Parallelism in C++

Higher-level Parallelization in C++ for Asynchronous Task-Based Programming

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State of the Art

- Modern architectures impose massive challenges on programmability in the context of performance portability
  - Massive increase in on-node parallelism
  - Deep memory hierarchies
- Only portable parallelization solution for C++ programmers: OpenMP and MPI
  - Hugely successful for years
  - Widely used and supported
  - Simple use for simple use cases
  - Very portable
  - Highly optimized


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Parallelism in C++

- C++11 introduced lower level abstractions
  - std::thread, std::mutex, std::future, etc.
  - Fairly limited, more is needed
  - C++ needs stronger support for higher-level parallelism
- Several proposals to the Standardization Committee are accepted or under consideration
  - Technical Specification: Concurrency (note: misnomer)
  - Technical Specification: Parallelism
  - Other smaller proposals: resumable functions, task regions, executors
- Currently there is no overarching vision related to higher-level parallelism
  - Goal is to standardize a 'big story' by 2020
  - No need for OpenMP, OpenACC, OpenCL, etc.
  - This talk tries to show results of our take on this

Concepts of Parallelism

Parallel Execution Properties

- The *execution restrictions* applicable for the work items
  - Restrictions imposed from thread-safety perspective
  - i.e. 'can be run concurrently', or 'has to be run sequentially', etc.
- In what *sequence* the work items have to be executed
  - Sometimes we know what needs to go first
  - i.e. 'this work item depends on the availability of a result', 'no restrictions apply', etc.
- *Where* the work items should be executed
  - i.e. 'on this core', 'on that node', 'on this NUMA domain', or 'wherever this data item is located', etc.
- The *parameters* of the execution environment
  - Controlling number of items directly or through execution time which should run together on the same thread of execution
  - i.e. grain size control

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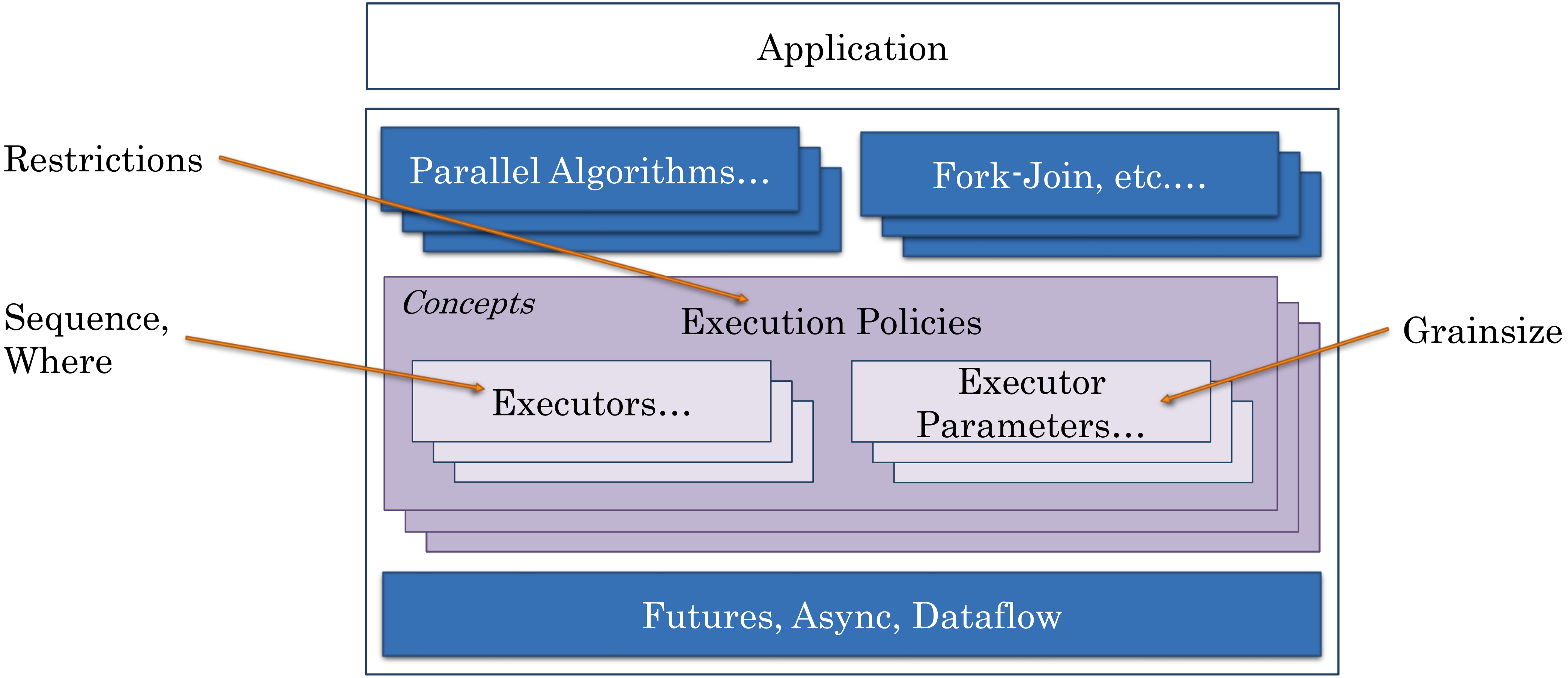
Concepts and Types of Parallelism



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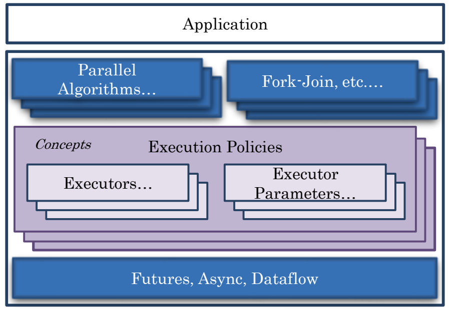
Execution Policies (std)



- Specify execution guarantees (in terms of thread-safety) for executed parallel tasks:
  - `sequential_execution_policy`: `seq`
  - `parallel_execution_policy`: `par`
  - `parallel_vector_execution_policy`: `par_vec`
  - Special rules related to exception handling
- In parallelism TS used for parallel algorithms only

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Execution Policies (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 both 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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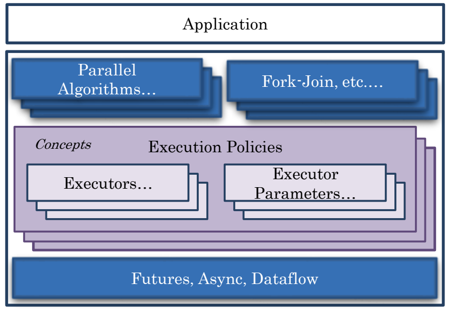
Executors



- Executor are objects responsible for
  - Creating execution agents on which work is performed (N4466)
  - In N4466 this is limited to parallel algorithms, here much broader use
- Thus they
  - Abstract the (potentially platform-specific) mechanisms for launching work
- Responsible for defining the *Where* and *How* of the execution of tasks

The simplest Executor possible

- Creating executors is trivial:

```
struct simplest_parallel_executor
{
    template <typename F>
    future<result_of_t<F()>>    // requires(is_callable<F()>)
    async_execute(F && f)
    {
        return async(std::forward<F>(f));
    }
};
```

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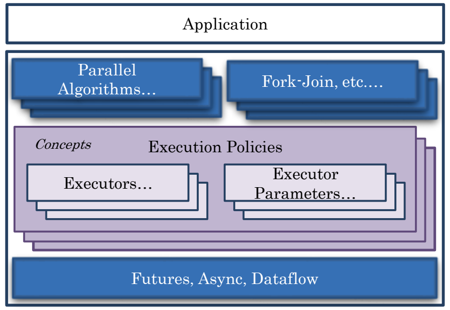
Execution Parameters



- Allows 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
  - Much more fine control

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The simplest Executor Parameters

- Creating executor parameter policies is trivial:

```
struct static_executor_parameter
{
    template <typename Executor, typename F>
    std::size_t get_chunk_size(Executor& exec, F &&, std::size_t num_tasks)
    {
        std::size_t const cores = num_processing_units(exec);

        return (num_tasks + cores – 1) / cores;
    }
};
```

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Rebind Execution Policies

- 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:

```
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
```

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Stepping Aside

HPX – A General Purpose Runtime System for Applications of Any Scale

HPX – A General Purpose Runtime System

- Solidly based on a theoretical foundation – a well defined, new execution model (ParalleX)
- Exposes a coherent and uniform, standards-oriented API for ease of programming parallel and distributed 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 (through percolation)

HPX – A General Purpose Runtime System

- Enables writing applications which out-perform and out-scale existing ones
  - A general purpose parallel C++ runtime system for applications of any scale
    - 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

HPX – The API

- As close as possible to C++11/14 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 (N3508)
• std::cout	hpx::cout
• std::parallel::for_each, etc.	hpx::parallel::for_each (N4105, 'Parallelism TS')
• std::parallel::task_region	hpx::parallel::task_region (N4088)

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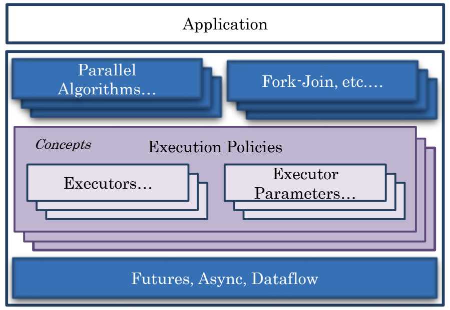
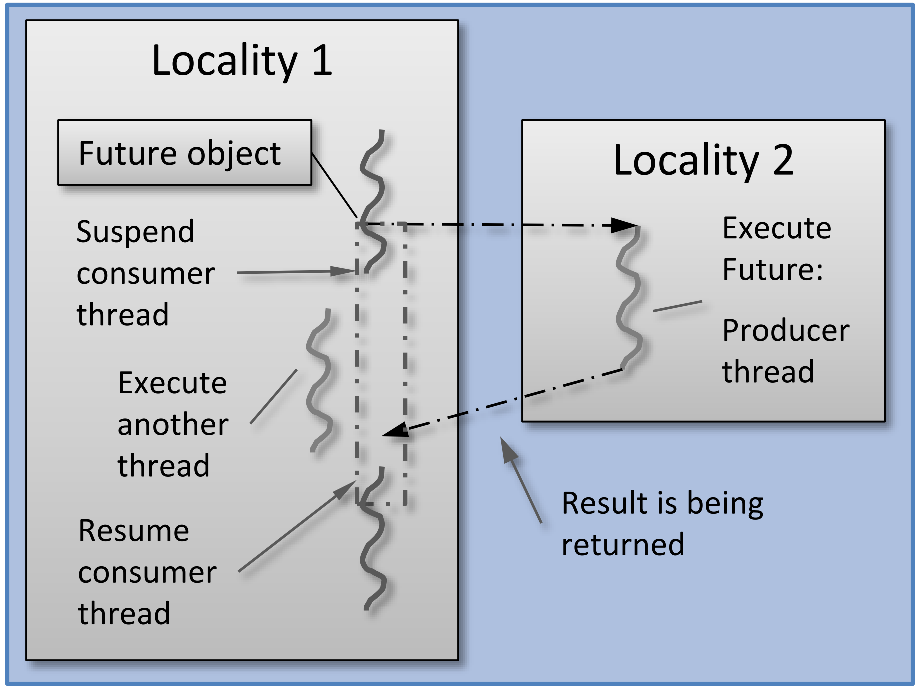


Futures, Async, Dataflow

Task-based Parallelism

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)

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, eventually
}
```

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Compositional facilities

- Sequential composition of futures

```
future<string> make_string()
{
    future<int> f1 = async([]() -> int { return 123; });

    future<string> f2 = f1.then(
        [](future<int> f) -> string
        {
            return to_string(f.get());    // here .get() won't block
        });

    return f2;
}
```

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Compositional facilities

- Parallel composition of futures

```
future<int> test_when_all()
{
    future<int> future1 = async([]() -> int { return 125; });
    future<string> future2 = async([]() -> string { return string("hi"); });

    // future<tuple<future<int>, future<string>>>
    auto all_f = when_all(future1, future2);     // also: when_any, etc.

    future<int> result = all_f.then(
        [](auto f) -> int {
            return do_work(f.get());
        });

    return result;
}
```

Dataflow – The New ‘async’ (HPX)

- What if one or more arguments to ‘`async`’ are futures themselves?
- Normal behavior: pass futures through to function
- Extended behavior: wait for futures to become ready before invoking the function:

```
template <typename F, typename... Arg>
future<result_of_t<F(Args...)>>          // requires(is_callable<F(Args…)>)
    dataflow(F && f, Arg &&... arg);
```

- If ArgN is a future, then the invocation of F will be delayed
- Non-future arguments are passed through

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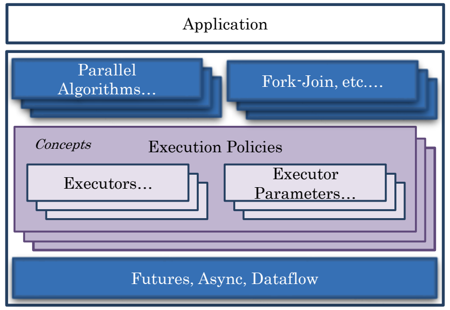

Parallel Algorithms

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		

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Parallel Algorithms

```
std::vector<int> v = { 1, 2, 3, 4, 5, 6 };
parallel::transform(
    parallel::par, begin(v), end(v),
    [](int i) -> int
    {
        return i + 1;
    });

// prints: 2,3,4,5,6,7,
for (int i : v) std::cout << i << ",";
```

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Parallel Algorithms

```
// uses default executor: 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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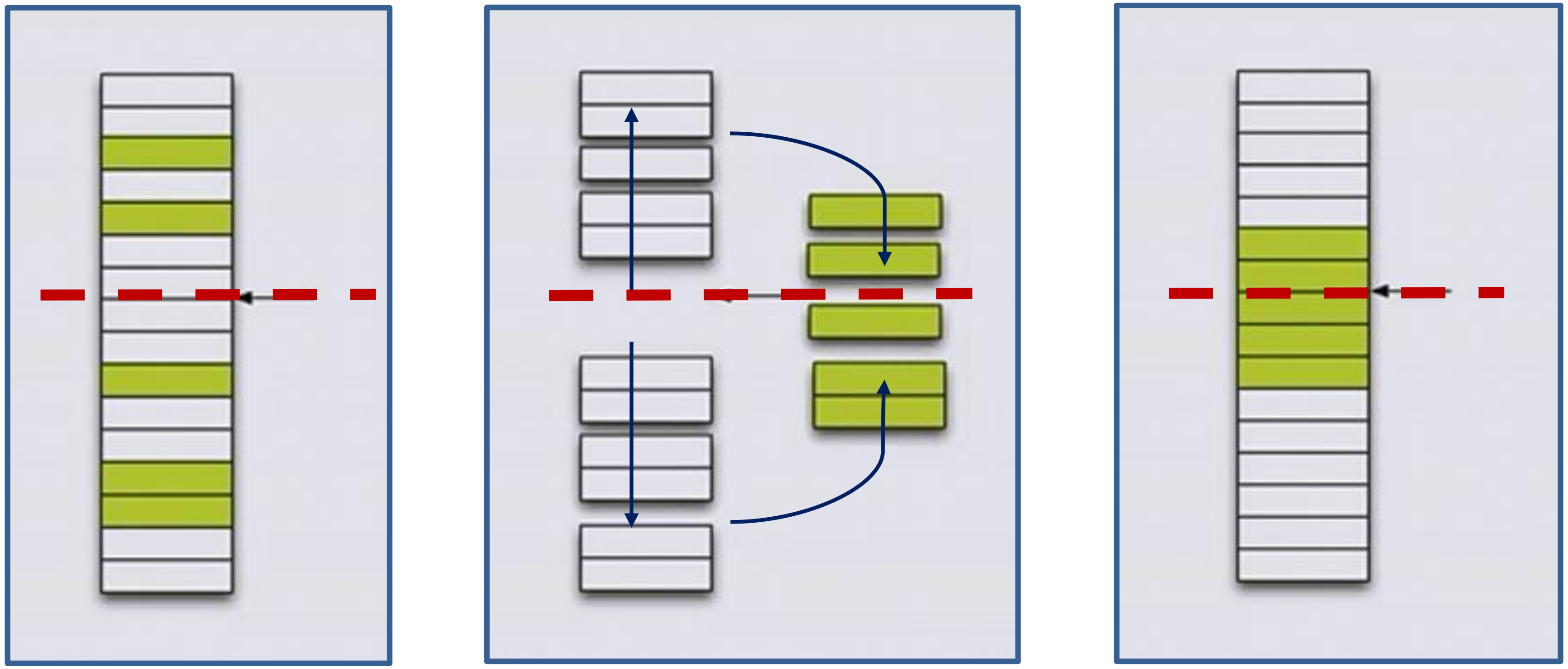
Extending Parallel Algorithms



Sean Parent: C++ Seasoning, Going Native 2013

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(await f1, await f2);
}
```

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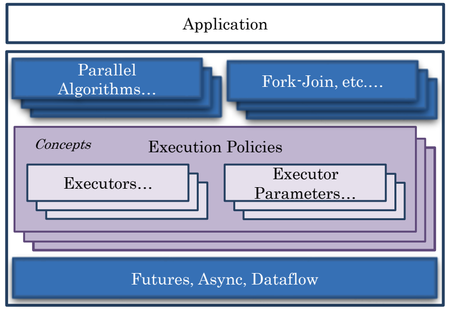

Fork-join Parallelism

Task blocks

- Canonic fork-join parallelism of independent and non-homogeneous code paths

```
template <typename Func>
int traverse(node const& n, Func compute)
{
    int left = 0, right = 0;

    define_task_block(
        policy,             // any (possibly rebound) execution policy
        [&](auto& tb)
        {
            if (n.left)  tb.run([&] { left = traverse(*n.left, compute); });
            if (n.right) tb.run([&] { right = traverse(*n.right, compute); });
        });

    return compute(n) + left + right;
}
```

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Two Examples

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)`

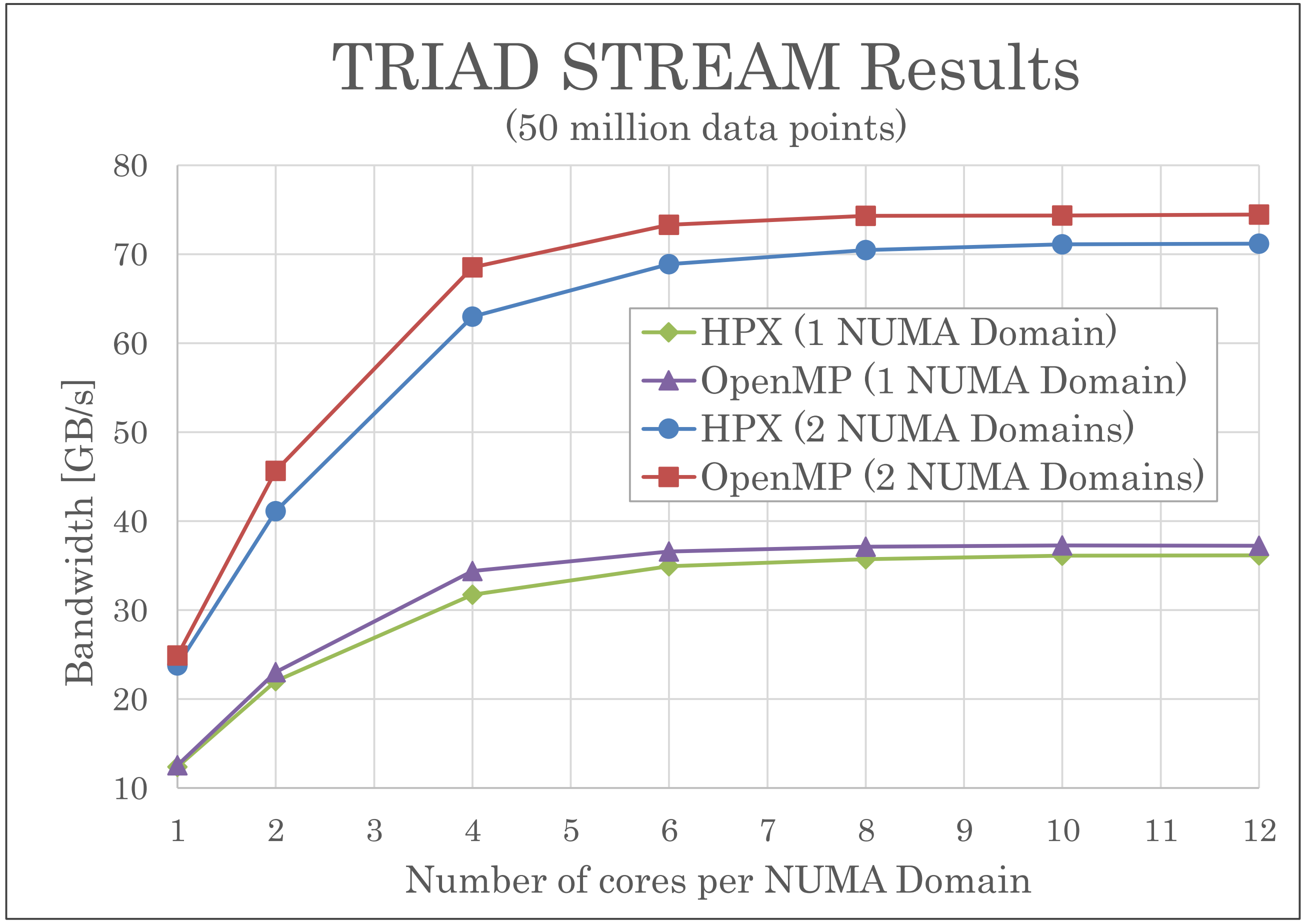
STREAM Benchmark: HPX

```
// create NUMA-aware executor, uses all cores of NUMA-domain zero
auto executor = numa_executor("numanode:0");

// create NUMA-aware allocator, uses executor for ‘first-touch’ initialization
auto allocator = numa_allocator(executor);

// create and initialize the three data arrays a, b, and c
std::vector<double, allocator> a(size, 0.0, allocator);
std::vector<double, allocator> b(size, 0.0, allocator);
std::vector<double, allocator> c(size, 0.0, allocator);
```

STREAM Benchmark: HPX

```
auto policy = par.on(executor);

parallel::copy(policy, begin(a), end(a), begin(c));

parallel::transform(policy, begin(c), end(c), begin(b),
    [k](double val) { return k * val; });

parallel::transform(policy, begin(a), end(a), begin(b), end(b), begin(c),
    [](double val1, double val2) { return val1 + val2; });

parallel::transform(policy, begin(b), end(b), begin(c), end(c), begin(a),
    [k](double val1, double val2) { return val1 + k * val2; });
```

STREAM Benchmark: HPX vs. OpenMP



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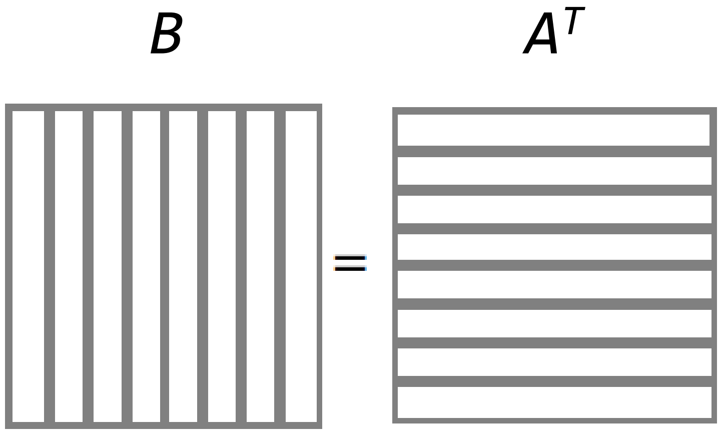
Matrix Transposition

An extended Example

Matrix Transposition

$B = A^T \Rightarrow$



Matrix Transposition

```
void transpose(std::vector<double>& A, std::vector<double>& B)
{
    #pragma omp parallel for
    for (std::size_t i = 0; i != order; ++i)
        for (std::size_t j = 0; j != order; ++j)
            B[i + order * j] = A[j + order * i];
}

int main()
{
    std::vector<double> A(order * order);
    std::vector<double> B(order * order);

    transpose(A, B);
}
```

Matrix Transposition

```
// parallel for
std::vector<double> A(order * order);
std::vector<double> B(order * order);
auto range = irange(0, order);
for_each(par, begin(range), end(range),
    [&](std::size_t i)
    {
        for (std::size_t j = 0; j != order; ++j)
        {
            B[i + order * j] = A[j + order * i];
        }
    });
```

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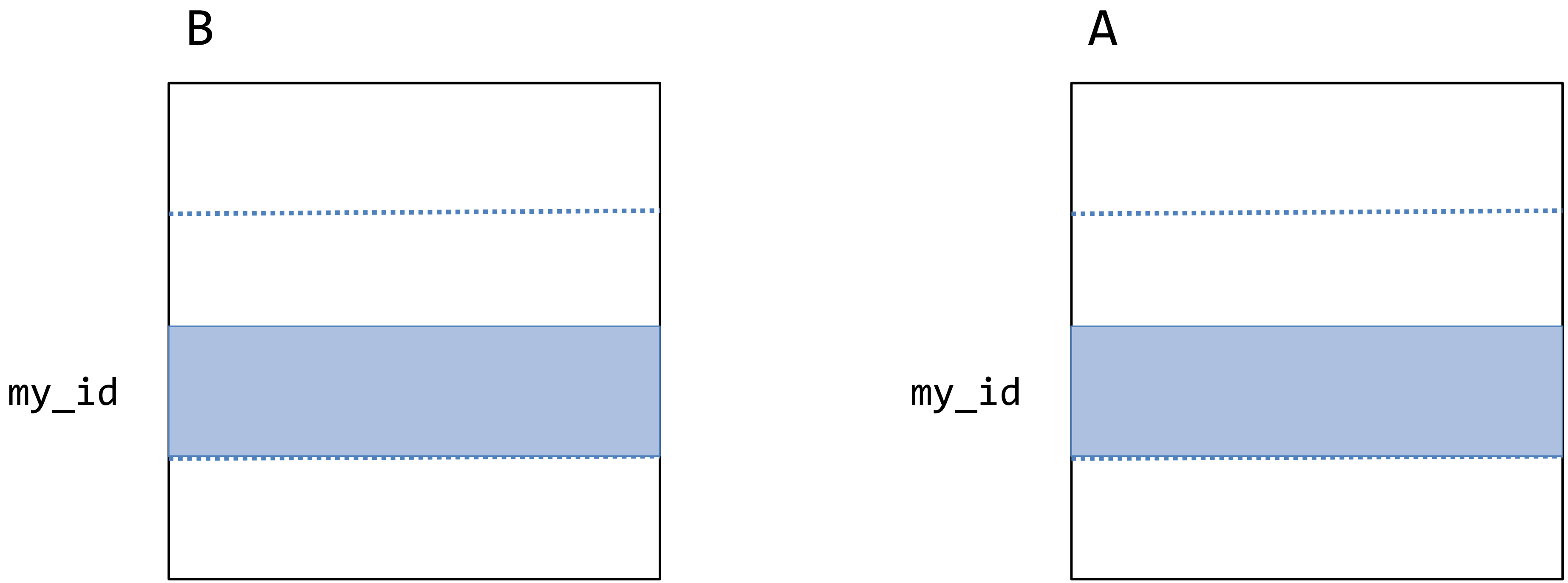
Matrix Transposition (distributed)



Matrix Transposition (distributed)

```
std::size_t my_id = hpx::get_locality_id();
std::size_t num_blocks = hpx::get_num_localities();
std::size_t block_order = order / num_blocks;

std::vector<block> A(num_blocks);
std::vector<block> B(num_blocks);
```

Matrix Transposition (distributed)

```
for (std::size_t b = 0; b != num_blocks; ++b) {
    if (b == my_id) {
        A[b] = block(block_order * order);
        B[b] = block(block_order * order);
        hpx::register_with_basename("A", A[b], b);
        hpx::register_with_basename("B", B[b], b);
    }
    else {
        A[b] = hpx::find_from_basename("A", b);
        B[b] = hpx::find_from_basename("B", b);
    }
}
```

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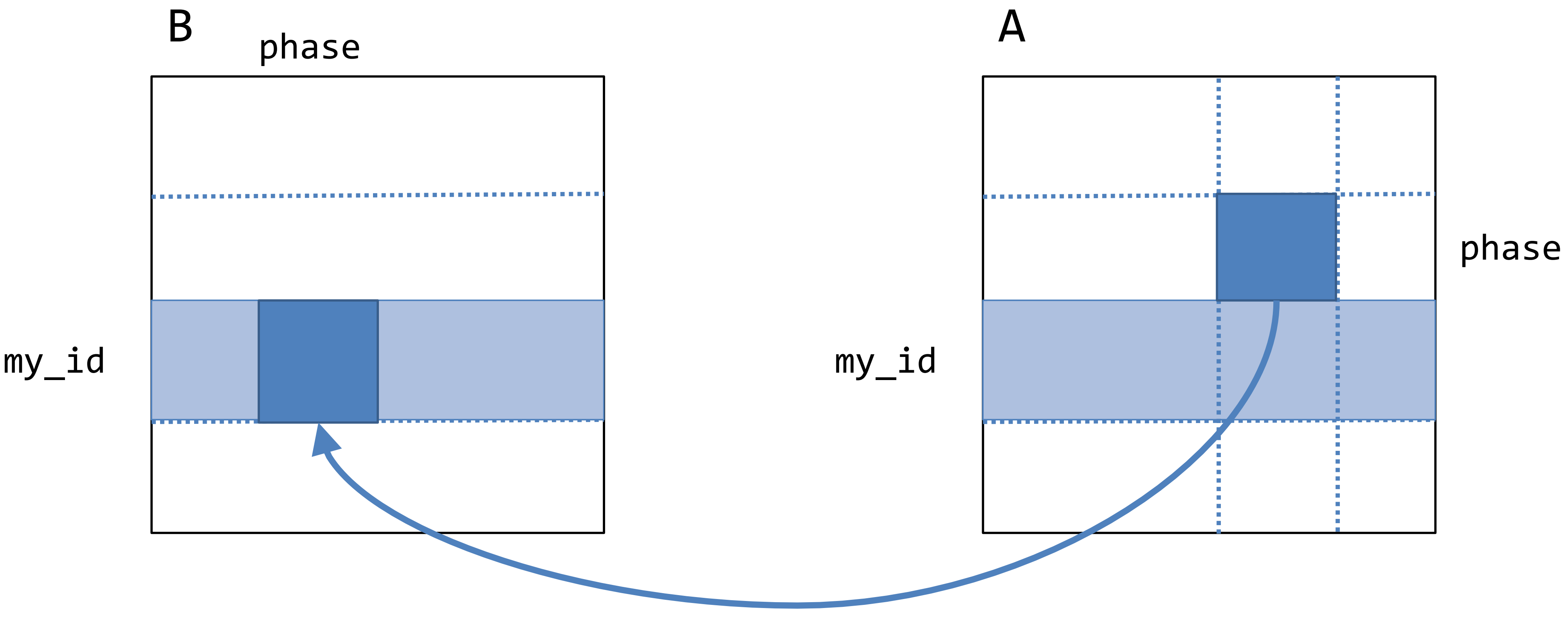
Matrix Transposition (distributed)



Matrix Transposition (distributed)

```
std::vector<future<void>> results;
auto range = irange(0, num_blocks);
for_each(seq, begin(range), end(range),
    [&](std::size_t phase)
    {
        future<block_data> f1 = A[phase].get_data(my_id, block_size);
        future<block_data> f2 = B[my_id].get_data(phase, block_size);
        results.push_back(hpx::dataflow(unwrapped(transpose), f1, f2));
    });
wait_all(results);
```

Matrix Transposition (await)

```
auto range = irange(0, num_blocks);
for_each(par, begin(range), end(range),
    [&](std::size_t phase)
    {
        future<block_data> f1 = A[phase].get_data(my_id, block_order);
        future<block_data> f2 = B[my_id].get_data(phase, block_order);
        transpose(await f1, await f2);
    });
```

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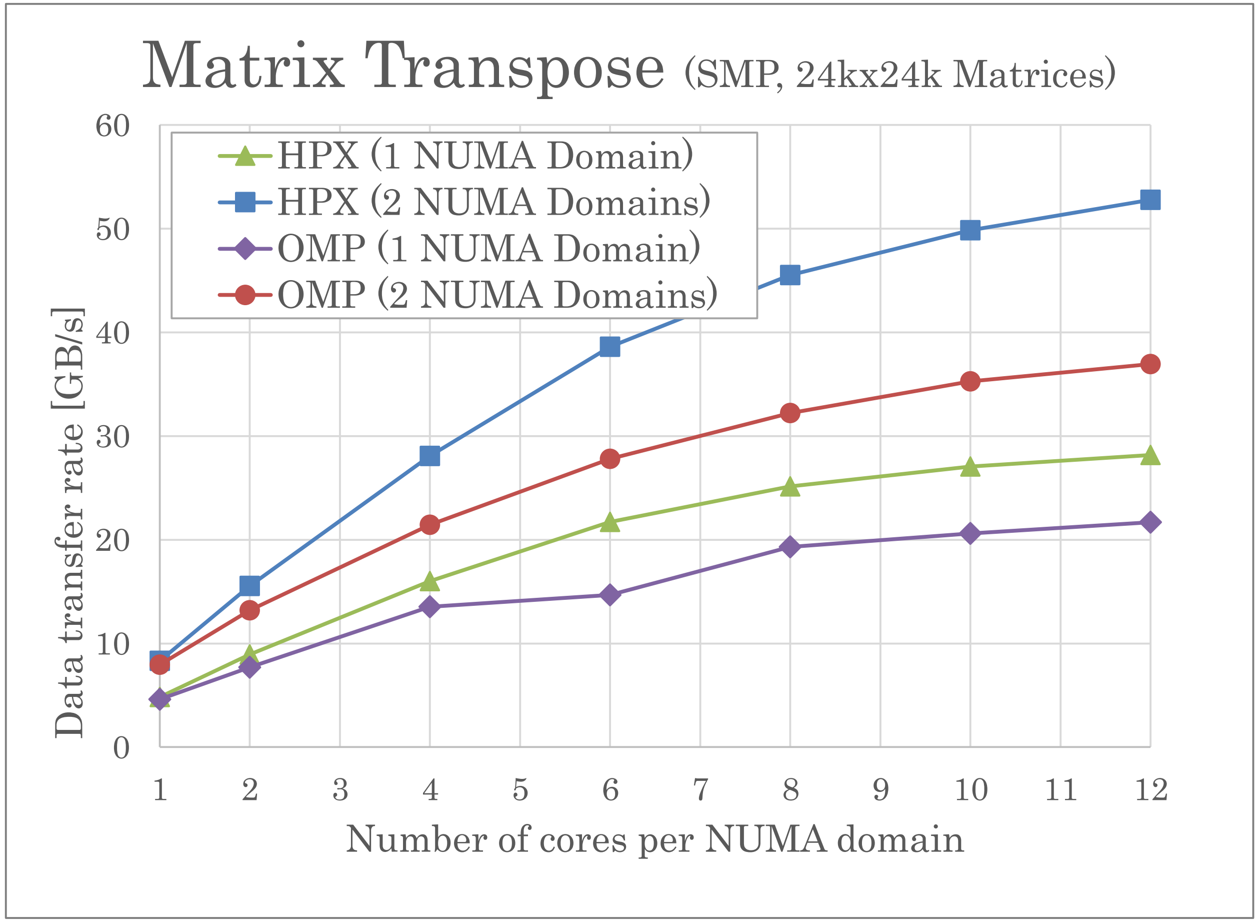
Matrix Transpose: HPX vs. OpenMP



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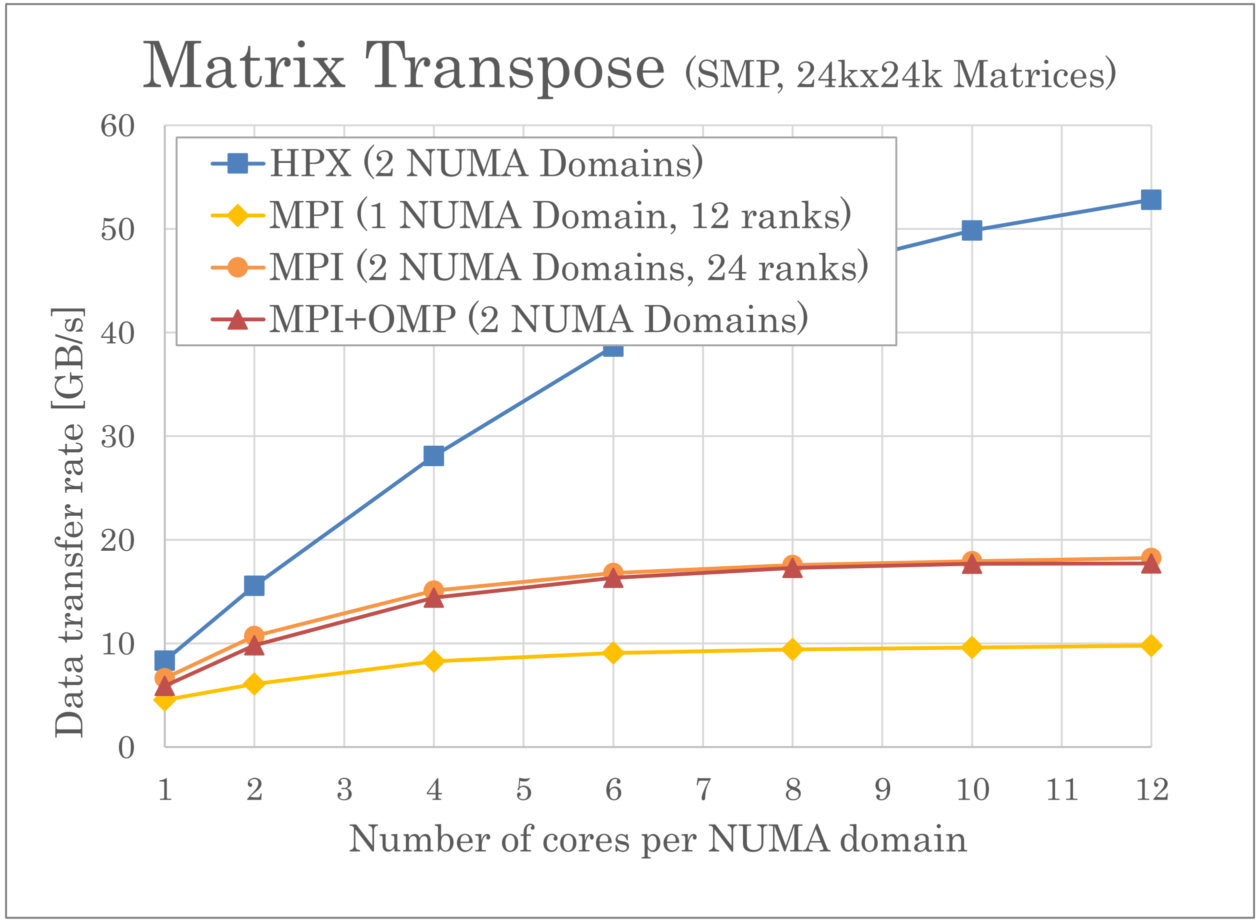
Matrix Transpose: HPX vs. MPI (SMP)



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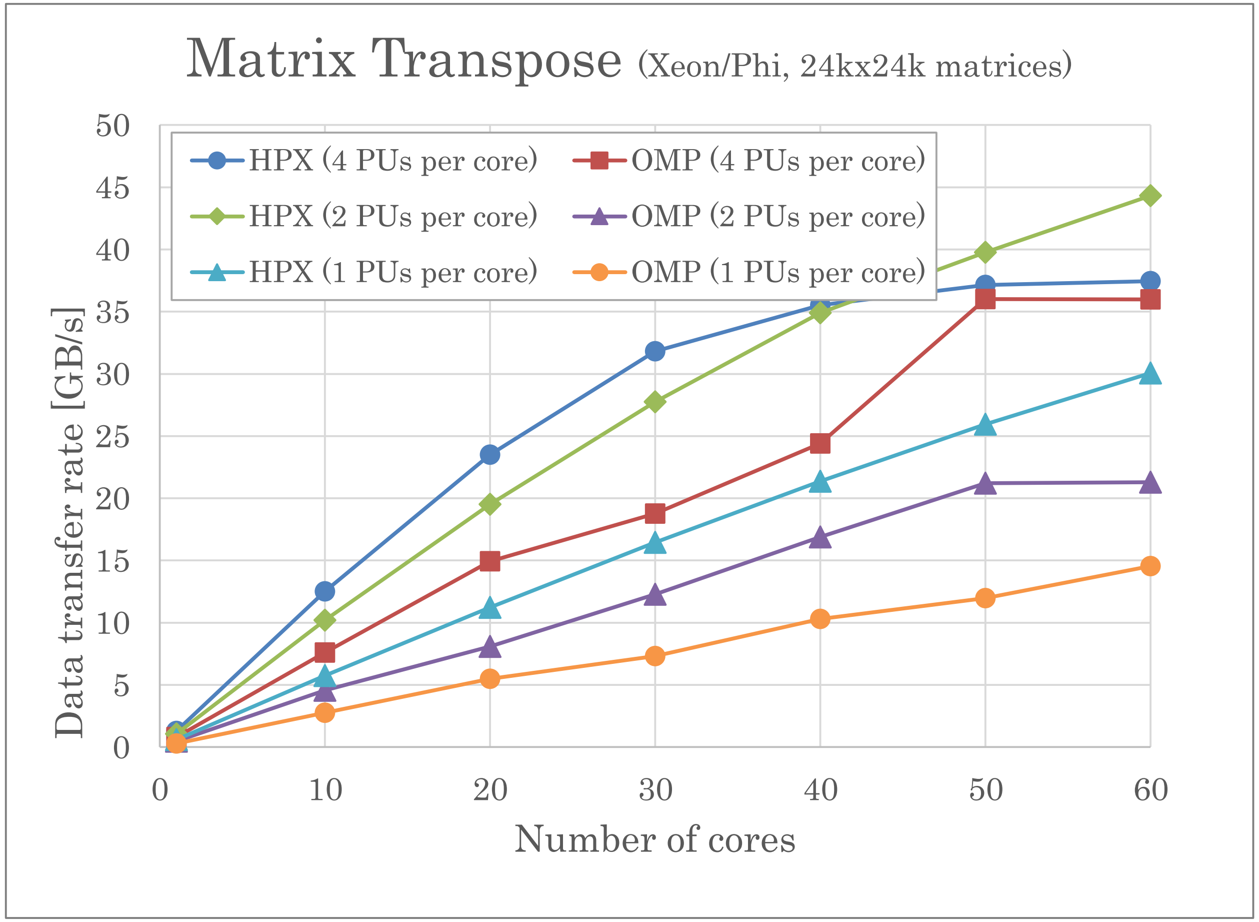
Matrix Transpose: HPX vs. OpenMP (Xeon Phi)



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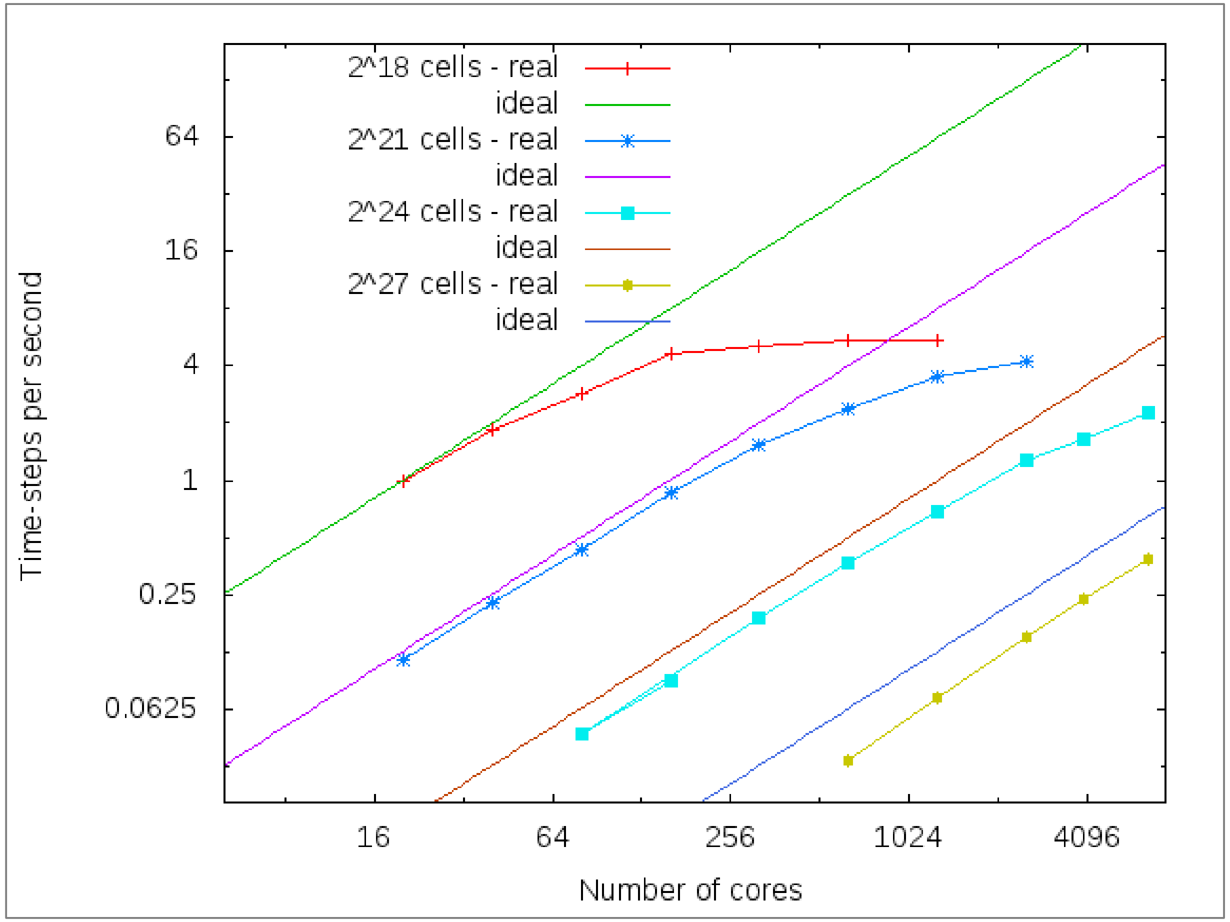
Real Application: Astrophysics, Hydrodynamics coupled with Gravity



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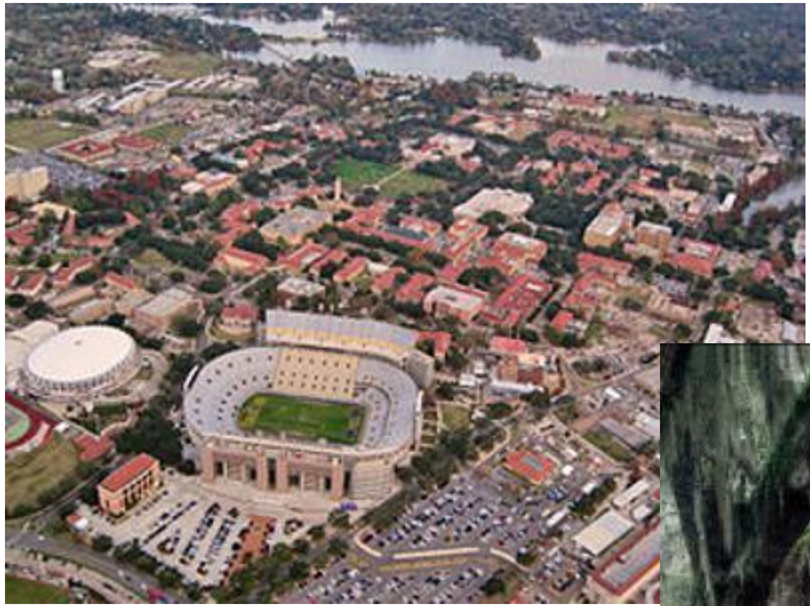
Conclusions

- Higher-level parallelization abstractions in C++:
  - uniform, versatile, and generic
- Not only possible, but necessary
  - Fork-join/loop-based parallelism: matching performance
  - New algorithms are not easily implementable using existing abstractions
- HPX code was identical for all benchmarks
- All of this is enabled by use of modern C++ facilities
  - On top of versatile runtime system (fine-grain, task-based schedulers)
- Shows great promise for distributed use cases
  - Parallel abstractions are not the cause for performance degradation
  - Insufficient quality of networking layer



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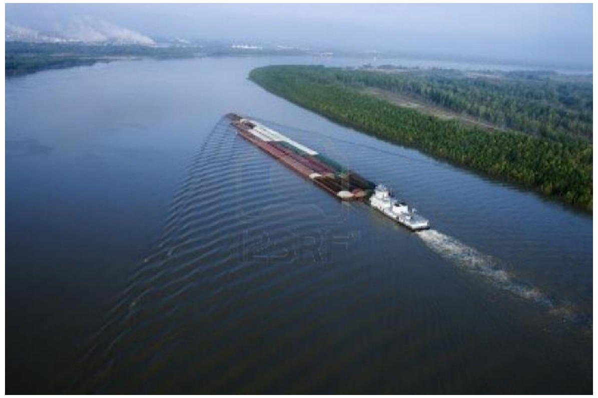

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