HPX and GPU-parallized STL

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May 13, 2016

GSoC '15 Project

Project: "Integrate a C++AMP Kernel with HPX"
Mentor: Hartmut Kaiser

Plan

HPX

Parallelism in C++

- Concepts

GPU in HPX

- Execution
- Data placement

GPU standards for C++

- C++AMP
- Khronos SYCL
- Compilers

Results

- Implementation
- STREAM benchmark

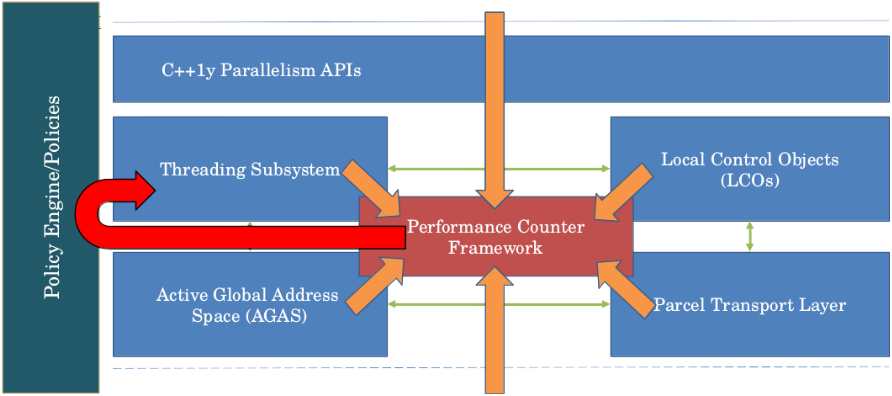
Goals

What is HPX?

- High Performance ParalleX [1,2]
- Runtime for parallel and distributed applications
- Written purely in C++, with large usage of Boost
- Unified and standard-conforming C++ API

[1] *Parallex an advanced parallel execution model for scaling-impaired applications*-H. Kaiser et al - ICPPW, 2009
[2] *A Task Based Programming Model in a Global Address Space* - H. Kaiser et al - PGAS, 2014

What is HPX?



Policy Engine/Policies
C++1y Parallelism APIs
Threading Subsystem
Local Control Objects (LCOs)
Performance Counter Framework
Active Global Address Space (AGAS)
Parcel Transport Layer

HPX and C++ standard

HPX implements and even extends:

- Concurrency TS, N4107
- Extended async, N3632
- Task block, N4411
- **Parallelism TS, N4105**
- **Executor, N4406**

[3] *Segmented Iterators and Hierarchical Algorithms*-Austern, Matthew H. - Generic Programming: International Seminar on Generic Programming, 2000

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Another components

- partitioned vector
- segmented algorithms[3]

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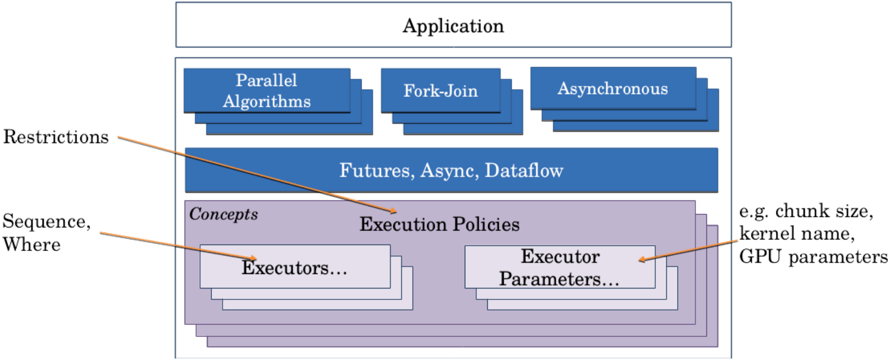
Overview



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Execution policy

Puts restriction on execution, ensuring thread-safety

Parallelism TS

- sequential
- parallel
- parallel_vector

HPX

- asynchronous sequential
- asynchronous parallel

Execution policy

Extended API for algorithms:

```
template<typename ExecutionPolicy, typename InputIt, typename
    UnaryFunction>
void for_each(ExecutionPolicy&& policy, InputIt first, InputIt
     last, UnaryFunction f)
```

Executor

Platform and vendor independent abstraction for launching work

- generic sequential and parallel executor
- core
- NUMA domain
- cluster node
- **accelerator**

Executor API

Requires only one function:

```
template <typename F>
hpx::future<typename hpx::util::result_of<
      typename hpx::util::decay<F>::type()
   >::type>
async_execute(F && f)
{
    return hpx::async(launch::async, std::forward<F>(f));
}
```

Synchronous execution and bulk overload may be provided through executor_traits

Algorithm example

```
std::vector<std::size_t> c(n);
std::iota(boost::begin(c), boost::end(c), std::rand());
/** Semantically same as std::for_each **/
hpx::parallel::for_each(hpx::parallel::seq, boost::begin(c),
 boost::end(c), [](std::size_t& v) { v = 42;});
/** Parallelize for_each **/
hpx::parallel::for_each(hpx::parallel::par, boost::begin(c),
 boost::end(c), [](std::size_t& v) { v = 43;});
```

Executor parameters

Provide specific launch parameters

- chunk size controls scheduling, similar to OpenMP

Bind executor with parameter

```
hpx::parallel::for_each(
    par.with(hpx::parallel::static_chunk_size(100)),
    ...)
```

Bind executor with tasking and parameter

```
hpx::parallel::for_each(
    par.on(hpx::parallel::task).with(hpx::parallel::
        static_chunk_size(100)),
    ...)
```

Asynchronous execution

Future

- represents result of an unfinished computation
- enables sending off operations to another thread
- TS allows for concurrent composition of different algorithms
- explicit depiction of data dependencies

Compose different operations

```
future<type> f1 = for_each(par_task, ...);
auto f2 = f1.then(
    [](future<type> f1) {
        for_each(par_task, ...);
    }
);
```

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GPU execution policy

Why a separate policy?

- allows to specialize algorithms behaviour
- explicit offloading of computation to a device
- wraps a default type of executor

GPU execution policy

Why a separate policy?

- allows to specialize algorithms behaviour
- explicit offloading of computation to a device
- wraps a default type of executor

Code does not depend on executor

```
#if defined(HPX_WITH_AMP)
 typedef parallel::gpu_amp_executor executor_type;
#else
 typedef parallel::gpu_sycl_executor executor_type;
...
gpu::executor_type my_exec;
```

GPU executor

- implements functions for synchronous and asynchronous execution
- currently provides interface for data allocation

GPU executors:

- C++AMP
- SYCL
- CUDA[4]
- probably HC in future

[4] Separate project

Data placement on device

Scheme of execution on GPU:

- transfer data from host to device
- submit kernel
- wait for finish
- transfer data back from device

Data placement on device

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Solution: algorithm automatically transfers data to GPU

\+ user is not aware of data transfer

\+ algorithms API does not change

Data placement on device

Scheme of execution on GPU:

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Data placement on device

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- transfer data back from device

Solution: algorithm automatically transfers data to GPU

+ user is not aware of data transfer
+ algorithms API does not change
− unnecessary data transfers for operations over the same data

Data placement on device

Solution: GPU iterator

- use executor API to place data on GPU
- run many algorithms using iterator defined in executor
- synchronize data on GPU with host when it's needed

```
std::vector<int> vec(10);
auto buffer = exec.create_buffers(vec.begin(), vec.end());
hpx::parallel::for_each(hpx::parallel::gpu, buffer.begin(),
    buffer.end(), ...);
buffer.synchronize();
```

Data placement on device

Solution: GPU iterator

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Solution: GPU iterator

\+ optimized data transfer
\+ algorithms API does not change
– explicit dependency on a GPU executor

Data placement on device

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- use executor API to place data on GPU
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Solution: GPU iterator

+ optimized data transfer
+ algorithms API does not change
− explicit dependency on a GPU executor → **GPU-aware data structure**

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C++AMP

- open specification proposed by Microsoft
- designed primarily for implementation based on DirectX
- allows for scheduling C++ kernels on *accelerators*
- current version 1.2, released in March 2013
- **warning:** Microsoft specific extensions, code may not be portable

Accelerators

accelerator

- abstract view of a computing device (e.g. CPU, GPU)
- provides necessary information, e.g. amount of memory
- standard specifies only two accelerator types: cpu and a default one
- may be used to control on which device place data and run job

accelerator_view

- a queue for submitting jobs
- enables synchronization through wait method
- multiple views are safe in a multi-threaded application

Data placement

array

- N-dimensional generic container for data on device
- type restrictions: proper alignment of compound types and at least for 4 bytes per fundamental type
- bound to a specific accelerator

array_view

- cached view of data with an implicit copy
- useful for containers or pointers

Kernel submission

parallel_for_each

- uses separate *extent* structure to specify number of threads created on device
- function executed on GPU has exactly one argument - index specifying location inside thread grid
- call should be synchronous, but may be optimized by compiler and return earlier
- first copy of data out of device enforces synchronization

extent

- creates N-dimensional grid of threads
- dimensionality known at compile time

Kernel submission

Restrictions

- no virtual functions
- no RTTI
- no exceptions
- recursion allowed since AMP 1.2
- functions called on device must be visible at compile time
- keyword **restrict(amp)** must be used on functions executed on device

Kernel submission for iterators

```
std::vector<int> v = { 'G', 'd', 'k', 'k', 'n', 31, 'v', 'n',
    'q', 'k', 'c'};
Concurrency::extent<1> extent(v.size());
Concurrency::array<int> data(extent, v.begin(), v.end());

Concurrency::parallel_for_each(extent,
  [&data, lambda](index<1> idx) restrict(amp) {
    lambda( data[idx[0]] );
  }
);
Concurrency::copy(data, v.begin());
```

Heterogeneous Computing

- modification of C++AMP designed by AMD
- very novel idea, no formal specification yet
- uses concepts and design from AMP, but lifts some restrictions

Changes:

- keyword *restrict* is no longer necessary
- dynamic choice of extent dimensionality
- common address space for both host and device on HSA platforms

SYCL

- proposed by Khronos Group
- brings many concepts known from OpenCL
- version 1.2 of specification released in May 2015
- version 2.2 released in March 2016
- targets devices supporting different versions of OpenCL

Accelerators

- similar to OpenCL in design - platform, context, device, queue
- device selection through a separate selector: default, gpu, cpu, host
- non standard device selection through a custom selector
- kernel submission in a queue

Data placement

buffer

- N-dimensional generic container for data
- type restrictions: C++11 standard layout

buffer accessor

- data accessor on host or device
- doesn't expose iterators, only index operator
- needs to be captured by lambda executed on device
- **device accessor can be created only in queue code**

Kernel submission for iterators

```
std::vector<int> data{ 'G', 'd', 'k', 'k', 'n', 31, 'v', 'n',
    'q', 'k', 'c'};
default_selector selector; queue myQueue(selector);
auto first = data.begin(); std::size_t size = data.size();

/** Create buffer with copy back**/
std::shared_ptr<int> buf_data{new int[size],
  [first, size](int * ptr) {
    std::copy(ptr, ptr + size, first);
    delete[] ptr;
  }
};
std::copy(data.begin(), data.end(), buf_data.get());
buffer<int, 1> buf(buf_data, cl::sycl::range<1>(size) );
```

Kernel submission for iterators

```
/** Send kernel **/
myQueue.submit([&](handler& cgh) {
  auto ptr = buf.get_access<access::mode::read_write>(cgh);
  auto lambda = [](int & v)  { ++v; };
  cgh.parallel_for<class HelloWorld>(range<1>(data.size()),
    [=](id<1> idx) {
      lambda( ptr[idx[0]] );
    }
  );
});
```

Kernel submission for iterators II

```
std::vector<int> data{ 'G', 'd', 'k', 'k', 'n', 31, 'v', 'n',
    'q', 'k', 'c'};
default_selector selector; queue myQueue(selector);
buffer<int, 1> buf(data.begin(), data.end());
myQueue.submit([&](handler& cgh) {
  auto ptr = buf.get_access<access::mode::read_write>(cgh);
  auto lambda = [](int & v)  { ++v; };
  cgh.parallel_for<class HelloWorld>(range<1>(data.size()),
    [=](id<1> idx) {
      lambda( ptr[idx[0]] );
    }
  );
});
auto host_acc = buf.get_access<access::mode::read, access::
    target::host_buffer>();
std::copy(host_acc.get_pointer(), host_acc.get_pointer() +
   buf.get_count(), data.begin());
```

Kernel restrictions

- no virtual functions
- no exceptions
- no RTTI
- **no recursion**
- functions called on device must be visible at compile time

Kernel name

- two-tier compilation needs to link kernel code and invocation
- name has to be unique across whole program
- breaks the standard API for STL algorithms
- different extensions to C++ may solve this problem[5]

[5] *Khronos's OpenCL SYCL to support Heterogeneous Devices for C++* - Wong, M. et al. - P0236R0

Kernel name

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C++ code

```
cgh.parallel_for_each<class KernelName>(...);
```

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Kernel name

Names in template methods

```
template<typename FloatingType>
void solve_pde(vector<FloatingType> & in, vector<FloatingType>
     & out)
{
    // ...
    cgh.parallel_for_each<class FDSolver>(...);
}
/* ... */
if (user_wants_less_precision)
  solve_pde(float_data, float_result);
else
  solve_pde(double_data, double_result);
```

Kernel name

Names in template methods

```
template<typename FloatingType>
void solve_pde(vector<FloatingType> & in, vector<FloatingType>
      & out)
{
    // ...
    cgh.parallel_for_each<class FDSolver>(...);
}
/* ... */
if (user_wants_less_precision)
  solve_pde(float_data, float_result);
else
  solve_pde(double_data, double_result);
```

error: definition with same mangled name as another definition

Names in template methods

```
template<typename FloatingType, typename SolverName>
void solve_pde(vector<FloatingType> & in, vector<FloatingType>
     & out)
{
    // ...
    cgh.parallel_for_each<SolverName>(...);
}
/* ... */
if (user_wants_less_precision)
  solve_pde<class FloatSolver>(float_data, float_result);
else
  solve_pde<class DoubleSolver>(double_data, double_result);
```

Named execution policy

- execution policy contains the name
- use the type of functor if no name is provided
- used in prototype implementation of ParallelSTL done by Khronos[6]

```
struct DefaultKernelName {};

template <class KernelName = DefaultKernelName>
class sycl_execution_policy {
    ...
};
```

[6] https://github.com/KhronosGroup/SyclParallelSTL/

HCC - Heterogeneous Computing Compiler

- started as Clamp for C++AMP, renamed later to Kalmar
- since November 2015 development supported by AMD
- LLVM-based compiler, two passes over source code
- **requires libc++**

Frontends

- C++AMP
- HC

Backends

- OpenCL C
- OpenCL SPIR
- HSAIL
- AMD Native GCN ISA

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ComputeCPP

- SYCL **device** compiler developed by Codeplay
- closed source, LLVM-based compiler
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computecpp

- device code
- .sycl header for C++

$+$

cxx

- host code
- includes kernel header

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Integration with HCC

- HPX needs to be compiled and linked with libc++
- HCC becomes the *CMAKE_CXX_COMPILER*
- expect that it may not always work out of the box

\+ easy integration with existing build system

– increased time and memory usage for compilation, even for non-GPU source code

Executor

- two phase compilation requires pseudo-dependencies on targets in CMake
- *CMAKE_CXX_COMPILER* doesn't change

+ no change in environment - same compiler, same implementation of C++
+ it is possible to apply new compiler only to files with GPU-code
– may be tricky to get it right with different build systems

Implementation of for_each_n

Current parallel implementation:

```
template <typename ExPolicy, typename F,
    typename Proj = util::projection_identity>
static typename detail::algorithm_result<ExPolicy, Iter>::type
parallel(ExPolicy policy, Iter first, std::size_t count,
   F && f, Proj && proj)
{
  if (count != 0)
  {
    return foreach_n_partitioner<ExPolicy>::call(policy,
      first, count, [f, proj](Iter begin, std::size_t size) {
        loop_n(begin, size, [=](Iter const& curr)
          {
            invoke(f, invoke(proj, *curr));
          }); });
  }
  return detail::algorithm_result<ExPolicy, Iter>::get(
        std::move(first));
}
```

Implementation of for_each_n

How do we implement synchronous bulk execution?

```
static typename detail::bulk_execute_result<F, Shape>::type
bulk_execute(F && f, Shape const& shape)
{
  // Shape elements are tuples with iterator, data count and
       chunk size
  typedef typename Shape::value_type tuple_t;
  for(auto const & elem : shape) {

    auto iter = hpx::util::get<0>(elem);
    std::size_t data_count = hpx::util::get<1>(elem);
    std::size_t chunk_size = hpx::util::get<2>(elem);

    std::size_t threads_to_run = data_count / chunk_size;
    std::size_t last_thread_chunk = data_count -
      (threads_to_run - 1)*chunk_size;
```

Implementation of for_each_n

How do we implement it?

```
    Concurrency::extent<1> e(threads_to_run);
    Concurrency::parallel_for_each(e, [=](Concurrency::index
        <1> idx) restrict(amp)
    {
      std::size_t part_size =
        idx[0] != static_cast<int>(threads_to_run - 1) ?
            chunk_size : last_thread_chunk;
      auto it = iter;
      it.advance(idx[0]*chunk_size);
      tuple_t tuple(it, 0, part_size);
      f(tuple);
    });
    accelerator_view.wait();
  }
}
```

Implementation of for_each_n

How do we call it?

```
std::vector<int> c(n);
std::iota(boost::begin(c), boost::end(c),  std::rand());

auto buffer = hpx::parallel::gpu.executor().create_buffers(c.
    begin(), c.end());
hpx::parallel::for_each(hpx::parallel::gpu,
  buffer.begin(), buffer.end(),
  [](int& v) {

    v = 400;
  });
buffer.sync();
```

Implementation of transform

What is an unary transform?

```
typedef hpx::util::zip_iterator<FwdIter, output_iterator>
                     zip_iterator;
typedef typename zip_iterator::reference reference;
for_each_n<zip_iterator>().call(policy,
  hpx::util::make_zip_iterator(first, dest),
  std::distance(first, last),
  [f, proj](reference t)
  {
    using hpx::util::get; get<1>(t) = f(get<0>(t));
  }));
```

What is a binary transform?

Same idea, just three iterators.

Implementation of transform

Wouldn't it be great if it worked immediately on GPUs?

gpu_amp_executor?

Implementation of transform

Wouldn't it be great if it worked immediately on GPUs?

gpu_amp_executor?
yes, I can do that!

Implementation of transform

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gpu_sycl_executor?

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error: can not capture object ptr of type 'class cl::sycl::accessor[...]' in a SYCL kernel, because it is a non standard-layout type

Implementation of transform

Wouldn't it be great if it worked immediately on GPUs?

gpu_sycl_executor?

error: can not capture object ptr of type 'class cl::sycl::accessor[...]' in a SYCL kernel, because it is a non standard-layout type
error: class std::tuple is not standard layout, because multiple classes among its base classes declare non-static fields

Executor parameters

Chunk size

- parallel algorithm exposes dynamic, static, guided, auto
- most of them doesn't make sense on GPU, where there is a certain overhead of launching small jobs
- GPU executor takes a static chunk size

Also:

- kernel name
- tiling size (local work size) in future

Name as an executor parameter

- name is still tied to an executor
- same API calls for both AMP and SYCL

```
#include <hpx/include/parallel_executor_parameters.hpp>

hpx::parallel::transform(hpx::parallel::gpu.with(
  hpx::parallel::static_chunk_size(32),
  hpx::parallel::kernel_name<class Add>()), ... );
```

Naming the kernel

- light wrapper around the kernel
- name is tied directly to the executed function
- not applicable for algorithms without user-defined operator

```
#include <hpx/parallel/executors/parallel_executor_parameters.
    hpp>
#include <hpx/parallel/kernel_name.hpp>

hpx::parallel::for_each(
  hpx::parallel::gpu.with(hpx::parallel::kernel_name<class
      FalseName>()),
  d.begin(), d.end(),
  hpx::parallel::make_kernel<class CorrectName>([](int & v) {
     v = 42;
  })
);
```

Known problems

HCC

- problems with correct linking of kernel (HPX only)
- known bugs in OpenCL backend which most likely won't be fixed

ComputeCPP

- incorrect capture of const integers in device lambda (HPX only)
- unfriendly build scripts

STREAM bechmark [7]

STREAM benchmark consists of:

1 scalar k, 3 input arrays a, b, c and 4 operations

[7] *Memory Bandwidth and Machine Balance in Current High Performance Computers* - McCalpin, John D - IEEE Computer Society Technical Committee on Computer Architecture (TCCA) Newsletter, December 1995

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$$c = a$$

scale

$$b = k * c$$

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$$c = a$$

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$$b = k * c$$

add

$$c = b + a$$

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$$c = a$$

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add

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triad

$$a = b + k * c$$

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Benchmarking hardware

C++AMP

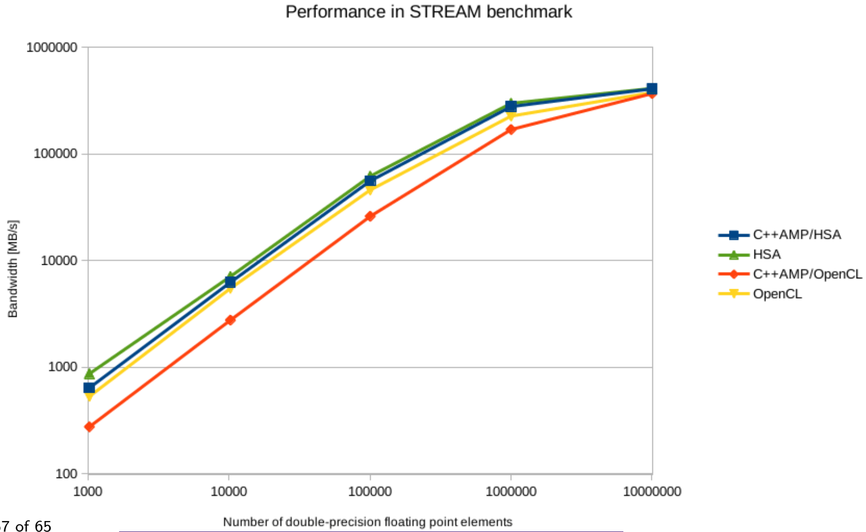
- **GPU:** AMD Radeon R9 Fury Nano
- **OpenCL:** AMD APP SDK 3.02
- **HSA:** AMD ROCm 1.0

Khronos SYCL

- **GPU:** AMD Radeon R9 Fury Nano
- **ComputeCPP:** 15.10
- **OpenCL:** AMD APP SDK 3.02

GPU-STREAM has been used to measure OpenCL and HSA performance: `https://github.com/UoB-HPC/GPU-STREAM`

How does AMP perform?



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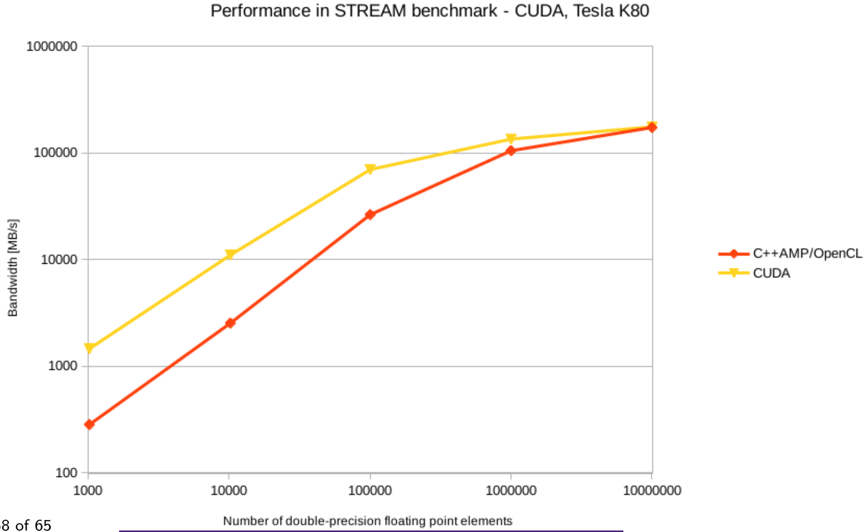

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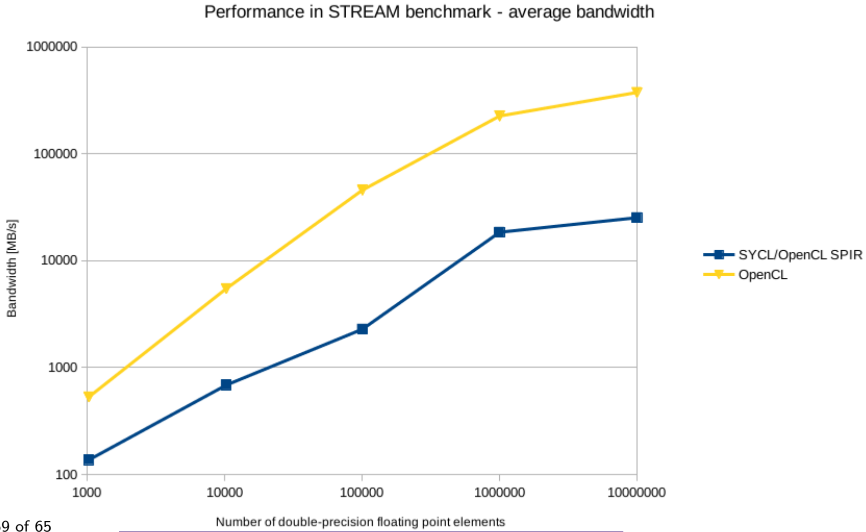
How does SYCL perform?



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Overhead

HCC

- Compilation of HPX is approximately **2.4x** slower
- Compilation of benchmark example increased from 20 to 48 seconds, **2.4x** slower
- Peak memory usage of compiler and binary size are both comparable

ComputeCPP

- For benchmark example, the overhead of device is compiler is 12 seconds to 20 seconds required by g++, slowing the compilation **1.6** times.
- Peak memory usage of compiler and binary size are both comparable

Plan

HPX
Parallelism in C++
- Concepts

GPU in HPX
- Execution
- Data placement

GPU standards for C++
- C++AMP
- Khronos SYCL
- Compilers

Results
- Implementation
- STREAM benchmark

Goals

Data placement revised

How and when to place data?

- in the current implementation algorithm is responsible for data allocation
- different types of memory on GPUs $\implies$ executor should know **where** execute kernel, not **how** to place data
- STL: algorithms and containers $\implies$ container with special allocator
- we want to support multiple GPUs $\implies$ a partitioned vector with segmented algorithms

Algorithms

adjacent_difference	adjacent_find	all_of	any_of
copy	copy_if	copy_n	count
count_if	equal	exclusive_scan	fill
fill_n	find	find_end	find_first_of
find_if	find_if_not	for_each	for_each_n
generate	generate_n	includes	inclusive_scan
inner_product	inplace_merge	is_heap	is_heap_until
is_partitioned	is_sorted	is_sorted_until	lexicographical_compare
max_element	merge	min_element	minmax_element
mismatch	move	none_of	nth_element
partial_sort	partial_sort_copy	partition	partition_copy
reduce	remove	remove_copy	remove_copy_if
remove_if	replace	replace_copy	replace_copy_if
replace_if	reverse	reverse_copy	rotate
rotate_copy	search	search_n	set_difference
set_intersection	set_symmetric_difference	set_union	sort
stable_partition	stable_sort	swap_ranges	transform
uninitialized_copy	uninitialized_copy_n	uninitialized_fill	uninitialized_fill_n
unique	unique_copy		

hpx::compute

- ongoing work to provide standard compliant GPU algorithms in an "STL way"
- includes AMP/SYCL backends presented here
- includes existing and developed support for CUDA and OpenCL
- focused on distributed computing

Thanks for your attention

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STE||AR GROUP