Parallelism in Modern C++

Task-based parallelism as the basis for all higher-level APIs

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HPX

A General Purpose Parallel Runtime System for Applications of any Scale

HPX – A General Purpose Runtime System

- General purpose parallel runtime system for applications of any scale
- Exposes a coherent and uniform, standards-oriented API for ease of programming parallel, distributed, and heterogeneous applications.
  - Enables to write fully asynchronous code using hundreds of millions of threads.
  - Provides unified syntax and semantics for local and remote operations.
- HPX represents an innovative mixture of
  - A global system-wide address space (AGAS - Active Global Address Space)
  - Fine grain parallelism and lightweight synchronization
  - Combined with implicit, work queue based, message driven computation
  - Full semantic equivalence of local and remote execution, and
  - Explicit support for hardware accelerators and vectorization

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HPX – A General Purpose Runtime System

- Enables writing applications which out-perform and out-scale existing applications based on OpenMP/MPI
  - http://stellar-group.org/libraries/hpx
  - https://github.com/STEllAR-GROUP/hpx/
- Is published under Boost license and has an open, active, and thriving developer community.
- Can be used as a platform for research and experimentation

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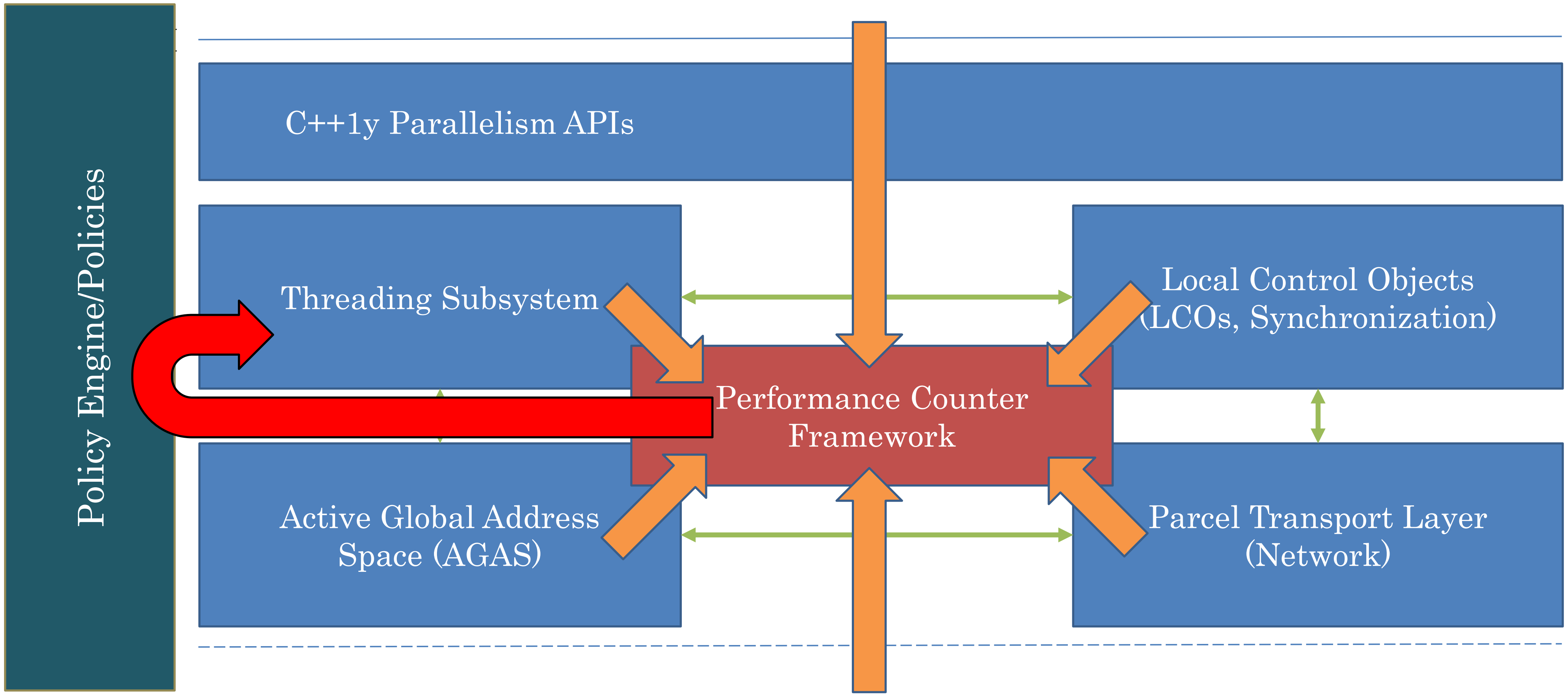
HPX – A General Purpose Runtime System


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

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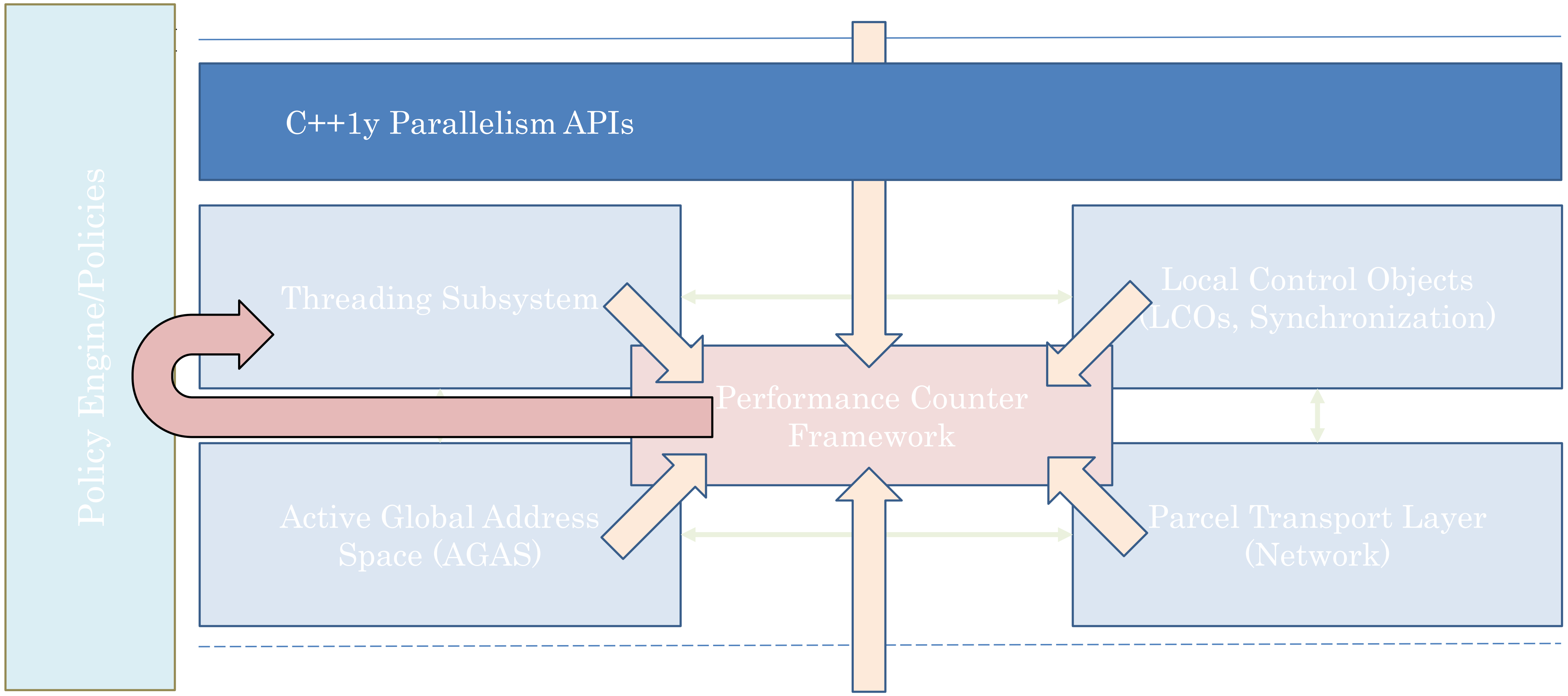
HPX – A General Purpose Runtime System


C++1y Parallelism APIs
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HPX – The API

- As close as possible to C++1y standard library, where appropriate, for instance

std::thread	hpx::thread
std::mutex	hpx::mutex
std::future	hpx::future (including N4107, ‘Concurrency TS’)
std::async	hpx::async (including N3632)
std::bind	hpx::bind
std::function	hpx::function
std::tuple	hpx::tuple
std::any	hpx::any (P0220, ‘Library Fundamentals TS’)
std::cout	hpx::cout
std::parallel::for_each, etc.	hpx::parallel::for_each (N4105, ‘Parallelism TS’)
std::parallel::task_block	hpx::parallel::task_block (N4411)
std::vector	hpx::vector, hpx::partitioned_vector

- Extensions to the standard APIs, where necessary
  - While maintaining full compatibility

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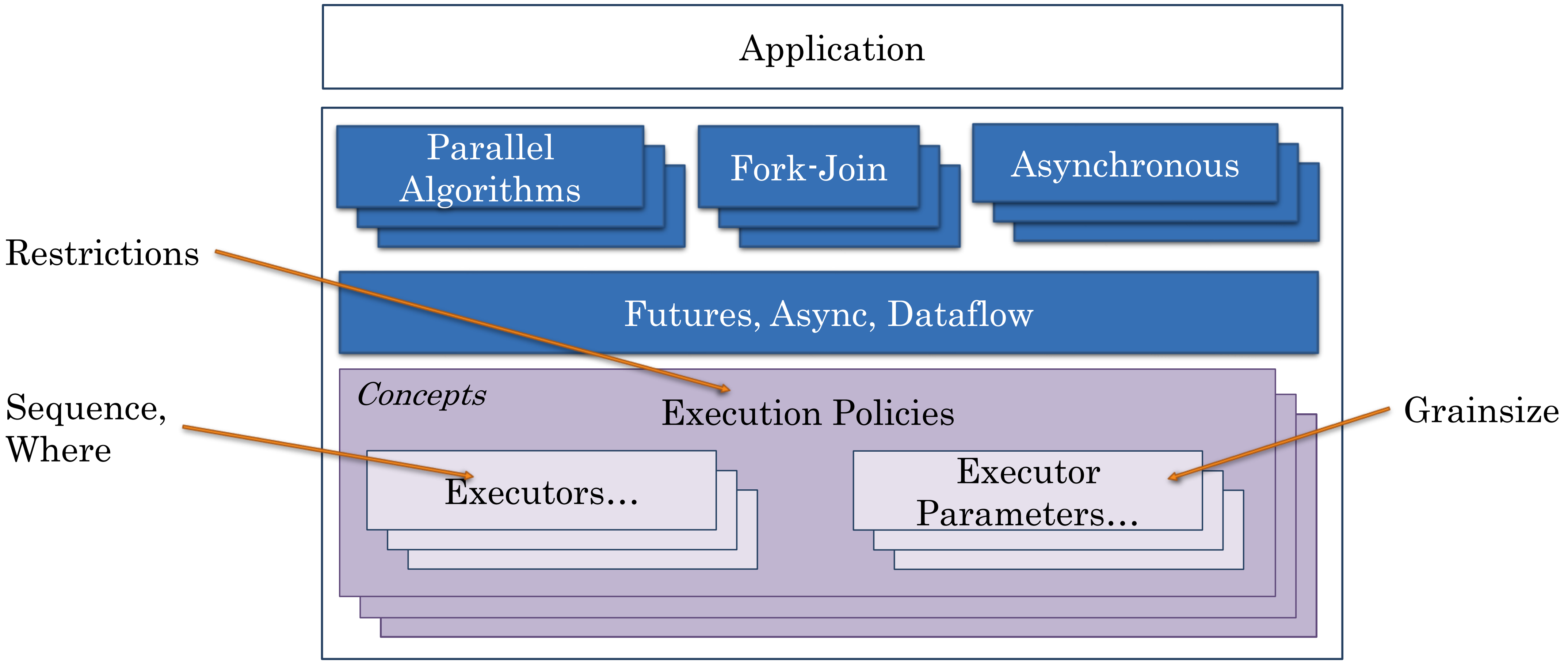
Parallelism in C++

A Vision for Coherent Higher-level APIs without the need for OpenMP, OpenAcc, or CUDA, etc.

Concepts and Types of Parallelism



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Types of Parallelism

- Current state of standard C++:
  - Parallelism TS: iterative parallelism (moved to be included into C++17)
  - Concurrency TS: task-based, asynchronous, and continuation style parallelism
  - N4411: task blocks for fork-join parallelism of heterogeneous tasks
  - N4406, PR0008R0: executors
  - PR0057R0: resumable functions (co_await, etc.)
- Missing:
  - Integration of the above
  - Parallel ranges
  - Vectorization is being discussed
  - Extensions for GPUs, many-core, distributed, and high-performance computing
- The goal has to be to make parallelism in C++ independent of any external solutions such as OpenMP, OpenACC, etc.
  - HPX makes C++ independent of MPI as well

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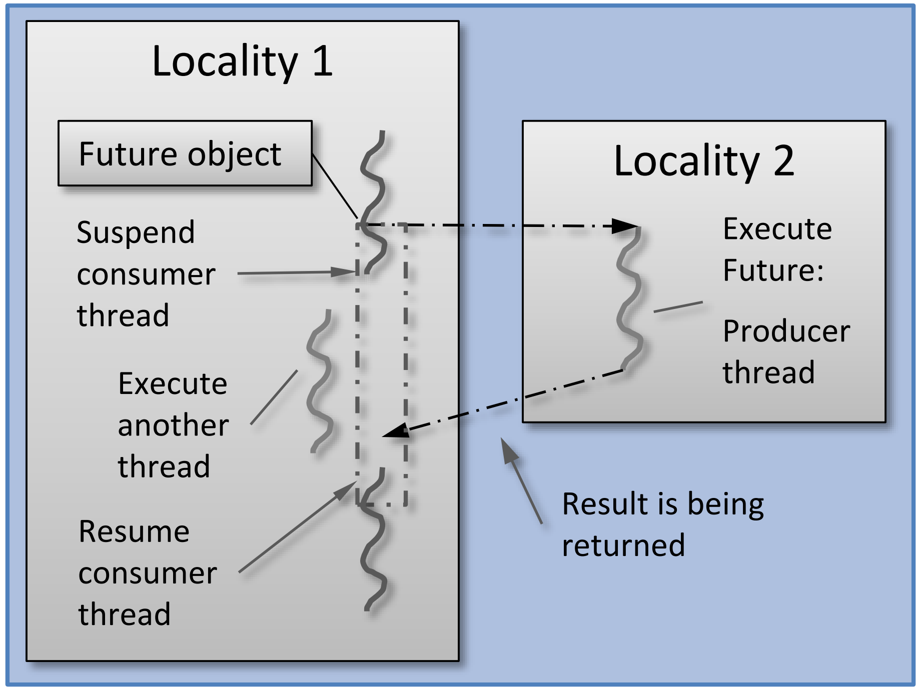
What is a (the) future

- A future is an object representing a result which has not been calculated yet



- Enables transparent synchronization with producer
- Hides notion of dealing with threads
- Makes asynchrony manageable
- Allows for composition of several asynchronous operations
- (Turns concurrency into parallelism)

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What is a (the) Future?

- Many ways to get hold of a future, simplest way is to use (std) async:

```
int universal_answer() { return 42; }

void deep_thought()
{
    future<int> promised_answer = async(&universal_answer);

    // do other things for 7.5 million years

    cout << promised_answer.get() << endl;   // prints 42
}
```

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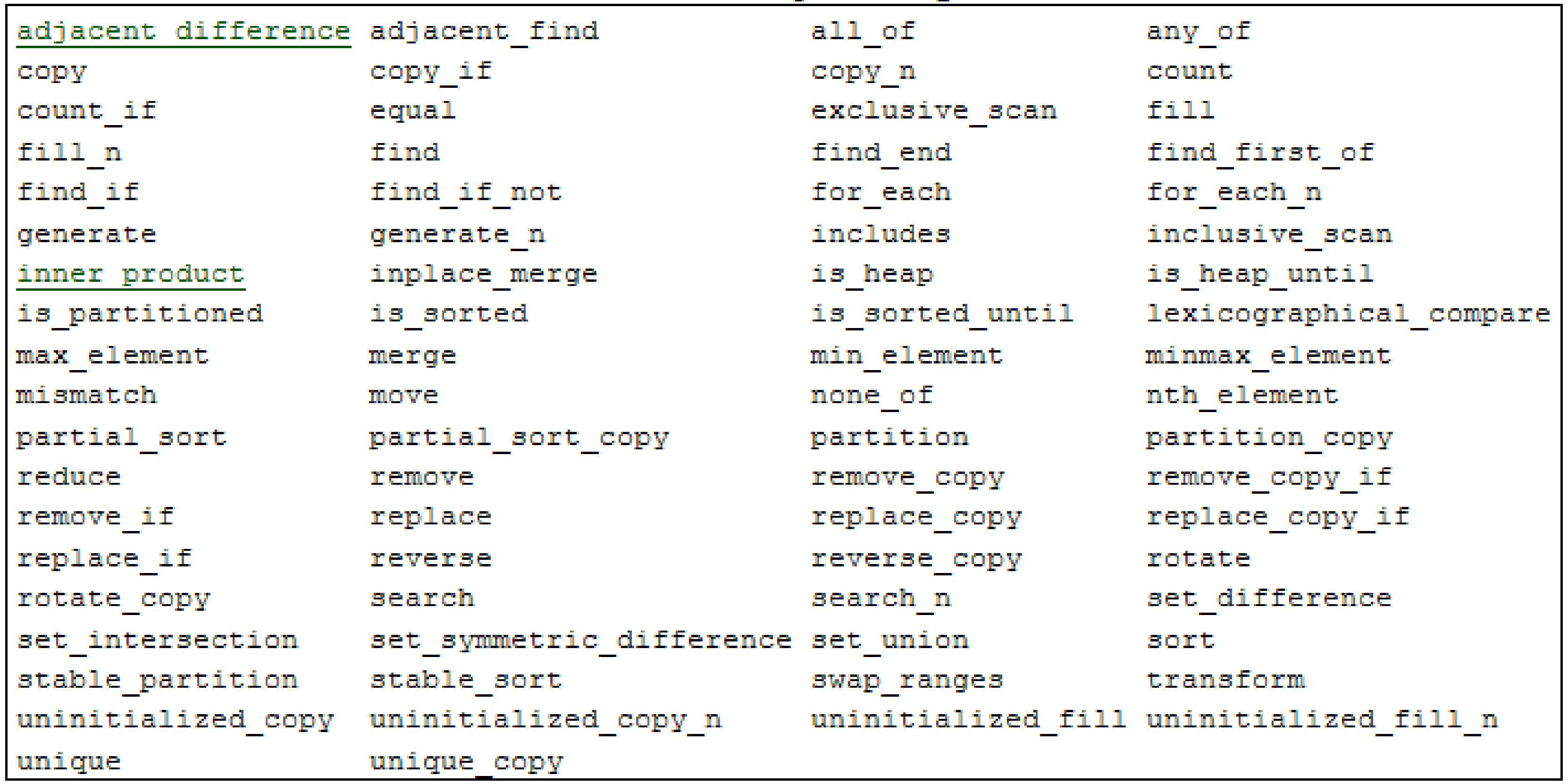
Parallel Algorithms

Parallel 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		

Parallel Algorithms

- Similar to standard library facilities known for years
  - Add execution policy as first argument
- Execution policies have associated default executor and default executor parameters
  - `par` → parallel executor, static chunk size
  - `seq` → sequential executor, no chunking
- Rebind executor and executor parameters:

```
//
// Simplest case: parallel execution policy
//
std::vector<double> d(1000);
parallel::fill(
    par,
    begin(d), end(d), 0.0);
```

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Parallel Algorithms

- Similar to standard library facilities known for years
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- Execution policies have associated default executor and default executor parameters
  - `par` → parallel executor, static chunk size
  - `seq` → sequential executor, no chunking
- Rebind executor and executor parameters:

```
// rebind execution policy
//     .on():    executor object, ‘where and when’
//     .with():  parameter object(s), possibly executor specific parameters
std::vector<double> d(1000);
parallel::fill(
    par.on(exec).with(par1, par2, ...),
    begin(d), end(d), 0.0);
```

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Rebind Execution Policies

```
numa_executor exec;
auto policy1 = par.on(exec);                // rebind only executor

static_chunk_size param;
auto policy2 = par.with(param);             // rebind only executor parameter

auto policy3 = par.on(exec).with(param);    // rebind both
```

Parallel Algorithms

```
// uses default execution policy: par
std::vector<double> d = { ... };
parallel::fill(par, begin(d), end(d), 0.0);

// rebind par to user-defined executor
my_executor my_exec = ...;
parallel::fill(par.on(my_exec), begin(d), end(d), 0.0);

// rebind par to user-defined executor and user defined executor parameters
my_params my_par = ...
parallel::fill(par.on(my_exec).with(my_par), begin(d), end(d), 0.0);
```

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Execution Policies (HPX Extensions)

- Extensions: asynchronous execution policies
  - `parallel_task_execution_policy` (asynchronous version of `parallel_execution_policy`), generated with `par(task)`
  - `sequential_task_execution_policy` (asynchronous version of `sequential_execution_policy`), generated with `seq(task)`

  - In all cases the formerly synchronous functions return a future<>
  - Instruct the parallel construct to be executed asynchronously
  - Allows integration with asynchronous control flow

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Execution Policies (HPX Extensions)

- Extensions: vectorization execution policies
  - `datapar_task_execution_policy` (asynchronous version of `datapar_execution_policy`), generated with `datapar, datapar(task)`
  - `dataseq_task_execution_policy` (asynchronous version of `dataseq_execution_policy`), generated with `dataseq, dataseq(task)`
  - Instruct the algorithm to apply certain transformations to used data types allowing for vectorization of code
    - Requires external library: currently Vc (https://github.com/VcDevel/Vc), possibly Boost.SIMD
    - Requires use of generic lambdas (C++14) or polymorphic function objects

Executors

- Executors must implement one function: `async_execute(F && f)`
- Invocation of executors happens through `executor_traits` which exposes (emulates) additional functionality:

```
executor_traits<my_executor_type>::execute(
    my_executor,
    [](...){ // perform task },
    ...);
```

- Four modes of invocation: single async, single sync, bulk async and bulk sync
  - The async calls return a future

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Executor Examples

- `sequential_executor`, `parallel_executor`:
  - Default executors corresponding to `par, seq`
- `this_thread_executor`
- `distribution_policy_executor`
  - Use one of HPX's (distributed) distribution policies, specify node(s) to run on
- `host::parallel_executor`
  - Specify core(s) to run on (NUMA aware)
- `cuda::default_executor`
  - Use for running things on GPU
- Etc.

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Executor Parameters (HPX Extension)

- Same scheme as for executor/executor_traits:
  - parameter/executor_parameter_traits
- Various execution parameters, possibly executor specific
- For instance:
  - Allow to control the grain size of work
    - i.e. amount of iterations of a parallel for_each run on the same thread
    - Similar to OpenMP scheduling policies: static, guided, dynamic
      - `auto_chunk_size`, `static_chunk_size`, `dynamic_chunk_size`
    - Much more fine control
    - Used by parallel algorithms to adjust chunk size
  - Specify GPU-kernel name for certain platforms
    - `gpu_kernel<foobar>`
  - Specify which other arrays to prefetch

Data placement

Data Placement

- Different strategies for different platforms
  - Need interface to control explicit placement of data
    - NUMA architectures
    - GPUs
    - Distributed systems
  - Use `std::allocator<T>` interfaces
    - NUMA architectures: first touch
    - Slightly extended: bulk-operations for allocation, construction, destruction, and deallocation

Data Placement

- HPX:
  - `hpx::vector<T, Alloc>`
    - Same interface as `std::vector<T>`
    - Manages data locality through allocator
    - Uses execution target objects for data placement
    - Allows for direct manipulation of data on NUMA domains, GPUs, remote nodes, etc.
  - `hpx::partitioned_vector<T>`
    - Same interface as `std::vector<T>`
    - Segmented data store
      - Segments can be `hpx::vector<T, Alloc>`
    - Uses `distribution_policy` for data placement
    - Allows for manipulation of data on several targets

Data Placement

- Extending `std::allocator_traits`
  - Adding functionality to copy data
    - CPU: trivial
    - GPU: platform specific data transfer, hooked into `parallel::copy`
    - Distributed: maps onto network, possibly RDMA (put/get)
  - Adding functionality to access single elements
    - CPU: trivial
    - GPU: slow, but possible
    - Distributed: maps onto network

Execution Targets

One Ring to Rule them All

Execution Targets

- Opaque types which represent a place in the system
  - Used to identify data placement
  - Used to specify execution site close to data
- Targets encapsulate architecture specifics
  - E.g. `cuda::target`, `host::target`
- Allocators to be initialized from targets
  - Customization of data placement
    - NUMA domain: `host::block_allocator`
    - (possibly remote) GPU device: `cuda::allocator`
    - Locality, i.e. (possibly remote) node
- Executors to be initialized from targets as well
  - Make sure code is executed close to placed data

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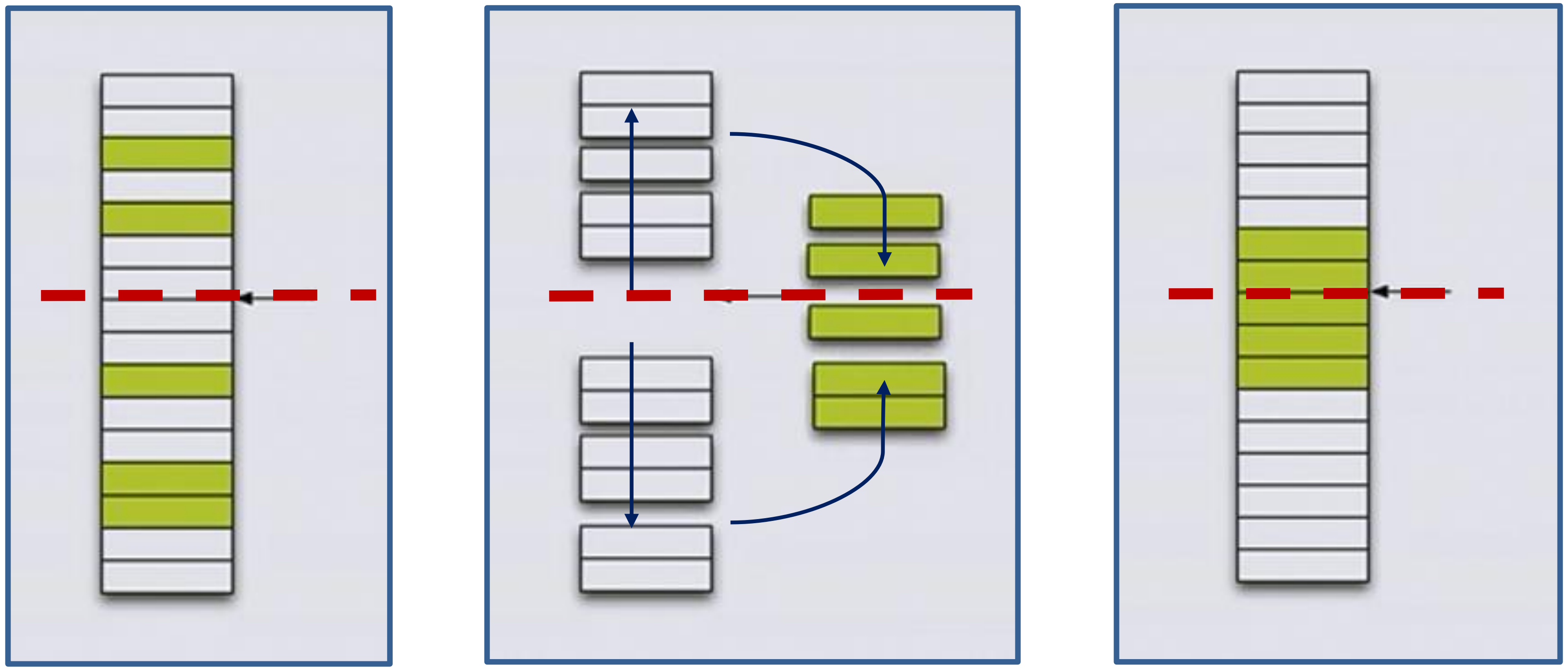
Examples and Results

Extending Parallel Algorithms



Sean Parent: C++ Seasoning, Going Native 2013

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Extending Parallel Algorithms

- New algorithm: gather

```
template <typename BiIter, typename Pred>
pair<BiIter, BiIter> gather(BiIter f, BiIter l, BiIter p, Pred pred)
{
    BiIter it1 = stable_partition(f, p, not1(pred));
    BiIter it2 = stable_partition(p, l, pred);
    return make_pair(it1, it2);
}
```

Sean Parent: C++ Seasoning, Going Native 2013

Extending Parallel Algorithms

- New algorithm: gather_async

```
template <typename BiIter, typename Pred>
future<pair<BiIter, BiIter>> gather_async(BiIter f, BiIter l, BiIter p, Pred pred)
{
    future<BiIter> f1 = parallel::stable_partition(par(task), f, p, not1(pred));
    future<BiIter> f2 = parallel::stable_partition(par(task), p, l, pred);
    return dataflow(
        unwrapped([](BiIter r1, BiIter r2) { return make_pair(r1, r2); }),
        f1, f2);
}
```

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Extending Parallel Algorithms (await)

- New algorithm: gather_async

```
template <typename BiIter, typename Pred>
future<pair<BiIter, BiIter>> gather_async(BiIter f, BiIter l, BiIter p, Pred pred)
{
    future<BiIter> f1 = parallel::stable_partition(par(task), f, p, not1(pred));
    future<BiIter> f2 = parallel::stable_partition(par(task), p, l, pred);
    return make_pair(co_await f1, co_await f2);
}
```

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STREAM Benchmark

- Assess memory bandwidth
- Series of parallel for loops, 3 arrays (a, b, c)
  - copy step: `c = a`
  - scale step: `b = k * c`
  - add two arrays: `c = a + b`
  - triad step: `a = b + k * c`
- Best possible performance possible only if data is placed properly
  - Data has to be located in memory of NUMA-domain where thread runs
- OpenMP: implicitly by using 'first touch', i.e. run initialization and actual benchmark using same thread
  - `#pragma omp parallel for schedule(static)`

STREAM Benchmark

```
std::vector<double> a, b, c;    // data

// ... init data

auto a_begin = a.begin(), a_end = a.end(), b_begin = b.begin() ...;

// STREAM benchmark
parallel::copy(par, a_begin, a_end, c_begin);                          // copy step: c = a
parallel::transform(par, c_begin, c_end, b_begin,                      // scale step: b = k * c
    [](double val) { return 3.0 * val; });
parallel::transform(par, a_begin, a_end, b_begin, b_end, c_begin,   // add two arrays: c = a + b
    [](double val1, double val2) { return val1 + val2; });
parallel::transform(par, b_begin, b_end, c_begin, c_end, a_begin,   // triad step: a = b + k * c
    [](double val1, double val2) { return val1 + 3.0 * val2; });
```

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STREAM Benchmark (CPU)

```
host::target tgt("numa=0");          // where and when, here CPU, NUMA domain 0

using executor = host::parallel_executor;
using allocator = host::block_allocator<double>;

executor exec(tgt);                  // define execution site
allocator alloc(tgt, ...);           // define data placement

vector<double, allocator> a(alloc), b(alloc), c(alloc);            // data
// ... init data

auto policy = par.on(exec).with(static_chunk_size());               // bound execution policy

// STREAM benchmark
parallel::copy(policy, a_begin, a_end, c_begin);
// ...
```

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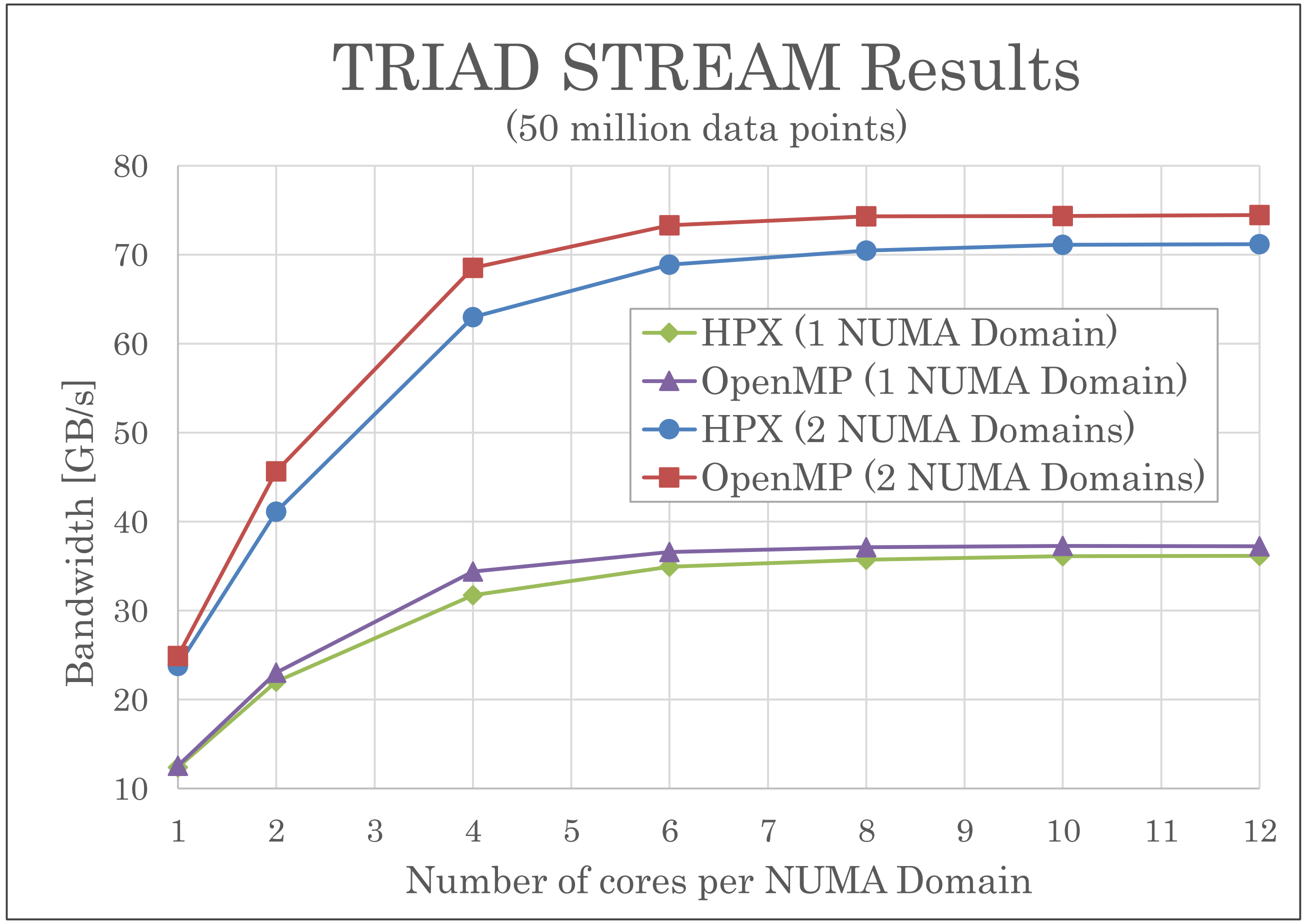
STREAM Benchmark: HPX vs. OpenMP



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Extending to GPUs

STREAM Benchmark (GPU)

```
cuda::target target("Tesla C2050");  // where and when, here NVidia GPU (CUDA)

using executor = cuda::default_executor;
using allocator = cuda::allocator<double>;

executor exec(tgt);                  // define execution site
allocator alloc(tgt);                // define data placement

std::vector<double> data = { ... };                          // init data on host
hpx::vector<double, allocator> a(alloc), b(alloc), c(alloc);        // data on device

parallel::copy(par, data.begin(), data.end(), a_begin);              // copy data to device

// STREAM benchmark
// ...
```

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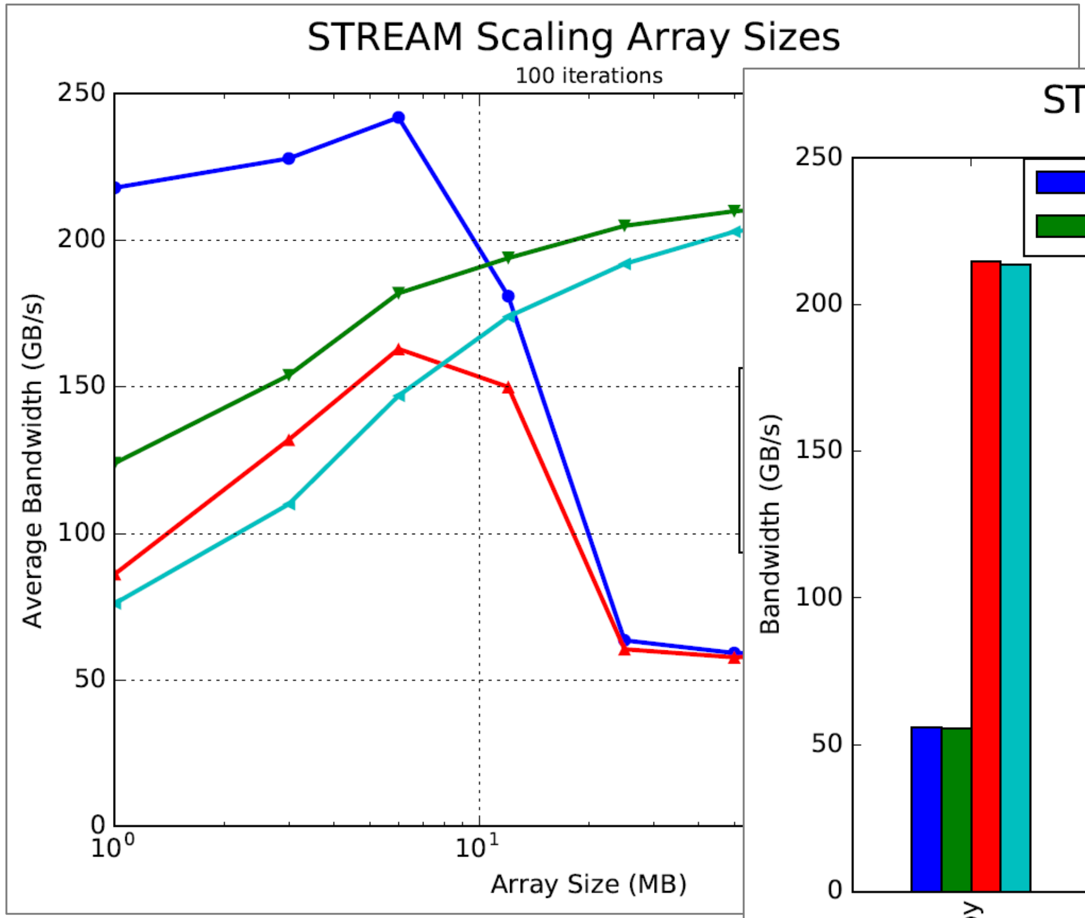
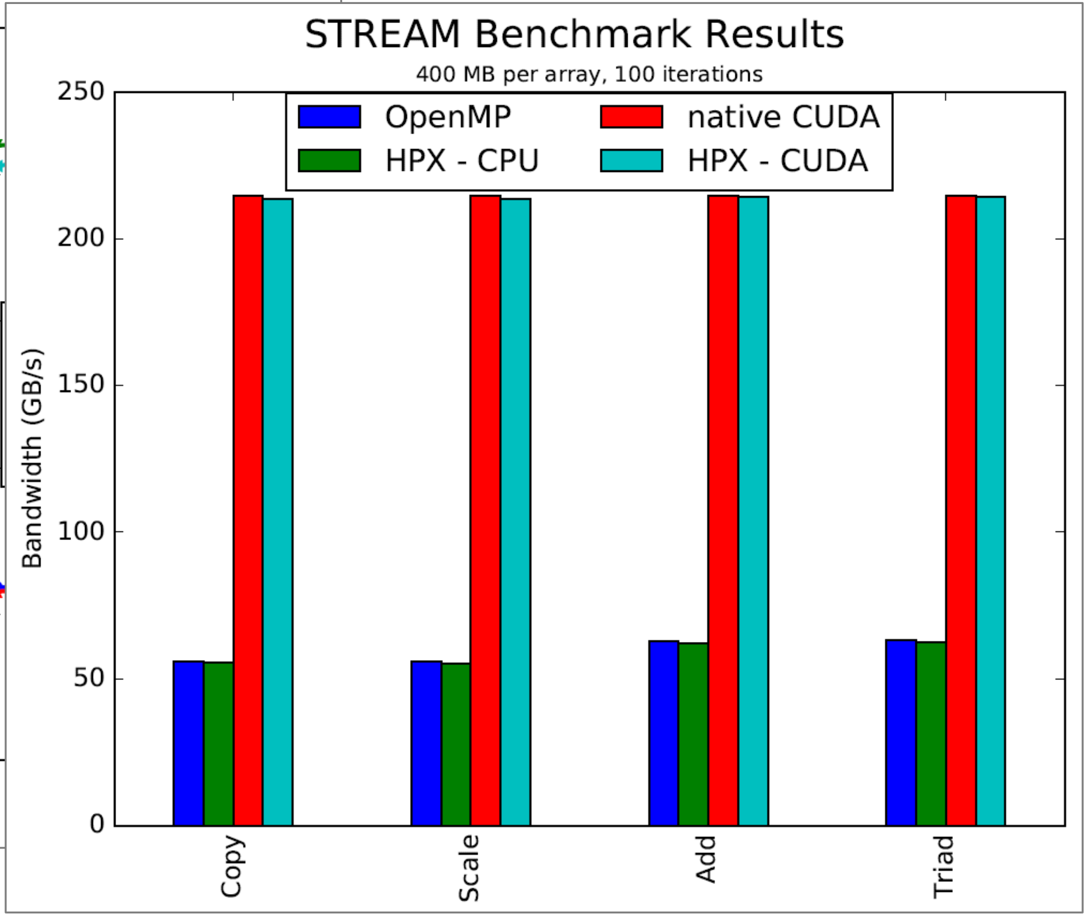
STREAM Benchmark: HPX vs. OpenCL





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Vectorization

Dot-product: Parallel Execution

```
std::vector<float> data1 = {...};
std::vector<float> data2 = {...};

inner_product(
   par,                                         // just parallel execution
   std::begin(data1), std::end(data1),
   std::begin(data2),
   0.0f,
   [](auto t1, auto t2) { return t1 + t2; }, // std::plus<>()
   [](auto t1, auto t2) { return t1 * t2; }  // std::multiplies<>()
);
```

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Dot-product: Vectorization

```
std::vector<float> data1 = {...};
std::vector<float> data2 = {...};

inner_product(
   datapar,                                    // parallel and vectorized execution
   std::begin(data1), std::end(data1),
   std::begin(data2),
   0.0f,
   [](auto t1, auto t2) { return t1 + t2; }, // std::plus<>()
   [](auto t1, auto t2) { return t1 * t2; }  // std::multiplies<>()
);
```

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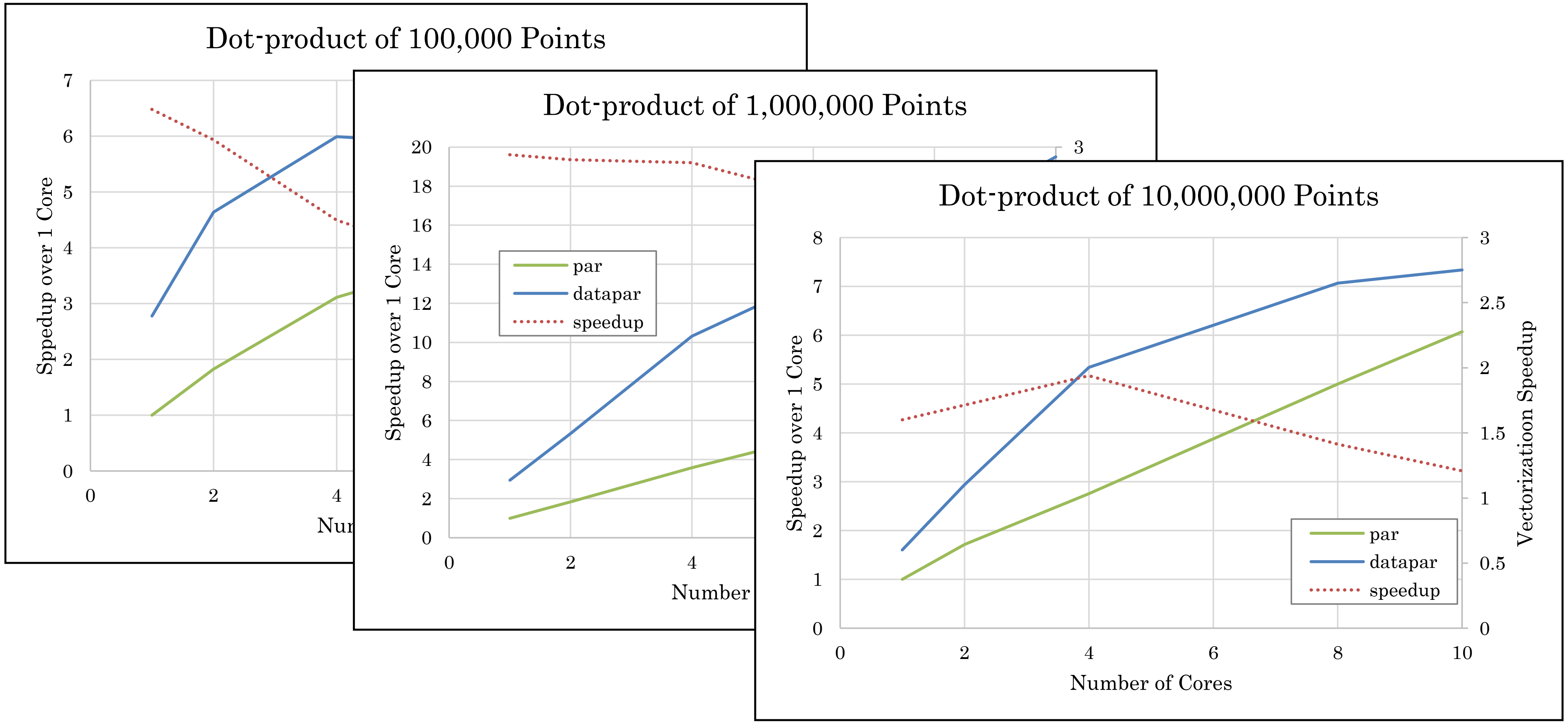
Dot-Product: Results



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Partitioned Vector

Finding Min/Max on Host

```
std::vector<targets> targets = host::get_numa_targets();
partitioned_vector<int> v(size,
    host::target_distribution_policy(targets));

host::numa_executor exec(targets);
generate(par.on(exec), v.begin(), v.end(), rand);

auto iters = minmax_element(par.on(exec), v.begin(), v.end());

std::cout << "Minimal element: " << *(iter.first);
std::cout << "Maximal element: " << *(iter.second);
```

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Finding Min/Max on GPU

```
std::vector<targets> targets = cuda::get_device_targets();
partitioned_vector<int> v(size,
    host::target_distribution_policy(targets));

cuda::default_executor exec(targets);
generate(par.on(exec), v.begin(), v.end(), rand);

auto iters = minmax_element(par.on(exec), v.begin(), v.end());

std::cout << "Minimal element: " << *(iter.first);
std::cout << "Maximal element: " << *(iter.second);
```

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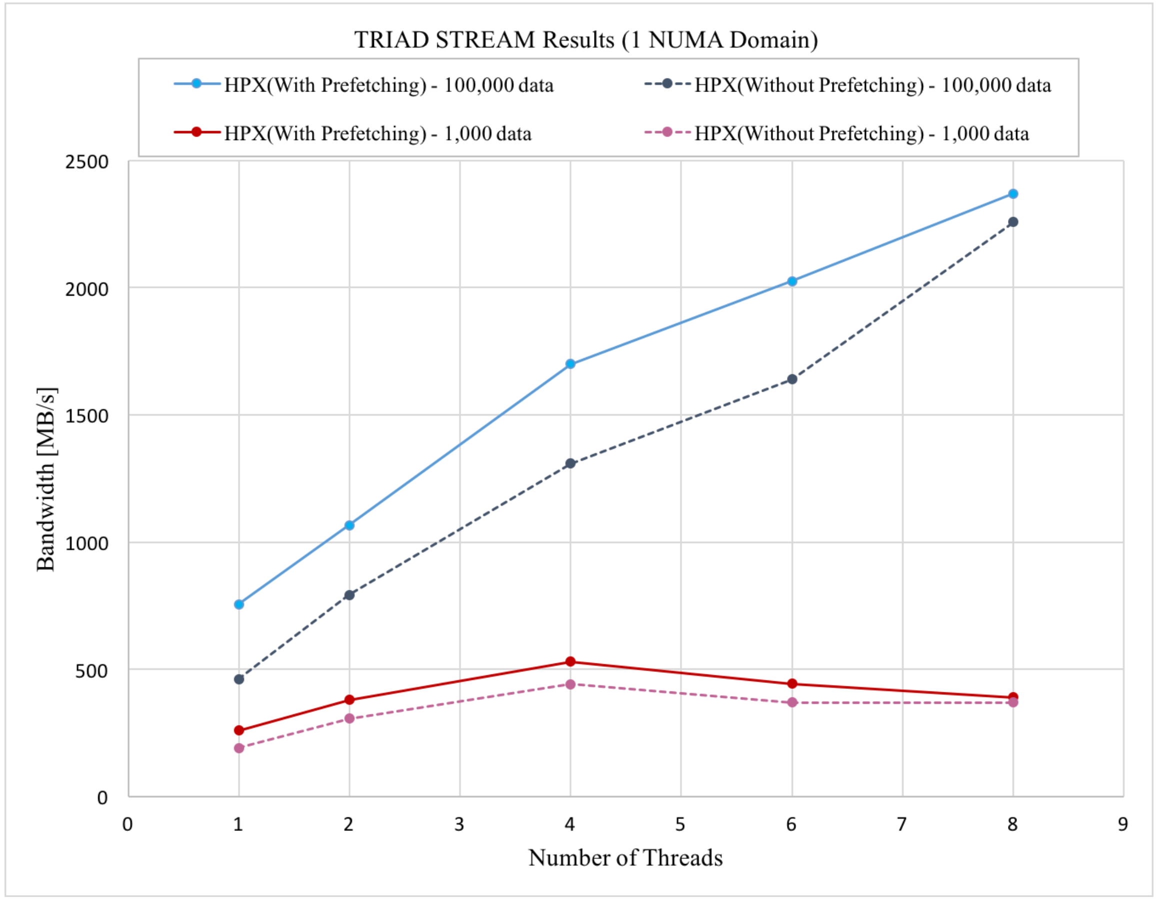
Loop Prefetching

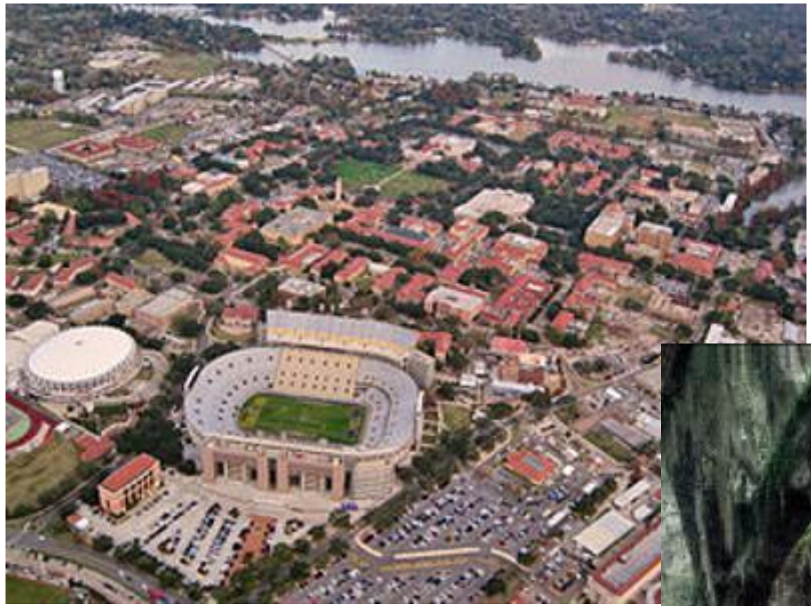
Automatic Loop Prefetching

```
std::vector<double> a, b, c;
parallel::for_loop(
    par, 0, a.size(),
    [&](int i) { a[i] = b[i] + 3.0 * c[i]; });

// add automatic prefetching for b and c
std::vector<double> a, b, c;
parallel::for_loop(
    par.with(prefetch(b, c)), 0, a.size(),
    [&](int i) { a[i] = b[i] + 3.0 * c[i]; });
```

Automatic Loop Prefetching (Results)

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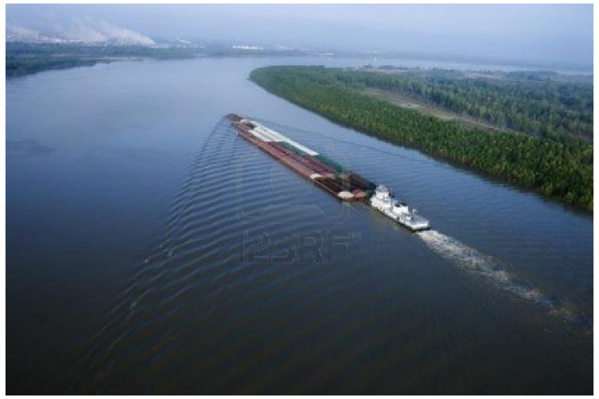

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