atomics
    - Enhances parallel programming freedom

Parallel Industry Initiatives

C++11

C++14

C++17

C++20

C++23

SYCL 1.2
C++11 Single source programming

SYCL 1.2.1
C++11 Single source programming

SYCL 2020
C++17 Single source programming
Many backend options

SYCL 202X
C++20 Single source programming
Many backend options

OpenCL 1.2
OpenCL C Kernel Language

OpenCL 2.1
SPIR-V in Core

OpenCL 2.2

OpenCL 3.0

2011

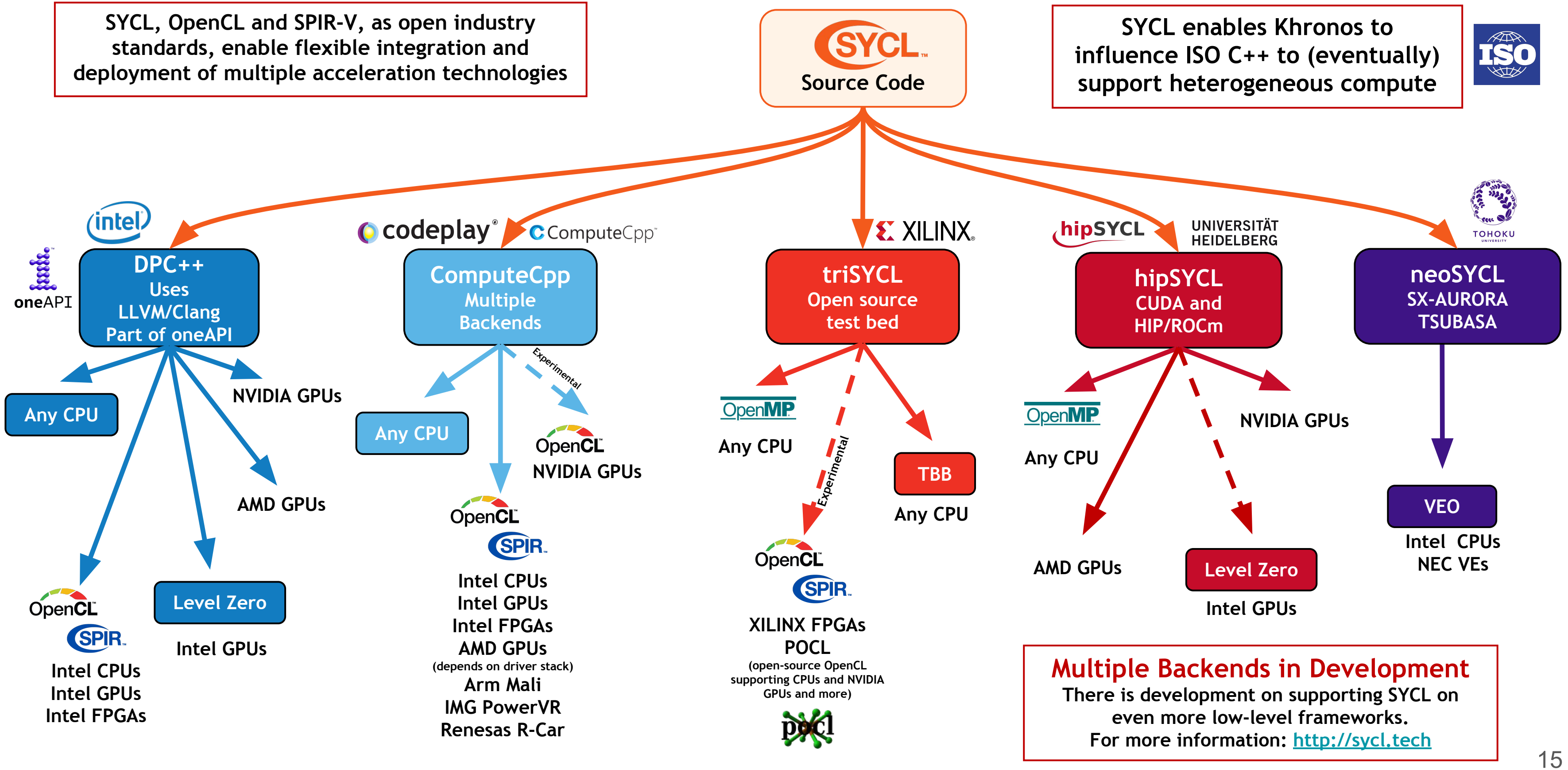
2015

2017

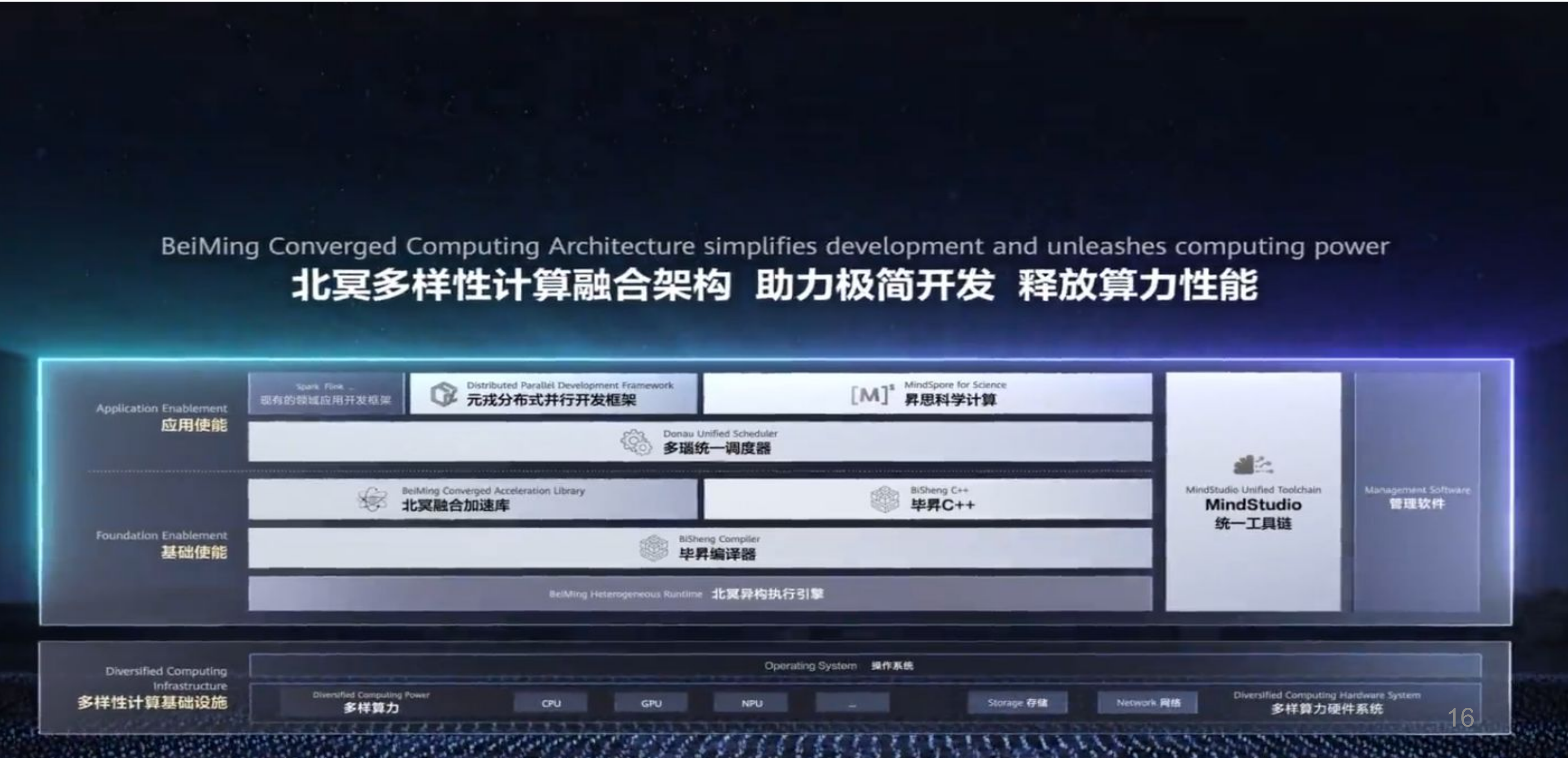
2020

202X

SYCL Implementations in Development



News: Huawei Bisheng（毕昇）C++



SYCL Ecosystem, Research and Benchmarks

Implementations

neoSYCL
SX-AURORA TSUBASA

triSYCL

oneAPI

oneAPI
DATA PARALLEL C++
Performant, Productive Programming for Heterogeneous Architecture

ComputeCpp

hipSYCL

Celerity
High-level C++ for Accelerator Clusters

EXASCALE COMPUTING PROJECT

kokkos

Taskflow: A General-purpose Parallel and Heterogeneous Task Programming System using Modern C++

Dr. Tsung-Wei (TW) Huang
Department of Electrical and Computer Engineering
University of Utah, Salt Lake City, UT
https://taskflow.github.io/

GROMACS
FAST. FLEXIBLE. FREE.

RAJA

Grid: A High-Performance and Portable Code for Quantum Chromodynamics. [E32016]

SYCL 2020 Programming E

ATLAS EXPERIMENT

alpaka

Benchmarks/Books

Direct Programming Benchmark

Data Parallel C++
Mastering DPC++ for Programming of Heterogeneous Systems using C++ and SYCL
James Reinders
Ben Ashbaugh
James Brodman
Michael Kinsner
John Pennycook
Xinmin Tian

SYCL-BENCH

FREE eBook

360k downloads

Linear Algebra Libraries

Machine Learning Libraries and Parallel Acceleration Frameworks

BLAS	FFT	Math	RAND
SYCLBLAS oneMKL	oneMKL	oneMKL	oneMKL
SOLVER	**SPARSE**	**TENSOR**	**STL**
oneMKL	oneMKL	SYCL-DNN Eigen oneDNN TensorFlow	SYCL Parallel STL oneDPL

STREAM HPC

Argonne NATIONAL LABORATORY

QUALCOMM

University of BRISTOL

arm

AMD

SYCL™

Working Group Members

codeplay

universität innsbruck

XILINX

intel

TOHOKU UNIVERSITY

SYCL in Embedded Systems, Automotive, and AI

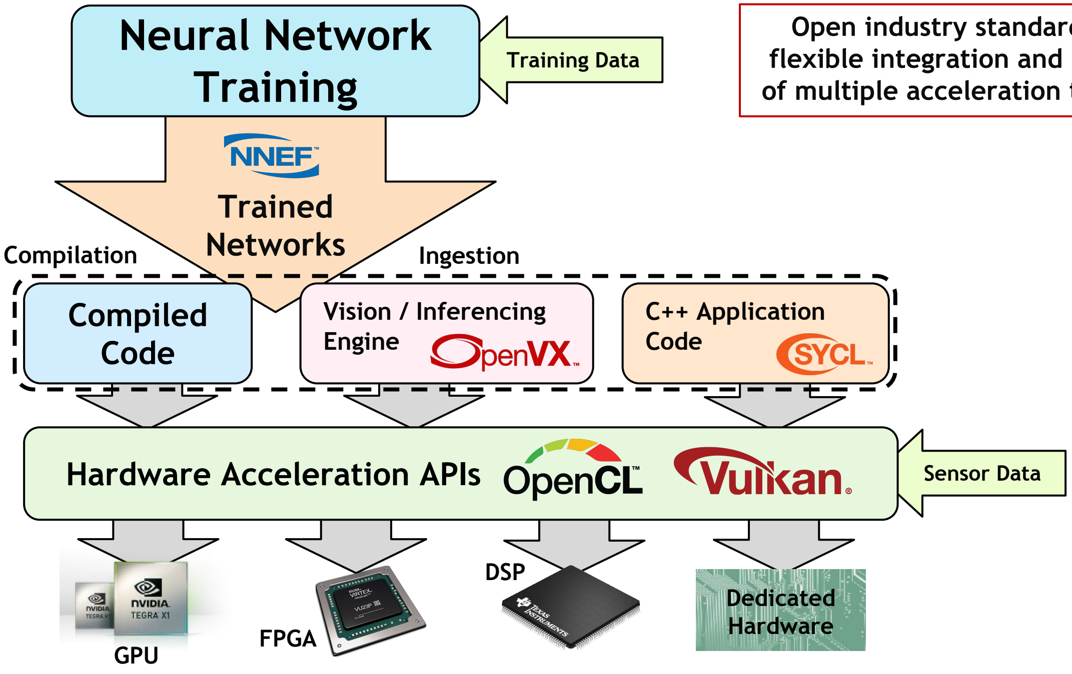
Open industry standards, enable flexible integration and deployment of multiple acceleration technologies

Networks trained on high-end desktop and cloud systems

Applications link to compiled inferencing code or call vision/inferencing API

Diverse Embedded Hardware

Multi-core CPUs, GPUs
DSPs, FPGAs, Tensor Cores
* Vulkan only runs on GPUs



Safety Critical API Evolution

New Generation Safety Critical APIs for Graphics, Compute and Display

OpenCL and SYCL SC work will minimize API surface area , reduce ambiguity, UB, increase determinism

OpenCL

SYCL™

Rendering Compute Display

Industry Need for GPU Acceleration APIs designed to ease system safety certification is increasing

ISO 26262 / ASIL-D

RISC-V

SCSC FOR EVERYONE WORKING IN SYSTEM SAFETY WWW.SCSC.UK

ISO International Organization for Standardization

UNECE WP.29

ISO 26262

ISO/PAS 21448

UL 4600

MISRA

SAE INTERNATIONAL

ISO/IEC JTC 1/SC 42
Artificial intelligence

SYCL in HPC/Supercomputers

Simulation
HPC Languages
Solver Libraries, Parallel RT

Data
Productivity Languages
Big Data Stack, Stats Lib, Databases

Learning
Productivity Languages
Deep Learning, Linear Alg, ML

Three Pillars of Science Problem

Today's Supercomputing Development Workflow needs knowledge of system architecture and tools that control data

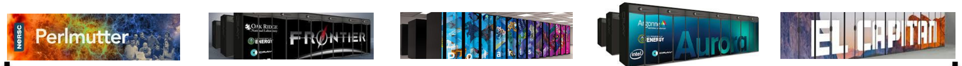
OpenMP for C and Fortran

CUDA/pthreads/ OpenACC/OpenCL

C++ Application uses SYCL, Kokkos, Raja

Math, ML, Data Libraries; C++ Std, C, Python Libraries

2021 | 2021 | 2022 | 2022 | 2023



SYCL

Need Languages that allow control of these Data Issues
Set Data affinity, Data Layout, Data movement, Data Locality, highly Parameterized Code and dynamically compose the algorithms (C++ templates, parallel STL, inlining and fusion, abstractions)

Libraries augment compiler optimizations for Performance Portable programs

Use open standards to run Performance Portable code on new generation, or different vendor's, hardware with compiler optimization, explicit parametrization and dynamically composed algorithm

Choose Algorithm for target

Implement and Test Algorithm

Optimize Algorithm

Agenda

1. SYCL, oneAPI, and ecosystem
2. SYCL 2020 features
   - Moving with the Times and Any Backend
   - Memory Spaces and Dimensions
   - Reductions and Group Algorithms
3. SYCL futures

Moving with the Times

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

First we include the **SYCL/sycl.hpp** header file

This includes the entire SYCL interface

SYCL 2020: Header file has changed from CL/sycl.hpp

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

In this example we want to add the values of two vectors in parallel on an accelerator

So we allocate two input vectors and an output vector of equal size

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

In SYCL all work is dispatch to an accelerator via a **queue**

Here we create a queue which will target a GPU device

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

The first parameter to construct the queue is a device selector which provides a heuristic for choosing a device

Here we use one of the standard device selectors **gpu_selector_v**

SYCL 2020: Device selectors are now simply a function object rather than requiring inheritance

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

The second parameter to construct the queue is an async handler which is a function object used to handle asynchronous exceptions thrown by the runtime

SYCL 2020: If an async handler is not provided the default behaviour is now to terminate on encountering an error

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

In SYCL there are two memory management models; buffers and USM - here we will focus on buffers

The buffers memory management model separates the storage and access of data and automatically handles data dependencies

USM provides a more explicit memory management

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

In the buffers memory management model there are **buffers** and **accessors**

A buffer manage data across the host and one or more devices

An accessor represents a request to access the data on a particular device with a particular set of properties

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

Here we create buffers for the input and output data

A buffer can be constructed with a pointer to the data on the host and a **range** object describing the number of elements in a multi-dimensional space

SYCL 2020: Buffers have CTAD so no longer require explicit template parameters

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

Buffers manage data during their lifetime

On destruction of the buffer it will wait for any work the queue is doing which accesses the buffer's data

It will then synchronize the data back to the original host pointer

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

All work enqueue to an accelerator in SYCL is done via a command group

Command groups are created by calling **submit()** on the queue with a function object which will construct the command group

The command group function takes a **handler** which is used to add commands and dependencies

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read only);
      sycl::accessor inB(bufB, cgh, sycl::read only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

Inside the command group we create accessors for each buffer

Accessors are used to create dependencies to the data managed by their respective buffers

They are also used to access the data once on the device

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

The accessors are constructed from their respective buffer, the handler and a tag which describes the access mode

The access mode is used by the SYCL runtime to manage data dependencies

SYCL 2020: Accessors have CTAD and tags so no longer require explicit template parameters

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

Inside the command group we also define the kernel function by calling **parallel_for()**

This defines a device function which is the entry point for the code which runs on the accelerator

SYCL 2020: Kernel functions no longer require a template parameter to name them

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

The first parameter to parallel_for is a **range** which describes the iteration space the kernel will execute across

The second parameter to parallel_for is a function object which defines the kernel function itself

The kernel function takes as a parameter an **id** which represents the currently executing work-item

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

Here the kernel function is a lambda

The body of the lambda is what is executed on the accelerator

If using a lambda accessors and other arguments must be captures by value

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
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      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

In the kernel function we do a simple vector add

Using the subscript operator of the accessors with the id to retrieve an element of data from the two inputs and then assign the sum of those to an element of the output

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

Finally we call **wait_and_throw()** to wait for the command group to complete

The wait_and_throw() function will also throw any asynchronous errors encountered

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

Any synchronous errors which are encountered are thrown immediately

Any asynchronous errors which are encountered are stored and then thrown when wait_and_throw() is called

It’s important to have a try-catch block to catch and handle any exceptions

SYCL 2020 Hello World

```
#include <SYCL/sycl.hpp>

int main(int argc, char *argv[]) {
  std::vector<float> dA{ … }, dB{ … }, dO{ … };

  try {
    sycl::queue gpuQueue{sycl::gpu_selector_v, async_handler{}};

    sycl::buffer bufA{dA.data(), sycl::range{dA.size()}};
    sycl::buffer bufB{dB.data(), sycl::range{dB.size()}};
    sycl::buffer bufO{dO.data(), sycl::range{dO.size()}};

    gpuQueue.submit([&](sycl::handler &cgh){

      sycl::accessor inA(bufA, cgh, sycl::read_only);
      sycl::accessor inB(bufB, cgh, sycl::read_only);
      sycl::accessor out(bufO, cgh, sycl::write_only);

      cgh.parallel_for(sycl::range{dA.size()},
        [=](id<1> i){ out[i] = inA[i] + inB[i]; });
    });

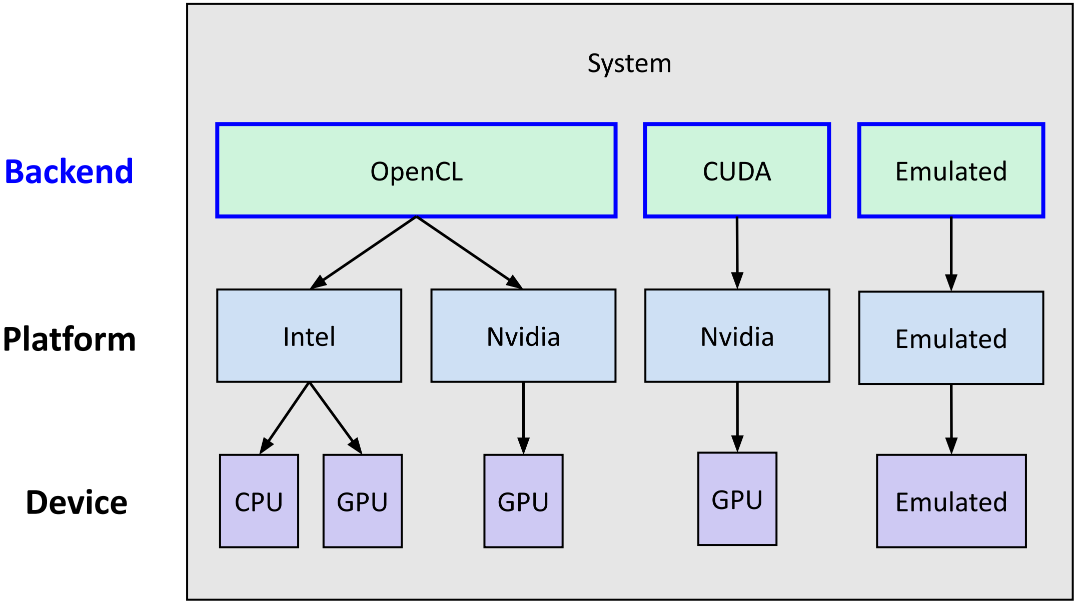
    gpuQueue.wait_and_throw();

  } catch (sycl::exception &e) {
    /* handle SYCL exception */
  }
}
```

Remember that upon leaving the scope containing the buffers the output data will be synchronized back with the original pointer

Any Backend

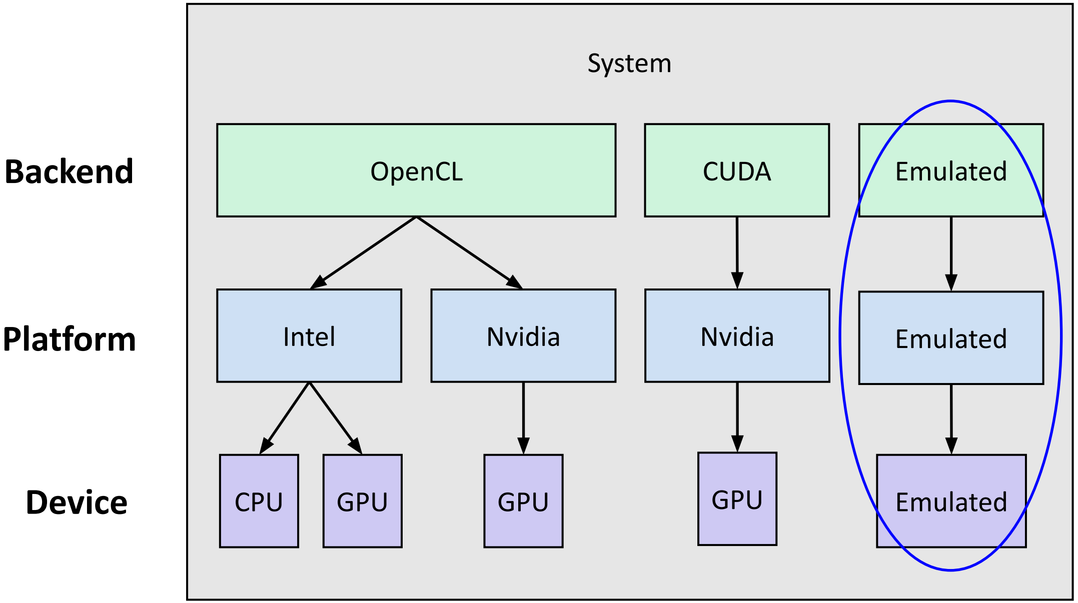
SYCL 2020 Backends



The SYCL topology has been extended to include backends

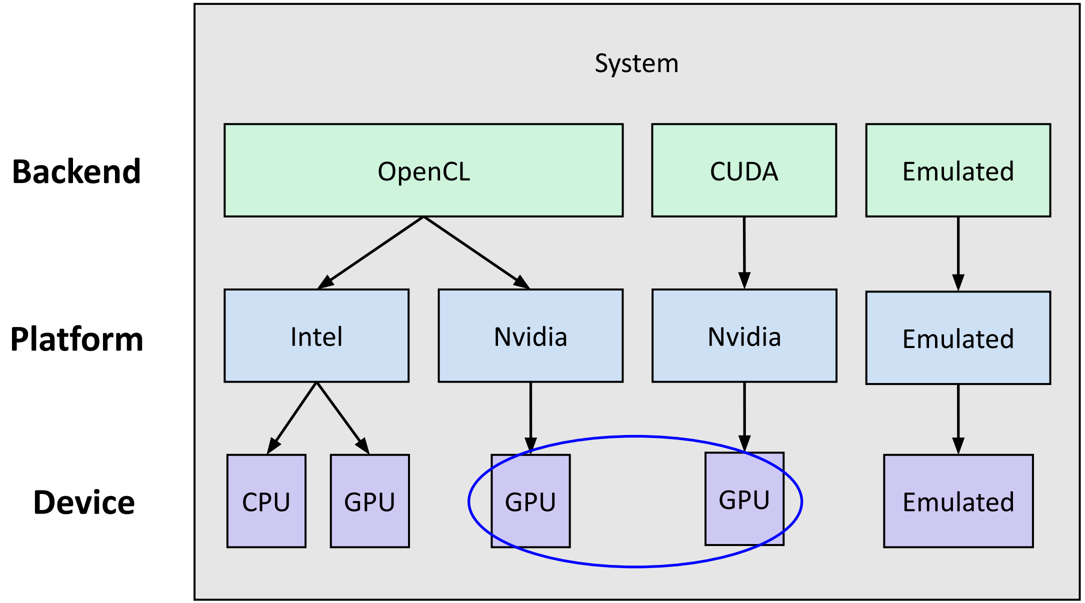
Device selectors can be used to find devices from any backend

SYCL 2020 Backends



The host device is now available via the **aspect::emulated** aspect

SYCL 2020 Backends



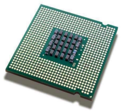
The same device can exist in more than one backend

Generic SYCL

Portable across any implementation

Interoperable SYCL

Portable across any implementation with the same backend



Vendor-specific SYCL

Non-portable

An application written to the core SYCL specification is portable to any SYCL implementation

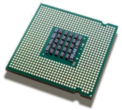
Generic SYCL

Portable across any implementation

Interoperable SYCL

Portable across any implementation with the same backend

Vendor-specific SYCL



Non-portable

An application written using the backend-specific interoperability API is portable to any SYCL implementation which supports that backend

SYCL™

Generic SYCL

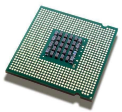
Portable across any implementation

SYCL™

Interoperable SYCL

Portable across any implementation with the same backend

SYCL™



Vendor-specific SYCL

Non-portable

An application written using a vendor-specific extension is not portable and can only be run by that vendor's SYCL implementation

Memory Spaces

SYCL Memory Model

- Initially based on OpenCL Memory Model
- Higher level of abstraction
- Buffers & Accessors
  - Buffers
    - Storage
  - Accessors
    - Access
  - Compiler automatically builds a DAG at runtime
- USM (Unified Shared Memory)
  - Explicit data allocation and movement
  - C++ pointers

Memory Spaces

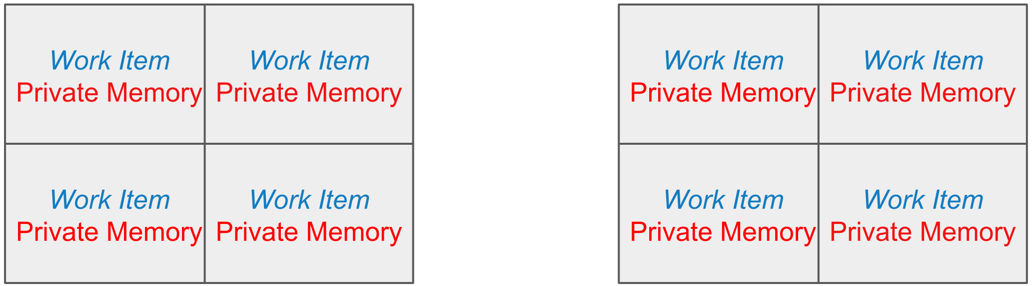
Buffers & Accessors

SYCL Memory Model - Buffers & Accessors

- Buffers & Accessors
  - Private memory
  - Local memory
  - Global memory
  - Generic memory
  - Constant memory

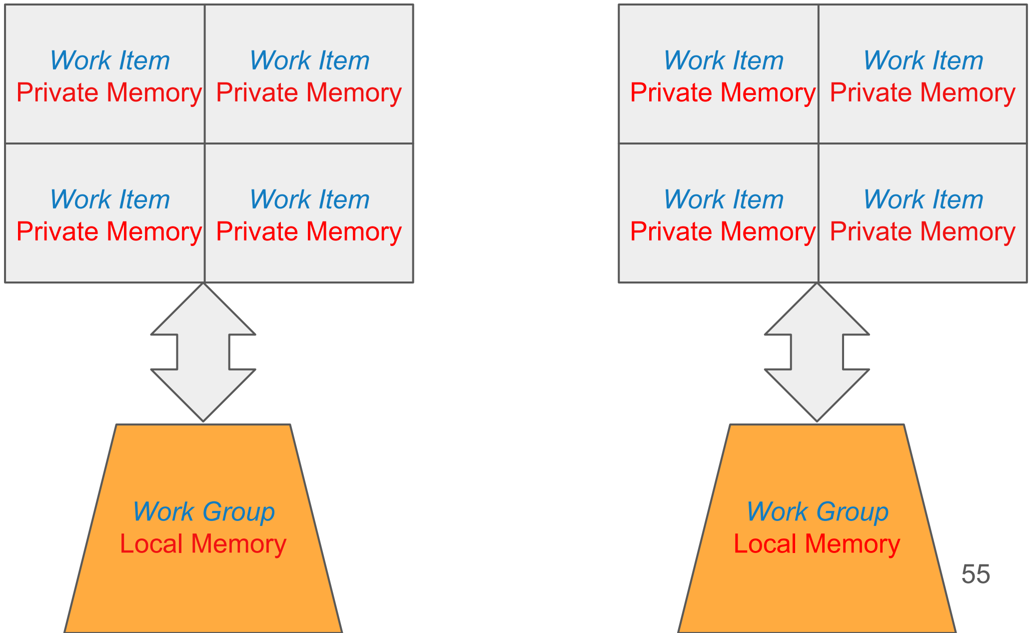
SYCL Memory Model - Buffers & Accessors

- Private memory
  - Private to a work item
  - Not accessible to other work items
  - Kernel memory
  - Local stack variables
- Work item
  - An instance of a kernel
  - Has a global id



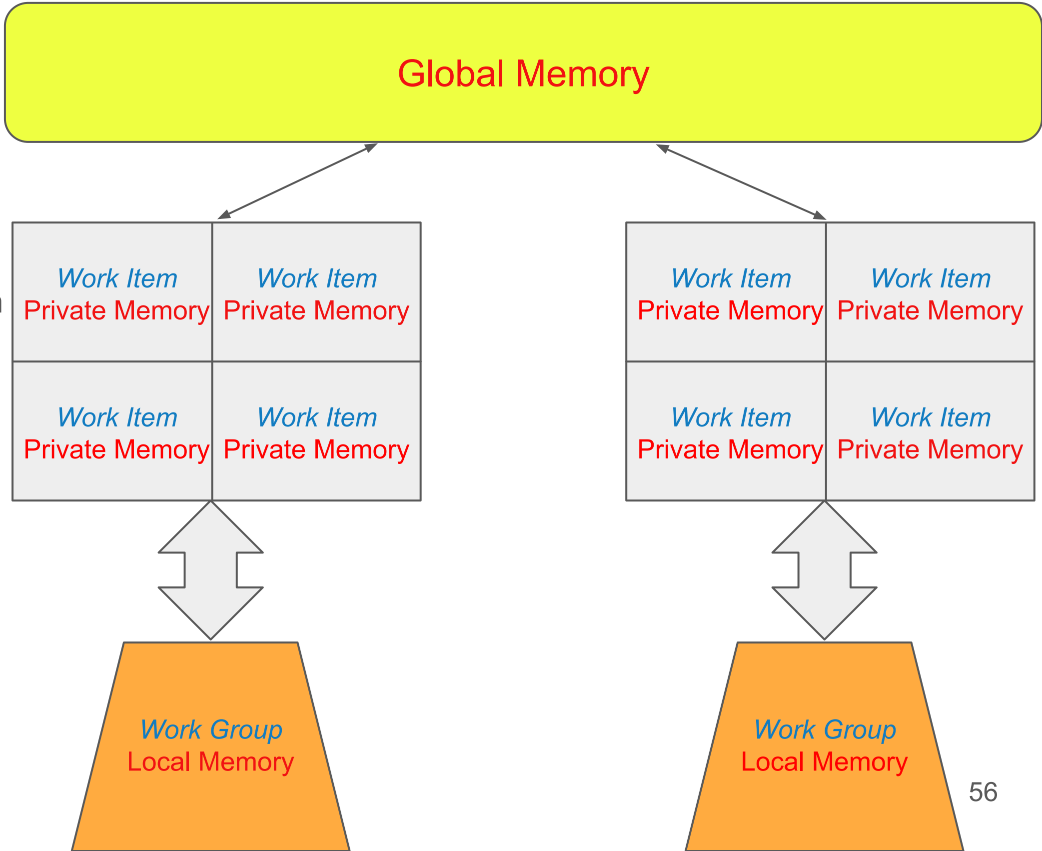
SYCL Memory Model - Buffers & Accessors

- Local memory
  - Accessible to all work items in a work group
  - For variables shared across work items
- Work group
  - Related work items
  - Single compute unit



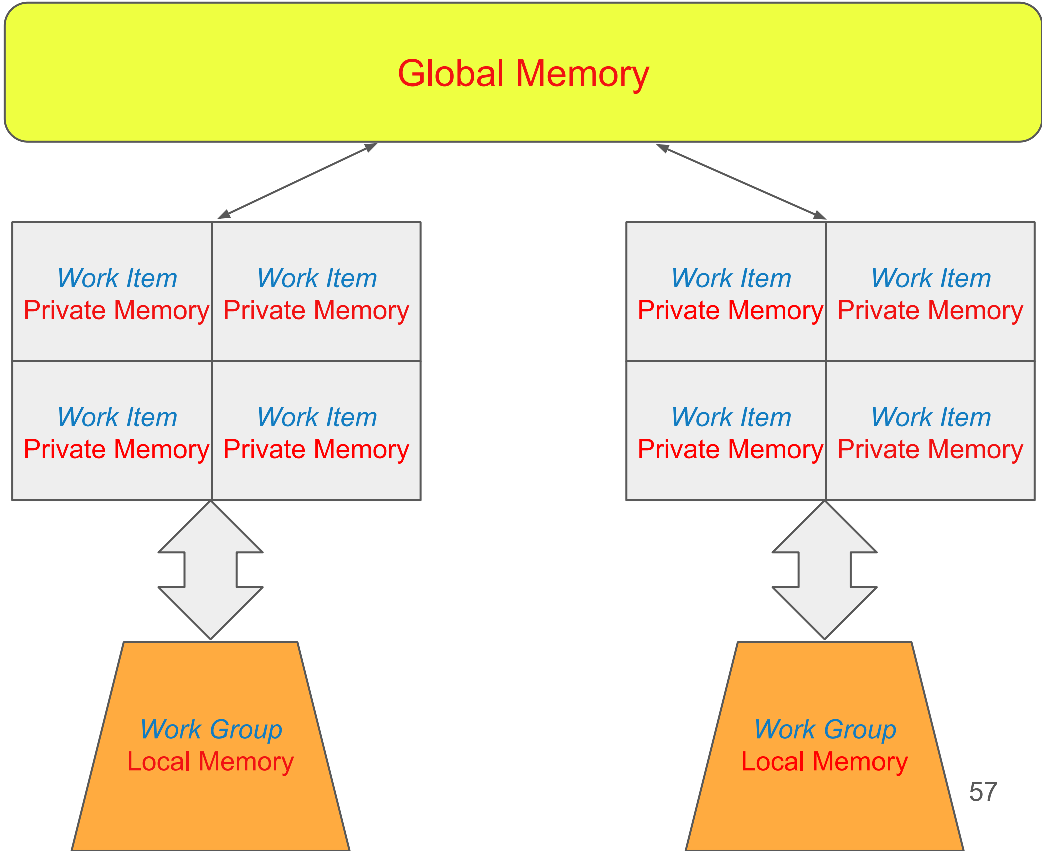
SYCL Memory Model - Buffers & Accessors

- Global memory
  - Accessible to all work items in all work groups
  - Persistent across kernel invocations
  - Different devices (in the same context) can access the memory
  - No implied synchronization for simultaneous writes from two different kernels



SYCL Memory Model - Buffers & Accessors

- Generic memory
    - Virtual address space encompassing the global, local and private address spaces



SYCL Memory Model - Buffers & Accessors

- Constant memory
    - OpenCL platforms
    - Remains constant during execution of a kernel
    - Not part of generic memory
    - `multi_ptr` support for constant memory deprecated in SYCL 2020

SYCL Memory Model - Buffers & Accessors

```
enum class address_space : int {
global_space,
local_space,
constant_space, // Deprecated in SYCL 2020
private_space,
generic_space,
};

enum class decorated : int { /* ... */ };

template <typename ElementType,
access::address_space Space,
Access::decorated DecorateAddress>
class multi_ptr { /* … */ };
```

- `multi_ptr`
  - Address space boundaries
  - Interoperability
- Raw pointers
  - Implementation defined
  - Sometimes requires explicit decoration for address space
    - Platform dependent keyword

SYCL Memory Model - Buffers & Accessors

```
enum class address_space : int {
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```

- `multi_ptr`
  - Address space boundaries
  - Interoperability
- Raw pointers
  - Implementation defined
  - Sometimes requires explicit decoration for address space
    - Platform dependent keyword

Memory Spaces

Unified Shared Memory (USM)

Unified Shared Memory (USM)

- Pointer based model
- Unified virtual address space
- An allocated pointer has the same value (object representation) on the host and on the device
    - Although there may be access restrictions when dereferencing

Unified Shared Memory (USM)

Allocation Type	Description	Accessible on host?	Accessible on device?	Located on
device	Allocations in device memory	X	√	device
host	Allocations in host memory	√	√	host
shared	Allocations shared between host and device	√	√	can migrate between host and device

Unified Shared Memory (USM)

- Device allocations
  - Memory attached to device
  - Not accessible on the host
    - If host needs access, must be explicitly copied via special `memcpy` calls

Allocation Type	Descriptio n	Accessible on host?	Accessible on device?	Located on
device	Allocations in device memory	X	√	device
host	Allocations in host memory	√	√	host
shared	Allocations shared between host and device	√	√	can migrate between host and device

Unified Shared Memory (USM)

- Host allocations
    - Resides on host
    - Implicitly accessible on host and device
        - Device access to data over bus (e.g., PCI-E)
            - Slower than device allocations
    - Rarely accessed data
    - Large data sets

Allocation Type	Description	Accessible on host?	Accessible on device?	Located on
device	Allocations in device memory	X	√	device
host	Allocations in host memory	√	√	host
shared	Allocations shared between host and device	√	√	can migrate between host and device

Unified Shared Memory (USM)

- Shared allocations
  - Implicitly accessible on host and device
    - Data *can* migrate to where it is used on-demand
      - Could be implemented as device allocation
      - Prefetch - start migration early
  - `mem_advise`

Allocation Type	Description	Accessible on host?	Accessible on device?	Located on
device	Allocations in device memory	X	√	device
host	Allocations in host memory	√	√	host
shared	Allocations shared between host and device	√	√	can migrate between host and device

Unified Shared Memory (USM)

- Allocation styles
  - C
    - `malloc`, `aligned_alloc`, `malloc_host`, etc.
    - Specify size of allocation
  - C++
    - `template<typename T> T* malloc_host(...)`, etc.
    - Stateful C++17 allocators

USM vs. Buffers / Accessors

- USM Pointers
  - Very close to regular C++ programming
- Accessors
  - Implicitly builds data dependency DAG between kernels

Device Copyable

Device Copyable

- How can we copy objects between a host or a device and another device?
- C++
  - Copy constructor `T::T(T const&)`
    - Running code
- SYCL
  - Where (what device) would the copy constructor run?
  - How would it gain access to both the source and destination bytes?
  - About all we can do in general is copy the bytes

Device Copyable

- Trivially copyable
    - Proxy
    - Bitwise copy (copy the bytes)
    - Some obvious C++ types aren’t trivially copyable for historical reasons
        - `pair<TriviallyCopyableTypes…>`
        - `tuple<TriviallyCopyableTypes…>`
    - Trivially copyable has other (unnecessary) requirements
        - At least one copy/move constructor/assignment operator
        - Destructor and non-deleted copy/move constructor/assignment operators must be public and trivial
        - Layout & ABI conflated into trivially copyable
            - Why we can’t fix `pair`

Device Copyable

```
struct A {
#ifndef __SYCL_DEVICE_ONLY__
    ~A() {} // Not trivially copyable
#endif
};

static_assert(std::is_trivially_copyable_v<A>);

template <bool B> void C() { /* ... */ }
C<std::is_trivially_copyable_v<A>>();
```

- `__SYCL_DEVICE_ONLY__`
  - Can violate the C++ One Define Rule (ODR)
  - `static_assert` only fires on the host
  - What is the value of that template parameter to `C`?
  - What does it mean to run the destructor on the host but not the device?

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```

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Device Copyable

```
struct A {
#ifndef __SYCL_DEVICE_ONLY__
    ~A() {} // Not trivially copyable
#endif
};

static_assert(std::is_trivially_copyable_v<A>);

template <bool B> void C() { /* ... */ }
C<std::is_trivially_copyable_v<A>>();
```

- `__SYCL_DEVICE_ONLY__`
  - Can violate the C++ One Define Rule (ODR)
  - `static_assert` only fires on the host
  - What is the value of that template parameter to `C`?
  - What does it mean to run the destructor on the host but not the device?

Device Copyable

```
struct A {
#ifndef __SYCL_DEVICE_ONLY__
    ~A() {} // Not trivially copyable
#endif
};

static_assert(std::is_trivially_copyable_v<A>);

template <bool B> void C() { /* ... */ }
C<std::is_trivially_copyable_v<A>>();
```

- `__SYCL_DEVICE_ONLY__`
  - Can violate the C++ One Define Rule (ODR)
  - `static_assert` only fires on the host
  - What is the value of that template parameter to `C`?
  - What does it mean to run the destructor on the host but not the device?

Device Copyable

- Manually copy the bytes to the device
    - Violates C++ Object Model (lifetime of objects)
    - Copying does not magically bring (non trivially copyable / non implicit lifetime) types into existence
    - Undefined behavior
        - May work today, but can easily break tomorrow

Device Copyable

- **`is_device_copyable`**
  - Defaults to `std::is_trivially_copyable`
  - Specialized for `array`, `optional`, `pair`, `tuple`, `variant` of *device copyable* types
    - Like trivially copyable, we need the recursive definition
    - C++ doesn't yet have reflection
  - Users can specialize it if their type can be bitwise copied
    - At their own risk!
  - Unspecified if/where copy/move constructor/assignment and destructor are run

atomic_ref

atomic_ref

- C++11 `std::atomic`
  - Always defaults to `seq_cst`
    - Safety / easiest to reason about
  - Owns the data
  - Always requires atomic access
    - Over-constraint
  - Cannot be moved or copied
    - Cannot create objects on the host and copy them to the device
- SYCL 1.2.1 `cl::sycl::atomic`
  - *Modeled* on `std::atomic`
    - Does not own its data
    - Defaults to `relaxed`
      - Compatible with OpenCL
  - Deprecated in SYCL 2020

atomic_ref

- C++11
  - No notion of non-owning interfaces
    - Raw pointers non-owning by convention
    - E.g., interfaces with strings
  - `void A(std::string const&)  { /* ... */ }`
    - owning; allocation?
  - `void A(char const*, size_t) { /* ... */ }`
    - non-owning; more efficient

- C++17
  - `std::string_view`
    - *Non-owning* reference to string data
      - Pointer and a size
    - Efficient
    - Great vocabulary type for interfaces
    - Separation of concerns - only concerned with operations
  - `void A(std::string_view)  { /* ... */ }`
    - Replace C++11 interfaces for `A`

atomic_ref

- C++20
  - `std::span`
    - *Non-owning* reference to contiguous data
  - Ranges
    - Non-owning views
  - `std::atomic_ref`
    - *Non-owning* atomic access to data
    - User promises only atomic access to data for lifetime of `atomic_ref` object
- SYCL 2020
  - **`sycl::atomic_ref`**
    - *Non-owning* atomic access to data
    - *Modeled* on C++20 `std::atomic_ref`
      - 3 more template arguments
    - SYCL only required to support `relaxed`
    - May support `acq_rel` and `seq_cst`

atomic_ref

```
namespace std { template<class T> struct atomic_ref
{
    T load(memory_order = memory_order::seq_cst)
const noexcept;
    //...
};}

namespace sycl { template <class T, memory_order
DefaultOrder, memory_scope DefaultScope, access
::address_space Space =
access::address_space::generic_space>
struct atomic_ref {
    T load(memory_order order = default_read_order,
memory_scope scope = DefaultScope) const noexcept;
    //...
};}
```

- `std::atomic_ref` vs. `sycl::atomic_ref`

atomic_ref

```
namespace std { template<class T> struct atomic_ref
{
    T load(memory_order = memory_order::seq_cst)
const noexcept;
    //...
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access::address_space::generic_space>
struct atomic_ref {
    T load(memory_order order = default_read_order,
memory_scope scope = DefaultScope) const noexcept;
    //...
};}
```

- C++20
  - `T` is trivially copyable
- SYCL 2020
  - `int`, `unsigned int`, `long`, `unsigned long`, `long long`, `unsigned long long`, `float`, `double`
    - Whether or not `float` & `double` supported natively
  - SYCL requires 32-bit support; 64-bit optional
  - No support for large types
    - `complex<double>`
    - Might require globally accessible lock table

atomic_ref

```
namespace std { template<class T> struct atomic_ref
{
    T load(memory_order = memory_order::seq_cst)
const noexcept;
    //...
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access::address_space::generic_space>
struct atomic_ref {
    T load(memory_order order = default_read_order,
memory_scope scope = DefaultScope) const noexcept;
    //...
};}
```

- `memory_order`
  - Why no default?
    - C++ `seq_cst` rules out lots of devices
    - Least common denominator `relaxed` leads to surprises when migrating existing code
  - `default_read_order` / `default_write_order` many be different than `DefaultOrder`
    - `DefaultOrder == acq_rel` -> `default_read_order==acquire`

atomic_ref

```
namespace std { template<class T> struct atomic_ref
{
    T load(memory_order = memory_order::seq_cst)
const noexcept;
    //...
};}

namespace sycl { template <class T, memory_order
DefaultOrder, memory_scope DefaultScope, access
::address_space Space =
access::address_space::generic_space>
struct atomic_ref {
    T load(memory_order order = default_read_order,
memory_scope scope = DefaultScope) const noexcept;
    //...
};}
```

- `memory_scope`
  - Memory ordering constraints
  - `work_item`, `sub_group`, `work_group`, `device`, `system`
  - Why no default?
    - Safest `system` rules out lots of devices
    - Least common denominator `work_group` leads to surprises when migrating existing code

atomic_ref

```
namespace std { template<class T> struct atomic_ref
{
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    //...
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    T load(memory_order order = default_read_order,
memory_scope scope = DefaultScope) const noexcept;
    //...
};}
```

- `address_space`
- Where the referenced object is allocated
  - `generic_space`, `global_space`, `local_space`
- Override default of `generic_space` for performance tuning

atomic_ref

```
namespace std { template<class T> struct atomic_ref
{
    T load(memory_order = memory_order::seq_cst)
const noexcept;
    //...
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    T load(memory_order order = default_read_order,
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    //...
};}
```

- `std::atomic_ref` vs. `sycl::atomic_ref`

Multidimensional subscript & mdspan

C++23

Multidimensional subscript operator[]

- C++ 20 deprecated a comma expression within square brackets
  - `a[b, c]; // deprecated; uses c as index/key`
  - `a[(b, c)] // ok; uses c as index/key`
- Comma expression now ill-formed in C++23
- Previous workarounds
  - `a(x, y, z)   // function call operator taking multiple indices`
  - `A[x][y][z]   // chain of single argument array access operators`
  - `a[{x, y, z}] // array index operator taking a tuple-like index`
- Definition & use match `operator()`
  - `A[b, c]; // calls A::operator[](B, C); uses b, c as two ordered indices`
- No change to C arrays

mdspan

```
template<class ElementType, class Extents,
         class LayoutPolicy = layout_right,
         class AccessorPolicy =
default_accessor<ElementType>>
struct mdspan {
    //...
    template<class... SizeTypes>
    constexpr reference
        operator[](SizeTypes... indices) const
        { /* ... */ }
    //...
};
```

- `std::mdspan`
  - *Non-owning* multi-dimensional array view
  - First standard library type to use multidimensional subscript `operator[]`

mdspan

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struct mdspan {
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        operator[](SizeTypes... indices) const
        { /* ... */ }
    //...
};
```

- `std::mdspan`
  - `Extents`
    - Describe each dimension
    - Both for sizes known at compile time and run time
  - `LayoutPolicy`
    - `Layout_right`
      - C
    - `layout_left`
      - FORTRAN
    - `layout_stride`
  - `AccessorPolicy`

mdspan

```
template<class ElementType, class Extents,
          class LayoutPolicy = layout_right,
          class AccessorPolicy =
default_accessor<ElementType>>
struct mdspan {
    //...
    template<class... SizeTypes>
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```

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struct mdspan {
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```

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- **std::mdspan**
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    - Describe each dimension
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  - LayoutPolicy
    - Layout_right
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mdspan

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struct mdspan {
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    constexpr reference
        operator[](SizeTypes... indices) const
        { /* ... */ }
    //...
};
```

- `std::mdspan`
  - `Extents`
    - Describe each dimension
    - Both for sizes known at compile time and run time
  - `LayoutPolicy`
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  - `AccessorPolicy`

mdspan

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template<class ElementType, class Extents,
         class LayoutPolicy = layout_right,
         class AccessorPolicy =
default_accessor<ElementType>>
struct mdspan {
    //...
    template<class... SizeTypes>
    constexpr reference
        operator[](SizeTypes... indices) const
        { /* ... */ }
    //...
};
```

- `std::mdspan`
  - SYCL design
    - *Early Days!*
    - More than three dimensions
      - How many?
    - Accessors
      - *`accessor`*-like indexing to USM pointer
    - Strides, offset and sub_buffers

Reductions and Group Algorithms

Reductions

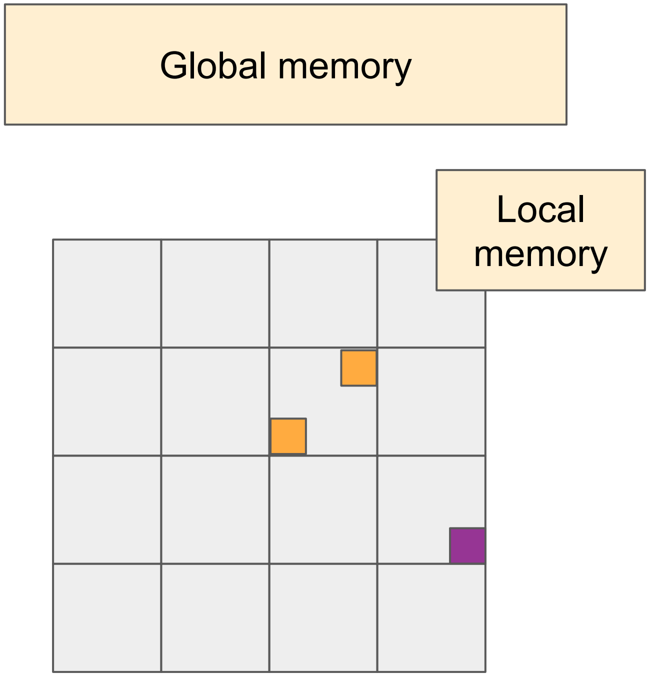
- Commonly occurring parallel pattern.
- Combine input to produce a single value:
  - E.g. `for (int i = 0; i < N; ++i) { r += a[i] * b[i]; }`
  - `std::transform_reduce(std::execution::par_unseq, a.begin(), a.end(), b.begin(), 0.0);`
- Reduction variable is output of the reduction.
  - The variable that accumulates results from multiple iterations.
  - Implementations may make zero or more copies.
- Reduction operator used to accumulate/combine copies of reduction variable.

SYCL 1.2.1: reductions with atomic

```
cl::sycl::queue Q;
int N = 1024;
cl::sycl::buffer<int> bufA {N};  // input array
{ // Initialize to integers 1..N inclusive.
  auto accA = bufA.get_access();
  std::iota(accA.begin(), accA.end(), 1);
}

cl::sycl::buffer<int> bufSum {1};  // reduction result
Q.submit([&](sycl::handler &cgh) {
  auto accA = bufA.get_access<cl::sycl::access::mode::read>(cgh);
  auto sum = bufSum.get_access<cl::sycl::access::mode::atomic>(cgh);
  cgh.parallel_for(cl::sycl::range<1>(N),
  [=](cl::sycl::id<1> id) {
    sum[0].fetch_add(accA[id]); // Atomic
}); });
assert(bufSum.get_access()[0] == (N * (N+1) / 2));  // Collect result on host
```

SYCL execution and memory model: recap



- Kernel invocations: work-items
- Work-items collected into work-groups, forming a 1-3 NDimensional grid of work-items
- Work-items can only synchronize **within** work-group
- Work-items collected into 1D sub-groups with extra execution guarantees:
  - Work-items in sub-group execute concurrently
  - Sub-groups make independent forward progress w.r.t other sub-groups in work-group

- All work-items have access to Global memory

- Work-items in a work-group can access Local memory

SYCL 1.2.1: reductions with local memory

```
cl::sycl::queue Q;
int N = 1024; assert(N % 16 == 0);  // Run with work-group size of 16
cl::sycl::buffer<int> bufA {N}; { auto accA = bufA.get_access(); std::iota(accA.begin(), accA.end(), 1);}

cl::sycl::buffer<int> bufSum {N/16};  //  global buffer of one partial value per work-group
Q.submit([&](sycl::handler &cgh) {
  auto accA = bufA.get_access<cl::sycl::access::mode::read>(cgh);
  auto sum = bufSum.get_access<cl::sycl::access::mode::write>(cgh);
  auto wg_sum = cl::sycl::accessor<int, 1, cl::sycl::access::mode::read_write,
                                  cl::sycl::access::target::local>(cl::sycl::range<1>(16), cgh);  // local mem
  cgh.parallel_for(cl::sycl::nd_range<1>{N, 16},
  [=](cl::sycl::nd_item<1> item) {
    // Copy to local memory, then reduce in work-group
    wg_sum[item.get_local_id(0)] = accA[item.get_global_id()];
    for (int off = item.get_local_range()[0] / 2; off > 0; off /= 2) {
      item.barrier(cl::sycl::access::fence_space::local_space);
      if (item.get_local_id(0) < off)
        wg_sum[item.get_local_id(0)] += wg_sum[item.get_local_id(0) + off];
    }
    if (item.get_local_id(0) == 0) sum[item.get_group(0)] = wg_sum[0]; // Write partial to global buffer
}); });
{ auto sum = bufSum.get_access();
  assert(std::accumulate(sum.begin(), sum.end(), 0) == (N * (N+1) / 2)); } // Host accumulates partials
```

Group algorithms

- Updated interface for broadcast and barrier functions.
- C++17-based algorithm library for work-group collectives.
- Often two versions:
  - Work-items supply single value directly.
  - Work-items work collectively on input iterator.
- Algorithms:
  - any_of() / all_of() / none_of()
  - shift_group_left() / shift_group_right()
  - permute_group_by_xor()
  - select_from_group()
  - reduce() / inclusive_scan() / exclusive_scan()

```
template <
  typename Group, typename Ptr,
  typename BinaryOperation>
std::iterator_traits<Ptr>::value_type
joint_reduce(
  Group g, Ptr first, Ptr last,
  BinaryOperation binary_op);

template <
  typename Group, typename Ptr,
  typename BinaryOperation>
T reduce_over_group(
  Group g, T x,
  BinaryOperation binary_op);
```

SYCL 2020: group reductions

```
sycl::queue Q;
int N = 1024; assert(N % 16 == 0);
sycl::buffer<int> bufA {N}; { sycl::host_accessor accA{bufA}; std::iota(accA.begin(), accA.end(), 1);}

sycl::buffer<int> bufSum {N/16};  // partial values
Q.submit([&](sycl::handler &cgh) {
  sycl::accessor accA {bufA, cgh, sycl::read_only};
  sycl::accessor sum {bufSum, cgh, sycl::write_only};
  cgh.parallel_for(sycl::nd_range<1>{N, 16},
  [=](sycl::nd_item<1> item) {
    // Group algorithm
    int partial_sum =
      sycl::reduce_over_group(item.get_group(), accA[item.get_global_id()], std::plus<>());

    if (item.get_group().leader()) sum[item.get_group(0)] = partial_sum;
}); });
{
 auto sum = bufSum.get_host_access();
 assert(std::accumulate(sum.begin(), sum.end(), 0) == (N * (N+1) / 2)); // Host accumulates partials
}
```

Reduction API in SYCL 2020

- `sycl::reduction` function to add reduction semantics to a variable.
  - Specify binary combination operation, and identity value if not known.
  - Variable contains final result when kernel finishes executing.
  - Pass return value to kernel invocation as a parameter pack.
    - i.e. tell the `parallel_for` it's a reduction.
- Implementation defined `reducer` class to wrap reduction variable inside kernel
  - Programmer adds `auto&` argument to lambda function.
  - Type restricts use to parallel-safe `combine()` only (equiv. `operator+=()`, etc).
  - Implementation responsible for combining with the original variable.
- Implementation given flexibility to combine reducers.
- Limited to compile-time size variables:
  - single variables.
  - `std::span` 1D-array reductions using USM.

SYCL 2020: reductions

```
sycl::queue Q;
int N = 1024;
sycl::buffer<int> bufA {N};
{ // Initialize to integers 1..N inclusive.
  sycl::host_accessor accA {bufA};
  std::iota(accA.begin(), accA.end(), 1);
}

sycl::buffer<int> bufSum {1};             // reduction variable
Q.submit([&](sycl::handler &cgh) {
  sycl::accessor accA {bufA, cgh, sycl::read_only};
  cgh.parallel_for(1024,
    sycl::reduction(bufSum, cgh, std::plus<>(),
                    sycl::property::reduction::initalize_to_identity),   // reduction function
    [=](sycl::id<1> id, auto &sum) {  // kernel variable on lambda
      sum += accA[id];
}); });
assert(bufSum.get_host_access()[0] == (N * (N+1) / 2));  // Host reads final value
```

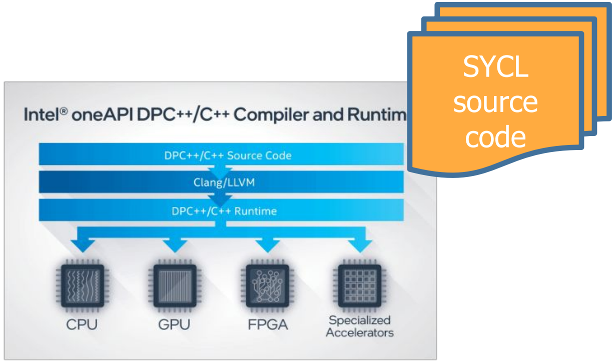
Agenda

1. SYCL, oneAPI, and ecosystem
2. SYCL 2020 features
   - Moving with the Times and Any Backend
   - Memory Spaces and Dimensions
   - Reductions and Group Algorithms
3. SYCL futures

oneAPI and SYCL

oneAPI

SYCL™

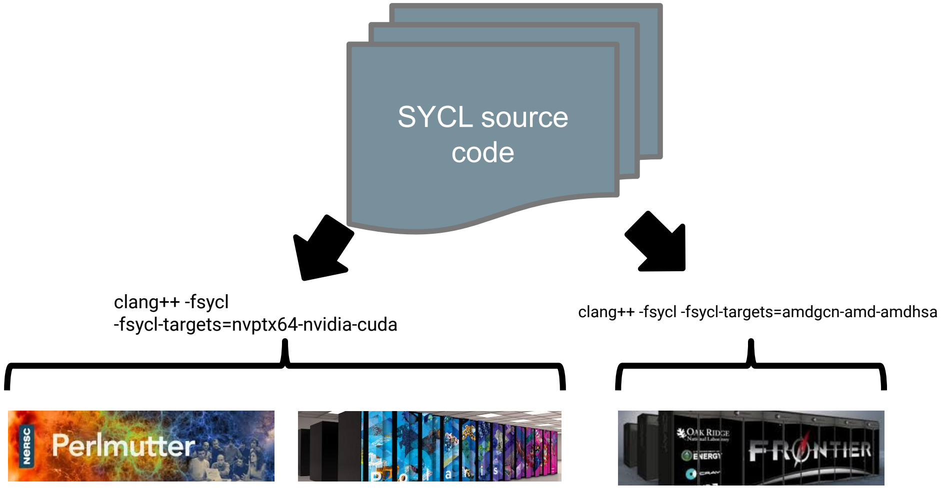


- SYCL sits at the heart of oneAPI
- Provides an open standard interface for developers
- Defined by the industry

Nvidia and AMD Support in oneAPI

- Extending DPC++ to target Nvidia and AMD GPUs
- Supporting Perlmutter, Polaris and Frontier supercomputers
- Open source and available to everyone

Different targets using a simple compiler flag

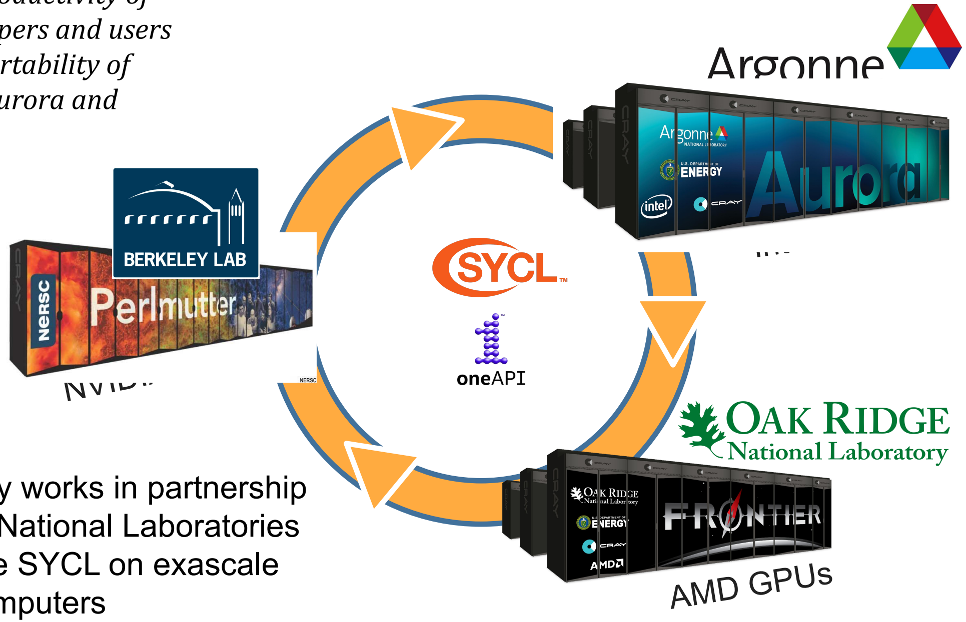


https://www.codeplay.com/oneapiforcuda
Resources for AMD coming soon

National Energy Research Scientific Computing Center

SYCL Enables Supercomputers

"this work supports the productivity of scientific application developers and users through performance portability of applications between Aurora and Perlmutter."



Codeplay works in partnership with US National Laboratories to enable SYCL on exascale supercomputers

Enables a broad range of software frameworks and applications

RAJA
Celerity
alpaka
BabelStream
GROMACS
fast, flexible & free

SYCL Future Evolution

SYCL 2020 compared with SYCL 1.2.1

- Easier to integrate with C++17 (CTAD, Deduction Guides...)
- Less verbose, smaller code size, simplify patterns
- Backend independent
- Multiple object archives aka modules simplify interoperability
- Ease porting C++ applications to SYCL
- Enable capabilities to improve programmability
- Backwards compatible but minor API break based on user feedback

SYCL Future Roadmap (MAY CHANGE)

SYCL 2020

Over 40 Selected Features for SYCL 2020

Unified Shared Memory)
Parallel Reductions adds a built in reduction operation
Work-group and sub-group algorithms
Improvements to atomic operations
Class template argument deduction (CTAD) and deduction guides
Simplification of accessors
Expanded interoperability with different backends
Extension mechanism
Address spaces
Vector rework
Specialization Constants
...

Improving Software Ecosystem

Books, Tutorials, Tool, libraries, GitHub

Expanding Implementations

DPC++
ComputeCpp
triSYCL
hipSYCL
neoSYCL

Regular Maintenance Updates

Spec clarifications, formatting and bug fixes
https://www.khronos.org/registry/SYCL/

Repeat The Cycle every 1.5-3 years

NEXT

Conformance Tests

Working on Implementations

Future SYCL NEXT Proposals

...

Integration of successful Extensions plus new Core functionality

Converge SYCL with ISO C++ and continue to support OpenCL to deploy on more devices

CPU
GPU
FPGA
AI processors
Custom Processors

SYCL 2020 is here!

Open Standard for Single Source C++ Parallel Heterogeneous Programming

SYCL 2020 is released after 3 years of intense work
Significant adoption in Embedded, Desktop and HPC markets
Improved programmability, smaller code size, faster performance
Based on C++17, backwards compatible with SYCL 1.2.1
Simplify porting of standard C++ applications to SYCL
Closer alignment and integration with ISO C++
Multiple Backend acceleration and API independent

SYCL 2020 increases expressiveness and simplicity
for modern C++ heterogeneous programming

Enabling Industry Engagement

- SYCL working group values industry feedback
  - https://community.khronos.org/c/sycl
  - https://sycl.tech
- SYCL FAQ
  - https://www.khronos.org/blog/sycl-2020-what-do-you-need-to-know
- What features would you like in future SYCL versions?

Open to all!
https://community.khronos.org/www.khr.io/slack
https://app.slack.com/client/TDMDFS87M/CE9UX4CHG
https://community.khronos.org/c/sycl/
https://stackoverflow.com/questions/tagged/sycl
https://www.reddit.com/r/sycl
https://github.com/codeplaysoftware/syclacademy
https://sycl.tech/

- Advisory Panel Chaired by Tom Deakin of U of Bristol
- SYCL Advisory Panel meeting here at IWOCL/SYCLCon
- Regular meetings to give feedback on roadmap and draft specifications

Public contributions to Specification, Conformance Tests and software
https://github.com/KhronosGroup/SYCL-CTS
https://github.com/KhronosGroup/SYCL-Docs
https://github.com/KhronosGroup/SYCL-Shared
https://github.com/KhronosGroup/SYCL-Registry
https://github.com/KhronosGroup/SyclParallelSTL

Invited Experts
https://www.khronos.org/advisors/

Khronos members
https://www.khronos.org/members/
https://www.khronos.org/registry/SYCL/