Backend interoperability in SYCL 2020

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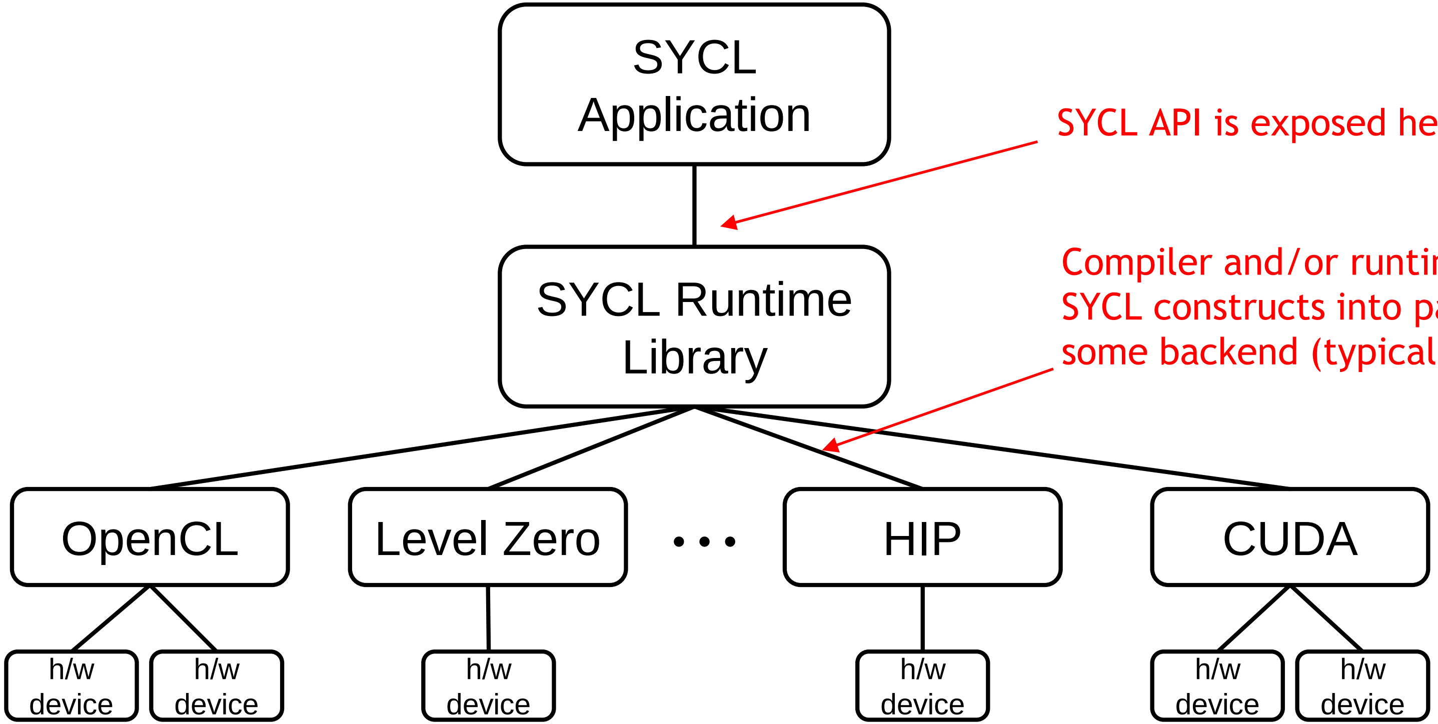
SYCL Backend Model



SYCL Application

SYCL Runtime Library

OpenCL

Level Zero

• • •

HIP

CUDA

h/w device

h/w device

h/w device

h/w device

h/w device

h/w device

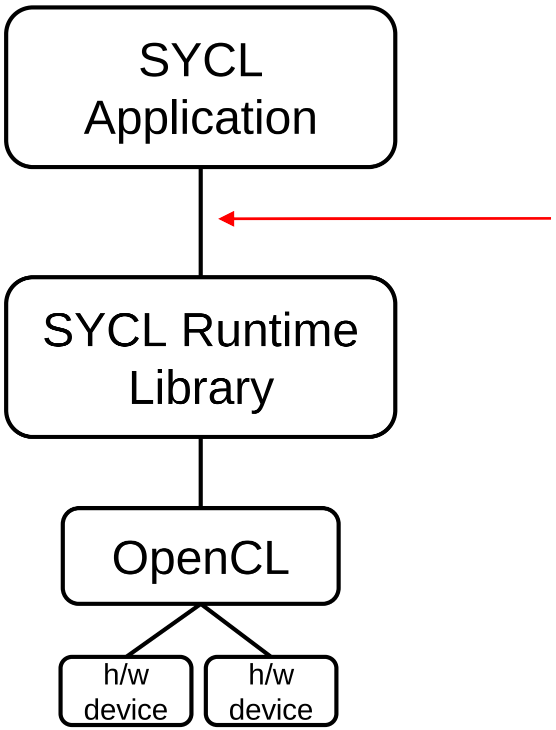
SYCL API is exposed here

Compiler and/or runtime translate SYCL constructs into parallelism on some backend (typically)

Some typical backends

NO guarantee that a SYCL implementation supports these (or any) backends!

What is SYCL Backend Interoperability?



I know my SYCL implementation runs on top of OpenCL (e.g) …

… so I want to call OpenCL APIs here intermixed with SYCL APIs

Reasons for Backend Interoperability

- **Porting existing code**
  - Code already based on OpenCL (or whatever backend)
  - Want to change just part of application to use SYCL
- **Incorporating a backend module into a SYCL application**
  - Application based on SYCL
  - Want to call some OpenCL library (or whatever backend)
- **Take advantage of backend-specific features**

- **Disadvantage: Reduces portability!**
  - Not all implementations may support your backend

Three Main Types of Backend Interoperability

Type 1: SYCL Object from Backend Object

```
void MyFunc(cl_device_id clDev) {
  sycl::device dev = sycl::make_device<sycl::backend::opencl>(clDev);

  sycl::queue q{dev};
  q.submit([&](sycl::handler &cgh) {
    cgh.parallel_for(/* ... */);
  }).wait();
}
```

Construct a SYCL device from an OpenCL device ID. Similar functions for most SYCL objects.

Typical usage: Adding SYCL functionality to an existing backend-specific application.

Type 2: Backend Object from SYCL Object

```
void MyFunc(sycl::device dev) {
#ifdef SYCL_BACKEND_OPENCL
  cl_device_id clDev = sycl::get_native<sycl::backend::opencl>(dev);

  char builtins[SIZE];
  size_t sz;
  clGetDeviceInfo(clDev, CL_DEVICE_BUILT_IN_KERNELS, SIZE, builtins, &sz);
  /* Use OpenCL builtin */
#else
  /* fallback if no OpenCL backend */
#endif
}
```

This macro only defined if implementation supports OpenCL

Get underlying OpenCL device ID from SYCL device.

Typical usage: Incorporate a backend-specific library into a SYCL application or take advantage of a backend-specific feature.

Type 3: Schedule a Backend Specific Command

```
void MyFunc(sycl::queue q, sycl::buffer<int> buf) {
#ifdef SYCL_BACKEND_OPENCL
  q.submit([&](sycl::handler &cgh) {
    sycl::accessor acc{buf, cgh};
    cgh.host_task([=](const sycl::interop_handle &ih) {
      cl_mem clMem = ih.get_native_mem<sycl::backend::opencl>(acc)[0];
      /* use OpenCL APIs with clMem */
    });
  });
#endif
}
```

This command scheduled according to dependency graph on accesses to buffer “buf”.

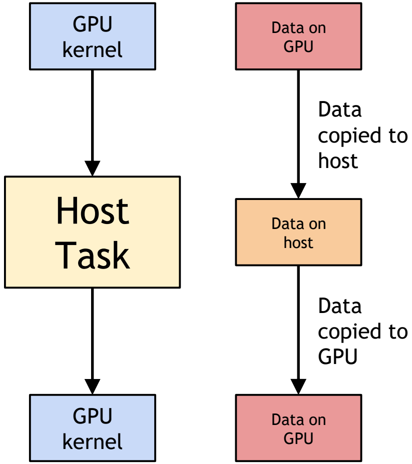
Get underlying cl_mem for a buffer accessor.

Typical usage: Same as previous.

Host Task

- The host_task schedule arbitrary C++ code within the SYCL data-dependency graph
- Work performed in a host_task must complete before the function returns

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

  sycl::accessor acc{buf, cgh, sycl::read_write_host_task};

  cgh.host_task([=]{

    auto ptr = acc.get_pointer();

    some_cpu_library(ptr);
  });
});
```



GPU kernel

Host Task

GPU kernel

Data on GPU

Data copied to host

Data on host

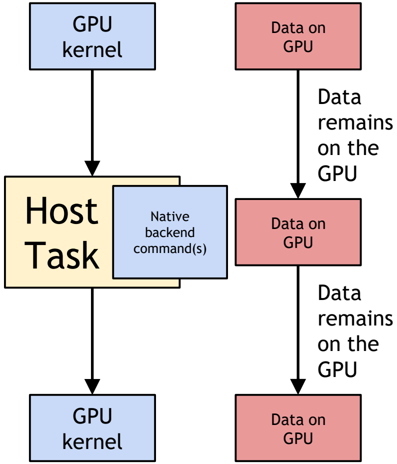
Data copied to GPU

Data on GPU

Host Task Interoperability

- An optional **interop_handle** parameter can be used to perform backend interoperability within a **host_task**
- The **interop_handle** is used to retrieve the native queue, event or memory objects

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

  sycl::accessor acc{buf, cgh, sycl::read_write_host_task};

  cgh.host_task([=](const sycl::interop_handle &ih){

    auto nativeStream
      = ih.get_native_queue<sycl::backend::cuda>();

    auto nativePtr
      = ih.get_native_mem<sycl::backend::cuda>(acc);

    some_native_library(nativeStream, nativePtr);
  });
});
```



Host Task interoperability in oneMKL and oneDNN

- The oneAPI libraries oneMKL and oneDNN provide an abstraction for BLAS, RAND and DNN operations across different SYCL backends
  - https://github.com/oneapi-src/oneDNN
  - https://github.com/oneapi-src/oneMKL
- For the Nvidia backend oneMKL and oneDNN map to the CUDA libraries cuBLAS, cuRAND, cuSolver and cuDNN
- Each oneMKL or oneDNN operation maps to a host_task executing the equivalent library function
- Each operation supports both buffer/accessor and USM memory management models
- As the host_task is executed within the SYCL data dependency graph these operations are automatically composable

Convolution Example from oneDNN

- **Example of host_task in oneDNN for Nvidia backend**
    - https://github.com/oneapi-src/oneDNN/blob/master/src/gpu/nvidia/cudnn_convolution.cpp

```
...
        compat::host_task(cgh, [=](const compat::interop_handle &ih) {
            auto &sycl_engine = *utils::downcast<sycl_cuda_engine_t *>(
                    cuda_stream->engine());
            auto sc = cuda_sycl_scoped_context_handler_t(sycl_engine);
            auto handle = cuda_stream->get_cudnn_handle();

            std::vector<void *> args;
            args.push_back(arg_src.get_native_pointer(ih));
            args.push_back(arg_weights.get_native_pointer(ih));
            args.push_back(arg_dst.get_native_pointer(ih));
            args.push_back(arg_bias.get_native_pointer(ih));
            args.push_back(arg_scratch.get_native_pointer(ih));
            args.push_back(arg_filter_scratch.get_native_pointer(ih));
            args.push_back(temp_dst.get_native_pointer(ih));
            args.push_back(temp_reorder.get_native_pointer(ih));

            pd()->impl_->execute(handle, args);
        });
...
```

Host Task Interoperability Conclusion

- The host_task interoperability is useful in cases where you have a SYCL application and you wish to call native backend APIs or libraries
- This can be any backend; OpenCL, OpenMP, CUDA, HIP, Level Zero, etc
- The backend interoperability within a host_task provides access to the native queue, event and memory objects
- The host_task is enqueued within the data dependency graphs synchronizes with other SYCL kernels

OpenMP ↔ SYCL: An HPC Story

- “Most” HPC applications are written in OpenMP
- But they may want to be interfaced with SYCL:
  - Some SYCL API are more flexible than the OpenMP counterpart
    - oneMKL provide both an OpenMP and SYCL API,
      but SYCL API give access to more function (batched DGEMM for example)
  - Some Library only provide a SYCL API
    - For example oneDPL (Intel oneAPI thrust)
- **Interoperability to the rescue!**

```
#pragma omp target enter data map(to: data[0:N])
T* data_gpu;
#pragma omp target data use_device_ptr(data)  { data_gpu = data }
sycl::queue q = get_interopt_queue(); //Magic Function, more about it later
//SYCL parallel stl using an OpenMP device pointer
std::sort(oneapi::dpl::execution::make_device_policy(q), data_gpu, data_gpu + N);
```

OpenMP → Backend → SYCL

- Use `#pragma omp interop` to get Native Handler (*OpenMP* 5.1)
- Use those handlers to create SYCL Object
- POC: Implementation using L0 API and ICPX:
  - https://github.com/argonne-lcf/HPC-Patterns/blob/main/sycl_omp_ze_interopt/interop_omp_ze_sycl.cpp
  - Ensure that SYCL and OpenMP use the same context

- **Code example:**

```
omp_interop_t o;
#pragma omp interop init(targetsync: o)
auto hDevice = static_cast<ze_device_handle_t>(
                    omp_get_interop_ptr(o, omp_ipr_device, &err));
#pragma omp interop destroy(o)
const sycl::device sycl_device =
          sycl::make_device<sycl::backend::ext_oneapi_level_zero>(hDevice);
```

OpenMP ↔ SYCL Work

- **Pro: It work!**

```
sycl::queue Q = get_intereopt_queue(); // Where the magic happens
T *ompMem = (T*) malloc(N*sizeof(T));
T *syclMem = sycl::malloc_device<T>(N,Q);
```

  - OpenMP using SYCL memory

```
#pragma omp target is_device_ptr(syclMem) map(from:ompMem[0:N])
for (size_t i=0 ; i < N; i++)
      ompMem[i] = syclMem[i];
```

  - SYCL using OpenMP memory

```
T* ompMem_gpu;
#pragma omp target enter data map(to:ompMem[0:N])
#pragma omp target data use_device_ptr(ompMem) { ompMem_gpu = ompMem }
Q.copy<T>(cpuMem, ompMem_gpu, N).wait();
```

- **Con:**
  - Backend specific (need to cast pointer | specialize the templated API)
  - Only tested on ICPX & need to use non-standard interoperability API to workaround some bugs

Collaboration are welcome to tests/implements support for more compiler / backend!

SYCL as a higher-level API for a native API?

- **Provide**
  - Modern C++
  - Simpler buffer allocation
  - Automatic data transfers with accessors
  - Embed existing API in SYCL task graph
  - Automatic compute & communication overlap between kernels
  - Asynchronous execution
  - …
  - Can mix and match OpenCL/CUDA/Level 0/HIP/XRT…
- **Yes, native APIs like OpenCL have already plenty of C++ wrappers!**
  - OpenCL.hpp from Khronos https://github.com/KhronosGroup/OpenCL-CLHPP/blob/main/include/CL/opencl.hpp
  - Boost.Compute https://github.com/boostorg/compute
  - …
- **SYCL: 1 high-level wrapper to rule them all, in the same application**
  - Just one to learn!
- **Important note: this is no longer normal single-source SYCL!**

Vector addition in OpenCL C + OpenCL host C API

```
#include <iostream>
#include <string>
#include <vector>

#include <CL/opencl.h>

/* Transform the value of a given symbol to a string. Since we expect a
  macro symbol, use a double evaluation... */
#define _strinG(s) #s

#define _stringifY(s) _strinG(s)

/** Throw a nicer error message in the code by adding the file name and
   the position */
#define THROW_ERROR(message)                                        \
 throw std::domain_error(std::string("In file " __FILE__ " at line "   \
                        _stringifY(__LINE__) "\n") + message)

/** Test for an OpenCL error and display a message */
#define OCL_TEST_ERROR_MSG(status, msg) do {                        \
   if ((status) !=  CL_SUCCESS)                                \
    THROW_ERROR(std::string(msg) + std::to_string(status));         \
 } while(0)

 /** Do an OpenCL function call and test for execution error */
#define OCL_ERROR(func) do {                                        \
   cl_int _st = func;                                        \
   if (_st !=  CL_SUCCESS)                                        \
    THROW_ERROR(_stringifY(func) " returns error " + std::to_string(_st)); \
 } while(0)

constexpr size_t N = 3;

using Vector = float[N];

int main() {
 Vector a = { 1, 2, 3 };
 Vector b = { 5, 6, 8 };
 Vector c;

 cl_int status;

 // Get the number of OpenCL platforms on the machine
 cl_uint num_platforms;
 OCL_ERROR(clGetPlatformIDs(0, NULL, &num_platforms));

 std::vector<cl_platform_id> platforms(num_platforms);
 OCL_ERROR(clGetPlatformIDs(num_platforms, platforms.data(), NULL));


 cl_context context;
 bool found_context = false;
 for (auto platform : platforms) {
  std::cout << platform << std::endl;
  // Describe the context to query
  cl_context_properties cps[] = {
   CL_CONTEXT_PLATFORM, (cl_context_properties)platform,
   0
  };
  // Create an OpenCL context from our platform
  context = clCreateContextFromType(cps,
                                    CL_DEVICE_TYPE_ALL,
                                    NULL,
                                    NULL,
                                    &status);
  if (status ==  CL_SUCCESS) {
   found_context = true;
   break;
  }
 }
 if (!found_context)
  THROW_ERROR("Cannot found a context");

 // Get the first device
 cl_device_id device;
 OCL_ERROR(clGetContextInfo(context, CL_CONTEXT_DEVICES,
                            sizeof(device), &device, NULL));

 // Create an OpenCL command queue
 cl_command_queue command_queue =
  clCreateCommandQueueWithProperties(context, device, NULL, &status);
 OCL_TEST_ERROR_MSG(status, "Cannot create the command queue");

 // The input buffers for OpenCL
  cl_mem buffer_a =
   clCreateBuffer(context, CL_MEM_READ_ONLY, sizeof(a), NULL, &status);
  OCL_TEST_ERROR_MSG(status, "Cannot create buffer_a");
  cl_mem buffer_b =
   clCreateBuffer(context, CL_MEM_READ_ONLY, sizeof(b), NULL, &status);
  OCL_TEST_ERROR_MSG(status, "Cannot create buffer_b");

 // The output buffer for OpenCL
  cl_mem buffer_c =
   clCreateBuffer(context, CL_MEM_WRITE_ONLY, sizeof(c), NULL, &status);
  OCL_TEST_ERROR_MSG(status, "Cannot create buffer_c");

 // Construct an OpenCL program from the source file
 const char kernel_source[] = R"(
__kernel void vector_add(const __global float *a,
                         const __global float *b,
                           __global float *c) {
 c[get_global_id(0)] = a[get_global_id(0)] + b[get_global_id(0)];
}
)";
 const char *kernel_sources = kernel_source;
 const size_t kernel_size = sizeof(kernel_source);

 cl_program program = clCreateProgramWithSource(context, 1, &kernel_sources,
                                                &kernel_size, &status);
 OCL_TEST_ERROR_MSG(status, "Cannot create program");

 OCL_ERROR(clBuildProgram(program, 1, &device, "", NULL, NULL));

 cl_kernel kernel = clCreateKernel(program, "vector_add", &status);
 OCL_TEST_ERROR_MSG(status, "Cannot find the kernel");

 // Send the input data to the accelerator
 OCL_ERROR(clEnqueueWriteBuffer(command_queue, buffer_a, true, 0 /* Offset */,
                                sizeof(a), &a[0], 0, NULL, NULL));
 OCL_ERROR(clEnqueueWriteBuffer(command_queue, buffer_b, true, 0 /* Offset */,
                                sizeof(b), &b[0], 0, NULL, NULL));

 OCL_ERROR(clSetKernelArg(kernel, 0, sizeof(buffer_a), &buffer_a));
 OCL_ERROR(clSetKernelArg(kernel, 1, sizeof(buffer_b), &buffer_b));
 OCL_ERROR(clSetKernelArg(kernel, 2, sizeof(buffer_c), &buffer_c));

 // Launch the kernel
 const size_t global_work_size { N };
 OCL_ERROR(clEnqueueNDRangeKernel(command_queue, kernel, 1, NULL,
                                  &global_work_size, NULL,
                                  0, NULL, NULL));

 // Get the output data from the accelerator
 OCL_ERROR(clEnqueueReadBuffer(command_queue, buffer_c, true, 0 /* Offset */,
                               sizeof(c), &c[0], 0, NULL, NULL));


 std::cout << std::endl << "Result:" << std::endl;
 for(auto e : c)
  std::cout << e << " ";
 std::cout << std::endl;
}
```

142 lines https://github.com/keryell/heterogeneous_examples/blob/main/vector_add/OpenCL/opencl_vector_add.cpp

SYCL as a high-level host API to run OpenCL kernels

```
#include <cassert>
#include <cstdlib>
#include <sycl/sycl.hpp>
#include <CL/opencl.h>

constexpr int size = 4;

auto check_error(auto&& function) {
  cl_int err;
  auto ret = function(&err);
  if (err != CL_SUCCESS)
    std::exit(err);
  return ret;
};

int main() {
  sycl::buffer<int> a { size };
  sycl::buffer<int> b { size };
  sycl::buffer<int> c { size };

  {
    sycl::host_accessor a_a { a };
    sycl::host_accessor a_b { b };
    for (int i = 0; i < size; ++i) {
      a_a[i] = i;
      a_b[i] = i + 42;
    }
  }

  sycl::queue q;
  std::array kernel_source { R"(
    __kernel void vector_add(const __global float *a,
                             const __global float *b,
                             __global float *c) {
      c[get_global_id(0)] = a[get_global_id(0)] + b[get_global_id(0)];
    }
  )" };
  cl_context oc = sycl::get_native<sycl::backend::opencl>(q.get_context());
  auto program = check_error([&](auto err) {
    return clCreateProgramWithSource(oc, kernel_source.size(),
                                     kernel_source.data(), nullptr, err);
  });
  check_error([&](auto err) {
    return (*err =
            clBuildProgram(program, 0, nullptr, nullptr, nullptr, nullptr));
  });
  sycl::kernel k = sycl::make_kernel<sycl::backend::opencl>(
    check_error(
      [&](auto err) { return clCreateKernel(program, "vector_add", err); }),
    q.get_context());

  q.submit([&](sycl::handler& cgh) {
    cgh.set_args(sycl::accessor { a, cgh, sycl::read_only },
                 sycl::accessor { b, cgh, sycl::read_only },
                 sycl::accessor { c, cgh, sycl::write_only, sycl::no_init });
    cgh.parallel_for(size, k);
  });

  {
    sycl::host_accessor a_a { a };
    sycl::host_accessor a_b { b };
    sycl::host_accessor a_c { c };
    for (int i = 0; i < size; ++i)
      assert(a_c[i] == a_a[i] + a_b[i]);
  }
}
```

66 lines

https://github.com/keryell/heterogeneous_examples/blob/main/vector_add/SYCL/vector_add_OpenCL_interoperability.cpp

FPGA kernels in HLS C++ + XRT host application

https://github.com/Xilinx/Vitis_Accel_Examples/tree/master/host_xrt/hello_world_xrt

- Kernel code `src/vadd.cpp` 64 lines of HLS C++
- Host code `src/host.cpp` 81 lines of C++
- Both are rather high-level

```
                                       _____________
                                      |             |<----- Input Vector 1 from Global Memory
                                      |  load_input |       __
                                      |_____________|----->|  |
                                       _____________       |  | in1_stream
Input Vector 2 from Global Memory --->|             |      |__|
                               __     |  load_input |        |
                              |  |<---|_____________|        |
                   in2_stream |  |     _____________         |
                              |__|--->|             |<--------
                                      | compute_add |      __
                                      |_____________|---->|  |
                                       ______________     |  | out_stream
                                      |              |<---|__|
                                      | store_result |
                                      |______________|-----> Output result to Global Memory
```

```
extern "C" {
void vadd(unsigned int* in1, unsigned int* in2, unsigned int* out, int size) {
    static hls::stream<unsigned int> inStream1("input_stream_1");
    static hls::stream<unsigned int> inStream2("input_stream_2");
    static hls::stream<unsigned int> outStream("output_stream");

#pragma HLS INTERFACE m_axi port = in1 bundle = gmem0
#pragma HLS INTERFACE m_axi port = in2 bundle = gmem1
#pragma HLS INTERFACE m_axi port = out bundle = gmem0

#pragma HLS dataflow
    // dataflow pragma instruct compiler to run following three APIs in parallel
    read_input(in1, inStream1, size);
    read_input(in2, inStream2, size);
    compute_add(inStream1, inStream2, outStream, size);
    write_result(out, outStream, size);
}
}
```

“Higher-level XRT” for FPGA in 43 lines with SYCL

```cpp
#include <cassert>
#include <sycl/sycl.hpp>
#include <sycl/ext/xilinx/xrt.hpp>
#include <xrt.h>
#include <xrt/xrt_kernel.h>

constexpr int size = 4;

int main() {
 sycl::buffer<int> a { size };
 sycl::buffer<int> b { size };
 sycl::buffer<int> c { size };

 {
  sycl::host_accessor a_a { a };
  sycl::host_accessor a_b { b };
  for (int i = 0; i < size; ++i) {
   a_a[i] = i;
   a_b[i] = i + 42;
  }
 }
```

```cpp
 sycl::queue q;
 xrt::device xdev = sycl::get_native<sycl::backend::xrt>(q.get_device());
 xrt::kernel xk { xdev, xdev.load_xclbin("vadd.hw_emu.xclbin"), "vadd" };
 sycl::kernel k { sycl::make_kernel<sycl::backend::xrt>(xk, q.get_context())
};

 q.submit([&](sycl::handler& cgh) {
  cgh.set_args(sycl::accessor { a, cgh, sycl::read_only },
               sycl::accessor { b, cgh, sycl::read_only },
               sycl::accessor { c, cgh, sycl::write_only, sycl::no_init },
               size);
  cgh.single_task(k);
 });

 {
  sycl::host_accessor a_a { a };
  sycl::host_accessor a_b { b };
  sycl::host_accessor a_c { c };
  for (int i = 0; i < size; ++i)
   assert(a_c[i] == a_a[i] + a_b[i]);
 }
}
```

https://github.com/keryell/heterogeneous_examples/blob/main/vector_add/SYCL/vector_add_XRT_interoperability.cpp

Conclusion

- **SYCL: open-standard for high-level heterogeneous accelerator programming**
- **Really targets broad range of architectures, back-ends and vendors**
- **“Normal” SYCL is single-source C++ and targets various native APIs**
  - Different backends are used behind the scene transparently
  - No need for interoperability mode for usual cases
- **Explicit interoperability features of SYCL are key for openness of the standard**
  - SYCL can use specific features of different back-ends at the same time
  - SYCL can be used from other heterogeneous programming frameworks
  - SYCL can be used as single unifying high-level C++ wrapper for lower-level APIs
    - Asynchronous execution, task graph, automatic data transfers & computation overlap…