Arm, Cambridge, UK

C++ for OpenCL Programming Language

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Why C++ for OpenCL?

- OpenCL is well-established technology in many areas.
- Growth in complexity of applications run on accelerators.
- Separate host-device flow allows max customization for any architecture.
  - Developing mature optimizing compilers is time consuming and not always practical.

What is C++ for OpenCL?

<u>OpenCL C v2.0</u>:
- kernels,
- address spaces,
- special types,
...

+

<u>C++17</u>:
- classes,
- inheritance,
- templates,
- type deduction,
...

=

C++ for OpenCL

```
$ cat test.cl
template<class T> T add( T x, T y ) {
  return x + y;
}
__kernel void test(__global float *a, __global float *b) {
  auto index = get_global_id(0);
  a[index] = add(b[index], b[index + 1]);
}

$ clang -std=clc++ test.cl
```

It is not OpenCL C++ from the Khronos Registry!

Design goals

- Backwards compatibility to OpenCL C (v2.0).
  - Reuse existing code, libraries.
  - Reuse existing tools.
  - Familiar development flow.
- Enable as much of modern C++ as possible.
  - Gradual transition to familiar C++ programming paradigms.

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Differences with OpenCL C

- Implicit conversions are stricter.

```
const int *ptrconst;
int *ptr = ptrconst; // invalid initialization discards const qualifier
```

- Explicit representation of NULL using `nullptr`.
- `restrict` is not supported.
  - Clang provides experimental support of `__restrict`.
- More restricted usage of `goto`.
- ObjC Blocks are not supported.

C++ feature restrictions

- Virtual functions.
- Exceptions.
- RTTI e.g. `dynamic_cast`, `typeid`.
- Non-placement `new`/`delete` operators.
- C++ std libs.

Improved OpenCL C features

- Variadic macros.
- Atomics.
  - Operators with C11 atomic types.
  - Legacy atomics with generic address space.
- ...

Address spaces in C++

In C++ there are abstractions that are specialized e.g. classes and objects.

```
__global MyClass c1; // MyClass allocated in global memory
c1.dosomething();    // implicitly dosomething(MyClass *this)
__local MyClass c2;  // MyClass allocated in local memory
c2.dosomething();    // implicitly dosomething(MyClass *this)
```

What address space should the `this` parameter point to?

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- Member function definitions are typically in a separate translation unit.

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- Class declarations are parsed ahead of object instantiations.
- Member function definitions are typically in a separate translation unit.
- Undesirable to duplicate member functions (at source or binary) for each address space.
  - Negatively impacts compilation speed and binary size.

Address spaces - OpenCL approach

- OpenCL v2.0 defines the *generic* address space.

```
__global int a;
__local int b;
/*__generic*/ int *ptr;
if (c)
  ptr = &a;
else
  ptr = &b;
// ptr can point into a segment in either local or global memory
```

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```

- We use generic address space for abstract behavior in C++.
  - Note: `__constant` cannot be converted to/from `/*__generic*/`.

Address spaces - OpenCL approach example

```
 1 class MyClass {
 2  void dosomething();           // void dosomething(__generic MyClass *this)
 3                                // MyClass(__generic MyClass *this)
 4  MyClass(MyClass &c);          // MyClass(__generic MyClass *this, __generic MyClass &c)
 5  MyClass(MyClass &c) __local; // MyClass(__local MyClass *this, __generic MyClass &c)
 6 }
 7 __global MyClass c1;    // calls ctor line 3 where arg 'this' is an addr space cast of
 8                         // ptr to 'c1' from '__global MyClass *' to '__generic MyClass *'
 9 __local MyClass c2(c1); // calls ctor line 5 where arg 'this' is an allocation 'c2' of
10                         // 'MyClass' in __local address space, 2nd arg is as on line 7
11 c1.dosomething();       // calls method from line 2 casting ptr to 'c1' to __generic
12 c2.dosomething();       // calls method from line 2 casting ptr to 'c2' to __generic
```

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```

Note: methods used with `__constant` addr space objects have to be overloaded using address space method qualifier explicitly.

Address spaces - other rules

- Default address space follows OpenCL C v2.0 logic.
  - References inherit rules from pointers => `/*__generic*/`.
  - Static data members are in `__global`.
  - No default for non-pointer/reference dependent types (i.e. template params), `decltype` or alias declarations.
- Lambdas can be qualified by an address space like methods.

```
[&] (int i)  __global { ... };
```

- Special `addrspace_cast` operator.

```
/*__generic*/ int *genptr = ...;
__global int *globptr = addrspace_cast<__global int*>(genptr);
```

- More elaborate description in the official documentation.

https://github.com/KhronosGroup/Khronosdotorg/blob/master/api/opencl/assets/CXX_for_OpenCL.pdf

Global constructors/destructors

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- Solution.
  - ctors - changed initialization stub to a kernel function.
    - Can be enqueued from host before kernel executions.
    - In OpenCL v2.0 drivers application has to perform this step manually.
    - Clang generates a kernel with initialization code per translation unit that can be queried from the binary (see `https://clang.llvm.org/docs/UsersManual.html#constructing-and-destroying-global-objects`).

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  - dtors - WIP, requires large ABI change due to incompatibility with OpenCL execution model.
    - Potentially less critical as program context is destroyed at this point.

Kernel function in C++ mode

OpenCL host API:

```
clCreateKernel(... "foo" ...); // create kernel with the name 'foo'
```

- Name has to be preserved during the device compilation to be referred to/from the host.
- Prevent mangling i.e. disallow C++-like function features:
  - Overloading.
  - Use as templates.
  - Use as member functions.

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  - Use as templates.
  - Use as member functions.
- => Implicitly `extern C`.

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Convolution from Arm Compute Library - row computation

Statically compute sum of N factors!

```
template<typename T /*conv data type*/, size_t N /*conv dim*/>
class onerow
{
  uchar16 data;
  const short (&mat)[N]; // matrix of coefficients
  ...
  template<size_t S /*step number*/> T mulacc() = delete;
  template<> T mulacc<0>() { return vec_cast<T>(data.s01234567) * mat[0];}
  template<> T mulacc<1>() { return vec_cast<T>(data.s12345678) * mat[1] + mulacc<0>();}
  ...
  // up to (conv dim - 1)
  template<> T mulacc<8>() { return vec_cast<T>(data.s89abcdef) * mat[8] + mulacc<7>();}
};
```

Convolution continued - NxN

Compute full NxN convolution using `onerow` helper.

```
template<typename T, size_t N>
inline T convolution(Image &src, const short (&mat)[N][N], uint scale)
{
    T pixels = 0;

    for (size_t i = 0; i < N; ++i)
    {
      uchar16 temp = vload16(0, src.offset(-((int)N) / 2, i - N / 2));
      onerow<T, N> rowi(temp, mat[i]);
      pixels += rowi.template mulacc<N - 1>();
    }

    return pixels / static_cast<T>(scale);
}
```

Convolution continued - kernel with 3x3 convolution

```
class Image {
   ...
   __global uchar *offset(int x, int y);
};

// using vector convert functions from OpenCL C
template<typename To, typename From> inline To vec_cast(From ty);

__kernel void convolution3x3_static(...) {
  ...
  short8 pixels = convolution<short8, 3>
      (src, {{MAT0, MAT1, MAT2}, {MAT3, MAT4, MAT5}, {MAT6, MAT7, MAT8}}, SCALE);
```

Convolution continued - kernel with 3x3 convolution

```
class Image {
   ...
   __global uchar *offset(int x, int y);
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// using vector convert functions from OpenCL C
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```

OpenCL C sources available in

`https://github.com/ARM-software/ComputeLibrary/tree/master/src/core/CL/cl_kernels`.

- ~200 lines of convolution (3x3, 5x5, 7x7, 9x9) can be replaced by ~30 lines in C++ for OpenCL.
- Without observable performance loss!

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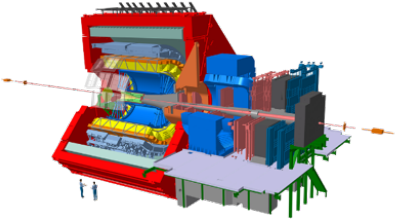
Evaluation

- OpenCL C content is nearly fully supported.
  - Most of conformance v2.0 tests pass (11 fail out of 1384).
  - Validation on benchmarks is in progress.
- Experimental testing for Vulkan using **clspv** and **clvk**.
- Porting applications from other languages.
  - ALICE experiment at CERN.

Porting ALICE event reconstruction to C++ for OpenCL



- ALICE: A Large Ion Collider Experiment.
  - From 2021 it will record collisions of lead nuclei at the LHC at a rate of 50 kHz.
  - Several thousand particles in each collision, whose trajectories must be found (using measured 3d space points).
  - All data will be processed in real time using GPUs.

- Written in generic C++ with preprocessor macros substituted into language keywords (`https://github.com/AliceO2Group/AliceO2`).
  - CUDA (since 2010) and OpenCL 1.2 with AMD C++ extensions (since 2015).
  - Ongoing research to support HIP and C++ for OpenCL.
    - Fully compiled (**~12K lines**) from C++ for OpenCL down to SPIR-V using **clang-10** and **llvm-spirv**.
    - CERN to test SPIR-V injection on Mali Driver.

Image courtesy of CERN

Overheads - compile and runtime, binary size

- OpenCL features are handled in the same way as for OpenCL C.
- C vs C++ is an old debate.
- Most of C style features have the same overhead in C++.
- C++ often hides overheads.
  - E.g. implicit object pointer parameter.
- C++ language facilitates more optimizations.
- Modern compilers are very good at optimizing C++ code.
  - E.g. devirtualization, ctor/dtor inlining.
- A lot of material about writing low overhead C++ code.
  - ISO/IEC TR 18015:2006 - Technical Report on C++ Performance.

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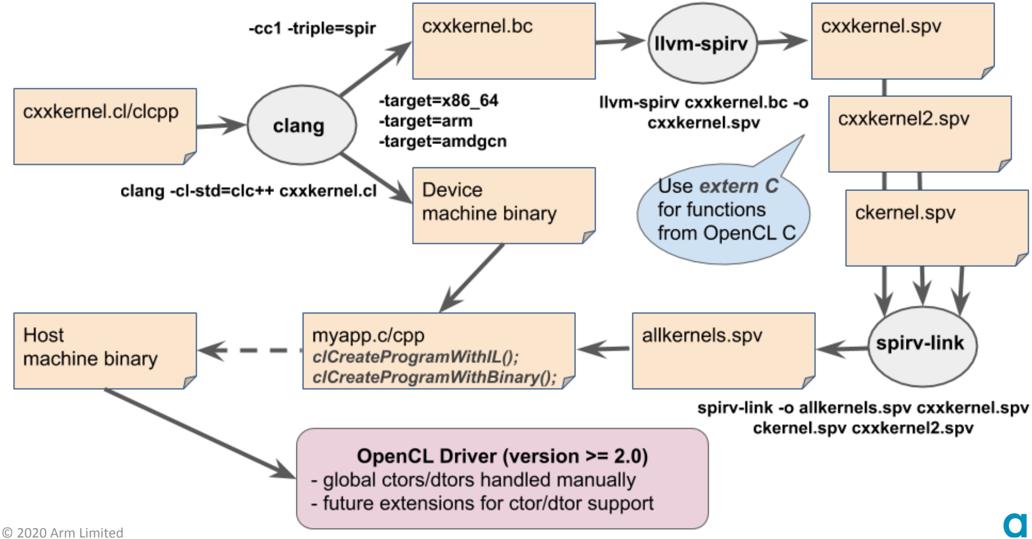
How can applications use C++ for OpenCL?



cxxkernel.cl/clcpp

clang

-cc1 -triple=spir

-target=x86_64
-target=arm
-target=amdgcn

clang -cl-std=clc++ cxxkernel.cl

cxxkernel.bc

llvm-spirv

llvm-spirv cxxkernel.bc -o cxxkernel.spv

cxxkernel.spv

cxxkernel2.spv

ckernel.spv

Use *extern C* for functions from OpenCL C

Device machine binary

spirv-link

spirv-link -o allkernels.spv cxxkernel.spv ckernel.spv cxxkernel2.spv

allkernels.spv

myapp.c/cpp
clCreateProgramWithIL();
clCreateProgramWithBinary();

Host machine binary

OpenCL Driver (version >= 2.0)
- global ctors/dtors handled manually
- future extensions for ctor/dtor support

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Comparison to other languages

Language	Vendors	Host/dev perf tuning	Host/dev compilation	Single source	Dev flow
C++ for OpenCL	Multiple	Fully manual for any arch	Separate phases	No	OpenCL style
SYCL	Multiple	Compiler / limited manual	Likely separate phases	Yes	C++ library / metaprogramming
CUDA	Nvidia	Compiler	Likely mixed separate + combined phases	Yes	C++ dialect
HIP	Multiple	Compiler	Currently separate	Yes	C++ dialect
Metal SL	Apple	Fully manual	Separate phases	No	OpenCL style

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- Detailed documentation can be found in
  `https://github.com/KhronosGroup/Khronosdotorg/blob/master/api/opencl/assets/CXX_for_OpenCL.pdf`
- Any feedback to documentation can be submitted in `https://github.com/KhronosGroup/OpenCL-Docs`
- Information about support in Clang `https://clang.llvm.org/docs/UsersManual.html#cxx-for-opencl`
- Implementation status can be tracked through `https://clang.llvm.org/docs/OpenCLSupport.html`
- Report bugs and any missing features on `https://bugs.llvm.org/`

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The plan from **the community**:

- Complete implementation in Clang i.e. missing features or bugs.
- Finalize documentation.
- Add support for C++ libraries.
- Perform full functionality testing.
- Provide more support to/maintenance for the application developers.

Special thanks to the community!!! <3

- To John McCall from Apple for invaluable feedback and reviews!
- To David Rohr from CERN for testing, submitting bugs, providing suggestions and being so patient while waiting for bugs to be fixed!
  - Very motivating use of the new language for experiments at CERN!
- To OpenCL WG at Khronos Group for supporting the idea and hosting the documentation!

Thanks!

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