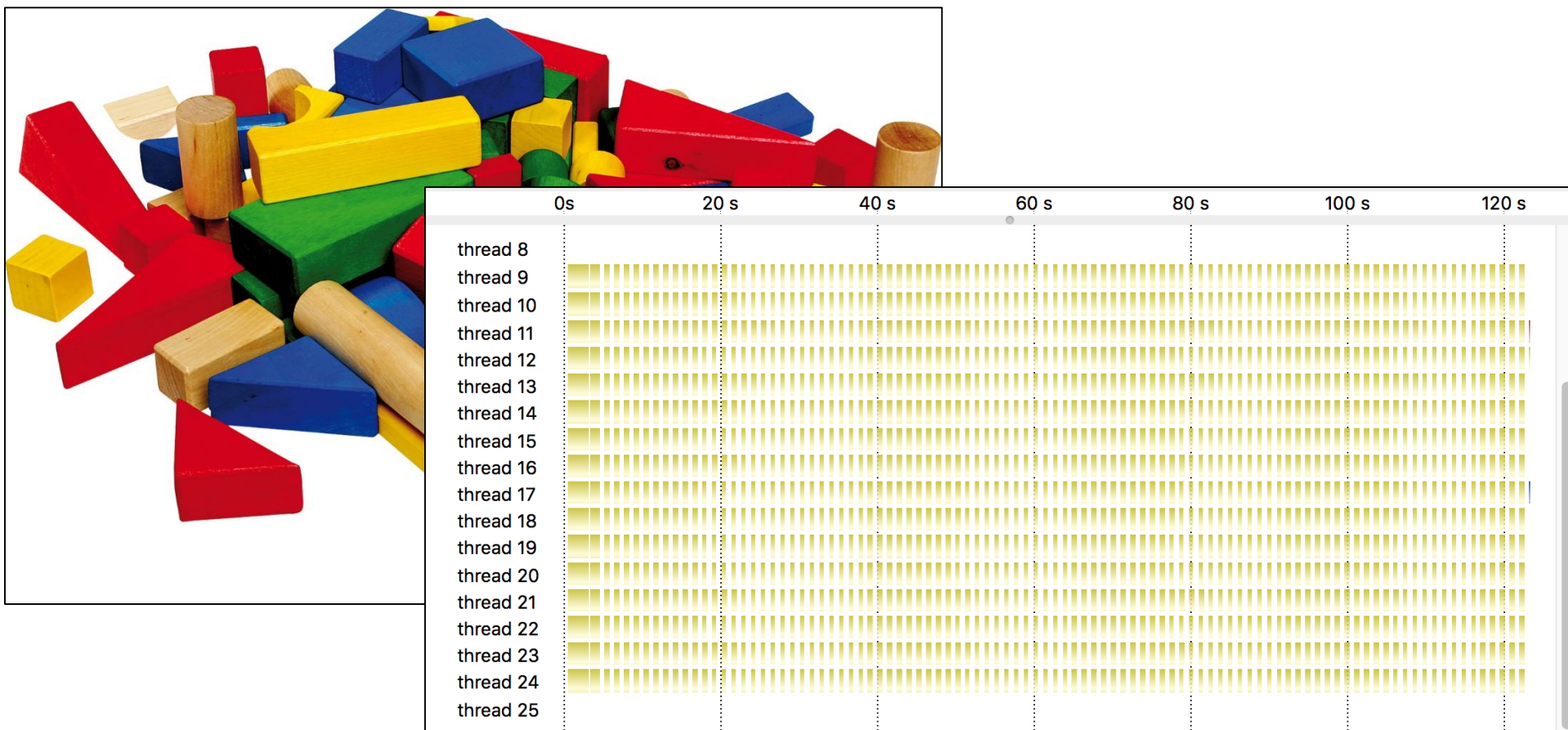


Asynchronous Programming in Modern C++

Futurize All The Things!

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Today's Parallel Applications



Real-world Problems

- Insufficient parallelism imposed by the programming model
 - OpenMP: enforced barrier at end of parallel loop
 - MPI: global (communication) barrier after each time step
- Over-synchronization of more things than required by algorithm
 - MPI: Lock-step between nodes (ranks)
- Insufficient coordination between on-node and off-node parallelism
 - MPI+X: insufficient co-design of tools for off-node, on-node, and accelerators
- Distinct programming models for different types of parallelism
 - Off-node: MPI, On-node: OpenMP, Accelerators: CUDA, etc.



Rules of Thumb for Parallelization

- Parallelize applications as much as humanly possible
 - Including nested parallelism
- Use a programming environment that embraces SLOW
 - Starvation, Latencies, Overheads, Waiting
- Allow for your grainsize to be variable
 - Make tasks as small as possible, but not smaller
- Oversubscribe and balance adaptively
 - Overheads are the worst, manage them wisely
- (CppCon 2017: Asynchronous C++ Programming Model)

The Challenges

- We need to find a usable way to fully parallelize our applications
- Goals are:
 - Expose asynchrony to the programmer without exposing additional concurrency
 - Make data dependencies explicit, hide notion of ‘thread’ and ‘communication’
 - Provide manageable paradigms for handling parallelism
- (CppCon 2017: Asynchronous C++ Programming Model)

HPX

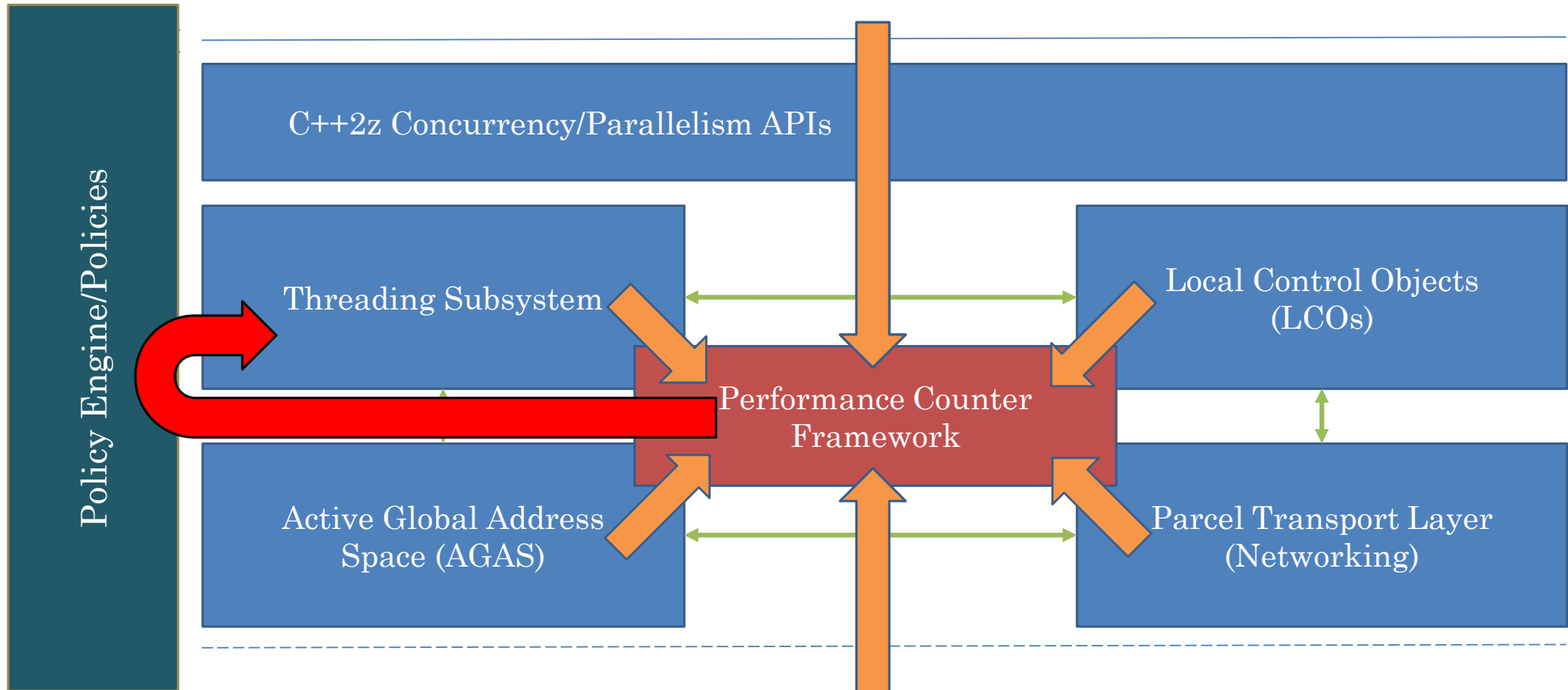
The C++ Standards Library for Concurrency and Parallelism

<https://github.com/STELLAR-GROUP/hpx>

HPX – The C++ Standards Library for Concurrency and Parallelism

- 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.
- Enables using the Asynchronous C++ Standard Programming Model
 - Emergent auto-parallelization, intrinsic hiding of latencies,

HPX – A C++ Standard Library



HPX – The API

- As close as possible to C++11/14/17/20 standard library, where appropriate, for instance
 - `std::thread`, `std::jthread` `hpx::thread` (C++11), `hpx::jthread` (C++20)
 - `std::mutex` `hpx::mutex`
 - `std::future` `hpx::future` (including N4538, ‘Concurrency TS’)
 - `std::async` `hpx::async` (including N3632)
 - `std::for_each(par, ...)`, etc. `hpx::parallel::for_each` (N4507, C++17)
 - `std::experimental::task_block` `hpx::parallel::task_block` (N4411)
 - `std::latch`, `std::barrier`, `std::for_loop` `hpx::latch`, `hpx::barrier`, `hpx::parallel::for_loop` (TS V2)
 - `std::bind` `hpx::bind`
 - `std::function` `hpx::function`
 - `std::any` `hpx::any` (N3508)
 - `std::cout` `hpx::cout`

Parallel Algorithms (C++17)

<u>adjacent_difference</u>	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
<u>inner_product</u>	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 (C++17)

- Add Execution Policy as first argument
- Execution policies have associated default executor and default executor parameters
 - `execution::parallel_policy`, generated with `par`
 - parallel executor, static chunk size
 - `execution::sequenced_policy`, generated with `seq`
 - sequential executor, no chunking

```
// add execution policy
std::fill(
    std::execution::par,
    begin(d), end(d), 0.0);
```

Parallel Algorithms (Extensions)

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

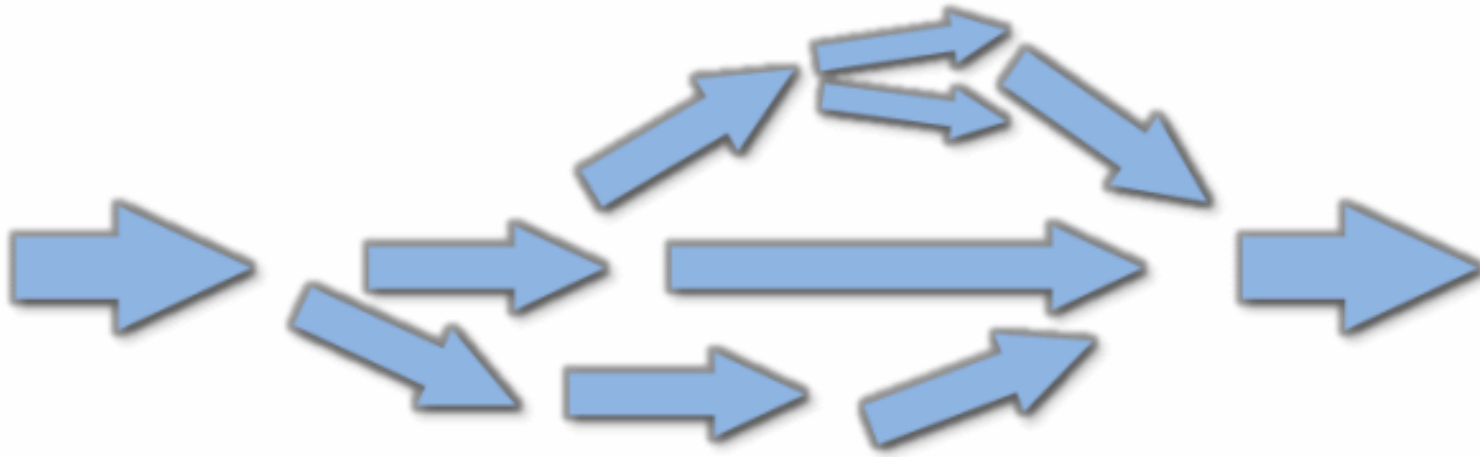
// rebind par to user-defined executor (where and how to execute)
my_executor my_exec = ...;
fill(execution::par.on(my_exec), begin(d), end(d), 0.0);

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

Execution Policies (Extensions)

- Extensions: asynchronous execution policies
 - `parallel_task_execution_policy` (asynchronous version of `parallel_execution_policy`), generated with `par(task)`
 - `sequenced_task_execution_policy` (asynchronous version of `sequenced_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

The Future of Computation



What is a (the) Future?

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

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

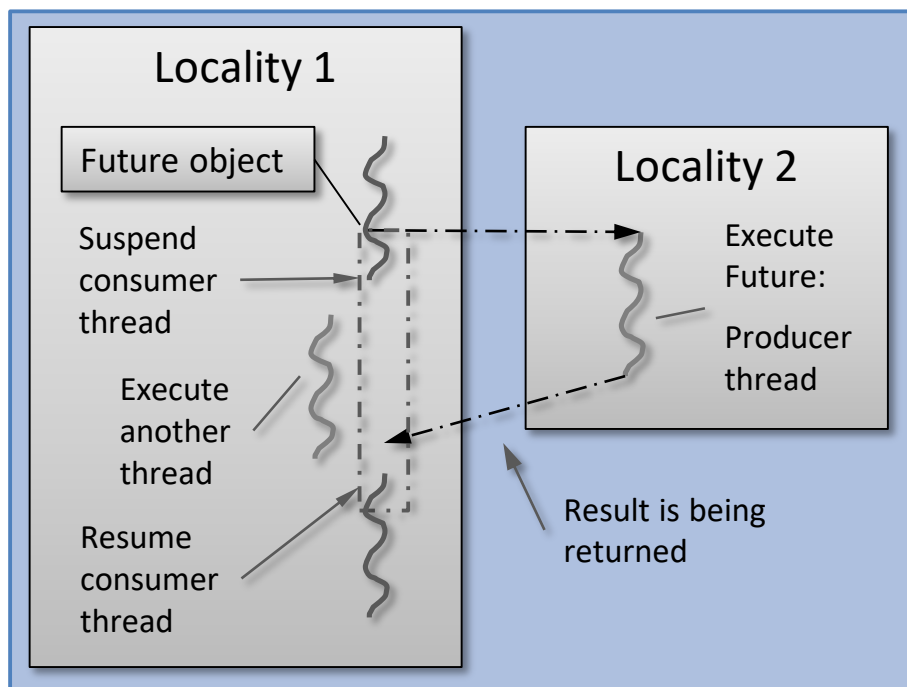
void deep_thought()
{
    future<int> promised_answer = async(&universal_answer);

    // do other things for 7.5 million years

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

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
- Represents a data-dependency
- Makes asynchrony manageable
- Allows for composition of several asynchronous operations
- (Turns concurrency into parallelism)

Recursive Parallelism



Parallel Quicksort

```
template <typename RandomIter>
void quick_sort(RandomIter first, RandomIter last)
{
    ptrdiff_t size = last - first;
    if (size > 1) {
        RandomIter pivot = partition(first, last,
            [p = first[size / 2]](auto v) { return v < p; });

        quick_sort(first, pivot);
        quick_sort(pivot, last);
    }
}
```

Parallel Quicksort: Parallel

```
template <typename RandomIter>
void quick_sort(RandomIter first, RandomIter last)
{
    ptrdiff_t size = last - first;
    if (size > threshold) {
        RandomIter pivot = partition(par, first, last,
                                     [p = first[size / 2]](auto v) { return v < p; });

        quick_sort(first, pivot);
        quick_sort(pivot, last);
    }
    else if (size > 1) {
        sort(seq, first, last);
    }
}
```

Parallel Quicksort: Futurized

```
template <typename RandomIter>
future<void> quick_sort(RandomIter first, RandomIter last)
{
    ptrdiff_t size = last - first;
    if (size > threshold) {
        future<RandomIter> pivot = partition(par(task), first, last,
            [p = first[size / 2]](auto v) { return v < p; });

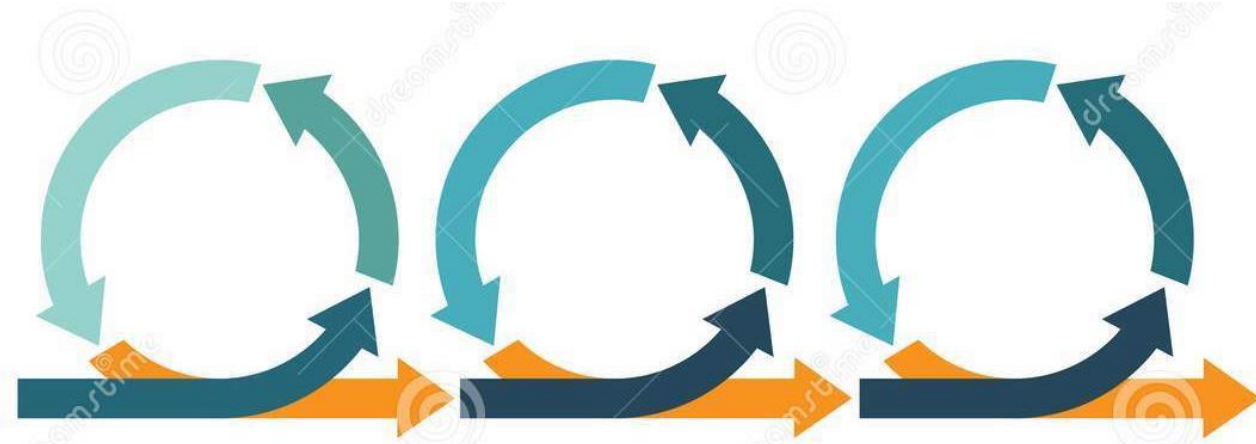
        return pivot.then([=](auto pf) {
            auto pivot = pf.get();
            return when_all(quick_sort(first, pivot), quick_sort(pivot, last));
        });
    }
    else if (size > 1) {
        sort(seq, first, last);
    }
    return make_ready_future();
}
```

Parallel Quicksort: co_await

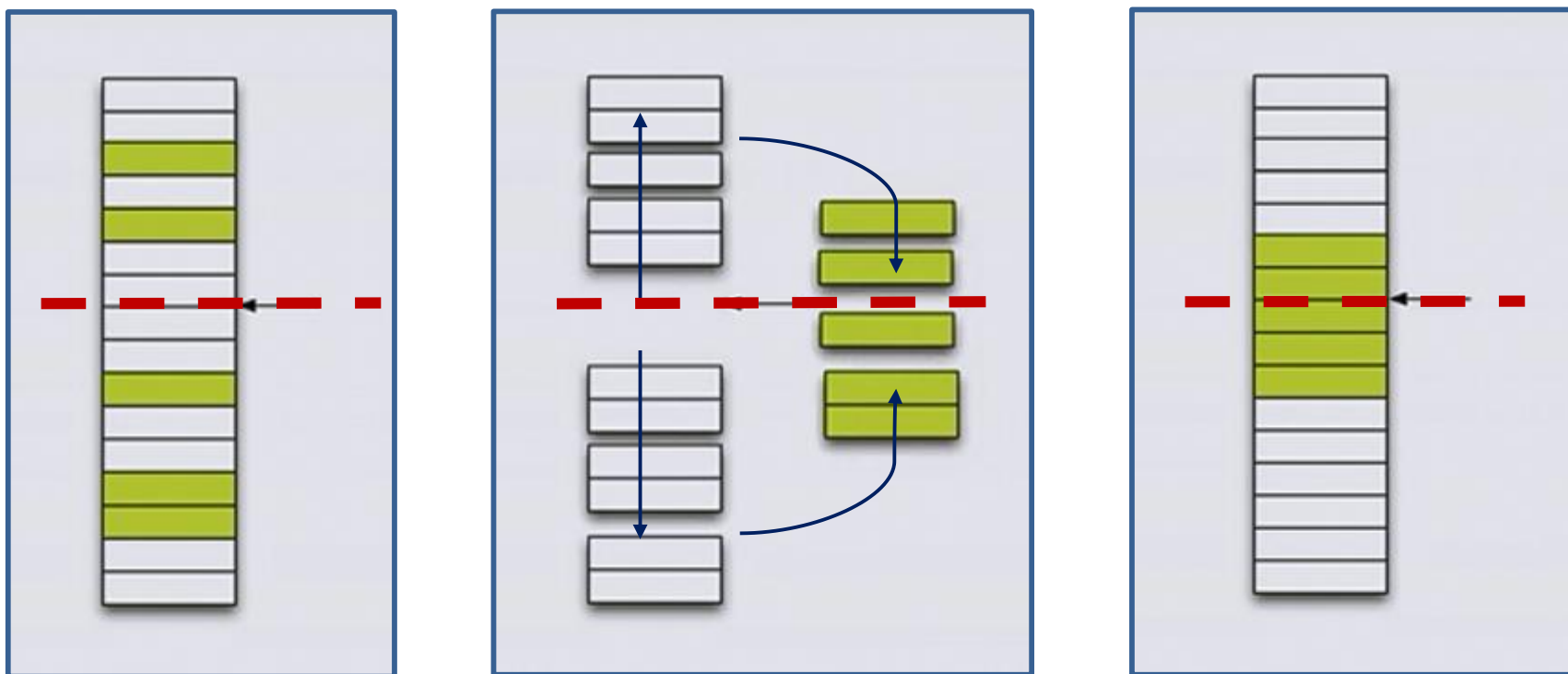
```
template <typename RandomIter>
future<void> quick_sort(RandomIter first, RandomIter last)
{
    ptrdiff_t size = last - first;
    if (size > threshold) {
        RandomIter pivot = co_await partition(par(task), first, last,
            [p = first[size / 2]](auto v) { return v < p; });

        co_await when_all(
            quick_sort(first, pivot), quick_sort(pivot, last));
    }
    else if (size > 1) {
        sort(seq, first, last);
    }
}
```

Iterative Parallelism



Extending Parallel Algorithms



Sean Parent: C++ Seasoning, Going Native 2013

Extending Parallel Algorithms

- New algorithm: gather

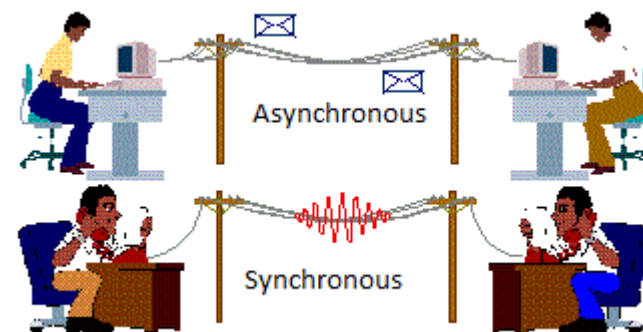
```
template <typename BiIter, typename Pred>
pair<BiIter, BiIter> gather(BiIter f, BiIter l, BiIter p, Pred pred)
{
    BiIter it1 = stable_partition(f, p, not1(pred));
    BiIter it2 = stable_partition(p, l, pred);
    return make_pair(it1, it2);
}
```

Sean Parent: C++ Seasoning, Going Native 2013

Extending Parallel Algorithms

- New algorithm: `gather_async`

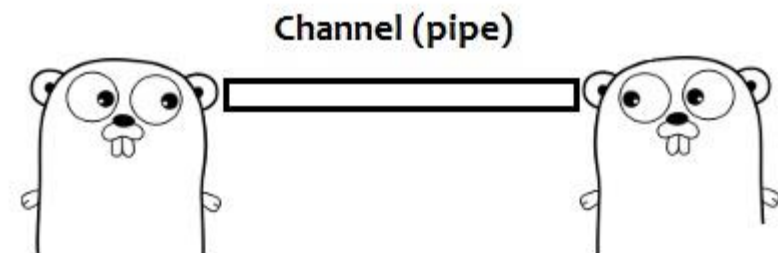
```
template <typename BiIter, typename Pred>
future<pair<BiIter, BiIter>> gather_async(BiIter f, BiIter l, BiIter p, Pred pred)
{
    future<BiIter> f1 = stable_partition(par(task), f, p, not1(pred));
    future<BiIter> f2 = stable_partition(par(task), p, l, pred);
    co_return make_pair(co_await f1,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



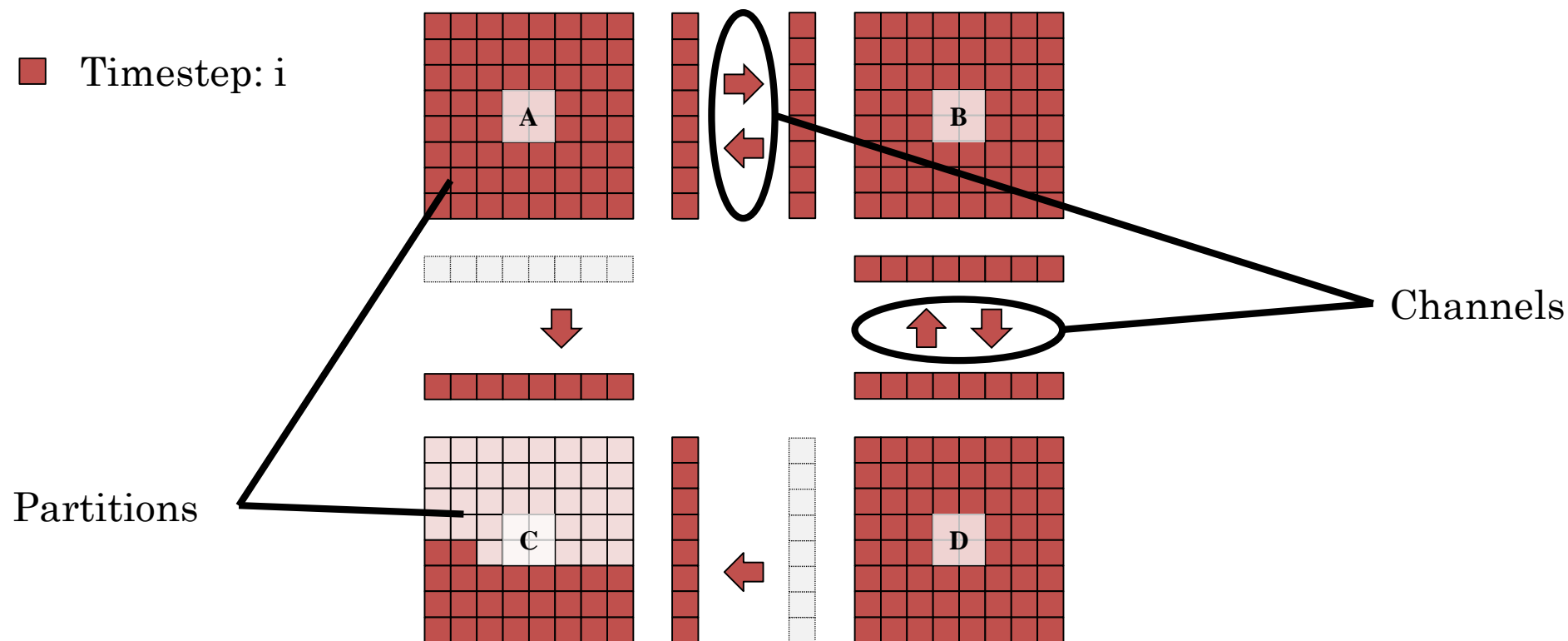
Asynchronous Communication

Asynchronous Channels

- High level abstraction of communication operations
 - Perfect for asynchronous boundary exchange
- Modelled after Go-channels
- Create on one thread, refer to it from another thread
 - Conceptually similar to bidirectional P2P (MPI) communicators
- Asynchronous in nature
 - `channel::get()` and `channel::set()` return futures

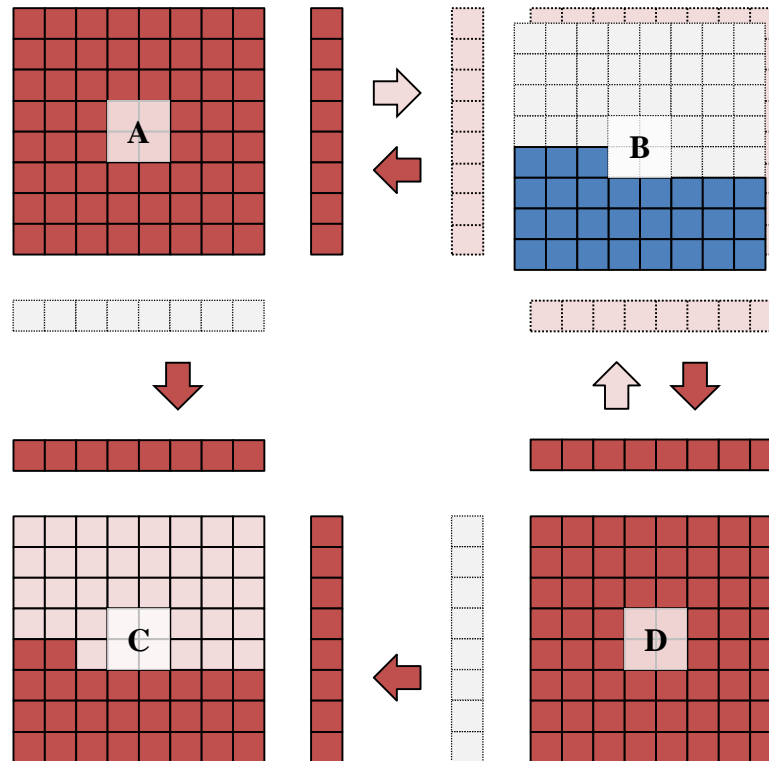


Futurized 2D Stencil: Timestep i



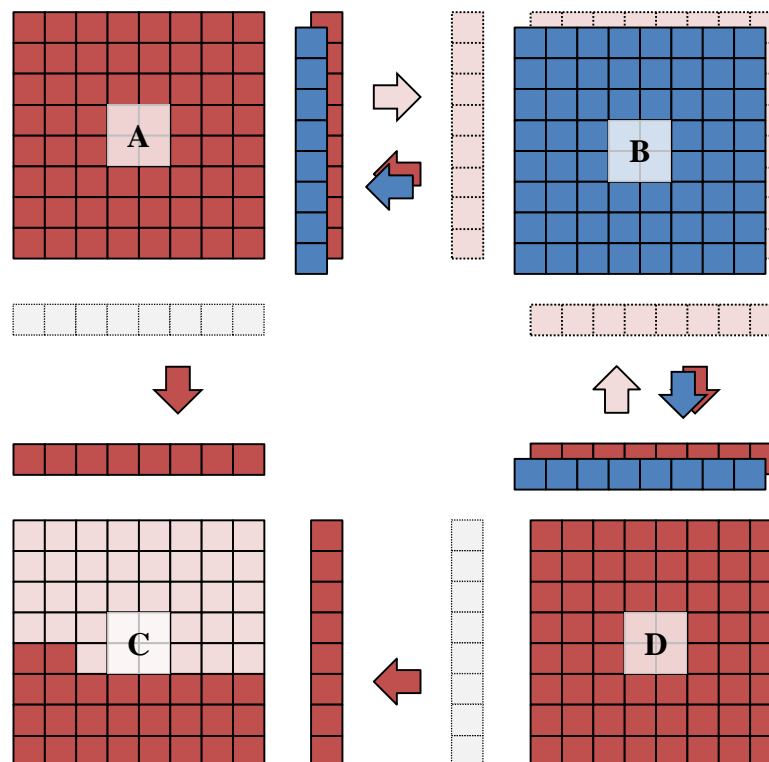
Futurized 2D Stencil: Timestep $i+1$

- Timestep: i
- Timestep: $i+1$



Futurized 2D Stencil

- Timestep: i
- Timestep: $i+1$



2D Stencil

- Partitions are distributed across machine
- More partitions per node (locality) than cores
 - Oversubscription
- Code equivalent regardless whether neighboring partition is on the same node
- Overlap of communication and computation
 - More parallelism (work) than compute resources (cores)

Futurized 2D Stencil: Main Loop

```
// execute this for each partition concurrently
hpx::future<void> simulate(std::size_t steps)
{
    for (size_t t = 0; t != steps; ++t)
    {
        co_await perform_one_time_step(t);
    }
    co_return;
}
```


One Timestep: Update Boundaries

```
future<void> upper_boundary(int t); // same for other boundaries

future<void> perform_one_time_step(int t)
{
    // Update our boundaries from neighbors
    co_await when_all(upper_boundary(t), right_boundary(t),
                     lower_boundary(t), left_boundary(t));

    // Apply stencil to partition
    co_await for_loop(par(task), min + 1, max - 1,
                     [&](size_t idx) { /* apply stencil to each inner point */ });
}
```

One Timestep: Interior

```
future<void> upper_boundary(int t)
{
    // Update upper boundary from upper neighbor
    vector<double> data = co_await channel_up_from.get(t);

    // process upper ghost-zone data using received data
    for_loop(seq, 1, size(data) - 1,
        [&](size_t idx) { /* apply stencil to each point in data */ });

    // send new ghost zone data to upper neighbor
    co_await channel_up_to.set(std::move(data), t + 1);
}
```

Asynchrony Everywhere

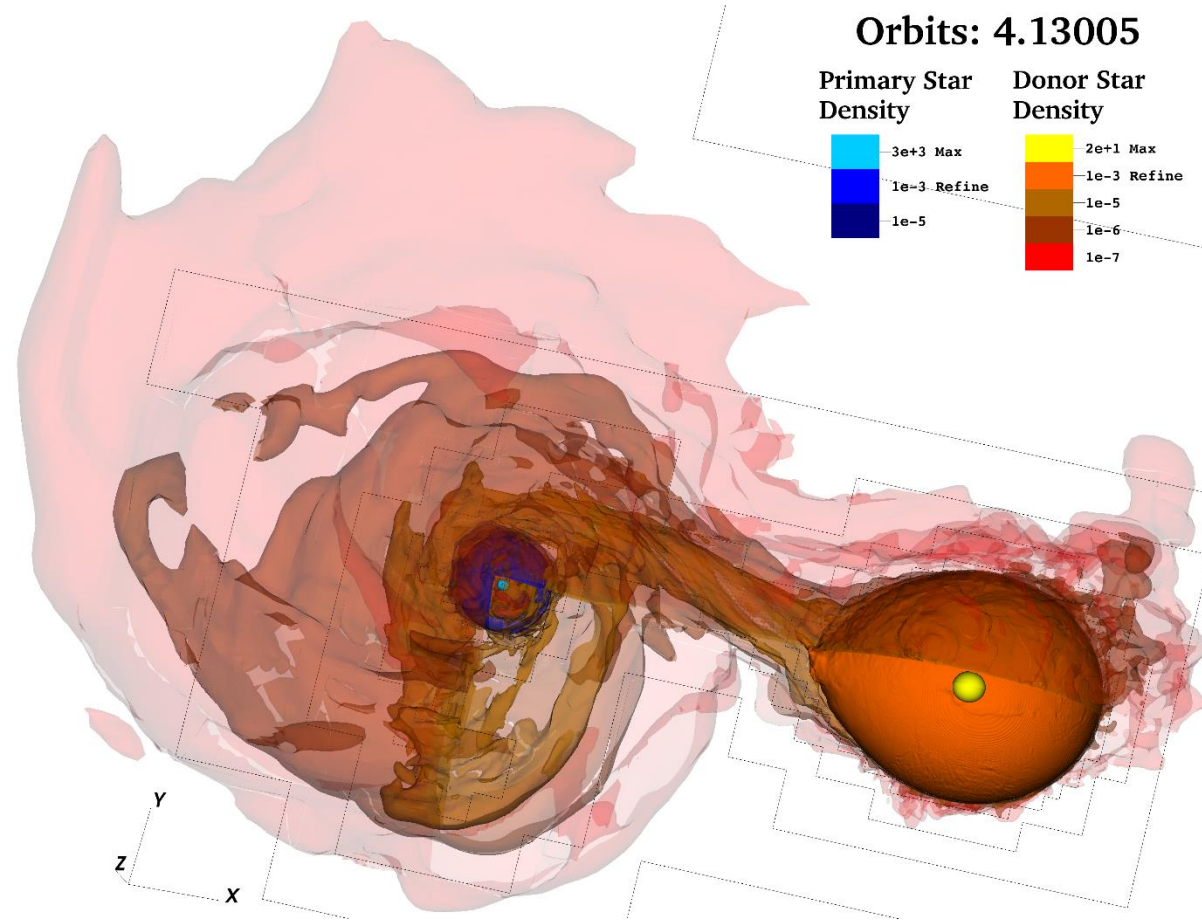


Futurization

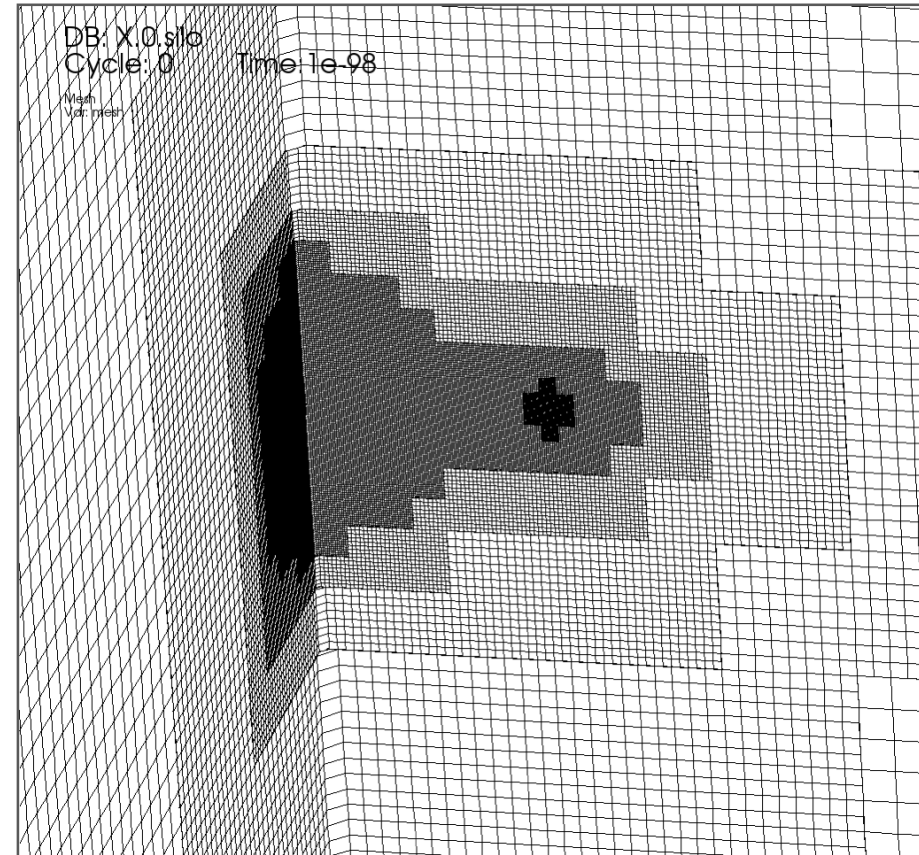
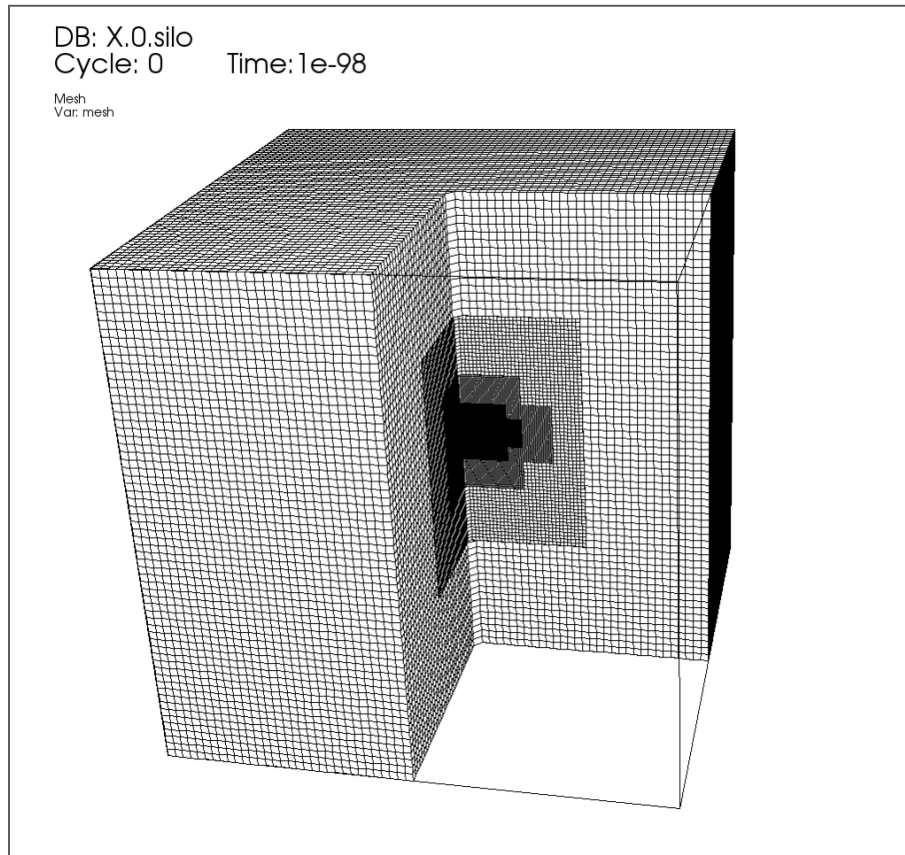
- Technique allowing to automatically transform code
 - Delay direct execution in order to avoid synchronization
 - Turns 'straight' code into 'futurized' code
 - Code no longer calculates results, but generates an execution tree representing the original algorithm
 - If the tree is executed it produces the same result as the original code
 - The execution of the tree is performed with maximum speed, depending only on the data dependencies of the original code
- Execution exposes the emergent property of being auto-parallelized

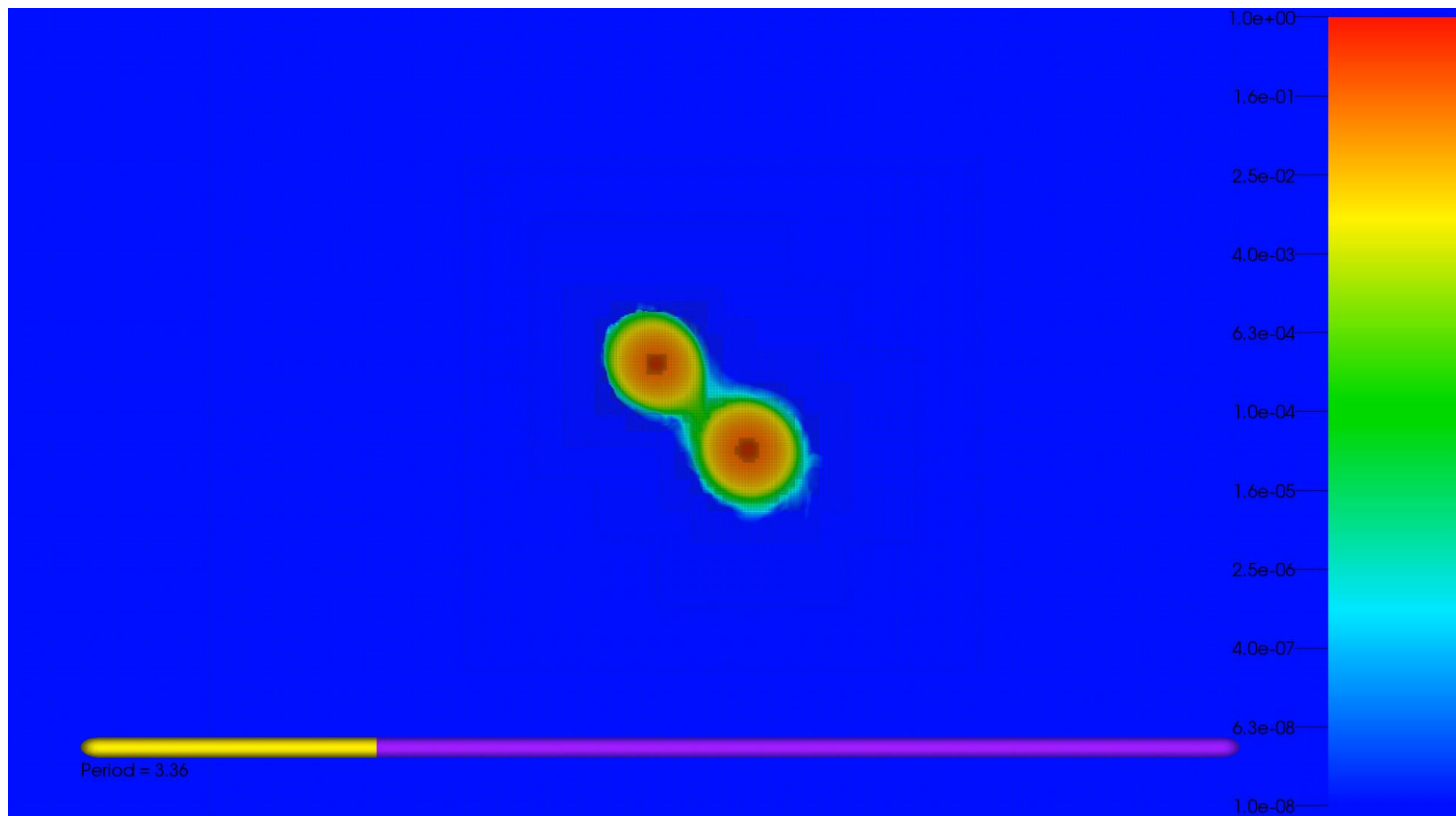
Recent Results

Merging White Dwarfs

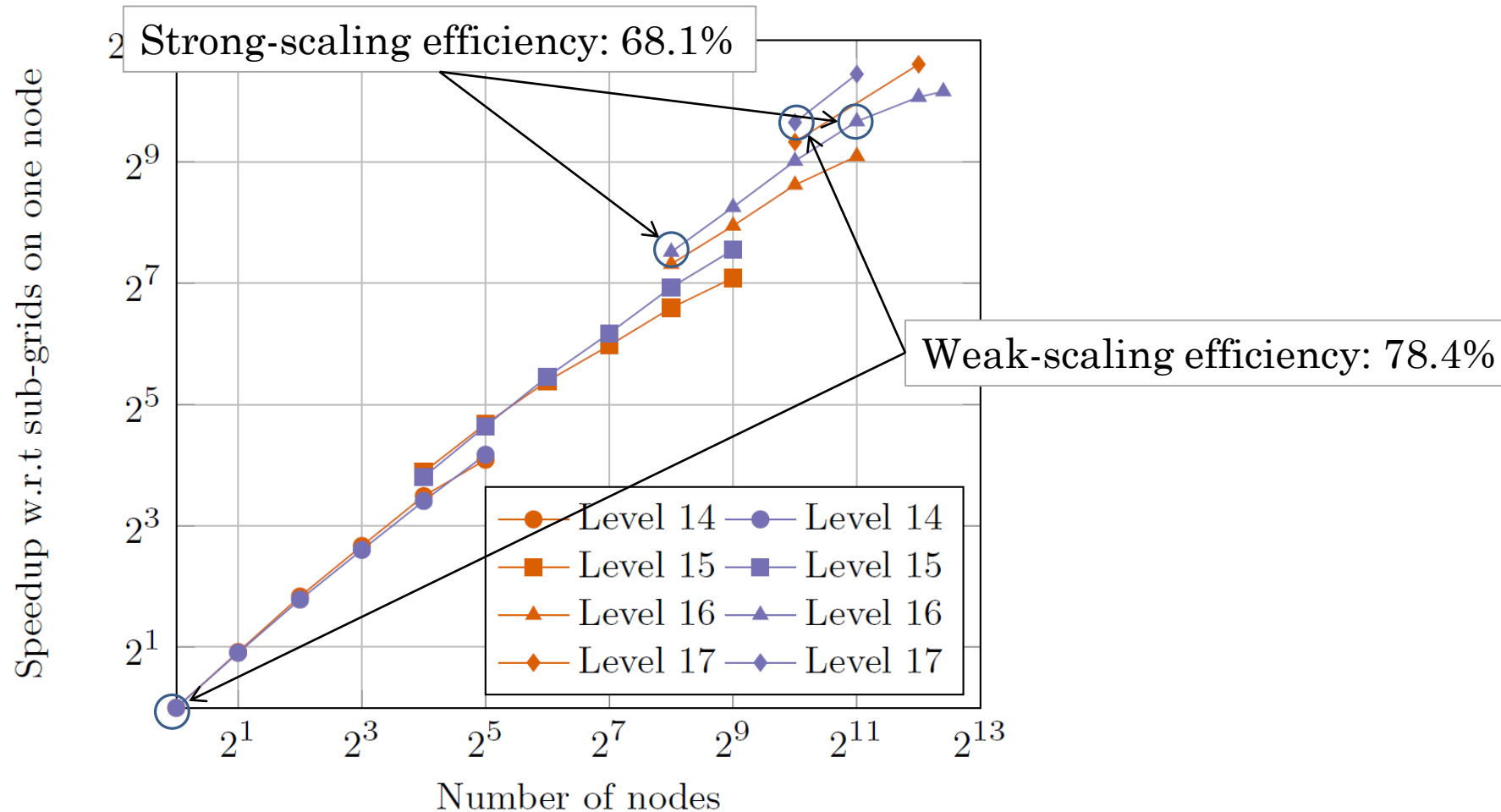


Adaptive Mesh Refinement

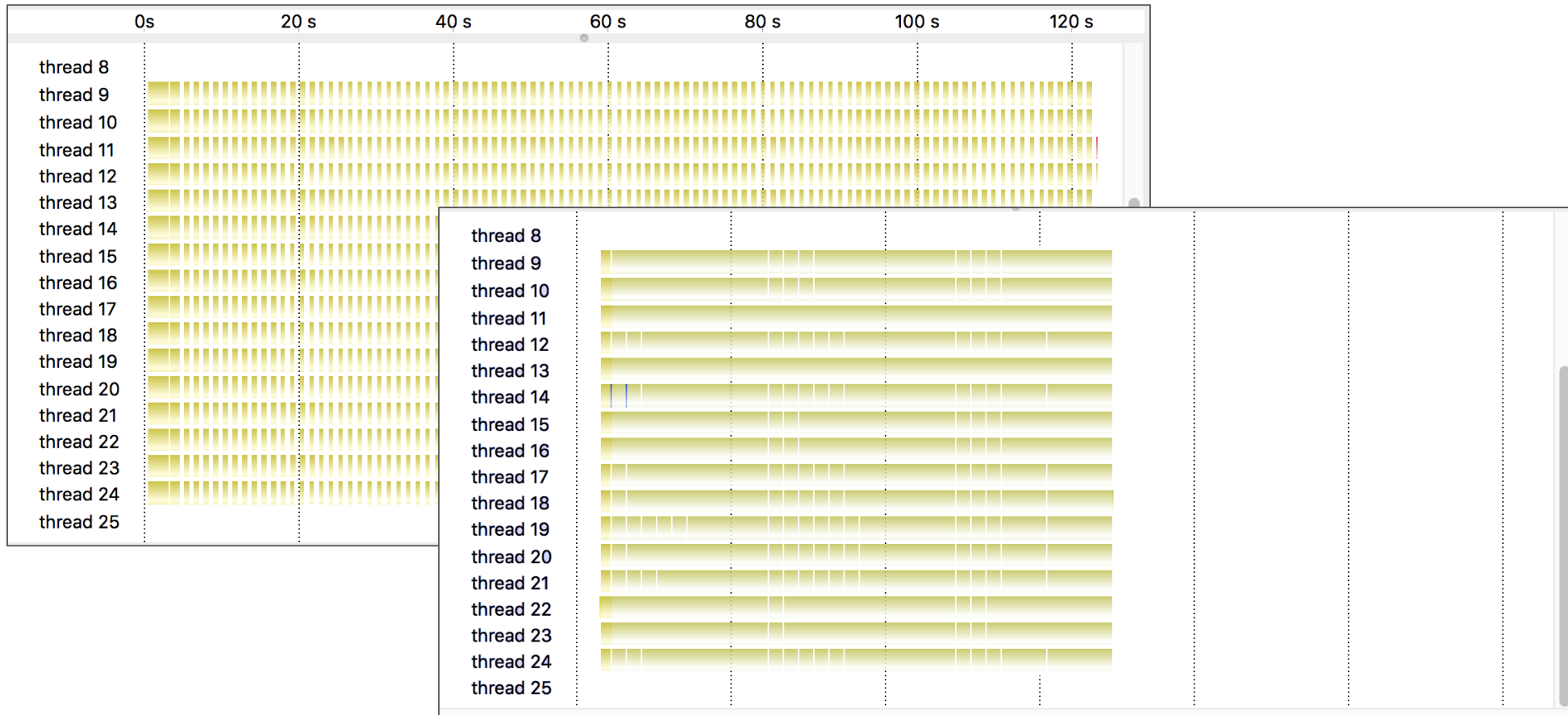




Adaptive Mesh Refinement



The Solution to the Application Problem



The Solution to the Application Problems





