Parallelizing the C++ Standard Template Library

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About Grant Mercer

- Third year student at UNLV, computer science major
- Recent work with the STE||AR research group
- Primarily worked on C++ Standards Proposal N4505 inside of HPX
- N4505 is a technical specification for extensions for parallelism

About Daniel Bourgeois

- Fourth year student at LSU, mathematics major
- Currently works with the STE||AR Research group
- Primarily worked on C++ Standards proposals N4505 and N4406 inside of HPX

Background Information

- STE||AR is about shaping a scalable future with a new approach to parallel computation

- Most notable ongoing project by STE||AR is HPX: A general purpose C++ runtime system for parallel and distributed applications of any scale

HPX

- HPX enables programmers to write fully asynchronous code using hundreds of millions of threads

- First open source implementation of the ParallelX execution model
    - Starvation
    - Latencies
    - Overhead
    - Waiting

Focus Points

- Reasons we should parallelize the STL
- Features these algorithms should offer
- Our experience at HPX
- Benchmarking
- Future work

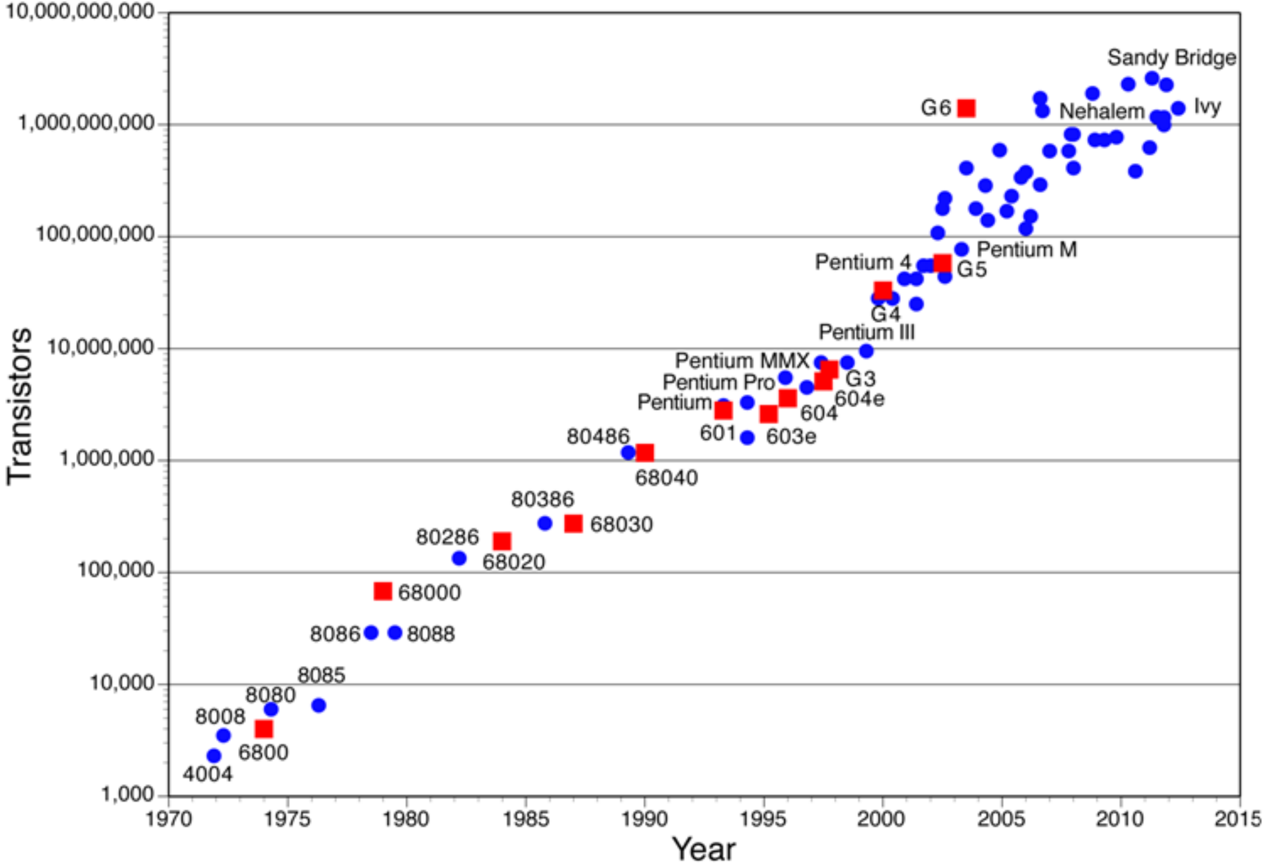
So Why Parallelize the STL?

- Multiple cores are here to stay, parallel programming is becoming more and more important.
  - Amping up processor speed only gives so much. Memory lag, RC delay and Power are all reasons why increasing the processor speed is not the answer

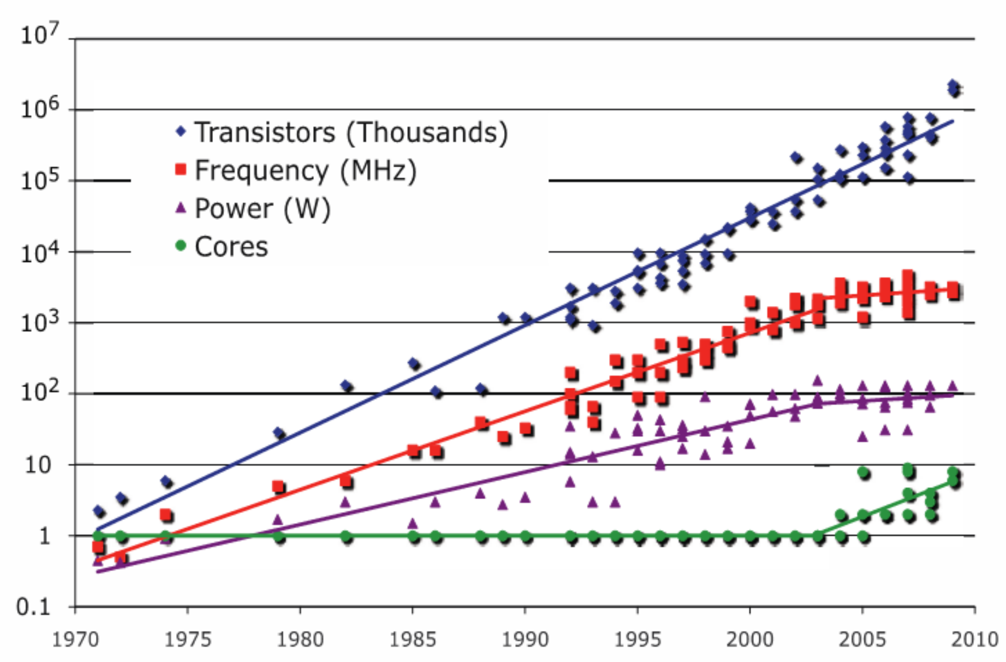
- Scalable performance gains, user flexibility

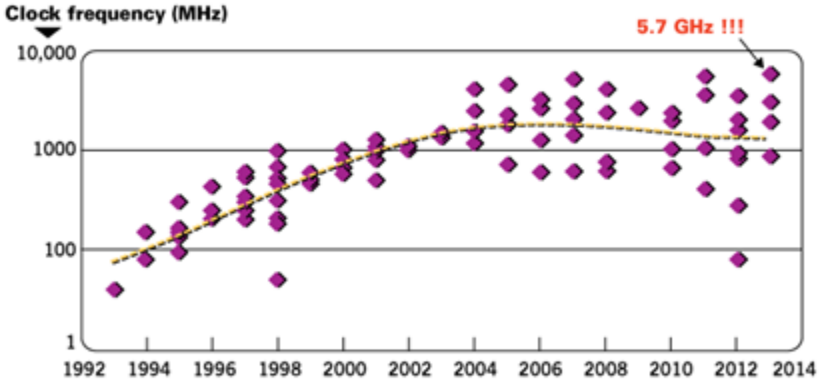
- Build widespread existing practice for parallelism in the C++ standard algorithms library

Moores law will eventually slow down



Parallelism is growing!





Standards Proposal N4505

- A technical specification for C++ extensions for parallelism, or implementation details for a parallel STL
- Not all algorithms can be parallelized (e.g. std::accumulate), so N4505 defines a list of algorithms to be reimplemented

Proposed 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
transform_exclusive_scan	transform_inclusive_scan	transform_reduce	uninitialized_copy
uninitialized_copy_n	uninitialized_fill	uninitialized_fill_n	unique
unique_copy			

Aimed for acceptance into C++17

- Implementation at HPX takes advantage of C++11
- Compenents of TS will lie in *std::parallel::experiemental::v1*. Once standardized, they are expected to be placed in *std*
- HPX implementation lies in *hpx::parallel*

- All algorithms will conform to their predecessors, no new requirements will be placed on the functions

```
template< class ForwardIt1, class ForwardIt2 >
ForwardIt1 search( ForwardIt1 first, ForwardIt1 last, ForwardIt2 s_first, ForwardIt2 s_last );

template< class ForwardIt1, class ForwardIt2, class BinaryPredicate >
ForwardIt1 search( ForwardIt1 first, ForwardIt1 last, ForwardIt2 s_first, ForwardIt2 s_last,
                   BinaryPredicate p );
```

Inside N4505: Execution Policies

- An object of an execution policy type indicates the kinds of parallelism allowed in the execution of the algorithm and express the consequent requirements on the element access functions
- Officially supports *seq, par, par_vec*

```cpp
std::vector<int> v = ...

// standard sequential sort
std::sort(v.begin(), v.end());

using namespace hpx::parallel;

// explicitly sequential sort
sort(seq, v.begin(), v.end());

// permitting parallel execution
sort(par, v.begin(), v.end());

// permitting vectorization as well
sort(par_vec, v.begin(), v.end());

// sort with dynamically-selected execution
size_t threshold = ...
execution_policy exec = seq;
if (v.size() > threshold)
{
  exec = par;
}

sort(exec, v.begin(), v.end());
```

- Par: It is the caller’s responsibility to ensure correctness
- Data races and deadlocks are the **caller’s** job to prevent, the algorithm will not do this for you
- Example of what **not** to do (data race)

```
using namespace hpx::parallel;

int a[] = {0,1};
std::vector<int> v;

for_each(par, std::begin(a), std::end(a), [&](int i) {
    v.push_back(i*2+1);
});
```

More about parallel execution policies

- Just because you type par, doesn't mean you're guaranteed parallel execution due to iterator requirements
- You are permitting the algorithm to execute in parallel, not **forcing it**
- For example, calling copy with input iterators and a *par* tag will execute **sequentially**. Input iterators cannot be parallelized!

Exception reporting behavior

- If temporary resources are required and none are available, throws *std::bad_alloc*
- If the invocation of the element access function terminates with an uncaught exception for *par, seq*: all uncaught exceptions will be contained in an *exception_list*

Task execution policy for HPX

- The task policy was added by us at HPX to give users a choice of when to join threads back into the main program. Returns and *hpx::future* of the result

```
// permitting parallel exeuction
auto f =
    sort(par(task), v.begin(), v.end());
...
f.wait();
```

User Interaction with the Algorithms

- Restrictions of execution
- Runtime decision making
- Where work is executed
- Size of work to be executed
- Abstractions usable for the parallel algorithms and elsewhere

```
// sort with dynamically-selected execution
size_t threshold = ...
execution_policy exec = seq;
if (v.size() > threshold)
{
    exec = par;
}
for_each(exec, v.begin(), v.end());
```

Inside N4406: Parallel Algorithms Need Executors

- Let the programmer specify where work is executed
- Attach to parallel algorithms

Extending *On* Execution Policies

- The .on syntax to attach to parallel algorithms
- Not all combinations of policies and executors should be allowed

```
// should compile, done in parallel
for_each(par.on(parallel_executor()), f, l, &F)

// should compile, but not done in parallel
for_each(par.on(sequential_executor()), f, l, &F)

// This does not make sense thus should not compile!
for_each(seq.on(parallel_executor()), f, l, &F)
```

But how, N4406? The requirements to be met…

- Execution policies should accept an executor
- An executor should advertise restrictions
- uniform API for parallel algorithms

Executor Traits for N4406

- Can be called with objects that meet the requirements of an executor
- Executor_traits provides four main function calls
  - `async_execute` - asynchronously calls a function once
  - `async_execute` - asynchronously calls a function more than once
  - `execute` - calls a function once
  - `execute` - calls a function more than once

Executor Traits for N4406: Example

```
// Some Definitions

some_executor_type exec;
some_shape_type inputs;

auto f1 = [](){ /*..compute..*/ return t_1; };
auto f2 = [](T t_a){ /*..compute..*/ return t_2; };

typedef executor_traits<some_executor_type> traits;
```

Executor Traits for N4406: Example

```
// Calls f1, returns a future containing the result of f1
future<T> myfut1 = traits::async_execute(exec, f1);

// Calls f2 for each of the inputs,
// returns a future indicating the completion of all of the calls
future<void> myfut2 = traits::async_execute(exec, f2, inputs);

// Calls f1, returns the result
T myval1 = traits::execute(exec, f1);

// Calls f2 and returns once all calls are completed
traits::execute(exec, f2, inputs);
```

HPX and N4406: Yes and Not Quite

Yes

- algorithms can be extended with the .on syntax
- executor_traits provides a convenient, uniform launch mechanism
- easy to define an object meeting executor requirements
- work can be executed in bulk quantities

HPX and N4406: Yes and Not Quite

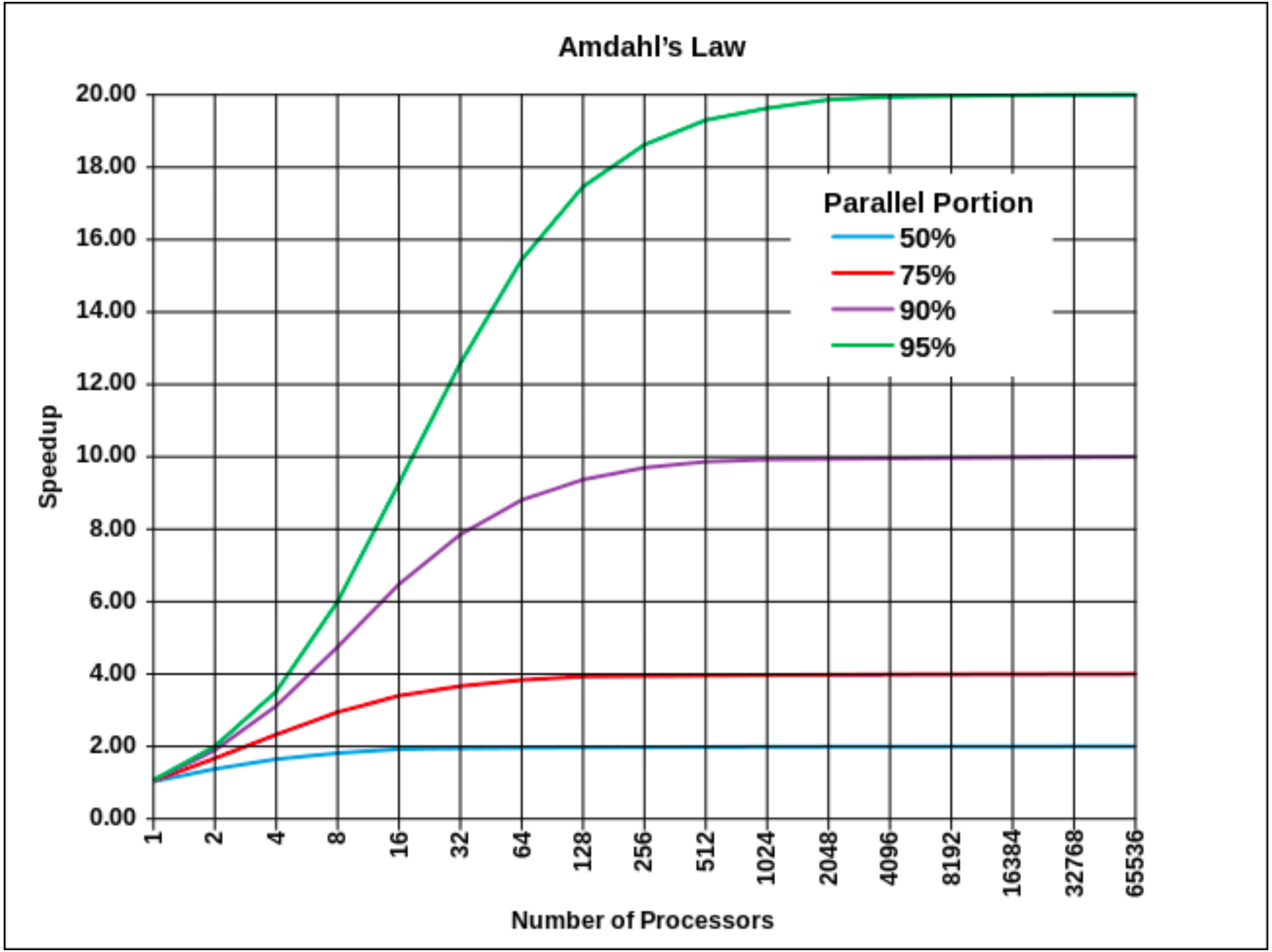
Not Quite

- Want to minimize waiting

```
future<void> myfut = N4406_traits::async_execute(exec, f2, inputs);
// Has to wait for all functions to finish before my_next_function gets called
myfut2.then(my_next_function);
```

- The HPX solution

```
std::vector<future<T> > myfuts = HPX_traits::async_execute(exec, f2, inputs);
// my_other_next_funcion can be called once each element in myfuts is ready
when_each(my_other_next_function, myfuts);
```


Amdahl's Law
Speedup
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
1
2
4
8
16
32
64
128
256
512
1024
2048
4096
8192
16384
32768
65536
Number of Processors
Parallel Portion
50%
75%
90%
95%

Executor Traits for HPX

```
template <typename Executor> // requires is_executor<Executor>
struct executor_traits
{
    using Executor = executor_type;

    using execution_category = /* category of Executor */;

    template <typename T>
    using future = /* future type of Executor or hpx::future<T> */;

    // … apply_execute, async_execute and execute implementation
};
```

Additional Traits

- executor_information_traits
  - retrieve number of processing units
  - test if pending closures exist
- timed_executor_traits
  - inherits from executor_traits
  - at and after functions

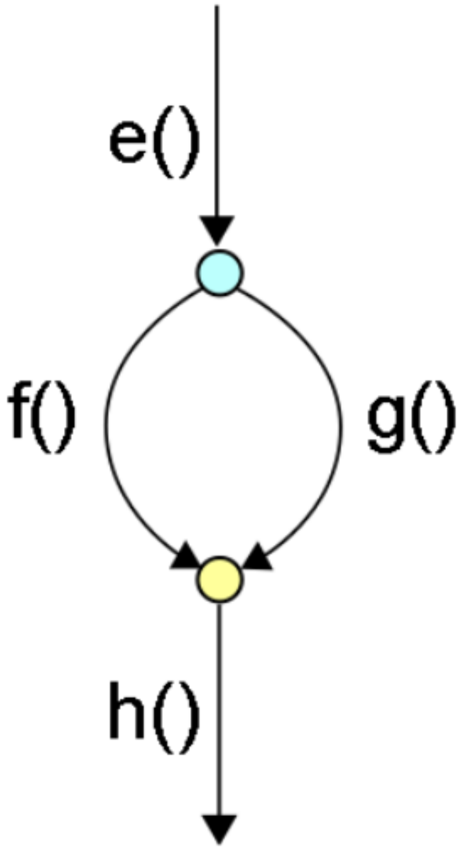
Parallel executor

```
struct parallel_executor : executor_tag
{
    explicit parallel_executor(BOOST_SCOPED_ENUM(launch) l = launch::async)
      : l_(l)
    {}

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

Sequence of Execution

- Primer on work stealing, N3872

```
e();
spawn f();
g();
sync;
h();


for(int i=0; i<n; ++i)
    spawn f(i);
sync;
```



Types of Executors in HPX

- standard executors
  - parallel, sequential
- this thread executors
  - static queue, static priority queue
- thread pool executors, and thread pool os executors
  - local queue, local priority queue
  - static queue, static priority queue
- service executors
  - io pool, parcel pool, timer pool, main pool
- distribution policy executor

Taking a Step Back

- Executors provide a mechanism for launching work
- Flexible decision making
- need a general mechanism for grain size control

Executor Parameters

- grain size control
- passing information to the partitioner
- Similar to OpenMP Dynamic, Static, Guided

Extending *with* Execution Policies

- The .with syntax to extend parallel algorithms

```
auto par_auto = par.with(auto_chunk_size()); // equivalent to par

auto par_static = par.with(static_chunk_size());

auto my_policy = par.with(my_exec).on(my_chunk_size);

auto my_task_policy = my_policy(task);
```

The Concepts for Execution Policies

Property	**C++ Concept Name**
Execution *restrictions*	`execution_policy`
Sequence of execution	`executor`
Where execution happens	`executor`
Grain size of work items	`executor_parameter`

Initial Parallel Design: Partitioning

- All algorithms given by the proposal are passed a range, which must be partitioned and executed in parallel.
- There are a couple different types of partitioners we implemented at HPX

foreach_partitioner

- The simplest of partitioners, splits a set of data into equal partitions and invokes a passed function on each subset of the data.
- Mainly used in algorithms such as *foreach*, *fill* where each element is independent and not part of any bigger picture

{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12}

{1, 2, 3, 4} | {5, 6, 7, 8} | {9, 10, 11, 12}

f([1,2,3,4]) | f([5,6,7,8]) | f([9, 10, 11, 12])

for_each_n

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

partitioner

- Similar to foreach, but the result of the invocation of the function on each subset is stored in a vector and an additional function is invoked and passed that vector.
- Useful in a majority of algorithms *copy, find, search, etc...*

{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12}

{1, 2, 3, 4} | {5, 6, 7, 8} | {9, 10, 11, 12}

v=
{f([1, 2, 3, 4] , f([5, 6, 7, 8]) , f([9, 10, 11, 12])}

g(v)

reduce

```
template <typename ExPolicy, typename FwdIter, typename T_, typename Reduce>
static typename detail::algorithm_result<ExPolicy, T>::type
parallel(ExPolicy, const& policy, FwdIter first, FwdIter last, T_ && init, Reduce && r)
{
    // check if first == last, return initial value if true

    return util::partitioner<ExPolicy, T>::call( policy,
        first, std::distance(first, last),
        [r](FwdIter part_begin, std::size_t part_size) -> T
        {
            T val = *part_begin;
            return util::accumulate_n(++part_begin, --part_size,
                std::move(val), r);
        },
        hpx::util::unwrapped([init, r](std::vector<T> && results)
        {
            return util::accumulate_n(boost::begin(results),
                boost::size(results), init, r);
        }));
}
```

parallel vector dot product

- No intermediate function, forces us to use a tuple instead of a simple double
- Reduce requirements can not be worked around, a new function is needed

```
int xvalues[] = //...
int yvalues[] = //...

double result =
    std::accumulate(
        make_zip_iterator(std::begin(xvalues), std::being(yvalues)),
        make_zip_iteartor(std::end(xvalues), std::end(yvalues)),
        0.0,
        [](double result, reference it) {
            return result + get<0>(it) + get<1>(it)
        });
```

parallel vector dot product

```
tuple<double, double> result =
hpx::parallel::reduce(hpx::parallel::par,
    make_zip_iterator(boost::begin(xvalues), boost::begin(yvalues)),
    make_zip_iterator(boost::end(xvalues), boost::end(yvalues)),
    hpx::util::make_tuple(0.0, 0.0),
    [](tuple<double, double> res, reference it) {
        return hpx::util::make_tuple(
            get<0>(res) + get<0>(it) * get<1>(it),
            1.0);
    });
```

- N4505 is the newest revision to include *transform_reduce*, as proposed by N4167
- Without *transform_reduce* the solution is horribly hacky

transform_reduce

```
template <typename ExPolicy, typename FwdIter, typename T_, typename Reduce, //…
static typename detail::algorithm_result<ExPolicy, T>::type
parallel(ExPolicy const& policy, FwdIter first, FwdIter last, T_ && init, Reduce && r, Convert && conv)
{
    typedef typename std::iterator_traits<FwdIter>::reference reference;
    return util::partitioner<ExPolicy, T>::call(policy, first,
        std::distance(first, last),
        [r, conv](FwdIter part_begin, std::size_t part_size) -> T
        {
            T val = conv(*part_begin);
            return util::accumulate(++part_begin, --partsize, std::move(val),
            [&r, &conv](T const& res, reference next)
            {
                return r(res, conv(next));
            });
        },
        hpx::util::unwrapped([init, r](std::vector<T> && results)
        {
            return util::accumulate_n(boost::begin(results),
                boost::size(results) init, r);
        }));
}
```

simplified dot product

```
int hpx_main()
{
    std::vector<double> xvalues(10007);
    std::vector<double> yvalues(10007);

    using ...;

    double result =
        hpx::parallel::transform_reduce(hpx::parallel::par,
            make_zip_iterator(boost::begin(xvalues), boost::begin(yvalues)),
            make_zip_iterator(boost::end(xvalues), boost::end(yvalues)),
            0.0,
            std::plus<double>(),
            [](tuple<double, double> r)
            {
                return get<0>(r) * get<1>(r);
            }
        );

    hpx::cout << result << hpx::endl;
    return hpx::finalize();
}
```

scan_partitioner

- The scan partitioner has 3 stepts
  - Partition the data and invoke the first function
  - Invoke a second function as soon as the **current** and **left** partition are ready
  - Invoke a third function on the resultant vector of step 2
- Specific cases such as *copy_if, inclusive/excusive_s*can

{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12}

{1, 2, 3, 4} | {5, 6, 7, 8} | {9, 10, 11, 12}

v_0 = {f[1,2,3,4}] , v_1 = {f[5,6,7,8]} , f[9,10,11,12]}

r = { g(v_0) , g(v_1) }

h(r)

copy_if

```
int lst[] = {1, 1, 1, 1, 2, 2, 1, 1, 2, 1, 2, 2, 1};

int res[8];

hpx::parallel::copy_if(par, boost::begin(lst), boost::end(lst), boost::begin(res),
    [](int i){ return i == 1; });
```

```
1 1 1 1 2 2 1 1 2 1 2 2 1
1 1 1 1     1 1   1     1
```

- Not just as simple as copying what returns true, the resultant arrays need's to be *squashed*

copy_if

```
typedef util::scan_partitioner(ExPolicy, Iter, std::size_t> scan_partitioner _type;
return scan_partitioner_type::call(
    policy, hpx::util::make_zip_iterator(first, flags.get()),
    count, init,
    [f](zip_iterator part_begin, std::size_t part_size) -> std::size_t
    {
        // flag any elements to be copied
    },
    hpx::until::unwrapped( [](std::size_t const& prev, std::size_t const& curr)
    {
        // determine distance to advance dest iter for each partition
        return prev + curr;
    }),
    [=](std::vector<hpx::shared_future<std::size_t> > && r,
    std::vector<std::size_t> const& chunk_sizes) mutable -> result_type
    {
        // copy element to dest in paralle;
    }
);
```

Designing Parallel Algorithms

- Some algorithms are easy to implement, other … not so much
- Start simple, work up the grape vine towards more difficult algorithms
- Concepts from simple algorithms can be brought into more difficult and complex solutions

fill_n

- fill_n can be implemented is two lines using for_each_n

```
template <typename ExPolicy, typename T>
static typename detail::algorithm_result<ExPolicy, OutIter>::type
parallel(ExPolicy const& policy, OutIter first, std::size_t count, T const& val)
{
    typedef typename std::iterator_traits<OutIter>::value_type type;

    return
        for_each_n<OutIter>().call(
            policy, boost::mpl::false_(), first, count,
            [val](type& v) {
                v = val;
            });
}
```

Completed algorithms as of today

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~~
transform_exclusive_scan	transform_inclusive_scan	~~transform_reduce~~	~~uninitialized_copy~~
~~uninitialized_copy_n~~	~~uninitialized_fill~~	~~uninitialized_fill_n~~	unique
unique_copy			

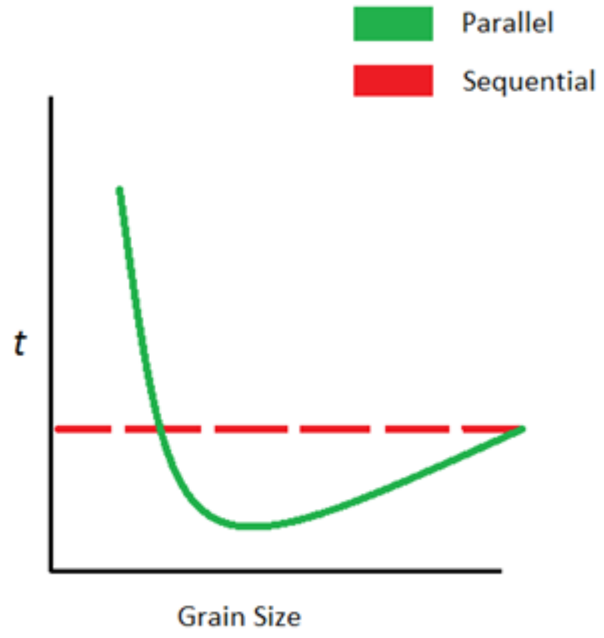
```cpp
void measure_parallel_foreach(std::size_t size)
{
   std::vector<std::size_t> data_representation(size);
   std::iota(boost::begin(data_representation),
       boost::end(data_representation),
       std::rand());

   // create executor parameters object
   hpx::parallel::static_chunk_size cs(chunk_size);

   // invoke parallel for_each
   hpx::parallel::for_each(hpx::parallel::par.with(cs),
       boost::begin(data_representation),
       boost::end(data_representation),
       [](std::size_t) {
           worker_timed(delay);
       });
}
boost::uint64_t average_out_parallel(std::size_t vector_size)
{
   boost::uint64_t start = hpx::util::high_resolution_clock::now();

   // average out 100 executions to avoid varying results
   for(auto i = 0; i < test_count; i++)
       measure_parallel_foreach(vector_size);

   return (hpx::util::high_resolution_clock::now() - start) / test_count;
}
```

Benchmarking

- Comparing *seq, par, task* execution policies
- Task is special in that executions can be written to **overlap**
- User can wait to join execution after multiple have been sent off

Getting the most out of performance

- The big question is whether these functions actually offer a gain in performance when used.
- Grain size: amount of work executed per thread.
- In order to test this we look to simulate the typical *strong scaling* graph:

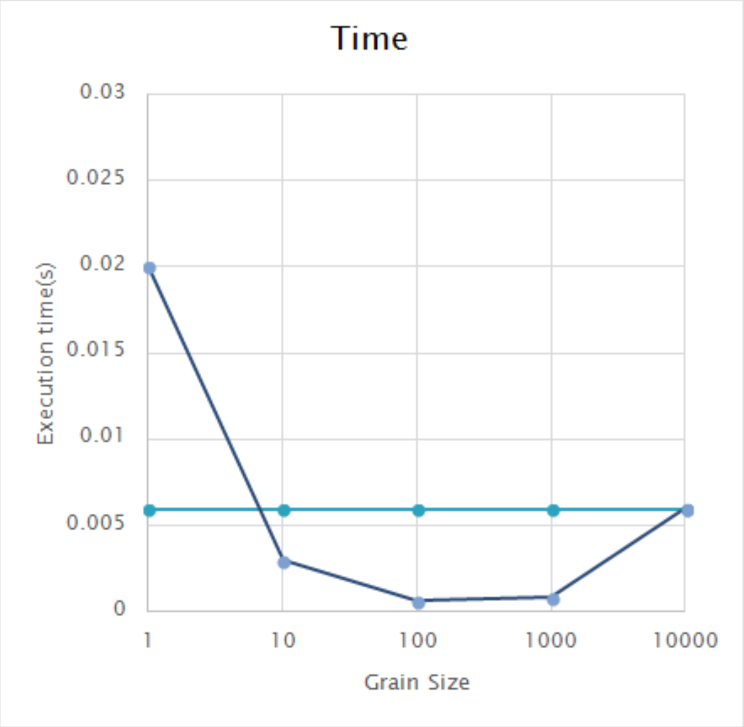


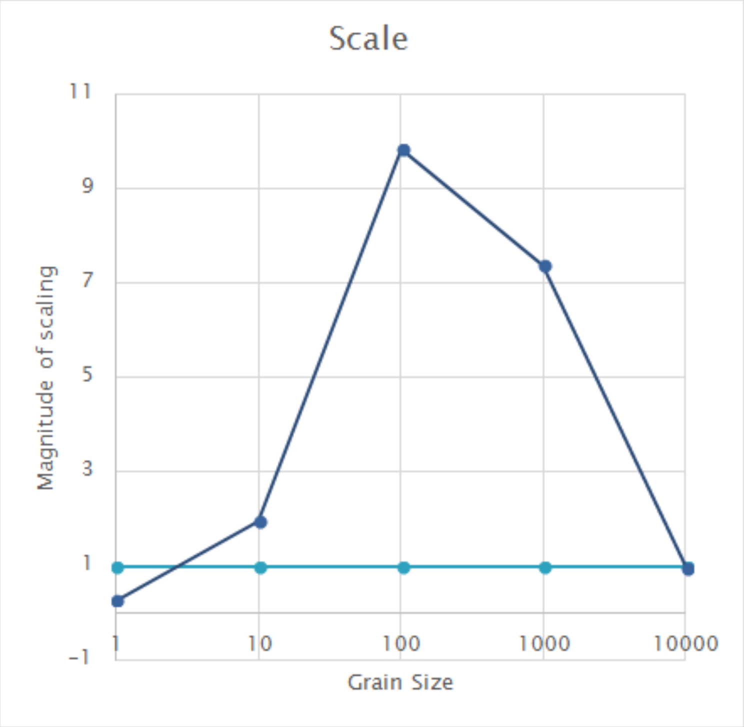
Hardware Used

Classification	Name	Wedge	Deneb	Tycho	Trillian	Lyra	Sheliak	Ariel	Marvin	Beowulf
	Role	Head + I/O	Development	GPGPU development	Fat compute	GPGPU/Fat compute	Fat compute	Fast compute	Thin compute	Thin compute
# of Nodes		1	1	1	2	2	2	2	16	16
System	OEM	Dell	HP	Supermicro	Dell	HP	Sun	Dell	Dell	HP
	Model	PowerEdge R720xd 12G	z800	X8DTG-D	PowerEdge R815 11G	ProLiant DL785 G6	Sun Fire X4600 M2	PowerEdge R620 12G	PowerEdge M520 12G	ProLiant DL120 G6
CPU(s)	IDM	Intel	Intel	Intel	AMD	AMD	AMD	Intel	Intel	Intel
	Model	Xeon E5-2670	Xeon E5649	Xeon E5620	Opteron 6272	Opteron 8431	Opteron 8384	Xeon E5-2690	Xeon E5-2450	Xeon X3430
	Frequency [GHz]	2.6	2.5	2.4	2.1	2.4	2.7	2.9	2.1	2.4
	# of CPUs	2	2	2	4	8	8	2	2	1
	# of Cores	16	12	8	64	48	32	16	16	4
Main Memory	Type	Registered	Unregistered	???	Registered	Registered	???	Unregistered	Registered	Registered
	Form Factor	DDR3	DDR3	DDR3	DDR3	DDR2	DDR2	DDR3	DDR3	DDR3
	Speed [MT/s]	1600	1333	1333	1333	533	333	1333	1333	1333
	# DIMMs	16	8	6	32	48		8	6	4
	RAM [GB]	128	32	24	128	96	64	32	48	12
Storage	Controller	Dell PERC H710	LSI SAS1068E	Intel 82801JI ICH	Dell PERC H200	HP Smart Array P400i	???	Dell PERC H310	Dell PERC S110	Intel BD3400 PCH
	Bus	???	???	???	???	SAS1/SATA1	???	???	???	SATA-2
	Frequency [RPM]	10000	7200	7200	7200	10000	???	7200	7200	7200
	# of Disk Drives	5	1	1	1	1	???	1	1	1
	Storage [TB]	3	1.5	0.32	1	0.3	???	1	1	0.25
Network	# of GigE ports	4	2	2	4	2	4	4	2	2
	# of QDR IB ports	1	0	0	1	1	0	1	1	0
Max Load [W]		750	???	???	1100	???	???	750	N/A	???
Out-of-band management		iDRAC7 Express	N/A	???	iDRAC6 Express	???	???	iDRAC7 Express	iDRAC7 Express	N/A

Sequential vs. Parallel

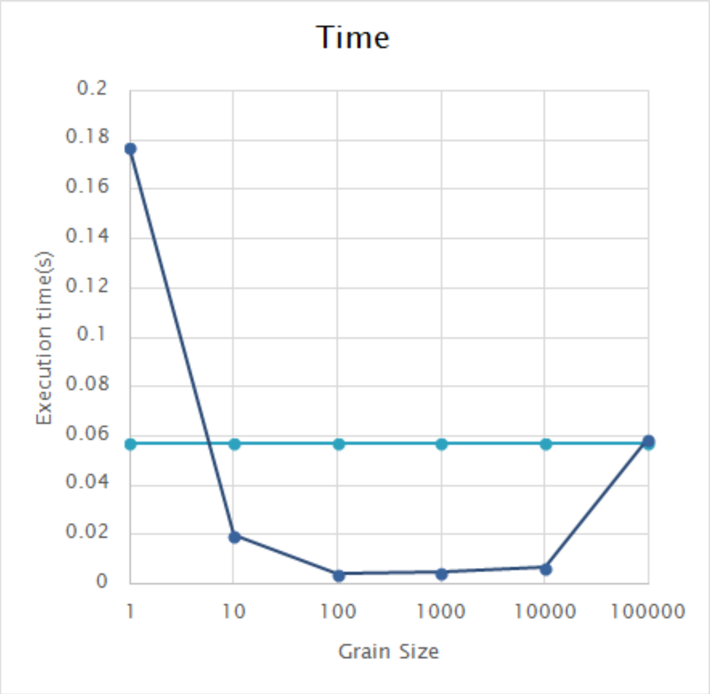
- 500 nanosecond delay per iteration
- Vector size of 10,000

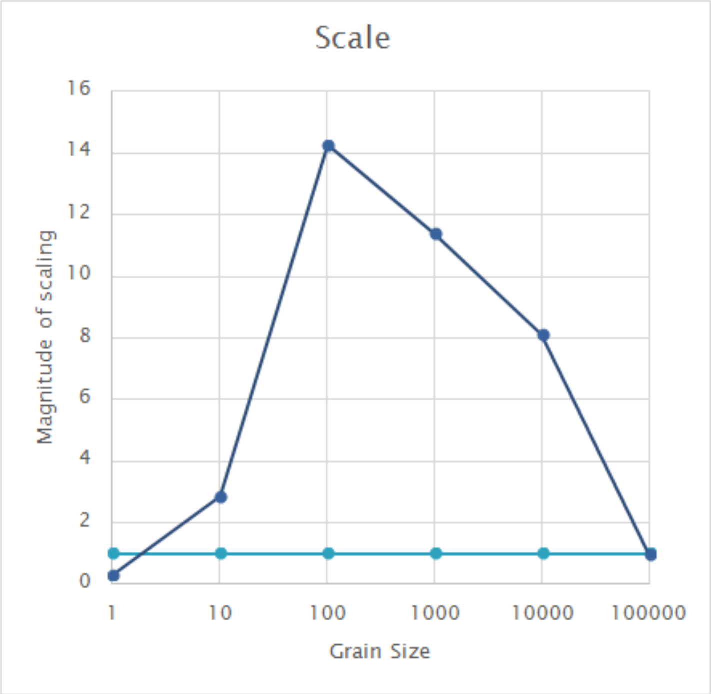




Sequential vs. Parallel

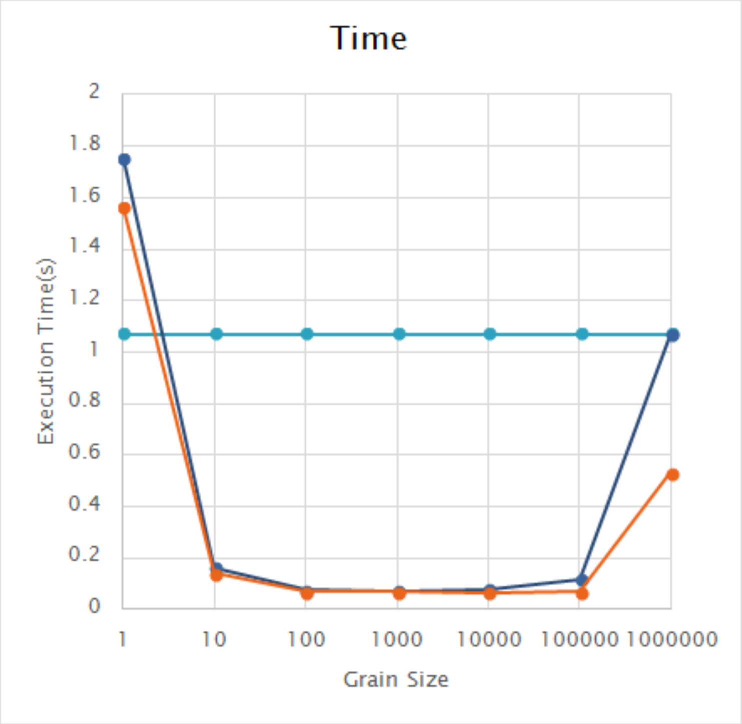
- 1000 nanosecond delay per iteration
- Vector size of 100,000

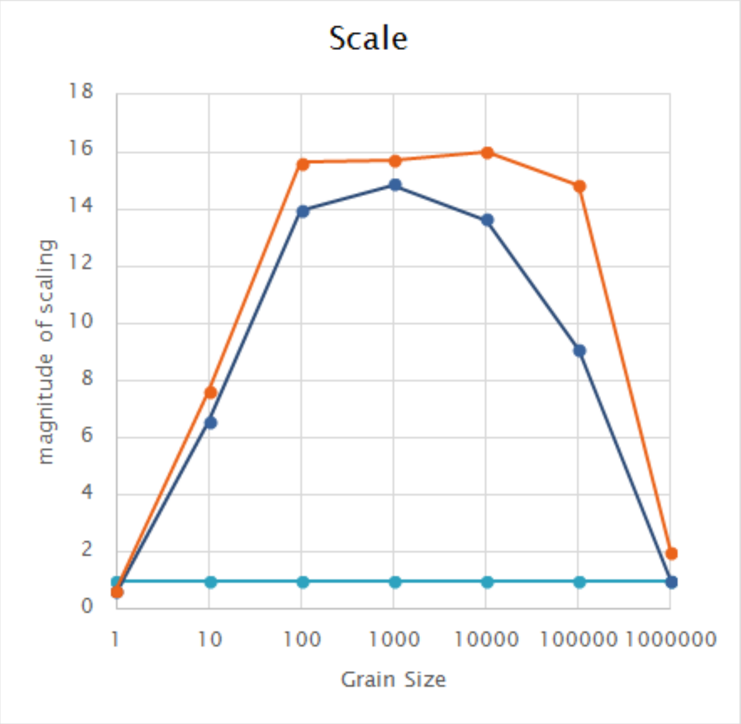




Parallel vs. Task

- 1000 nanosecond delay per iteration
- Vector size of 1,000,000

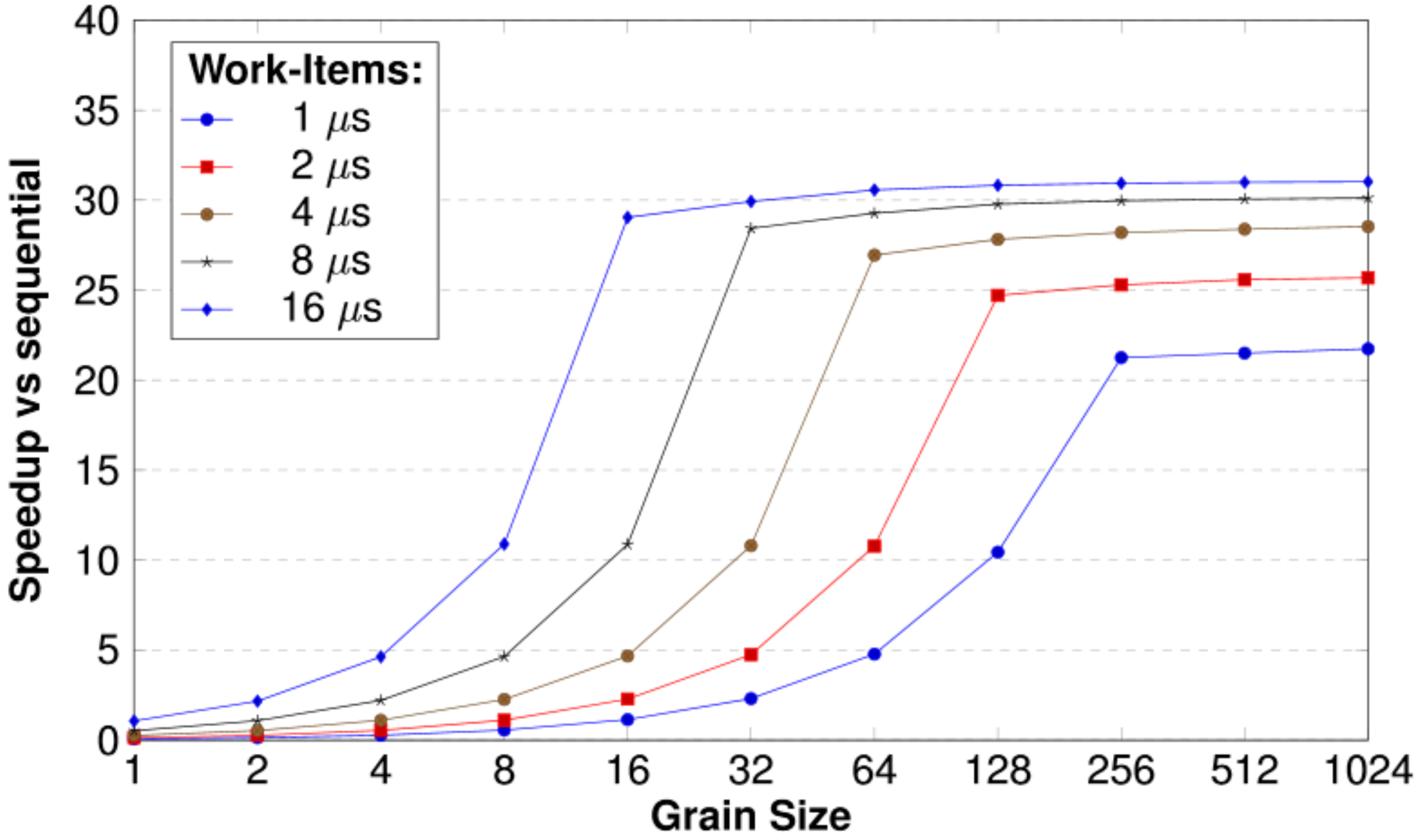




HPXCL: OpenCL backend

- Uses *hpx::parallel::for_each*
    - Grouping work-items into work packets

```
hpx::parallel::for_each(hpx::parallel::par,
    nd_range_iterator::begin(dim_x, dim_y, dim_z),
    nd_range_iterator::end(dim_x, dim_y, dim_z),
    [&ta](nd_pos const& gid)
    {
        workgroup_thread(&ta, gid);
    });
```


Work-Items:
1 μs
2 μs
4 μs
8 μs
16 μs
Speedup vs sequential
Grain Size
0
5
10
15
20
25
30
35
40
1
2
4
8
16
32
64
128
256
512
1024

Future Work

- Not all of the algorithms are implemented
- Perform more benchmarking on different algorithms
- Grain size control and non-partitioned algorithms
- Experiment with custom policies
    - if_gpu_then.on(numa).with(chunker)
- introspection tools (using performance counters to make adjustments)
- minimization executor (power, idle_rate, other performance counter stuff)

Additional Resources

- HPX - https://github.com/STEllAR-GROUP/hpx
- STE||AR - http://stellar.cct.lsu.edu/
- N4505 - http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2015/n4505.pdf
- N4406 - http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2015/n4406.pdf