HPX

The C++ Standards Library for Concurrency and Parallelism

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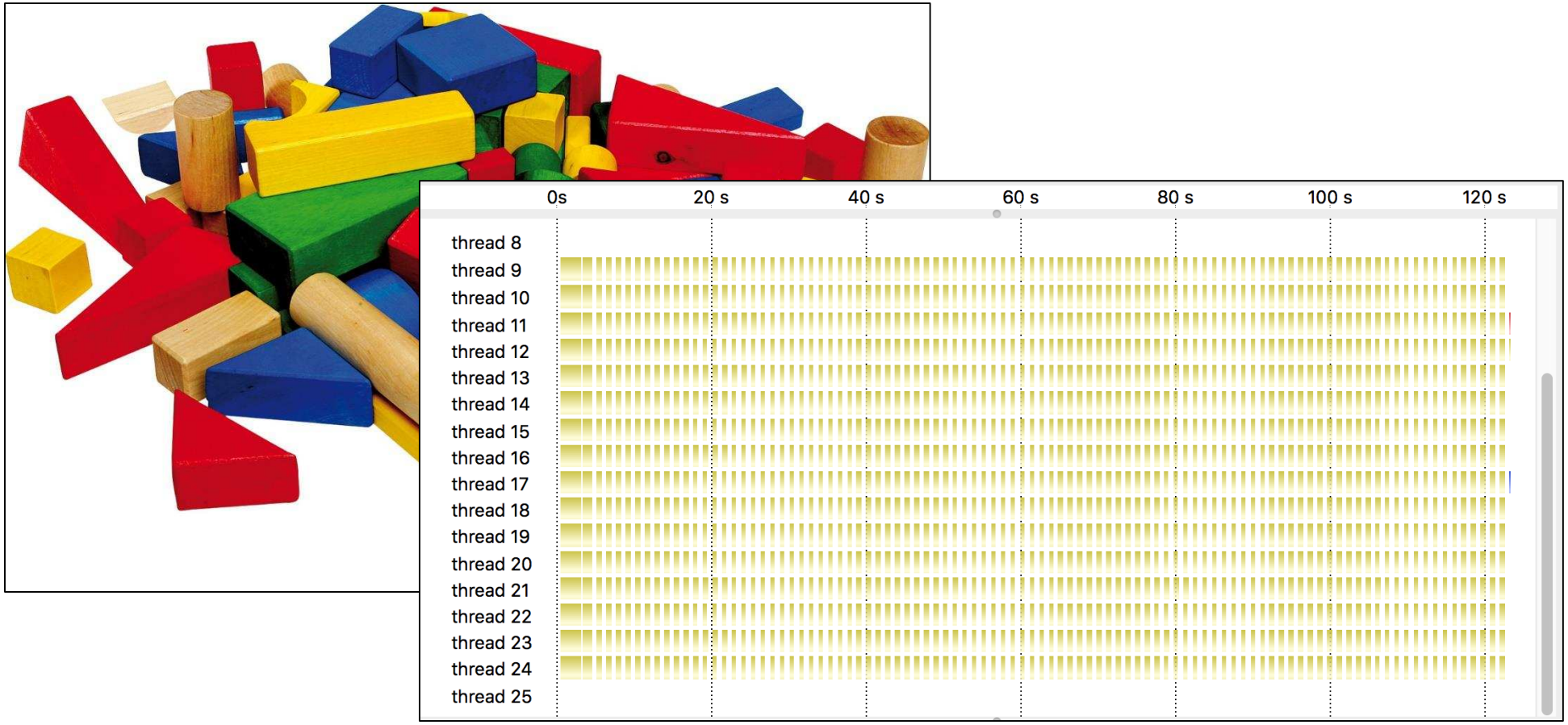
The Application Problems



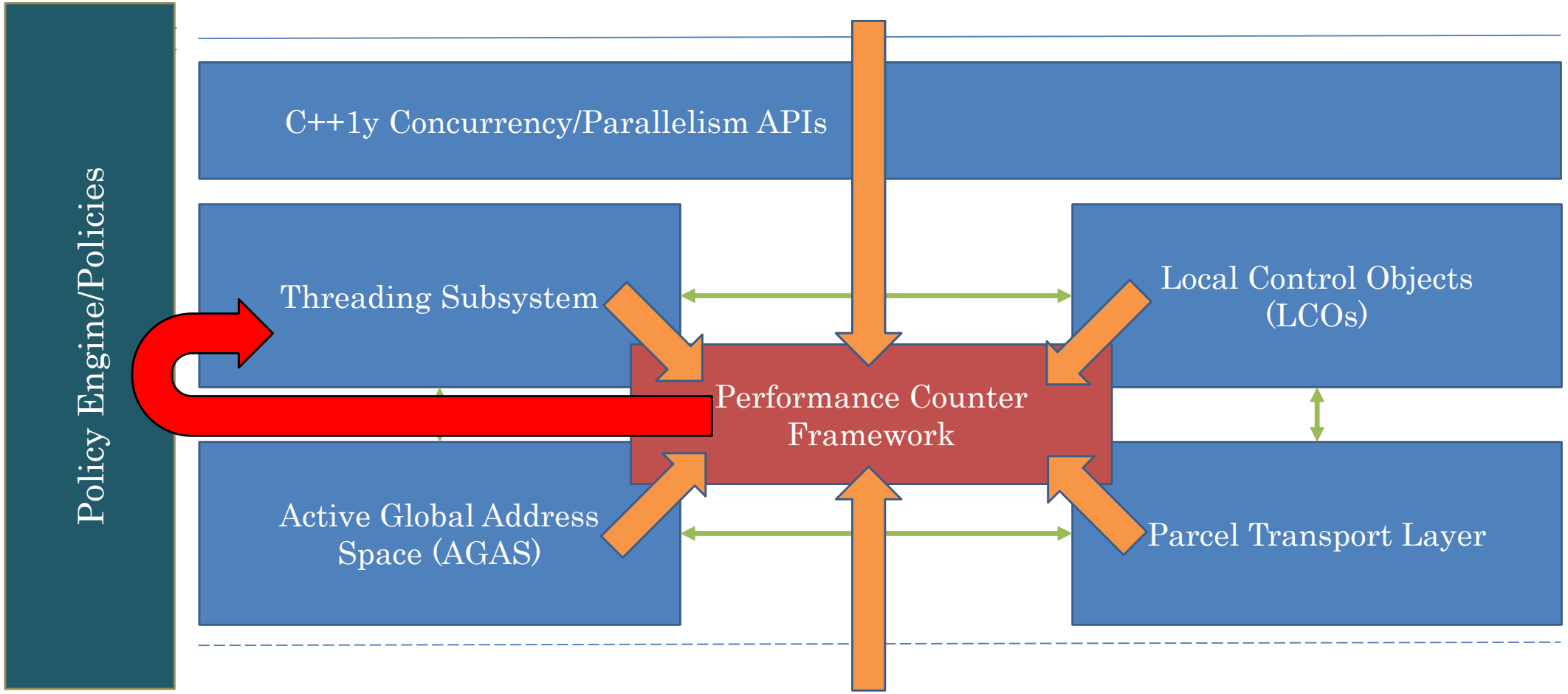
HPX – A General Purpose Runtime System

- The C++ Standards Library for Concurrency and Parallelism
- Exposes a coherent and uniform, C++ standards-conforming 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 seamless data parallelism orthogonally to task-based parallelism
- 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
  - Support for hardware accelerators

HPX – A C++ Standard Library

- Widely portable
  - Platforms: x86/64, Xeon/Phi, ARM 32/64, Power, BlueGene/Q
  - Operating systems: Linux, Windows, Android, OS/X
- Well integrated with compiler's C++ Standard libraries
- 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

HPX – A C++ Standard Library



Programming Model

- Focus on the logical composition of data processing, rather than the physical orchestration of parallel computation
- Provide useful abstractions that shield programmer from low-level details of parallel and distributed processing
- Centered around data dependencies not communication patterns
- Make data dependencies explicit to system thus allows for auto-magic parallelization
- Basis for various types of higher level parallelism, such as iterative, fork-join, continuation-style, asynchronous, data-parallelism
- Enable runtime-based adaptivity while applying application-defined policies

Programming Model

- The consequent application of the Concept of Futures
  - Make data dependencies explicit and visible to the runtime
- Implicit and explicit asynchrony
  - Transparently hide communication and other latencies
  - Makes over-subscription manageable
  - Uniform API for local and remote operation
    - Local operation: create new thread
    - Remote operation: send parcel (active message), create thread on behalf of sender
- Work-stealing scheduler
  - Inherently multi-threaded environment
  - Supports millions of concurrently active threads, minimal thread overhead
  - Enables transparent load balancing of work across all execution resources inside a locality
- API is fully conforming with C++11/C++17 and ongoing standardization efforts

HPX – The API

- As close as possible to C++11/14/17 standard library, where appropriate, for instance

std::thread	hpx::thread
std::mutex	hpx::mutex
std::future	hpx::future (including N4538, '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::for_each(par, …), etc.	hpx::parallel::for_each (C++17)
std::experimental::task_block	hpx::parallel::task_block (Parallelism TS 2)

Control Model: How is parallelism achieved?

- Explicit parallelism:
  - Low-level: thread
  - Middle-level: async(), dataflow(), future::then()
- Higher-level constructs
  - Parallel algorithms (parallel::for_each and friends, fork-join parallelism for homogeneous tasks)
    - Asynchronous algorithms (alleviates bad effect of fork/join)
  - Task-block (fork-join parallelism of heterogeneous tasks)
    - Asynchronous task-blocks
  - Continuation-style parallelism based on composing futures (task-based parallelism)
  - Data-parallelism on accelerator architectures (vector-ops, GPUs)
    - Same code used for CPU and accelerators

Parallel Algorithms (C++17)

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		

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; });
```

Dot-product: Vectorization

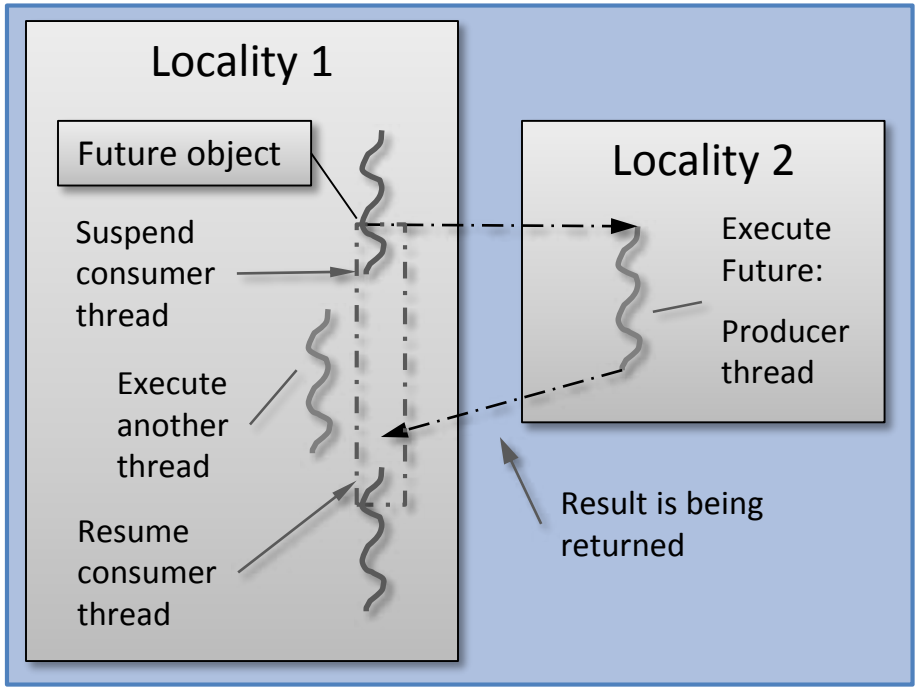
```
std::vector<float> data1 = {...};
std::vector<float> data2 = {...};

double p = parallel::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<>()
);
```

Control Model: How is synchronization expressed?

- Low-level (thread-level) synchronization: mutex, condition_variable, etc.
- Replace (global) barriers with finer-grain synchronization (synchronize of a 'as-need-basis')
  - Wait only for immediately necessary dependencies, forward progress as much as possible
- Many APIs hand out a future representing the result
  - Parallel and sequential composition of futures (future::then(), when_all(), etc.)
  - Orchestration of parallelism through launching and synchronizing with asynchronous tasks
- Synchronization primitives: barrier, latch, semaphore, channel,
  - Synchronize using futures

Synchonization with Futures

- 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:

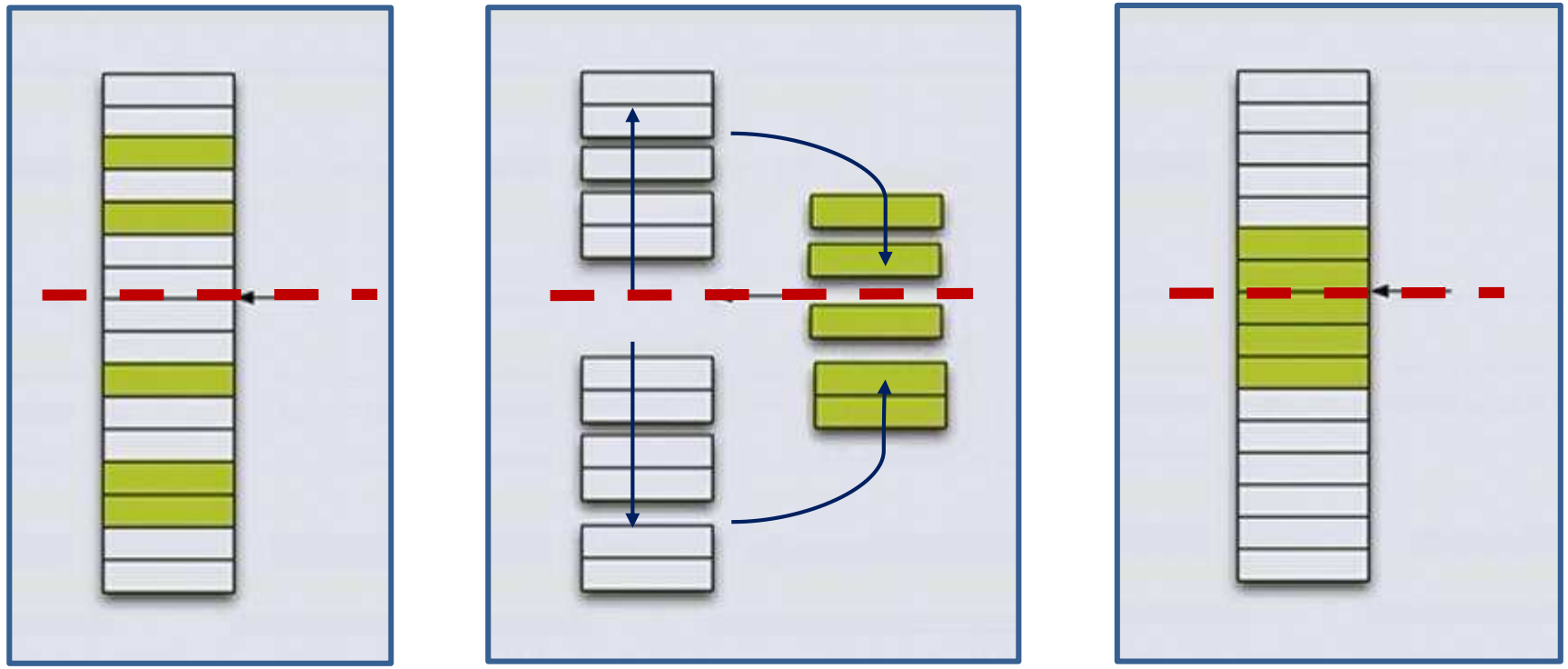
```
int universal_answer() { return 42; }

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
}
```

Data Model

- AGAS essential underpinning for all data management
  - Foundation for syntactic semantic equivalence of local and remote operations
- Full spectrum of C++ data structures are available
  - Either as distributed data structures or for SPMD style computation
- Explicit data partitioning, manually orchestrated boundary exchange
  - Using existing synchronization primitives (for instance channels)
- Use of distributed data structures, like partitioned_vector
  - Use of parallel algorithms
  - Use of co-array like layer (FORTRAN users like that)
- Load balancing: migration
  - Move objects around in between nodes without stopping the application

Small Example

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(
        unwrapping([](BiIter r1, BiIter r2) { return make_pair(r1, r2); }),
        f1, f2);
}
```

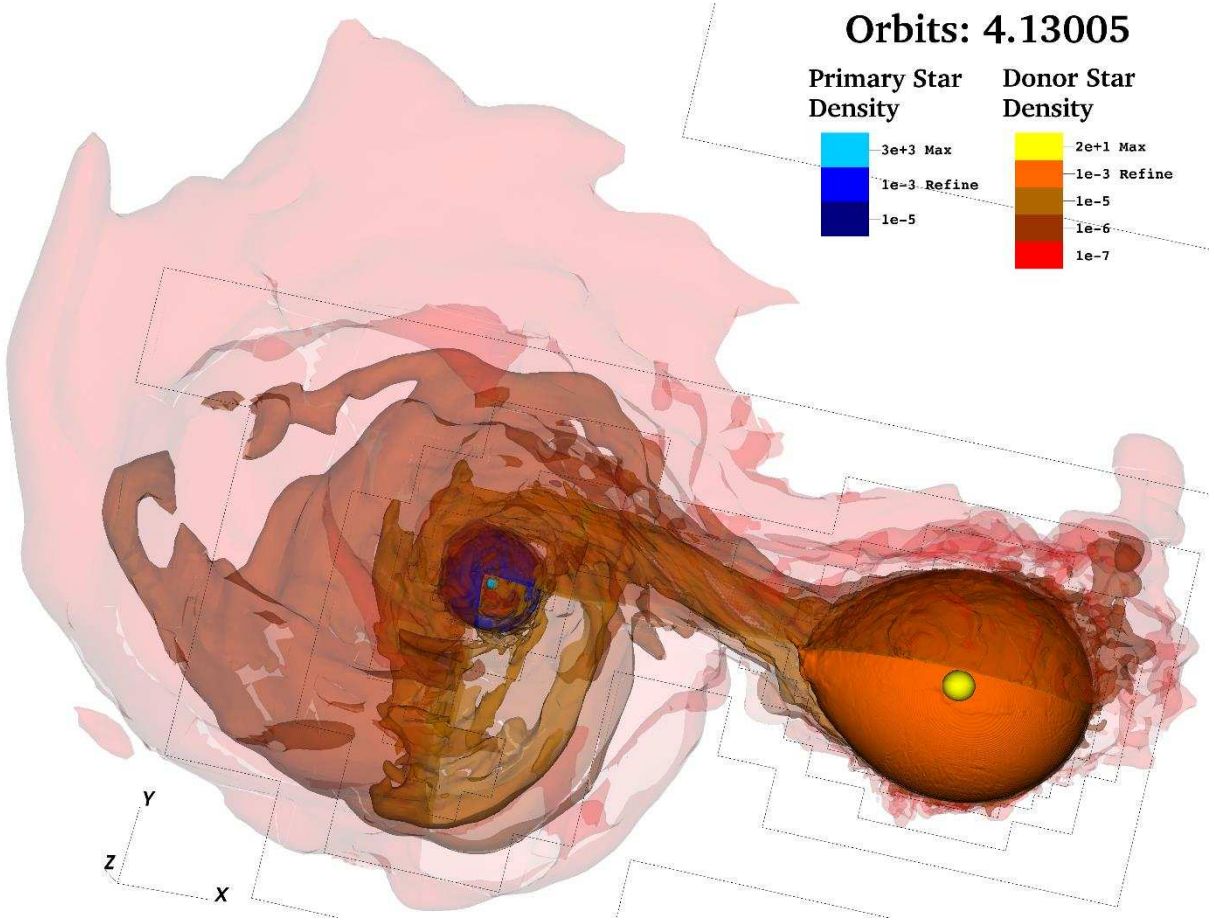
Extending Parallel Algorithms (await)

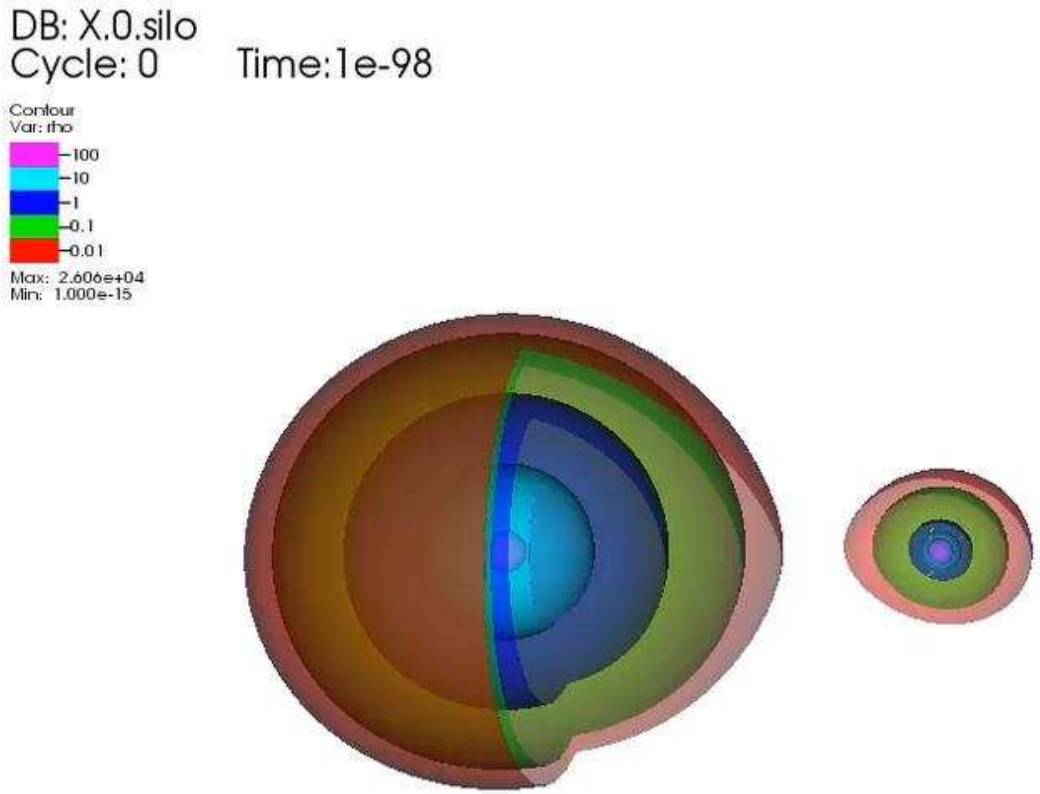
- New algorithm: gather_async

```
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);
    co_return make_pair(co_await f1, co_await f2);
}
```

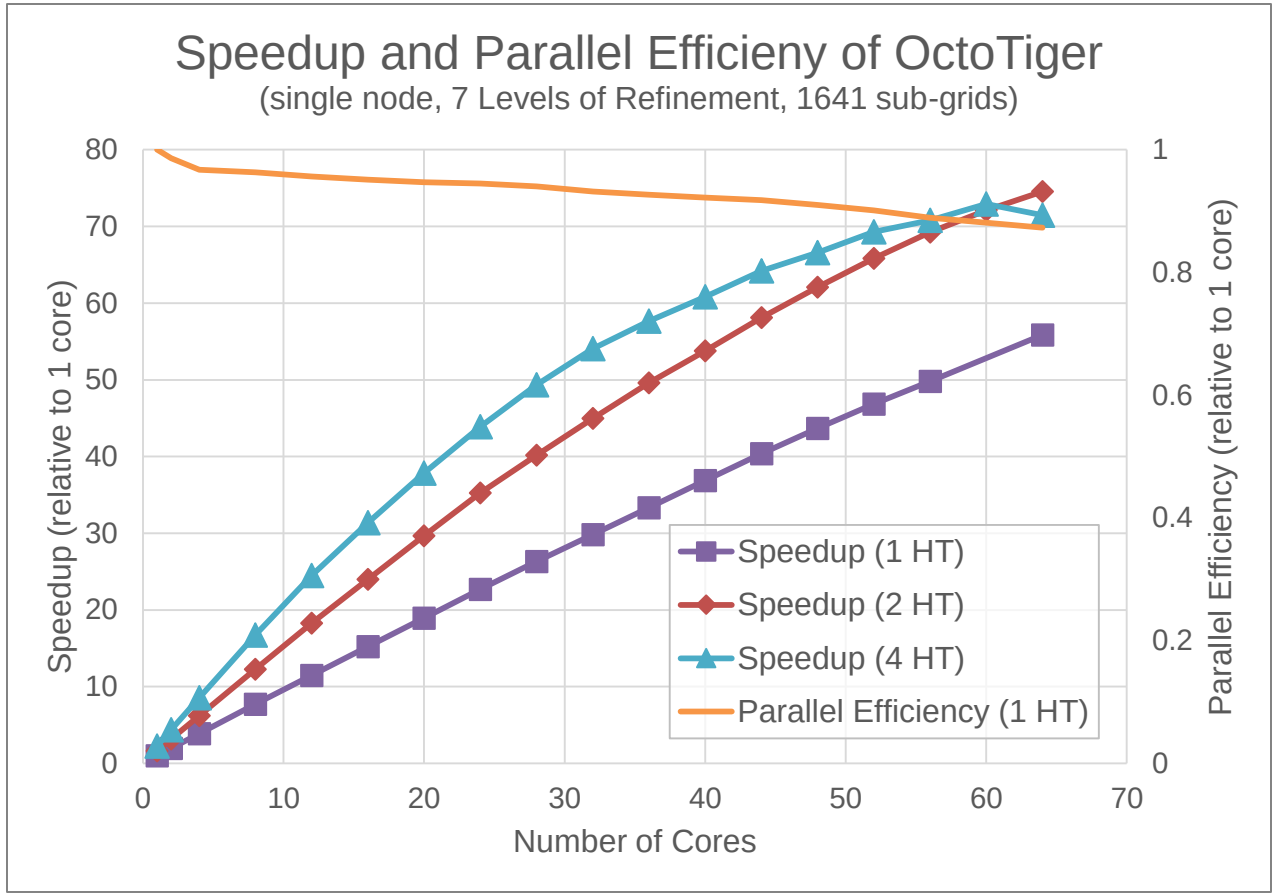
Recent Results

Merging White Dwarfs



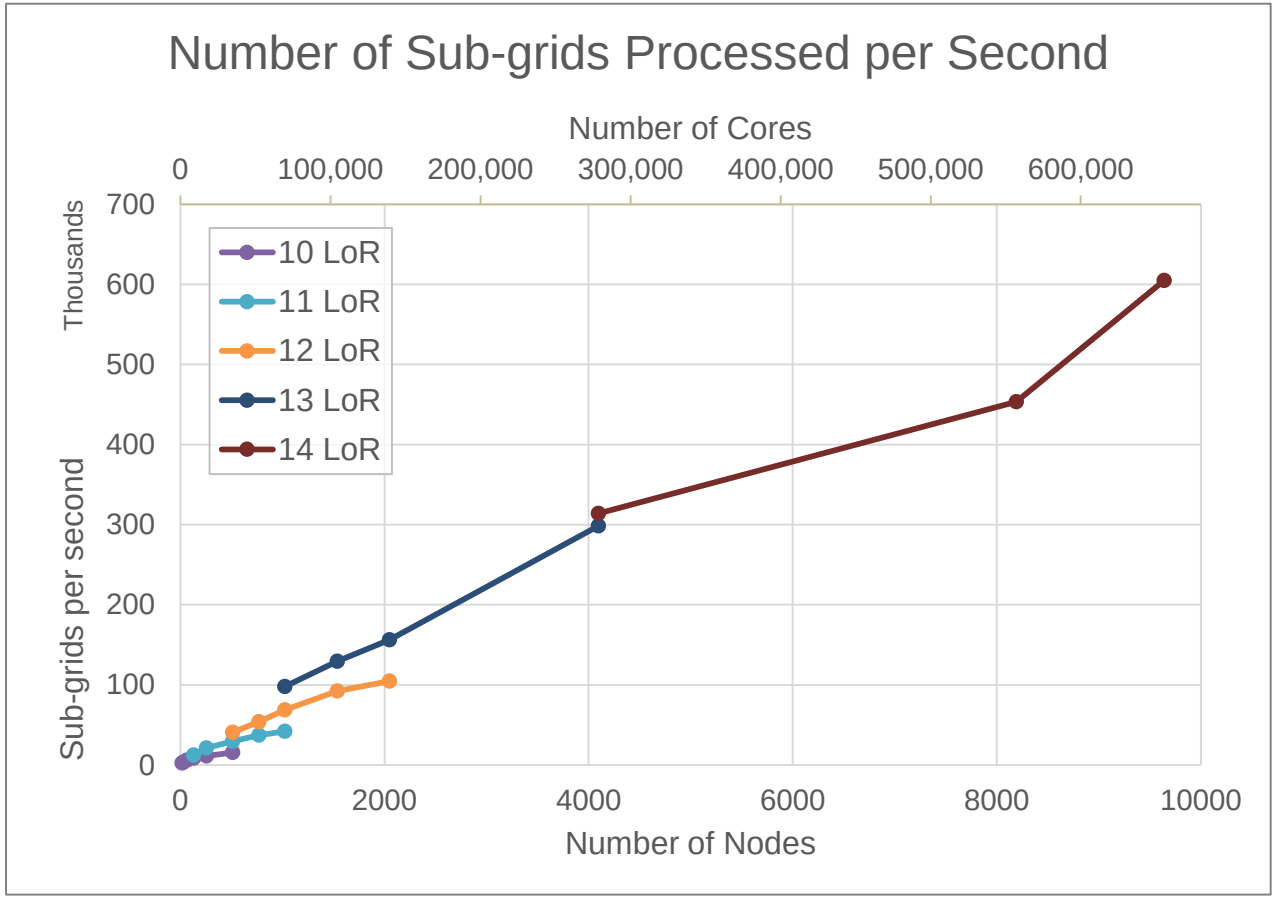

DB: X.0.silo
Cycle: 0
Time:1e-98
Contour
Var: rho
100
10
1
0.1
0.01
Max: 2.606e+04
Min: 1.000e-15

Adaptive Mesh Refinement



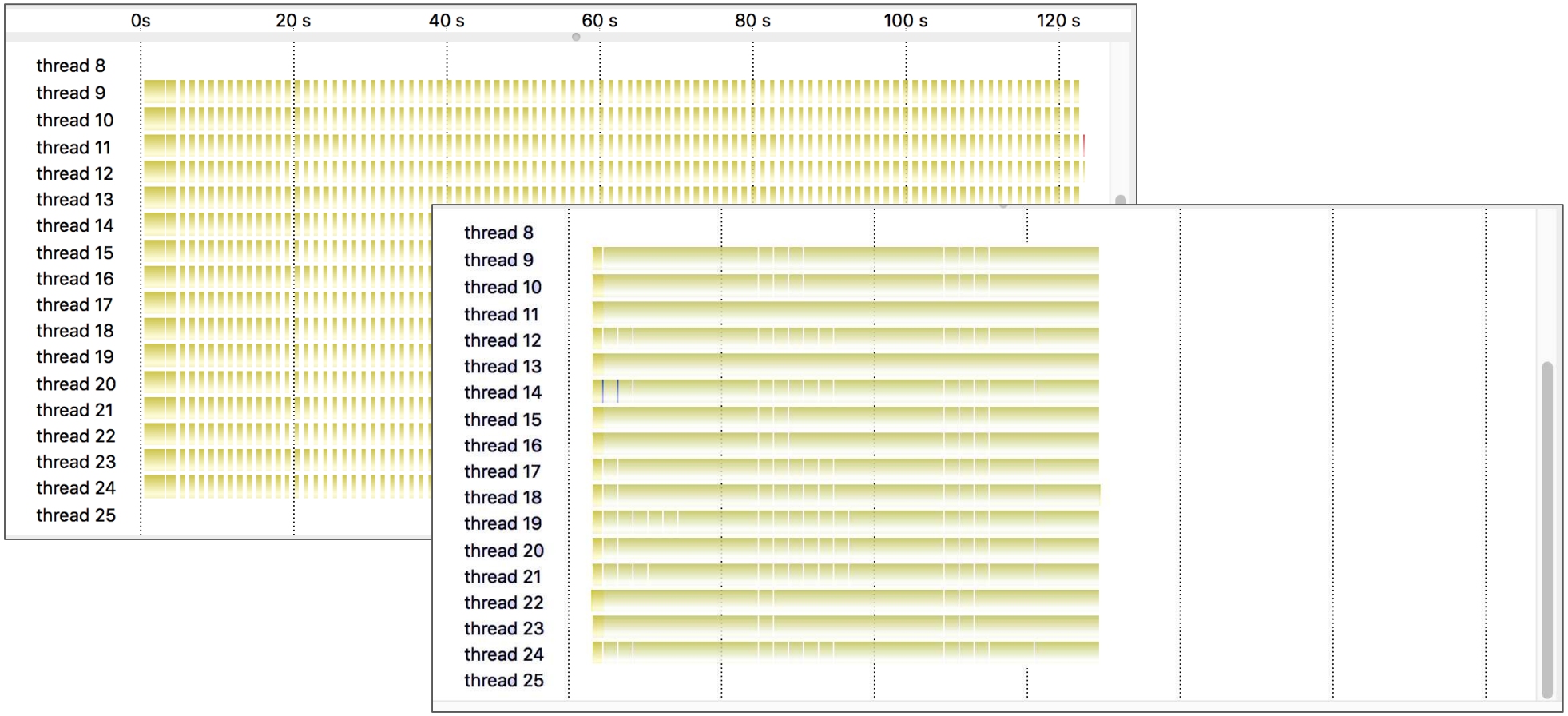
Cori II (NERSC)

Adaptive Mesh Refinement

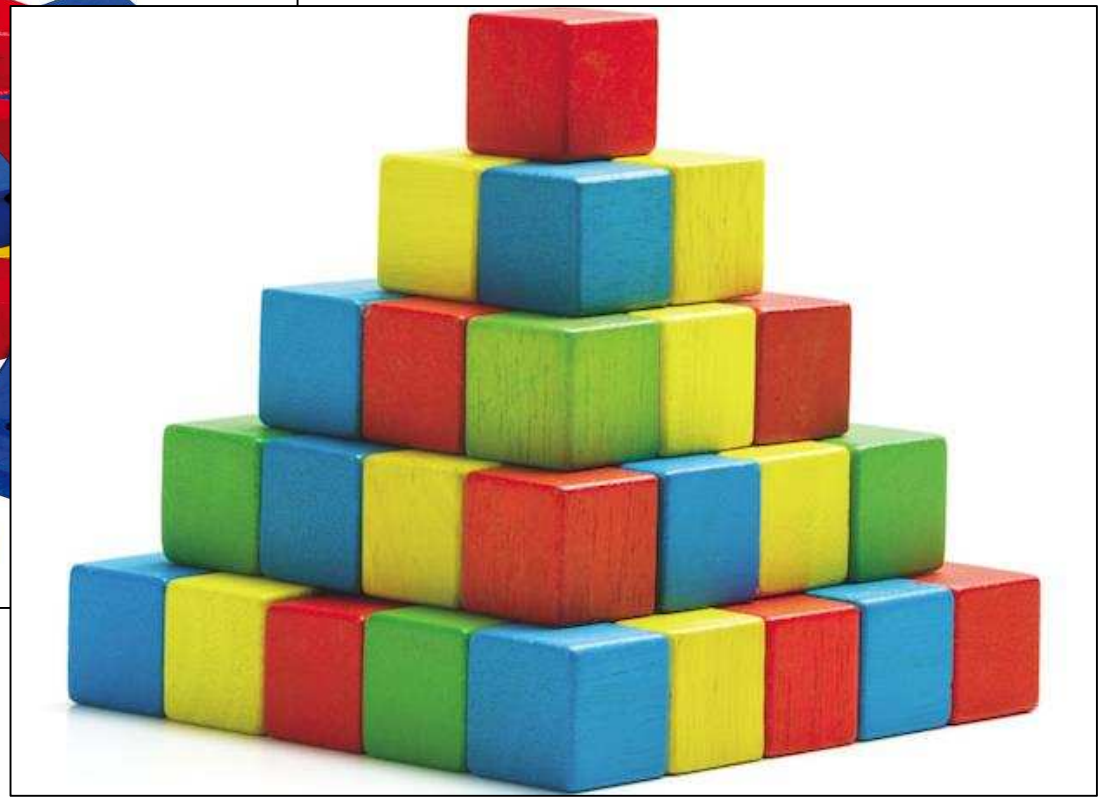


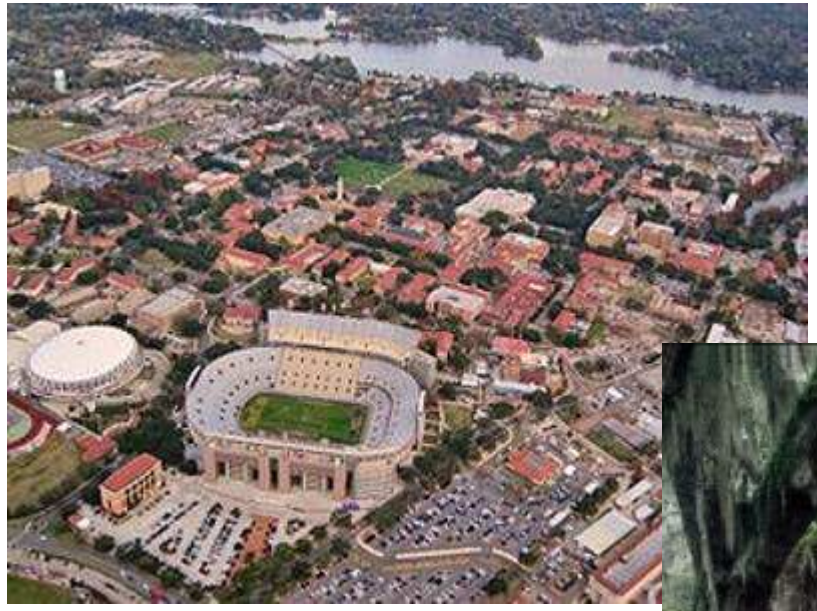
Cori II (NERSC)

The Solution to the Application Problem



The Solution to the Application Problem





LSU CENTER FOR COMPUTATION & TECHNOLOGY

STE||AR GROUP

HPX + Cling + Jupyter

This tutorial works in a special Jupyter notebook that can be used in one of two ways:

- From this website: https://hpx-jupyter.cct.lsu.edu (https://hpx-jupyter.cct.lsu.edu)
- From the docker image: stevenrbrandt/fedora-hpx-cling
- Normally, each cell should contain declarations, e.g. definitions of functions, variables, or `#include` statements.

  ```#include using namespace std;```
- If you wish to process an expression, e.g. `cout << "hello world\n"` you can put `.expr` at the front of the cell.

  ```.expr cout << "hello, world\n";```
- Sometimes you will want to test a cell because you are uncertain whether it might cause a segfault or some other error that will kill your kernel. Othertimes, you might want to test a definition without permanently adding it to the current namespace. You can do this by prefixing your cell with `.test`. Whatever is calculated in a test cell will be thrown away after evaluation and will not kill your kernel.

  ```.test.expr int foo[5]; foo[10] = 1;```
  ## Docker Instructions
- Frist, install Docker on your local resource
- Second, start Docker, e.g. `sudo service docker start`
- Third, run the fedora-hpx-cling container, e.g.

  ```$docker pull stevenrbrandt/fedora-hpx-cling$ docker run -it -p 8000:8000 stevenrbrandt/fedora-hpx-cling```

  After you do this, docker will respond with something like

  `http://0.0.0.0:8000/?token=5d1eb8a4797851910de481985a54c2fdc3be80280023bac5`

  Paste that URL into your browser, and you will be able to interact with the notebook.
- Fourth, play with the existing ipynb files or create new ones.
- Fifth, save your work! This is an important step. If you simply quit the container, everything you did will be lost. To save your work, first find your docker image using `docker ps`.

  ```$ docker ps CONTAINER ID IMAGE COMMAND CREATED STATUS PORTS NAMES 4f806b5f4fb3 stevenrbrandt/fedora-hpx-cling "/bin/sh -c 'jupyter " 11 minutes ago Up 11 minutes 0.0.0.0:8000->8000/tcp dreamy_turing```

  Once you have it (in this case, it's 4f806b5f4fb3), you can use `docker cp` to transfer files to or from your image.

  ```$docker cp 4f806b5f4fb3:/home/jup/HPX_by_example.ipynb. docker cp HPX_by_example.ipynb 4f806b5f4fb3:/home/jup```

```
In [1]: #include <hpx/hpx.hpp>

Out[1]:
```

In [2]:
```
using namespace std;
using namespace hpx;
```

Out[2]:

What is a (the) Future?

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

In [3]:
```
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
}
```

Out[3]:

If we want to do something other than a declaration, use the ".expr" prefix.

In [4]:
```
.expr deep_thought()
```

```
42
```

Out[4]:

Compositional Facilities

In [5]:
```
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;
}
```

Out[5]:

In [6]:
```
.expr cout << make_string().get() << endl;
```

```
123
```

Out[6]:

In [7]:
```
int do_work(hpx::lcos::future<hpx::util::tuple<hpx::lcos::future<int>,
      hpx::lcos::future<std::basic_string<char> > > >& w) {
  // extract the value of the first argument.
  return hpx::util::get<0>(w.get()).get();
}

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

  auto all_f = when_all(future1,future2);

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

Out[7]:

In [8]:
```
.test.expr cout << test_when_all().get() << endl;
```

```
125
```

```
Test
```

Out[8]:

Parallel Algorithms

HPX allows you to write loop parallel algorithms in a generic fashion, applying to specify the way in which parallelism is achieved (i.e. threads, distributed, cuda, etc.) through polcies.

In [9]:
```
#include <hpx/include/parallel_for_each.hpp>
#include <hpx/parallel/algorithms/transform.hpp>
#include <boost/iterator/counting_iterator.hpp>
```

Out[9]:

In [10]:
```
vector<int> v = { 1, 2, 3, 4, 5, 6 };
```

Out[10]:

Transform

Here we demonstrate the transformation of a vector, and the various mechnanisms by which it can performed in parallel.

In [11]:
```
.expr
// This parallel tranformation of vector v
// is done using thread parallelism. An
// implicit barrier is present at the end.
parallel::transform (
  parallel::execution::par,
  begin(v), end(v), begin(v),
  [](int i) -> int
  {
    return i+1;
  });
for(int i : v) cout << i << ",";
```

```
2,3,4,5,6,7,
```

Out[11]:

In [12]:
```
.expr
// This parallel tranformation of vector v
// is done using thread parallelism. There
// is no implicit barrier. Instead, the
// transform returns a future.
auto  f = parallel::transform (
  parallel::par (parallel::execution::task),
  begin(v), end(v), begin(v),
  [](int i) -> int
  {
    return i+1;
  });
  // work here...
// wait for the future to be ready.
f.wait();

for(int i : v) cout << i << ",";
```

```
3,4,5,6,7,8,
```

Out[12]:

In [13]:
```
#include <hpx/include/parallel_fill.hpp>
#include <hpx/include/compute.hpp>
#include <hpx/include/parallel_executors.hpp>
```

Out[13]:

In [14]:
```
auto host_targets = hpx::compute::host::get_local_targets();
typedef hpx::compute::host::block_executor<> executor_type;
executor_type exec(host_targets);
```

Out[14]:

In [15]:
```
.expr
// Print out a list of the localities, i.e. hosts
// that can potentially be involved in this calculation.
// This notebook will probably show 1, alas.
for(auto host : host_targets)
  cout << host.get_locality() << endl;
```

```
{0000000100000000, 0000000000000000}
```

Out[15]:

Other Algorithms

There are a great many algorithms. Here we demonstrate a handful of them.

In [16]:
```
.expr
std::vector<float> vd;
for(int i=0;i<10;i++) vd.push_back(1.f);
parallel::fill(parallel::execution::par.on(exec),vd.begin(),vd.end(),
0.0f);
```

Out[16]:

In [17]:
```
#include <hpx/parallel/algorithms/reverse.hpp>
```

Out[17]:

In [18]:
```
.expr
std::vector<float> vd;
for(int i=0;i<10;i++) vd.push_back(1.f*i);
parallel::reverse(parallel::par,vd.begin(),vd.end());
for(int val : vd) cout << val << " ";
```

```
9 8 7 6 5 4 3 2 1 0
```

Out[18]:

In [19]:
```
#include <hpx/include/parallel_minmax.hpp>
```

Out[19]:

In [20]:
```
.expr
std::vector<float> vd;
for(int i=0;i<10;i++) vd.push_back(1.f*rand());
auto ptr = parallel::max_element(parallel::par,vd,std::less<float>());
for(float val : vd) cout << val << " ";
cout << endl << *ptr << endl;
```

```
8.02369e+08 1.63599e+09 1.60543e+09 3.22506e+08 4.34983e+08 1.87237e+0
9 2.04466e+09 1.82667e+09 1.27975e+09 1.95976e+09
2.04466e+09
```

Out[20]:

In [21]:
```
#include <hpx/traits/is_executor.hpp>
#include <hpx/include/parallel_executors.hpp>
```

Out[21]:

In [22]:
```
int count_async = 0;
struct test_async_executor
{
    typedef hpx::parallel::parallel_execution_tag execution_category;

    template <typename F, typename ... Ts>
    static hpx::future<typename hpx::util::result_of<F&&(Ts&&...)>::ty
pe>
    async_execute(F && f, Ts &&... ts)
    {
        ++count_async;
        return hpx::async(hpx::launch::async, std::forward<F>(f),
            std::forward<Ts>(ts)...);
    }
};
```

Out[22]:

In [23]:
```
// Note that the exact way to specify this trait for an executor is in
 flux
// and the code here is tied to the specific version of HPX on the tes
t machine.
namespace hpx { namespace traits
{
    template<>
    struct is_two_way_executor<test_async_executor>
      : std::true_type
    {};
}}
```

Out[23]:

In [24]:
```
.test.expr
// This parallel tranformation of vector v
// is done using using distributed parallelism.
test_async_executor e;
parallel::transform (
  parallel::execution::par.on(e),
  begin(v), end(v), begin(v),
  [](int i) -> int
  {
    return i+1;
  });
cout << "count=" << count_async << endl;
```

```
count=3
```

```
Test
```

Out[24]:

Let’s Parallelize It – Adding Real Asynchrony

Here we take a step back. Instead of using a pre-designed parallel operation on a vector, we instead introduce task-level parallelism to an existing program.

Calculate Fibonacci numbers in parallel (1st attempt)

In [25]:
```
uint64_t fibonacci(uint64_t n)
{
  // if we know the answer, we return the value
  if (n < 2) return n;
  // asynchronously calculate one of the sub-terms
  future<uint64_t> f = async(launch::async, &fibonacci, n-2);
  // synchronously calculate the other sub-term
  uint64_t r = fibonacci(n-1);
  // wait for the future and calculate the result
  return f.get() + r;
}
```

Out[25]:

In [26]:
```
.expr cout << fibonacci(10) << endl;
```

```
55
```

Out[26]:

Let’s Parallelize It – Introducing Control of Grain Size

Parallel calculation, switching to serial execution below given threshold

In [27]:
```
const int threshold = 20;

uint64_t fibonacci_serial(uint64_t n)
{
  if (n < 2) return n;
  uint64_t f1 = fibonacci_serial(n-2);
  uint64_t f2 = fibonacci_serial(n-1);
  return f1 + f2;
}

uint64_t fibonacci2(uint64_t n)
{
  if (n < 2) return n;
  if (n < threshold) return fibonacci_serial(n);
  // asynchronously calculate one of the sub-terms
  future<uint64_t> f = async(launch::async, &fibonacci2, n-2);
  // synchronously calculate the other sub-term
  uint64_t r = fibonacci2(n-1);
  // wait for the future and calculate the result
  return f.get() + r;
}
```

Out[27]:

In [28]:
```
.expr cout << fibonacci2(22) << endl;
```

```
17711
```

Out[28]:

Let’s Parallelize It – Apply Futurization

Parallel way, futurize algorithm to remove suspension points

In [29]:
```
future<uint64_t> fibonacci3(uint64_t n)
{
  if(n < 2) return make_ready_future(n);
  if(n < threshold) return make_ready_future(fibonacci_serial(n));

  future<uint64_t> f = async(launch::async, &fibonacci3, n-2);
  future<uint64_t> r = fibonacci3(n-1);

  return dataflow(
    [](future<uint64_t> f1, future<uint64_t> f2) {
      return f1.get() + f2.get();
    },
    f, r);
}
```

Out[29]:

In [30]:
```
.expr cout << fibonacci3(22).get() << endl;
```

```
17711
```

Out[30]:

Let’s Parallelize It – Unwrap Argument Futures

In [31]:
```
#include <hpx/util/unwrapped.hpp>

using hpx::util::unwrapping;

future<uint64_t> fibonacci4(uint64_t n)
{
  if(n < 2) return make_ready_future(n);
  if(n < threshold) return make_ready_future(fibonacci_serial(n));

  future<uint64_t> f = async(launch::async, &fibonacci4, n-2);
  future<uint64_t> r = fibonacci4(n-1);

  return dataflow(
    unwrapping([](uint64_t f1, uint64_t f2) {
      return f1+f2;
    }),
    f, r);
}
```

Out[31]:

In [32]:
```
.expr cout << fibonacci4(22).get() << endl;
```

```
17711
```

Out[32]:

Excercise: Parallelize a sort

Test what you've learned. See if you can speed up the quicksort program below by find a place to:

1. parallelize the code with async
2. use parallel transforms

In [33]:
```
#include <unistd.h>
#include <stdlib.h>
#include <iostream>
#include <vector>
#include <functional>
using namespace std;
function<void(vector<int>&)> myqsort = [](vector<int>& v)->void {};
```

Out[33]:

Discussion

We want to define the myqsort function repeatedly, and call it recursively. This is hard to do in C++. So we define it as a std::function<>. There is a slight awkwardness to this. If you want to call myqsort() with an async function, you have to do it like this:

```
auto f = hpx::async([&arg](){ myqsort(arg); });
```

Not like this

```
auto f = hpx::async(myqsort,arg);
```

In [42]:
```
.test.expr
myqsort = [](vector<int>& v)->void {
  if(v.size()<2) return;
  vector<int> pre, eq, post;
  int pivot = v[rand() % v.size()];
  for(int val : v) {
    if(val < pivot) pre.push_back(val);
    else if(pivot < val) post.push_back(val);
    else eq.push_back(val);
  }
  myqsort(pre);
  myqsort(post);
  //for(int i=0;i<eq.size();i++) v[i+pre.size()] = eq[i];
  parallel::transform(parallel::par,
    eq.begin(), eq.end(), v.begin()+pre.size(),[](int i) { return i;
});
  for(int i=0;i<post.size();i++) v[i+pre.size()+eq.size()] = post[i];
  for(int i=0;i<pre.size();i++) v[i] = pre[i];
};
vector<int> vv{20};
for(int i=0;i<20;i++) vv.push_back(rand() % 100);
for(int val : vv) cout << val << " ";
cout << endl;
myqsort(vv);
for(int val : vv) cout << val << " ";
cout << endl;
```

```
20 26 32 84 5 66 50 81 7 5 53 69 45 84 94 59 21 80 96 17 6
5 5 6 7 17 20 21 26 32 45 50 53 59 66 69 80 81 84 84 94 96
```

Test

Out[42]:

The Wave Equation

This problem file sets up a very simple physical system, a wave propagating in one dimension. It is a nice example because it requires several loops in sequence and presents an opportunity to practice creating and using HPX parallel algorithms.

In [1]:
```
#include <hpx/hpx.hpp>
#include <vector>
#include <hpx/include/parallel_for_each.hpp>
#include <hpx/parallel/algorithms/transform.hpp>
#include <boost/iterator/counting_iterator.hpp>
```

Out[1]:

Basic Variables

We are going to evolve two variables, phi and psi on a grid described by N, dx, and x_0. The system of equations we will solve is

$\partial_t \phi = c \partial_x \psi$

$\partial_t \psi = c \partial_x \phi$

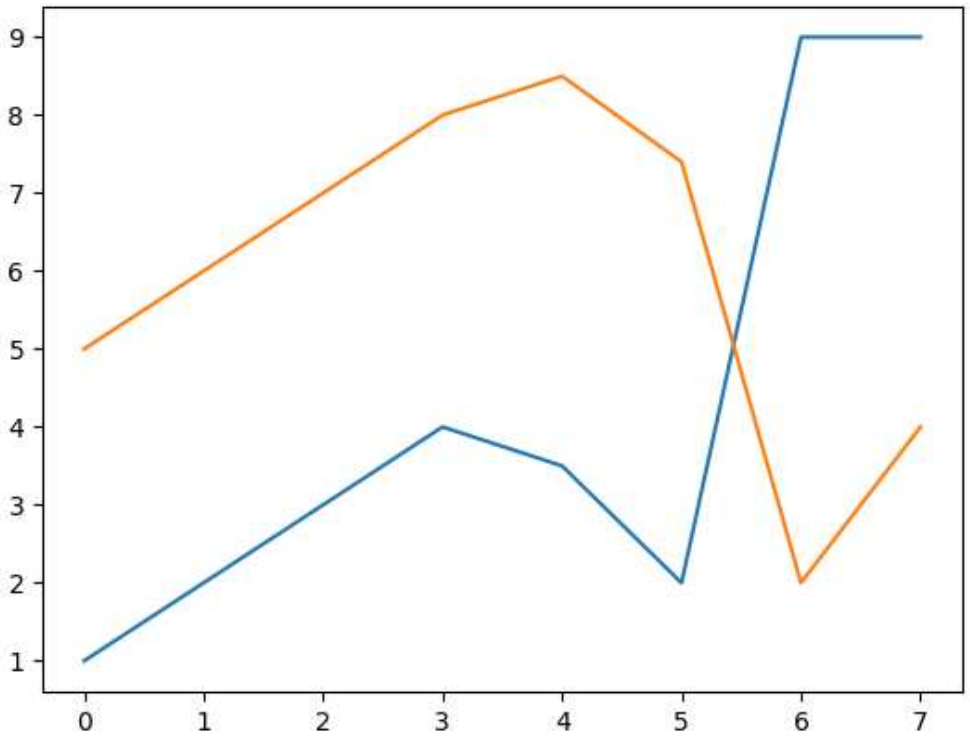
In [2]:
```
const int N = 300;
std::vector<double> phi(N),psi(N);
const double dx = 0.01, x0 = -1.5;
```

Out[2]:

In [3]:
```
#include <fstream>
#include <sstream>
#include <iostream>
#include <vector>
#include <content.hpp>

/**
 * The following function plots an array of vectors
 * of doubles in a single overlapping plot.
 */
void plot_vector(std::vector<std::vector<double>> v,std::string iname)
 {
  // Store the data in a text file
  const char *fname = "data.txt";
  std::ofstream o(fname);
  for(int n=0;n<v.size();n++) {
    const std::vector<double>& vv = v[n];
    for(int i=0;i<vv.size();i++) {
      if(i > 0) o << ' ';
      o << i;
    }
    o << std::endl;
    for(int i=0;i<vv.size();i++) {
      if(i > 0) o << ' ';
      o << vv[i];
    }
    o << std::endl;
  }
  o.close();

  // Create a python script to run matplotlib
  std::ostringstream cmd;
  cmd << "import matplotlib\n";
  cmd << "matplotlib.use('Agg')\n";
  cmd << "import numpy as np\n";
  cmd << "import matplotlib.pyplot as plt\n";
  cmd << "f = np.genfromtxt('" << fname << "')\n";
  cmd << "plt.figure()\n";
  cmd << "for n in range(0,f.shape[0],2):\n";
  cmd << "  plt.plot(f[n,:],f[n+1,:])\n";
  cmd << "plt.savefig('" << iname << ".png')\n";
  cmd << "exit(0)\n";
  std::ofstream o2("p.py");
  o2 << cmd.str();
  o2.close();
  system("python3 p.py");

  // Create the html. The pid is added to prevent caching.
  // Note that the pid changes with every cell with the
  // current implementation of HPX/cling.
  std::ostringstream html;
  html << "<img src='" << iname << ".png?pid=" << getpid() << "-" << r
and() << "'>";
  std::string htmls = html.str();
  create_content(htmls.c_str());
}
```

Out[3]:

In [4]:
```
.expr
// What follows is a random test of the plot function.
std::vector<double> v1 = {1,2,3,4,3.5,2,9,9};
std::vector<double> v2 = {5,6,7,8,8.5,7.4,2,4};
std::vector<std::vector<double>> plots;
plots.push_back(v1);
plots.push_back(v2);
plot_vector(plots,"test");
```



Out[4]:

In [8]:
```
// This version of plot_vector plots a single vector only.
void plot_vector(const std::vector<double>& v) {
  std::vector<std::vector<double>> vv;
  vv.push_back(v);
  plot_vector(vv,"vec");
}
```

Out[8]:

In [9]:
```
// Apply boundary conditions. In this case, we are using periodic boun
dary
// conditions, i.e. if we move N-2 points to the right we come back to
 where we were.
void boundary(std::vector<double>& vv) {
    const int n = vv.size();
    vv[0] = vv[n-2];
    vv[n-1] = vv[1];
}
```

Out[9]:

In [10]:
```
// The following are auxiliary variables which are required by our Run
ge-Kutta
// time integration scheme.
std::vector<double> phi2(N), psi2(N), phi3(N), psi3(N);
std::vector<double> k1_phi(N), k1_psi(N), k2_phi(N), k2_psi(N), k3_phi
(N), k3_psi(N);
```

Out[10]:

In [11]:
```
#include <hpx/include/parallel_for_each.hpp>
#include <hpx/parallel/algorithms/transform.hpp>
#include <boost/iterator/counting_iterator.hpp>
```

Out[11]:

The Wave Equation Evolution Code

The sequence of loops below will perform an evolution of the wave equation, essentially, a sine wave that propagates unchanged to the right. The important thing is not understanding the physics, but in parallelizing the loops and recognizing the dependencies between them.

As an example, the first loop is already parallelized with for_each. Note: You should be able to find a place to use parallel::execution::task.

In [15]:
```
.expr
std::vector<std::vector<double>> plots;
double t = 0.0,t_end = 1.0;
double t_every = t_end/10;
double t_plot = 0;
double dt = dx/2.0;

const double w = 1;
const double pi = 4.0*atan2(1.0,1.0);
const double k = 2.0*pi/(dx*(N-2));

const double c = w/k;
const double A = 1.0;
const double B = c*k*A/w; // == 1.0

// Initialize the physical variables
/*
```

```
for(int i=0;i<N;i++) {
   // psi = A*cos(k*x + w*t)
   // phi = B*cos(k*x + w*t)
   // d(phi)/dt = c*d(psi)/dx
   // w*B*sin(k*x + w*t) = c*k*A*sin(k*x + w*t)
   // B = -c*k*A/w
   // d(psi)/dt = c*d(phi)/dx
   // w*A*sin(k*x + w*t) = c*k*B*sin(k*x + w*t)
   double x = x0 + i*dx;
   phi[i] = B*sin(k*x);
   psi[i] = A*sin(k*x);
}
*/
hpx::parallel::for_each(
      hpx::parallel::par,
      boost::counting_iterator<int>(0),
      boost::counting_iterator<int>(N),
      [&]( int i ) {
   double x = x0 + i*dx;
   phi[i] = B*sin(k*x);
   psi[i] = A*sin(k*x);
});
while(t < t_end) {
  for(int i=1;i<N-1;i++) {
    k1_phi[i] = c*(psi[i+1]-psi[i-1])/(2*dx);
    k1_psi[i] = c*(phi[i+1]-phi[i-1])/(2*dx);
  }
  for(int i=1;i<N-1;i++) {
    phi2[i] = phi[i] + (1./3.)*dt*k1_phi[i];
    psi2[i] = psi[i] + (1./3.)*dt*k1_psi[i];
  }
  // the boundary routines can be parallelized also
  boundary(phi2);
  boundary(psi2);
  for(int i=1;i<N-1;i++) {
    k2_phi[i] = c*(psi2[i+1]-psi2[i-1])/(2*dx);
    k2_psi[i] = c*(phi2[i+1]-phi2[i-1])/(2*dx);
  }
  for(int i=1;i<N-1;i++) {
    phi3[i] = phi[i] + (2./3.)*dt*k1_phi[i];
    psi3[i] = psi[i] + (2./3.)*dt*k1_psi[i];
  }
  boundary(phi3);
  boundary(psi3);
  for(int i=1;i<N-1;i++) {
    k3_phi[i] = c*(psi3[i+1]-psi3[i-1])/(2*dx);
    k3_psi[i] = c*(phi3[i+1]-phi3[i-1])/(2*dx);
  }
  for(int i=1;i<N-1;i++) {
    phi[i] = phi[i] + 0.5*dt*(k2_phi[i]+k3_phi[i]);
    psi[i] = psi[i] + 0.5*dt*(k2_psi[i]+k3_phi[i]);
  }
  boundary(phi);
  boundary(psi);
  t += dt;
  t_plot += dt;
  if(t_plot >= t_every) {
```

Performance Analysis of HPX in Jupyter Notebooks using APEX

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http://github.com/khuck/xpress-apex

Download slides from: http://tau.uoregon.edu/SC17-HPX-APEX.pdf

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Install Docker image from USB

- Install Docker (if necessary)
- Insert USB key, open a terminal, navigate to key directory and:
- (sudo) docker load -i fedora-hpx-cling
- (sudo) docker pull stevenrbrandt/fedora-hpx-cling
- (sudo) docker run -it -p 8000:8000 stevenrbrandt/fedora-hpx-cling

- “sudo” may be necessary on some machines

Outline

- Introduction to APEX – *Autonomic Performance Environment for eXascale*
- Motivation, overview, API
- Integration with HPX
- Building HPX with APEX
- APEX event listeners
- Postmortem analysis of HPX applications
  - Gnuplot/Python visualizations of APEX data
  - OTF2 output to Vampir
  - Profile output to TAU

APEX Measurement : Motivation

- **Originally designed as a performance measurement library for distributed, asynchronous tasking models/runtimes**
  - i.e. HPX, but there are others
- **Why another measurement library?**
  - "not invented here" mentality? Reinventing the wheel? No.
- **New challenges:**
  - Lightweight measurement (tasks <1ms)
  - High concurrency (both OS threads and tasks in flight)
  - Distinction between OS and runtime (HPX) thread context
  - Lack of a traditional call stack
    - Task dependency chain instead
  - Runtime controlled task switching
  - ***Dynamic runtime control***

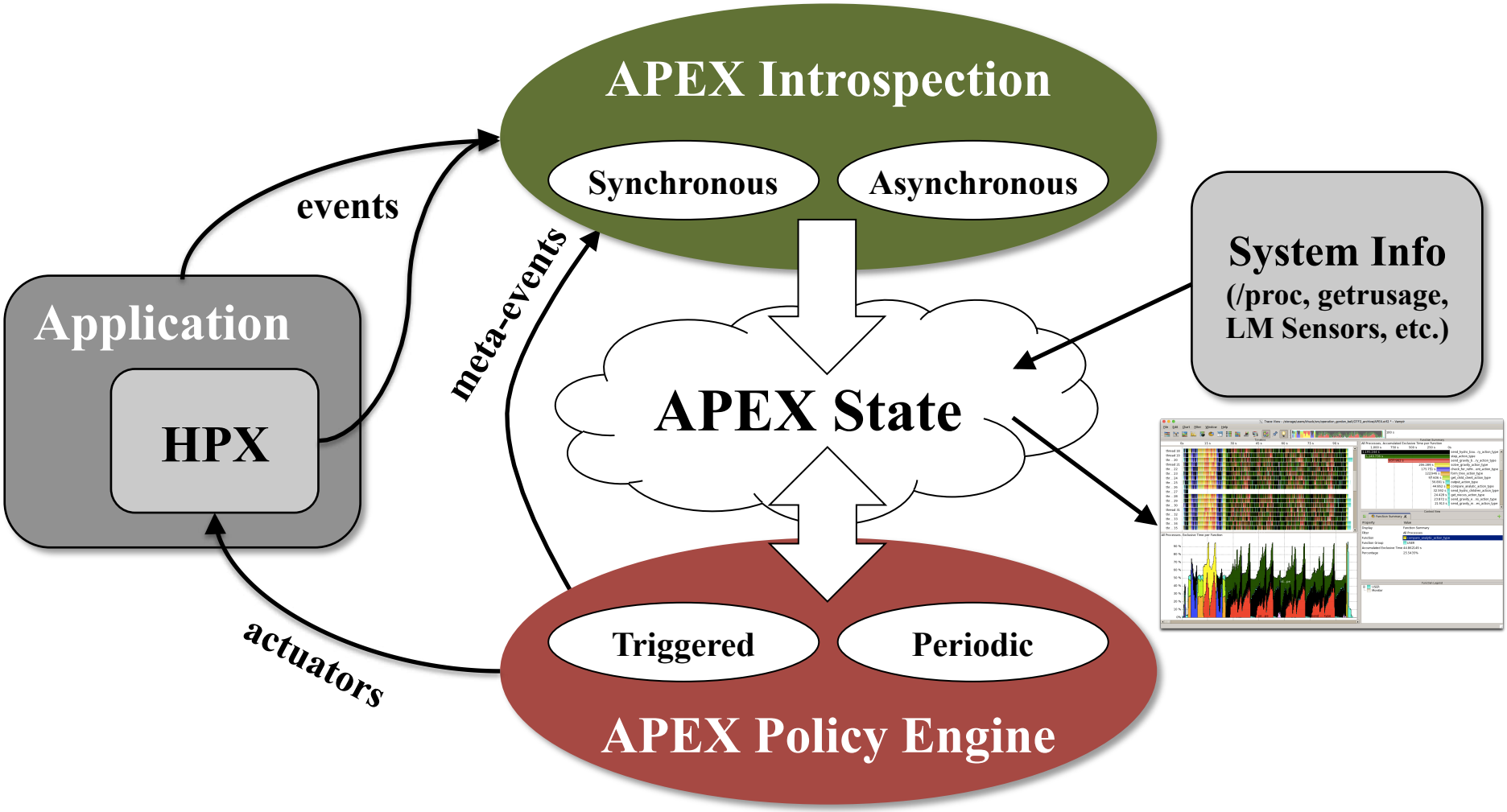
APEX Runtime Adaptation : Motivation

- **Controlling concurrency**
  - Energy efficiency
  - Performance
- **Parametric variability**
  - Granularity for this machine / dataset?
- **Load Balancing**
  - When to perform AGAS migration?
- **Parallel Algorithms (for_each…)**
  - Separate *what* from *how*
- **Address the "SLOW(ER)" performance model**

Introduction to APEX

- **Performance awareness and performance adaptation**
- **Top down** and **bottom up** performance mapping / feedback
  - Make node-wide resource utilization data and analysis, energy consumption, and health information available in real time
  - Associate performance state with policy for feedback control
- **APEX introspection**
  - OS: track system resources, utilization, job contention, overhead
  - Runtime (HPX): track threads, queues, concurrency, remote operations, parcels, memory management
  - Application timer / counter observation
- **Post-mortem performance analysis**
  - "secondary" goal, but has been useful
- **Integrated with HPX performance counters**

APEX architecture



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APEX Introspection

- **APEX collects data through "inspectors"**
  - *Synchronous* uses an event API and event "listeners"
    - Initialize, terminate, new thread – added to HPX runtime
    - Timer start, stop, yield*, resume* - added to HPX task scheduler
    - Sampled value (counters from HPX)
    - Custom events (meta-events)
  - *Asynchonous* do not rely on events, but occur periodically
- **APEX exploits access to performance data from lower stack components**
  - "Health" data through other interfaces (/proc/stat, cpuinfo, meminfo, net/dev, self/status, lm_sensors, power*, etc.)

APEX Measurement API (subset)

Starting Timers:

```
apex::profiler* apex::start(const string &name,
   void** data_ptr = 0LL);
apex::profiler* apex::start(const uint64_t
   address, void** data_ptr = 0LL);
apex::profiler* apex::resume(const string name,
   void** context = 0LL);
apex::profiler* apex::resume(const uint64_t
   address, void** context = 0LL);
```

Stopping Timers:

```
void apex::stop(apex::profiler* p);
void apex::yield(apex::profiler* p);
```

Sampling a counter:

```
void apex::sample_value(const string name,
   double value);
```


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- Note about yield, resume – exist for accurate counting of “number of calls” in the face of pre-emption (usually handled by HPX scheduler):

Timer Start Command	Timer Stop Command	Call count is increased by:
apex::start()	apex::stop()	1
apex::start()	apex::yield()	0
apex::resume()	apex::yield()	0
apex::resume()	apex::stop()	0

APEX Measurement API example

```
void foo(int x) {
  // sample the argument, for example
  apex::sample_counter("foo(x)", x);
  // start a timer
  apex::profiler* p = apex::start(&foo);
  /* do some work in function foo */
  ...
  // stop the current timer to wait on some asynchronous subtask
  apex::yield(p);
  /* wait on result from "subtask" */
  result = some_future.get();
  // "resume" the APEX timer
  p = apex::start(&foo);
  /* do some more work in function foo */
  ...
  // stop the timer
  apex::stop(p);
}
```


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HPX and APEX - Integration

- In HPX, all tasks scheduled by the thread scheduler are “automatically” timed − with some caveats
- HPX registered actions are automatically timed
- All threads/tasks are timed, attribution is the required user intervention
  - Asynchronous functions, direct actions are correctly attributed if wrapped with an `hpx::util::annotated_function` object.
  - See notebook examples for details

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Annotation examples:

```
// Forward declaration of the action
uint64_t fibonacci_a(uint64_t n);
// This is to generate the required boilerplate we need for the remote
// invocation to work.
HPX_PLAIN_ACTION(fibonacci_a, fibonacci_action);
/* ... */
future<uint64_t> n1 = async(fib, locality_id, n - 1);
```

```
using namespace hpx::util;
future<uint64_t> f = async(launch::async,
    annotated_function(unwrapping(&fibonacci3), "fibonacci3"), n-2);
```


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APEX Event Listeners

- **Profiling listener**
  - Start event: input name/address, get timestamp, return profiler handle
  - Stop event: get timestamp, put profiler object in a queue for back-end processing, return
  - Sample event: put the name & value in the queue
  - Asynchronous consumer thread: process profiler objects and samples to build statistical profile (in HPX, processed/scheduled as a thread/task)
  - Optional: screen/CSV output, build task scatterplot, build taskgraph, etc.
- **TAU Listener (postmortem analysis)**
  - Synchronously passes all measurement events to TAU to build an offline profile
- **OTF2 Listener (postmortem analysis)**
  - Synchronously passes all measurement events to libotf2 for trace analysis
- **Concurrency listener (postmortem analysis)**
  - Start event: push timer ID on stack
  - Stop event: pop timer ID off stack
  - Asynchronous consumer thread: periodically log current timer for each thread, output report at termination

APEX Policy Listener

- ***Policies*** are rules that decide on outcomes based on observed state
  - *Triggered* policies are invoked by introspection API events
  - *Periodic* policies are run periodically on asynchronous thread
- Polices are registered with the Policy Engine
  - Applications, runtimes, and/or OS register callback functions
- Callback functions define the policy rules
  - "If x < y then…"
- Enables runtime adaptation using introspection data
  - Feedback and control mechanism
  - Engages actuators across stack layers
  - Could also be used to involve online auto-tuning support*
    - Active Harmony http://www.dyninst.org/harmony

APEX Policy API (subset)

```
apex_event_type
    apex::register_custom_event(const
    string &name);
apex::custom_event(apex_event_type, void*
    event_data);
apex_tuning_session_handle
    apex::setup_custom_tuning(std::functio
    n<double(void)> metric,
    apex_event_type event_type, int
    num_inputs, long** inputs, long* mins,
    long* maxs, long* steps);
```


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APEX Policy API example

See last example in notebook:

```
apex::register_custom_event() in
    setup_counters()

apex::get_profile() (as potential
    exercise) in get_counter_value()

apex::setup_custom_tuning() in
    do_1d_solve_repart()
```


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Building HPX with APEX

$ cmake <usual HPX settings>…

-DHPX_WITH_APEX=TRUE \

-DAPEX_WITH_ACTIVEHARMONY=TRUE/FALSE \

-DAPEX_WITH_PAPI=TRUE/FALSE \

-DAPEX_WITH_MSR=TRUE/FALSE \

-DAPEX_WITH_OTF2=TRUE/FALSE \

…

$ make (as usual) i.e. “make –j 8 core examples tests”

APEX environment variables

APEX_DISABLE : 0
APEX_SUSPEND : 0
APEX_PAPI_SUSPEND : 0
APEX_PROCESS_ASYNC_STATE : 1
APEX_TAU : 0
APEX_POLICY : 1
APEX_MEASURE_CONCURRENCY : 0
APEX_MEASURE_CONCURRENCY_PERIOD : 1000000
APEX_SCREEN_OUTPUT : 1
APEX_PROFILE_OUTPUT : 0
APEX_CSV_OUTPUT : 0
APEX_TASKGRAPH_OUTPUT : 0
APEX_PROC_CPUINFO : 0
APEX_PROC_MEMINFO : 0
APEX_PROC_NET_DEV : 0
APEX_PROC_SELF_STATUS : 0
APEX_PROC_SELF_IO : 0
APEX_PROC_STAT : 1
APEX_PROC_PERIOD : 1000000

APEX_THROTTLE_CONCURRENCY : 0
APEX_THROTTLING_MAX_THREADS : 4
APEX_THROTTLING_MIN_THREADS : 1
APEX_THROTTLE_ENERGY : 0
APEX_THROTTLE_ENERGY_PERIOD : 1000000
APEX_THROTTLING_MAX_WATTS : 300
APEX_THROTTLING_MIN_WATTS : 150
APEX_PTHREAD_WRAPPER_STACK_SIZE : 0
APEX_OMPT_REQUIRED_EVENTS_ONLY : 0
APEX_OMPT_HIGH_OVERHEAD_EVENTS : 0
APEX_PIN_APEX_THREADS : 1
APEX_TASK_SCATTERPLOT : 1
APEX_POLICY_DRAIN_TIMEOUT : 1000
APEX_PAPI_METRICS :
APEX_PLUGINS :
APEX_PLUGINS_PATH : ./
APEX_OTF2 : 0
APEX_OTF2_ARCHIVE_PATH : OTF2_archive
APEX_OTF2_ARCHIVE_NAME : APEX

Note about environment variables…

- Some batch submission systems do not pass environment variables to the application without considerable effort
- APEX will read environment variables from $PWD/apex.conf file
- All variables also have API calls for getting/setting
  - Note: some are only effective at startup because they change/set the APEX configuration
    - i.e. APEX_DISABLE, APEX_TAU, APEX_PAPI_METRICS, …

Post-mortem output examples

Example Screen Output

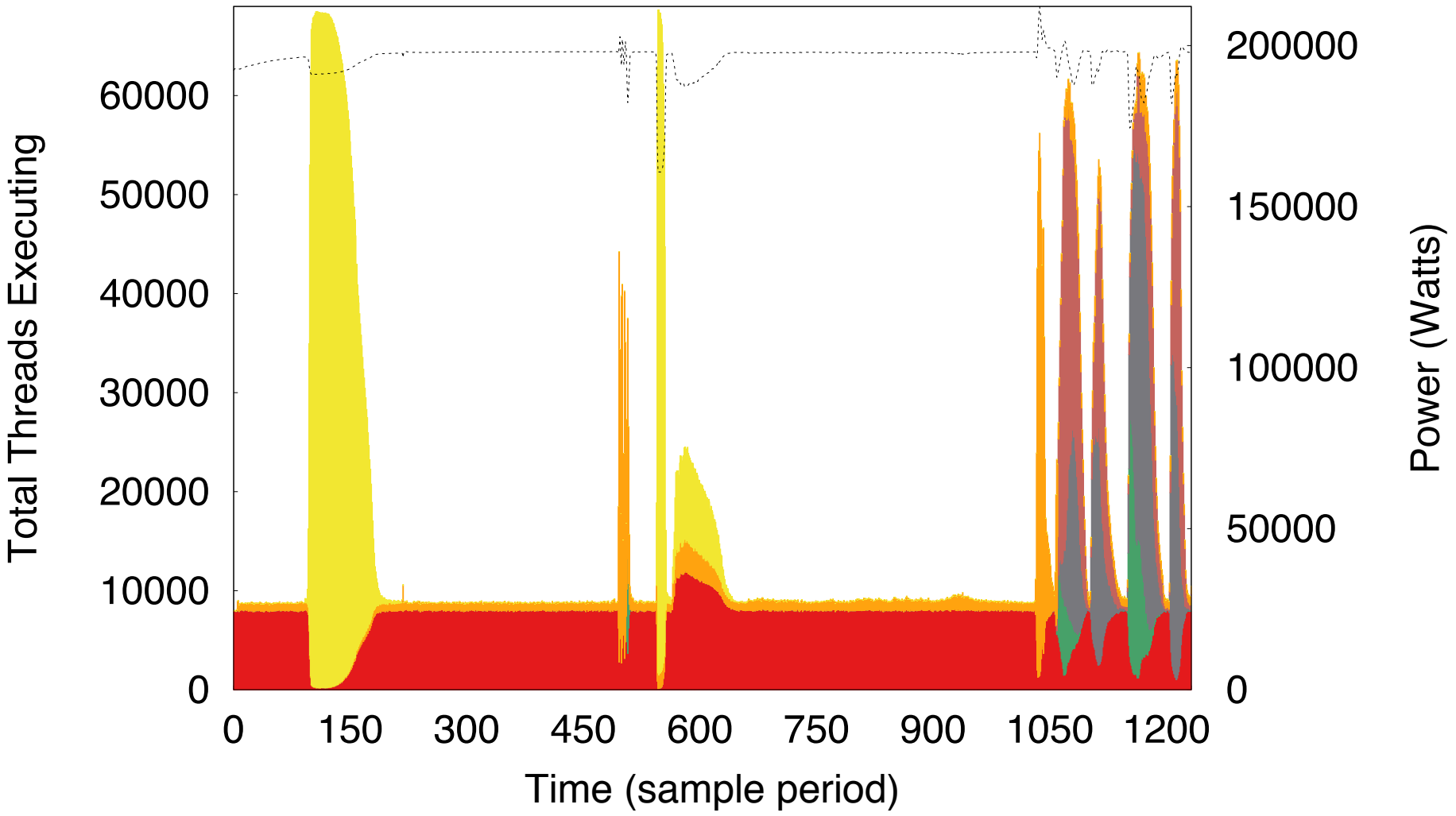
```
Elapsed time: 2.40514 seconds
Cores detected: 4
Worker Threads observed: 5
Available CPU time: 9.62057 seconds

Timer                                                :  #calls  |    mean  |   total  |  % total
-----------------------------------------------------------------------------------------------
                                  someThread(void*)  :       2   1.39e+00   2.79e+00     28.965
                                          foo(int)   :  131072   2.00e-05   2.63e+00     27.306
                bar(int, apex::profiler**, void**)   :  131072   9.69e-06   1.27e+00     13.198
                          someUntimedThread(void*)   :       2   1.12e+00   2.24e+00     23.271
                                              main   :       1   1.40e+00   1.40e+00     14.548
                                         APEX MAIN   :       1   2.41e+00   2.41e+00    100.000
-----------------------------------------------------------------------------------------------

                                        Total timers : 262,150
```

To enable:

`export APEX_SCREEN_OUTPUT=1`

or, call `apex::dump(bool reset);`

Concurrency View (before fix)



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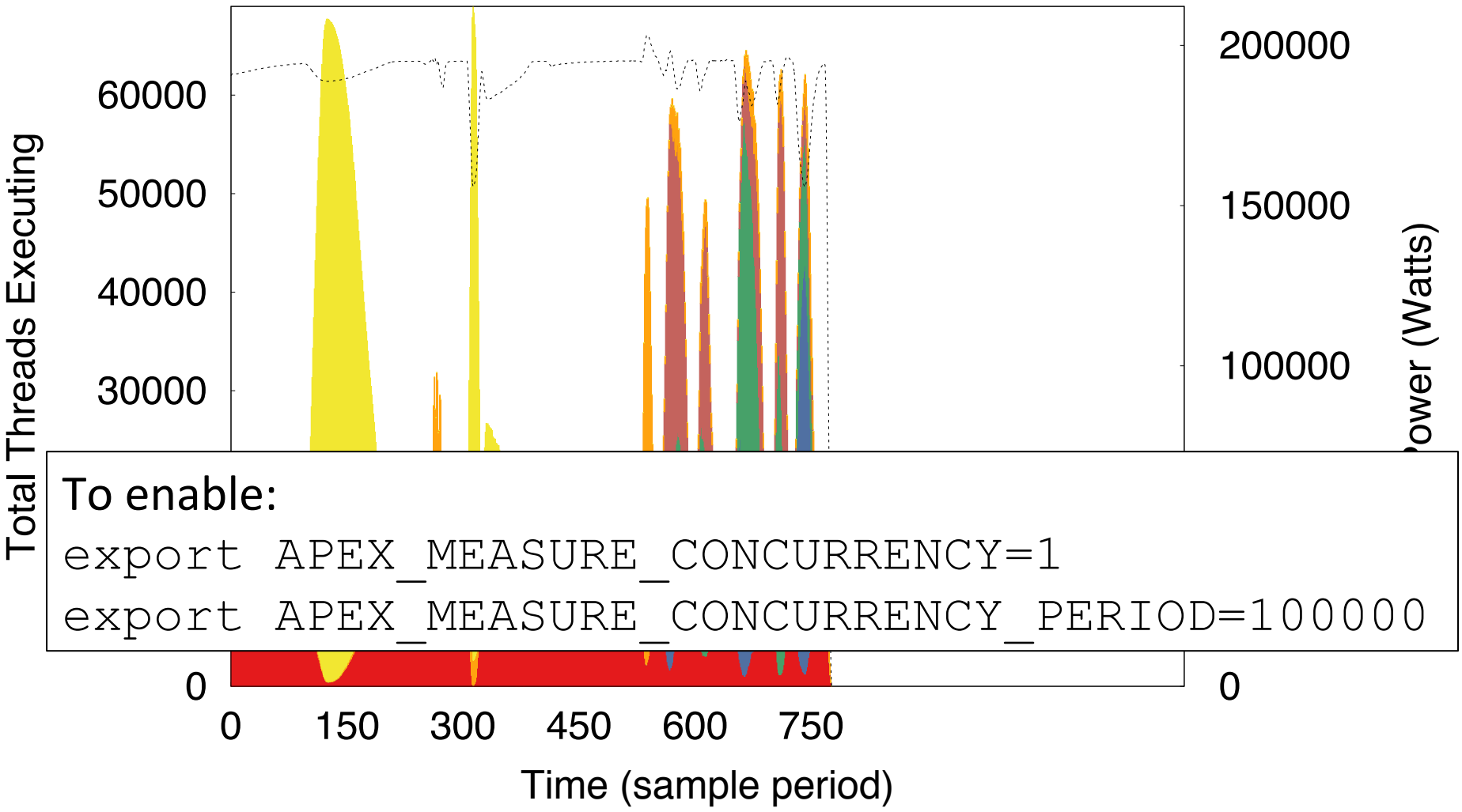
Concurrency View (after fix)



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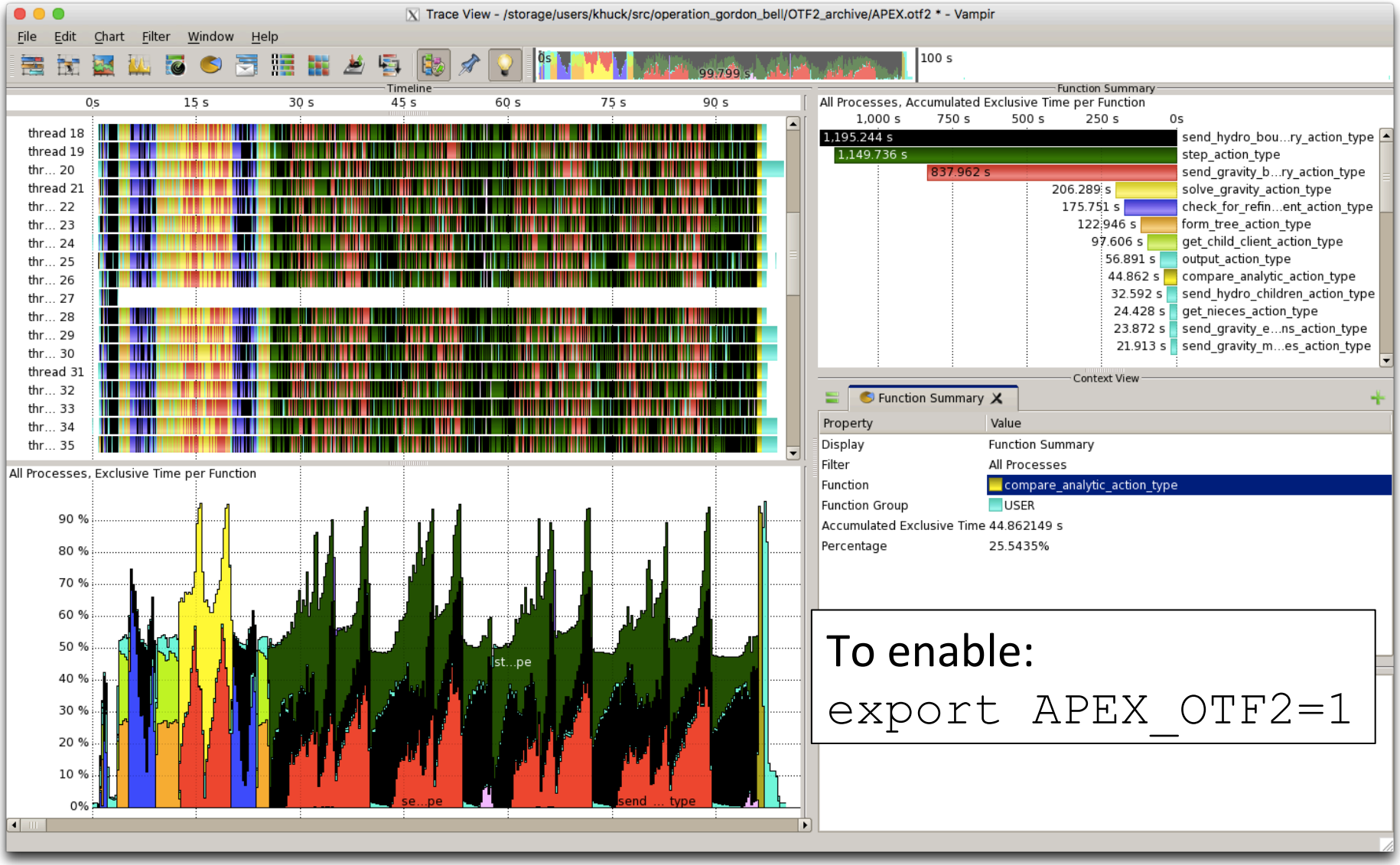
OTF2 View in Vampir



To enable:

```
export APEX_OTF2=1
```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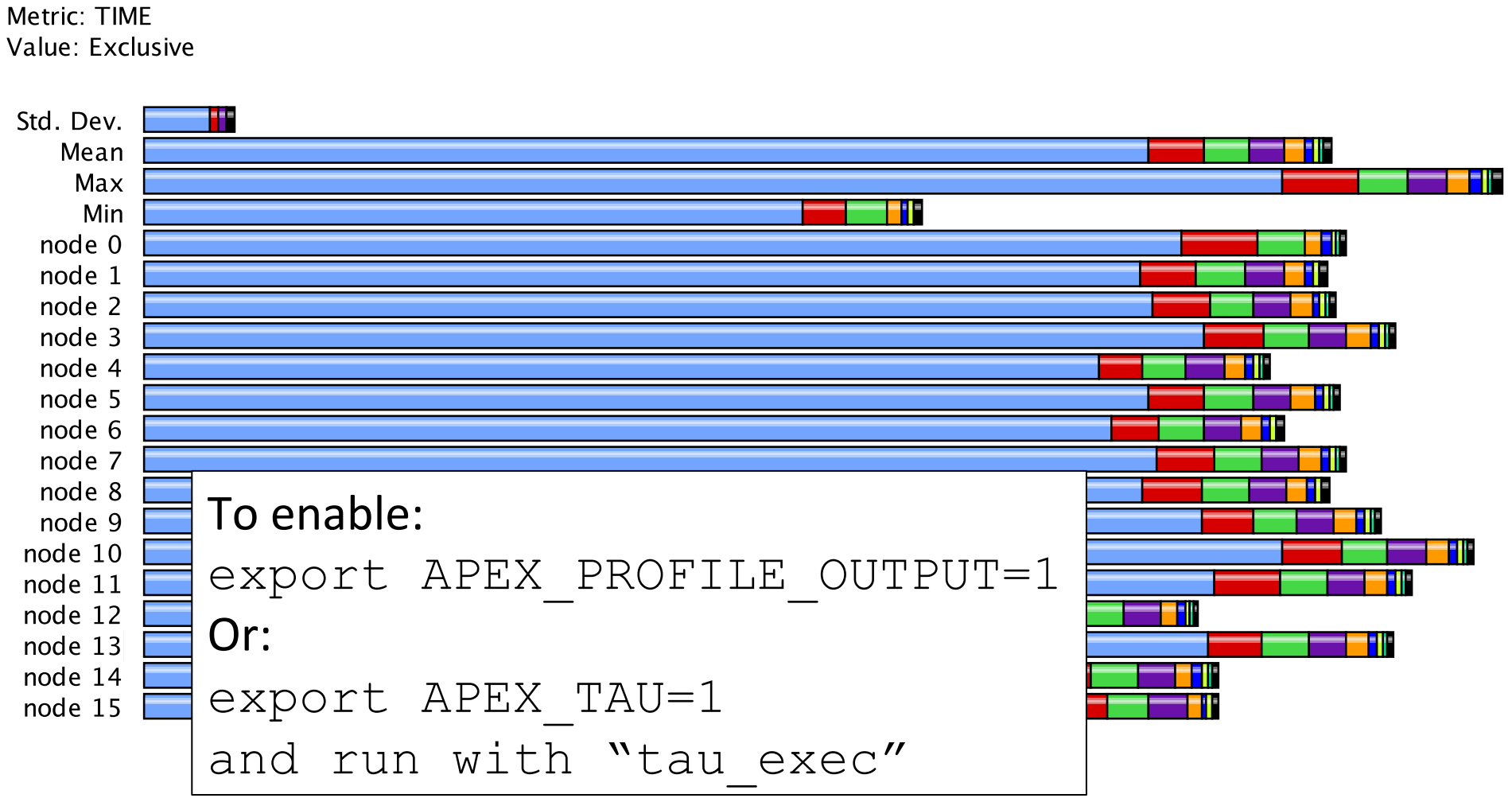
Profile View in TAU ParaProf



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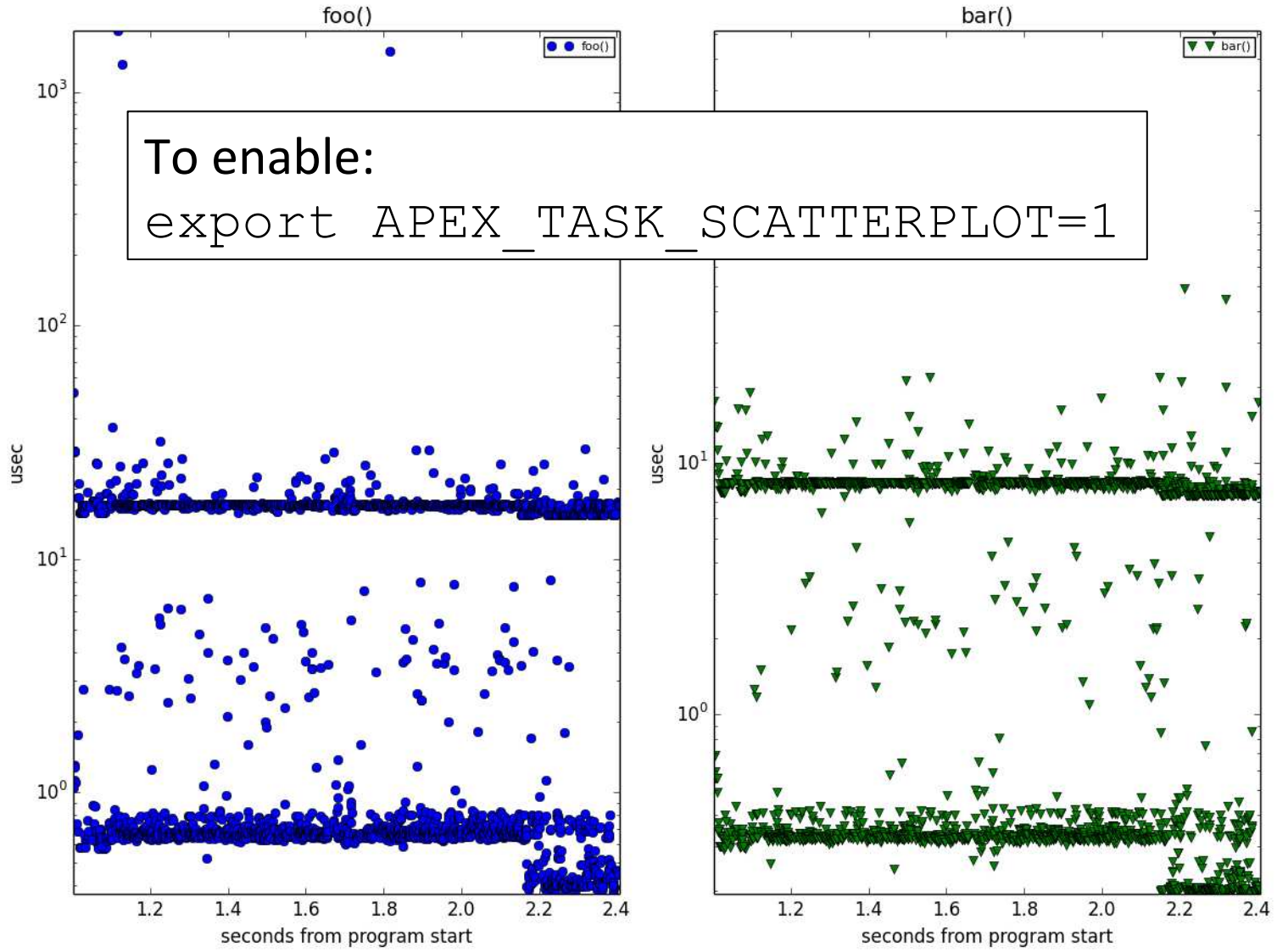
Task Scatterplot Analysis (prototype)



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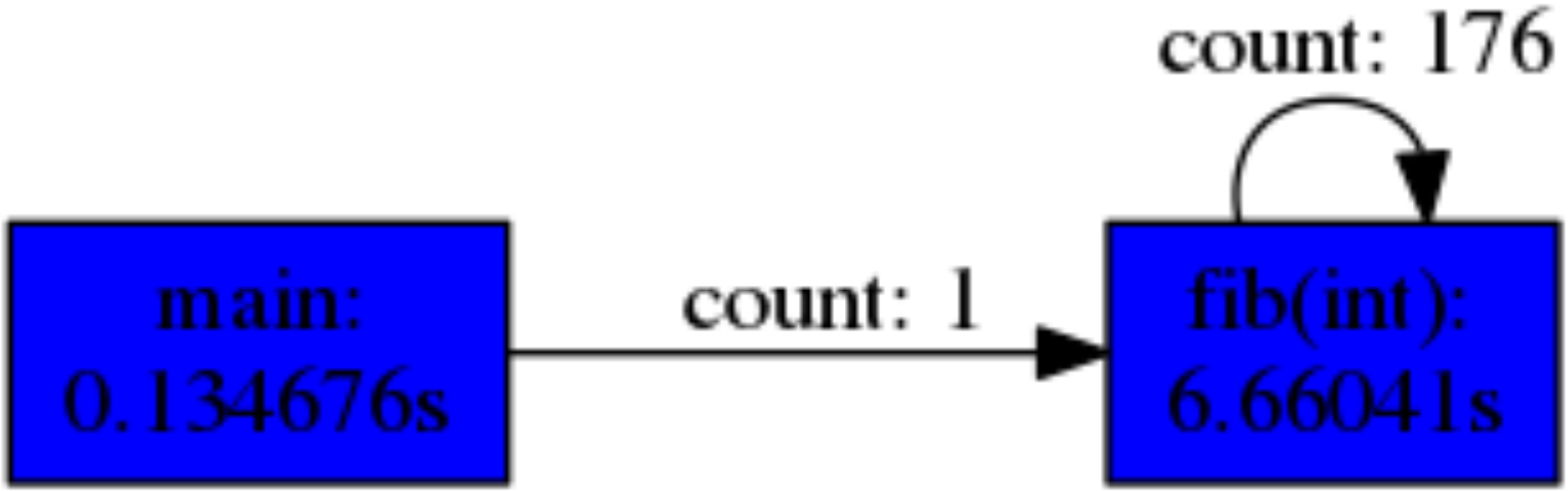
Taskgraph View (prototype)

To enable:

```
export APEX_TASKGRAPH_OUTPUT=1
```



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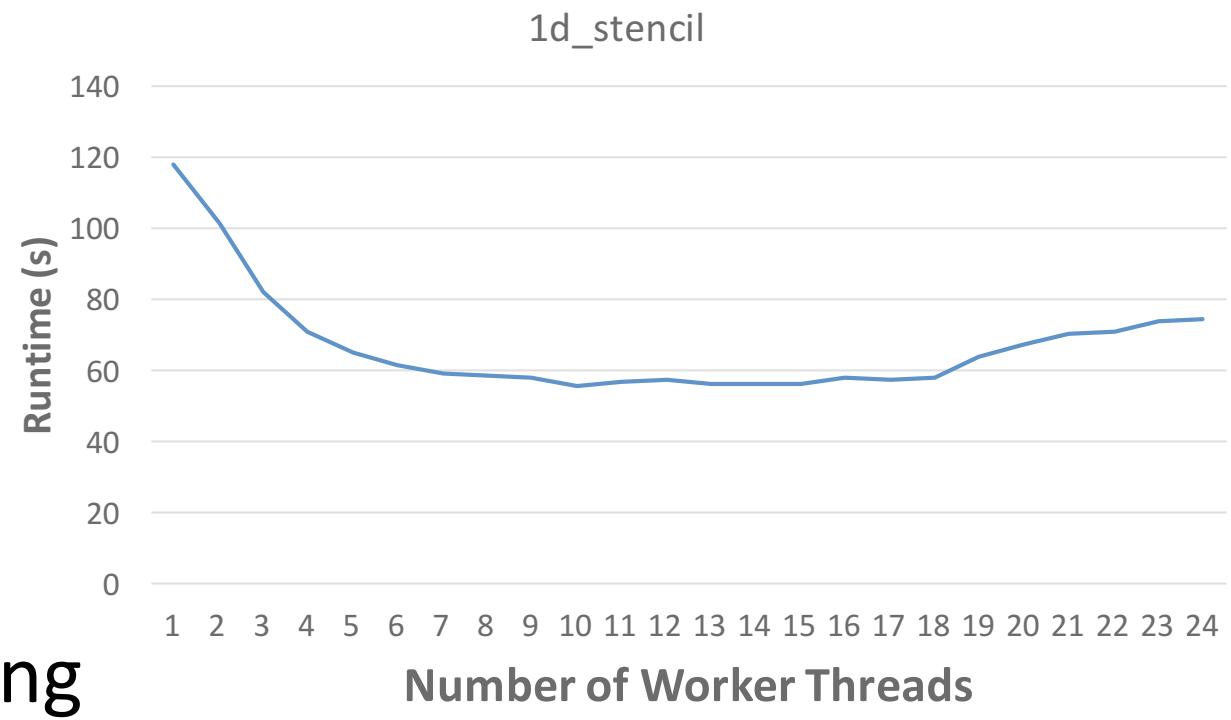
HPX + APEX Policy Examples

Example : HPX+APEX

- Heat diffusion
- 1D stencil code
- Data array partitioned into chunks
- 1 node with no hyperthreading



- Performance increases to a point with increasing worker threads, then decreases

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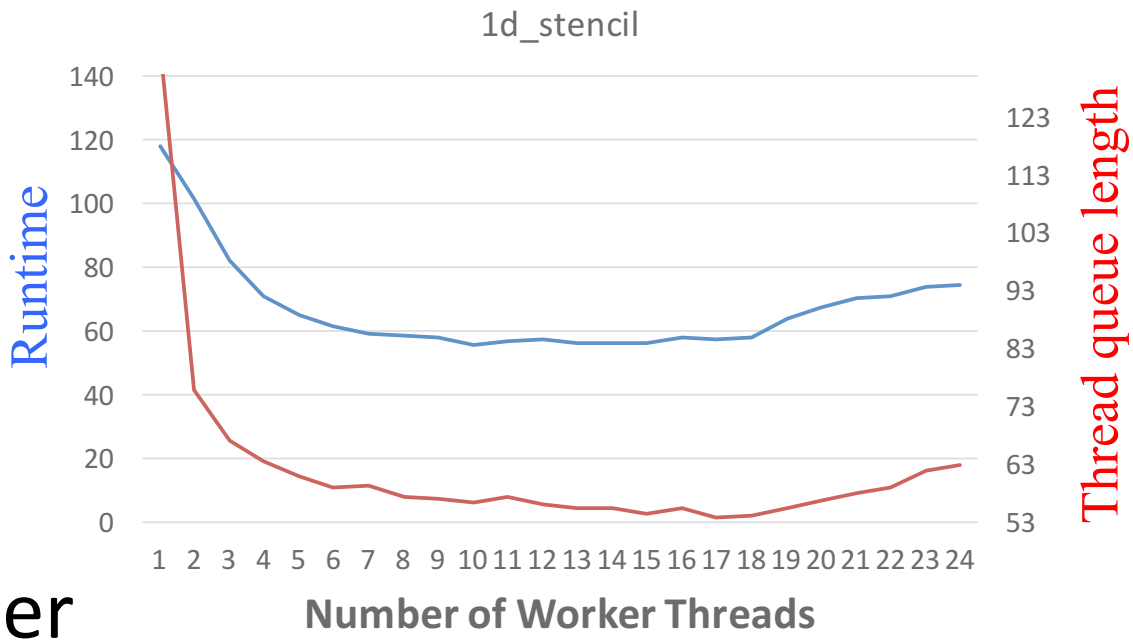
Concurrency & Performance

- Region of maximum performance correlates with thread queue length runtime performance counter
  - Represents # tasks currently waiting to execute
- Could do introspection on this to control concurrency throttling policy (see next example)



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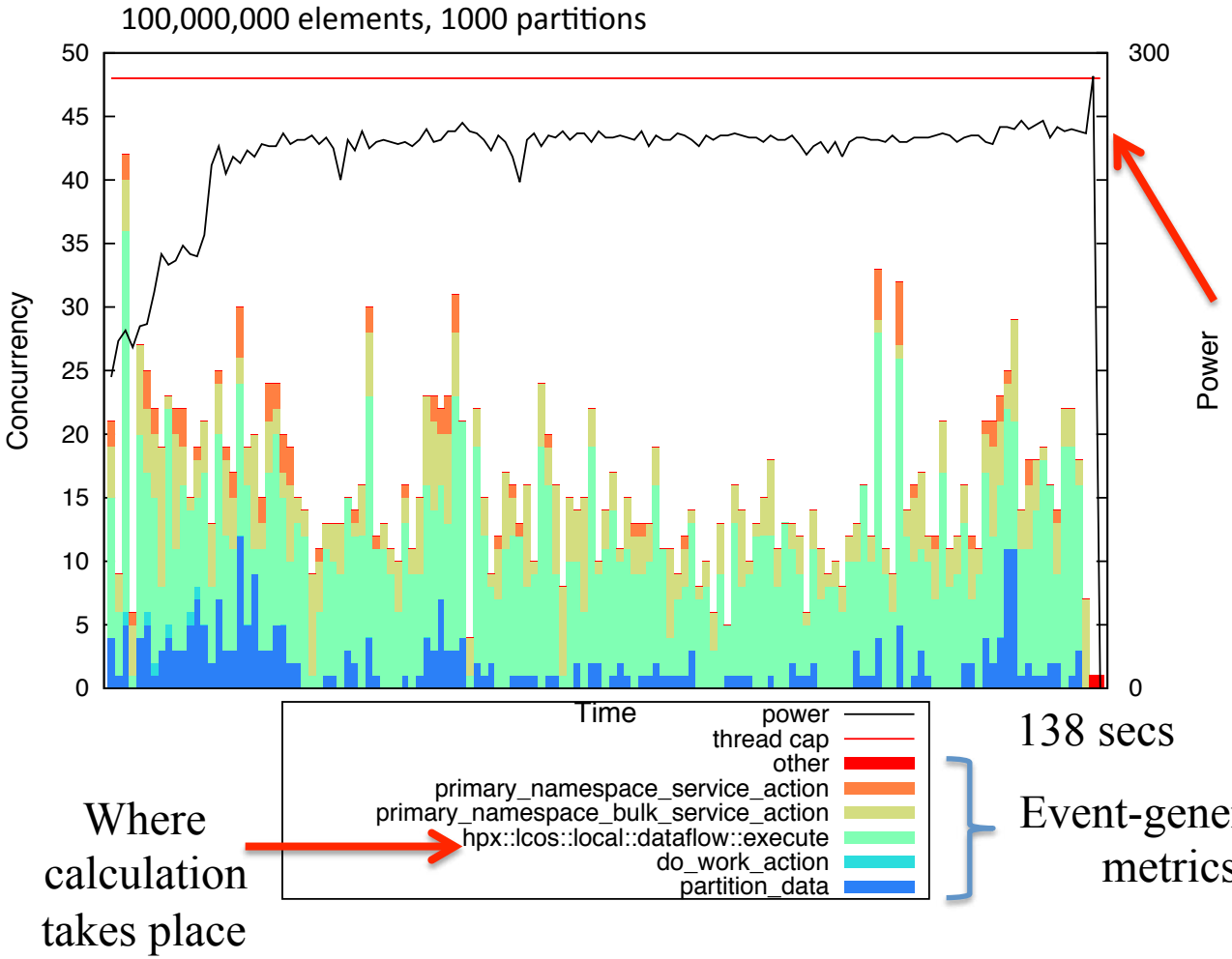
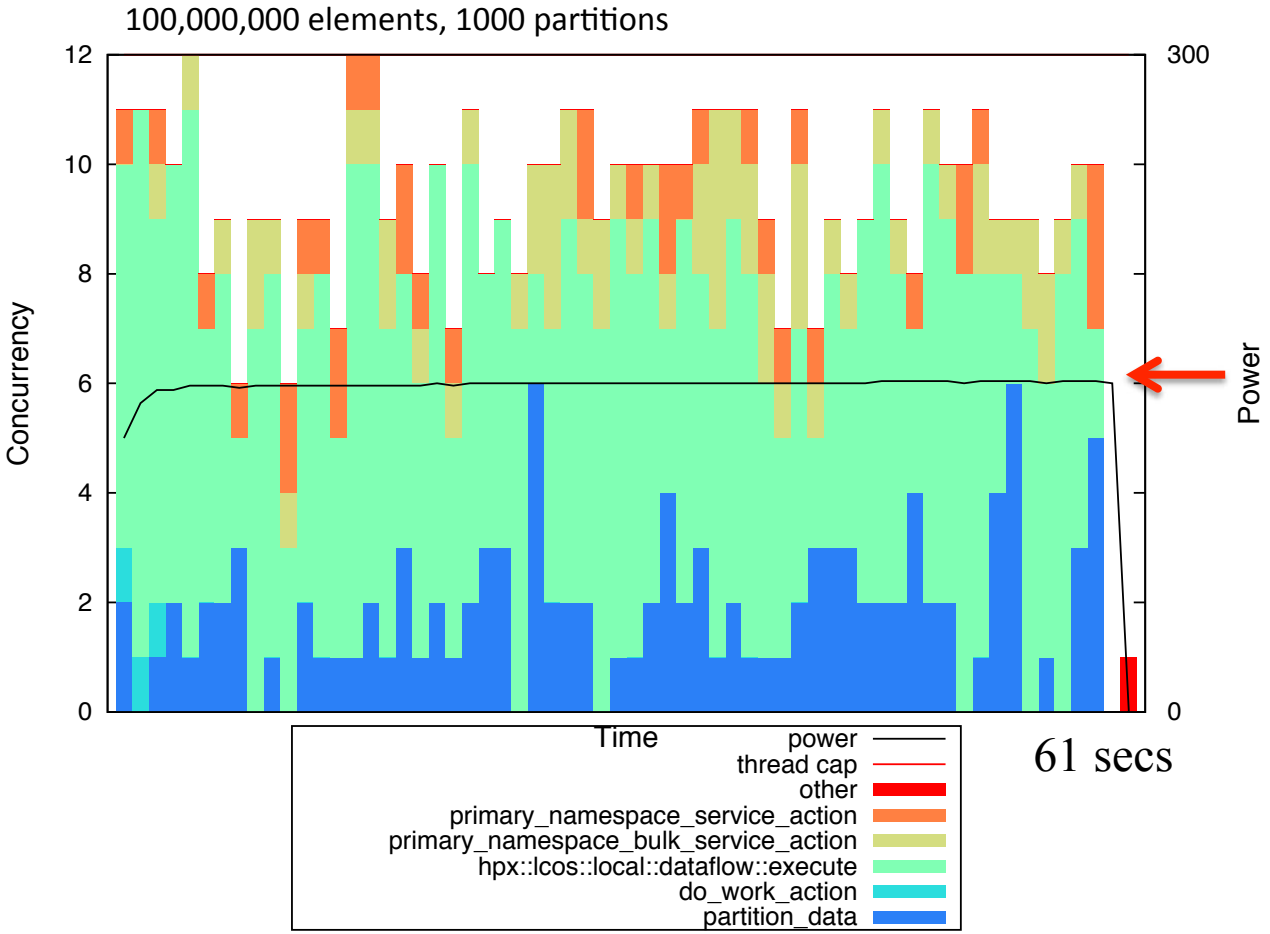
1d_stencil_4 Baseline



- 48 worker threads (with hyperthreading, on Edison)
- Actual concurrency much lower
  - Implementation is memory bound
- Large variation in concurrency over time
  - Tasks waiting on prior tasks to complete

1d_stencil w/optimal # of Threads



- 12 worker threads on Edison
- Greater proportion of threads kept busy
  - Less interference between active threads and threads waiting for memory
- Much faster
  - 61 sec. vs 138 sec.

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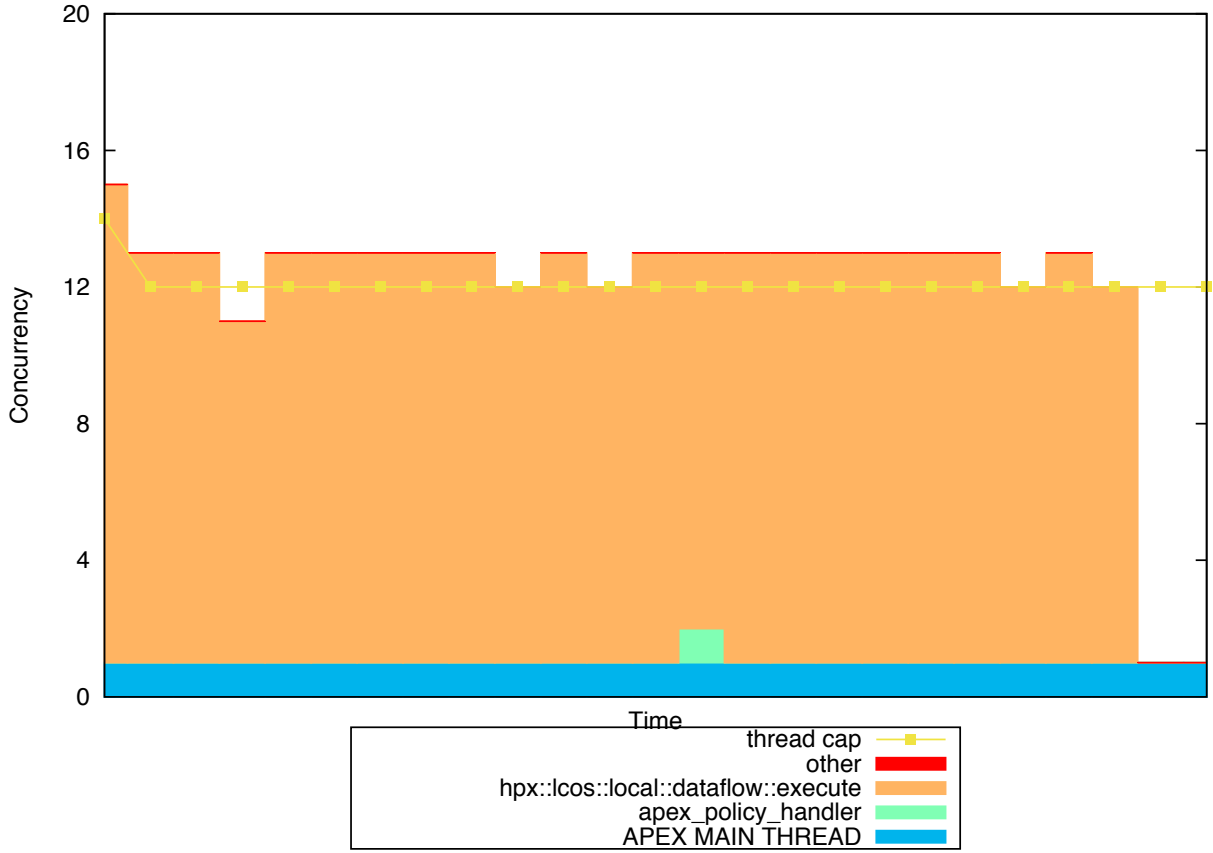
1d_stencil Adaptation with APEX



- Initially 32 worker threads
- ActiveHarmony searches for minimal thread queue length
- Quickly converges on 12

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Adapting Block Size

- Is 1000 partitions of 100000 cells the best partitioning?
- Parametric studies say “no”.
- Can we modify the example to repartition as necessary to find better performance?

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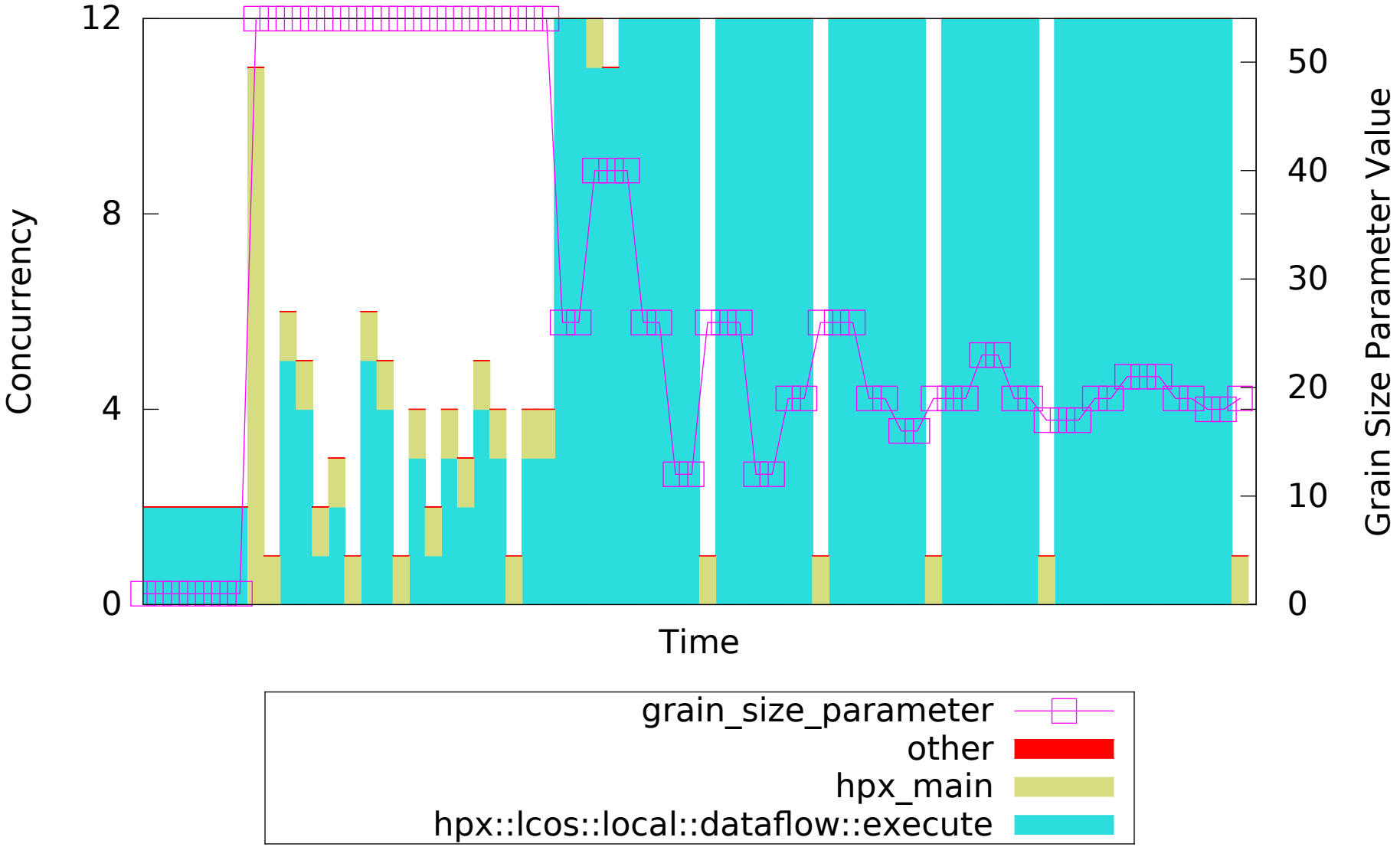
1d_stencil: adapting block size



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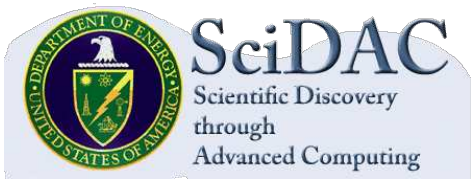
- The authors acknowledge that the Talapas HPC cluster and the High Performance Computing Research Core Facility at The University of Oregon have contributed to the research results reported within this paper.



HPX + Cling + Jupyter

This tutorial works in a special Jupyter notebook that can be used in one of two ways:

- From this website: https://hpx-jupyter.cct.lsu.edu (https://hpx-jupyter.cct.lsu.edu)
- From the docker image: stevenrbrandt/fedora-hpx-cling
- Normally, each cell should contain declarations, e.g. definitions of functions, variables, or `#include` statements.

  ```#include using namespace std;```
- If you wish to process an expression, e.g. `cout << "hello world\n"` you can put `.expr` at the front of the cell.

  ```.expr cout << "hello, world\n";```
- Sometimes you will want to test a cell because you are uncertain whether it might cause a segfault or some other error that will kill your kernel. Othertimes, you might want to test a definition without permanently adding it to the current namespace. You can do this by prefixing your cell with `.test`. Whatever is calculated in a test cell will be thrown away after evaluation and will not kill your kernel.

  ```.test.expr int foo[5]; foo[10] = 1;```

  ## Docker Instructions
- Frist, install Docker on your local resource
- Second, start Docker, e.g. `sudo service docker start`
- Third, run the fedora-hpx-cling container, e.g.

  ```$docker pull stevenrbrandt/fedora-hpx-cling$ docker run -it -p 8000:8000 stevenrbrandt/fedora-hpx-cling```

  After you do this, docker will respond with something like

  `http://0.0.0.0:8000/?token=5d1eb8a4797851910de481985a54c2fdc3be80280023bac5`

  Paste that URL into your browser, and you will be able to interact with the notebook.
- Fourth, play with the existing ipynb files or create new ones.
- Fifth, save your work! This is an important step. If you simply quit the container, everything you did will be lost. To save your work, first find your docker image using `docker ps`.

  ```$ docker ps CONTAINER ID IMAGE COMMAND CREATED STATUS PORTS NAMES 4f806b5f4fb3 stevenrbrandt/fedora-hpx-cling "/bin/sh -c 'jupyter " 11 minutes ago Up 11 minutes 0.0.0.0:8000->8000/tcp dreamy_turing```

  Once you have it (in this case, it's 4f806b5f4fb3), you can use `docker cp` to transfer files to or from your image.

  ```$ docker cp 4f806b5f4fb3:/home/jup/HPX_by_example.ipynb . docker cp HPX_by_example.ipynb 4f806b5f4fb3:/home/jup```

Measuring HPX performance

HPX is integraged with APEX, "An Autonomic Performance Environment for eXascale". APEX serves two primary roles in HPX - to measure the HPX runtime and applicaiton tasks, and to use introspection of those measurements to control behavior.

Measurement

APEX provides an API for measuring actions within a runtime. The API includes methods for timer start/stop, as well as sampled counter values. APEX is designed to be integrated into a runtime, library and/or application and provide performance introspection for the purpose of runtime adaptation. While APEX can provide rudimentary post-mortem performance analysis measurement, there are many other performance measurement tools that perform that task much better (such as TAU http://tau.uoregon.edu (http://tau.uoregon.edu)). That said, APEX includes an event listener that integrates with the TAU measurement system, so APEX events can be forwarded to TAU and collected in a TAU profile and/or trace to be used for post-mortem performance anlaysis. That process is not covered in this tutorial, but for more information, see http://github.com/khuck/xpress-apex (http://github.com/khuck/xpress-apex).

Runtime Adaptation

APEX provides a mechanism for dynamic runtime feedback and control, either for autotuning or adaptation to changing environment. The infrastruture that provides the adaptation in APEX is the Policy Engine, which executes policies either periodically or triggered by events. The policies have access to the performance state as observed by the APEX introspection API. APEX is integrated with Active Harmony (http://www.dyninst.org/harmony (http://www.dyninst.org/harmony)) to provide dynamic search for autotuning.

Fibonacci example - what's the performance?

Using the first fibonacci implementation from the HPX introduction, let's examine the performance. To get a simple text report of performance from HPX in a regular program, you would set the `APEX_SCREEN_OUTPUT` environment variable to a postitive number (i.e. "1"). In the Jupyter notebook, we will use the `apex::dump(bool reset);` method instead. Because the HPX environment is continuously running in the Jupyter kernel, we also need to reset the timers before executing our test.

First, include the HPX header for our example, and declare some useful namespaces.

In [ ]:
```
#include <hpx/hpx.hpp>
using namespace std;
using namespace hpx;
```

Next, we will define the first implementation of the fibonacci algorithm from the previous presentation.

In [ ]:
```
uint64_t fibonacci(uint64_t n)
{
  // if we know the answer, we return the value
  if (n < 2) return n;
  // asynchronously calculate one of the sub-terms
  future<uint64_t> f = async(launch::async, &fibonacci, n-2);
  // synchronously calculate the other sub-term
  uint64_t r = fibonacci(n-1);
  // wait for the future and calculate the result
  return f.get() + r;
}
```

And we will execute that definition:

In [ ]:
```
.expr
apex::reset(0L);
cout << fibonacci(22) << endl;
apex::dump(true);
```

We get some useful information, but what is `task_object::apply`? That is the HPX runtime executing asynchronous tasks. To get a useful label for that function (and distinguish the different task types), we will use `hpx::util::annotated_function`. Note carefully that we will add the hpx::util namespace, and also that we will change the name to fibonacci2, to distinguish from the previous definition (that still exists in this compilation unit). We will use that renaming pattern throughout this tutorial.

(markdown padding for proper formatting)

In [ ]:
```
using namespace hpx::util;
```

In [ ]:
```
uint64_t fibonacci2(uint64_t n)
{
  // if we know the answer, we return the value
  if (n < 2) return n;
  // asynchronously calculate one of the sub-terms
  future<uint64_t> f = async(launch::async, annotated_function(unwrapp
ing(&fibonacci2), "fibonacci2 asynchronous"), n-2);
  // synchronously calculate the other sub-term
  apex::profiler *p = apex::start("fibonacci2 synchronous");
  uint64_t r = fibonacci2(n-1);
  apex::stop(p);
  // wait for the future and calculate the result
  return f.get() + r;
}
```

Next, we will execute the fibonacci2 method with the annotated function:

In [ ]:
```
.expr
apex::reset(0L);
cout << fibonacci2(22) << endl;
apex::dump(true);
```

That's better, but not quite right. Note carefully that the fibonacci2 synchronous events are double-counting -- the synchronous timer for (n) includes the time spent computing both (n-1) and (n-2). Let's see what happens with the example that uses a serial cutoff:

In [ ]:
```
const int threshold = 10;

uint64_t fibonacci_serial(uint64_t n)
{
  if (n < 2) return n;
  uint64_t f1 = fibonacci_serial(n-2);
  uint64_t f2 = fibonacci_serial(n-1);
  return f1 + f2;
}

future<uint64_t> fibonacci3(uint64_t n)
{
  if(n < 2) return make_ready_future(n);
  if(n < threshold) return make_ready_future(fibonacci_serial(n));

  future<uint64_t> f = async(launch::async, annotated_function(unwrapp
ing(&fibonacci3), "fibonacci3"), n-2);
  future<uint64_t> r = fibonacci3(n-1);

  return dataflow(
    [](future<uint64_t> f1, future<uint64_t> f2) {
      return f1.get() + f2.get();
    },
    f, r);
}
```

In [ ]:
```
.expr
apex::reset(false);
cout << fibonacci3(22).get() << endl;
apex::dump(true);
```

Note that the timers are only around the calls where 10 > n >= 22. We are now under-counting, because the synchronous executions aren't measured. If we were interested in a careful evaluation of the serial execution, we would include a third function with a timer that is called once. That function would then recursively call fibonacci_serial. Feel free to implement that version as an exercise.

.

What if we want to compare the different methods? We can put them all into one compilation unit, and execute them in the same cell for a clearer comparison:

In [ ]:
```
.expr
apex::reset(0L);
cout << fibonacci(22) << endl;
cout << fibonacci2(22) << endl;
cout << fibonacci3(22).get() << endl;
apex::dump(true);
```

Well, there is some useful data in there - but we need to do some aggregation. We could add them up, or we could wrap the top level calls with a timer and get the wall clock time for each approach:

In [ ]:
```
.expr
apex::reset(0L);
apex::profiler *p1 = apex::start("Version 1");
cout << fibonacci(22) << endl;
apex::stop(p1);
apex::profiler *p2 = apex::start("Version 2");
cout << fibonacci2(22) << endl;
apex::stop(p2);
apex::profiler *p3 = apex::start("Version 3");
cout << fibonacci3(22).get() << endl;
apex::stop(p3);
apex::dump(true);
```

Heat Equation Example

In [ ]:
```
#include <hpx/include/parallel_algorithm.hpp>
#include <boost/range/irange.hpp>
#include <boost/format.hpp>

#include <cstddef>
#include <cstdint>
#include <iostream>
#include <memory>
#include <utility>
#include <vector>
#include <stdexcept>
#include <string>

////////////////////////////////////////////////////////////////////////

void print_time_results(
    std::uint32_t num_localities
  , std::uint64_t num_os_threads
  , std::uint64_t elapsed
  , std::uint64_t nx
  , std::uint64_t np
  , std::uint64_t nt
  , bool header
    )
{
    if (header)
```

```
        std::cout << "Localities,OS_Threads,Execution_Time_sec,"
                "Points_per_Partition,Partitions,Time_Steps\n"
             << std::flush;

    std::string const locs_str = boost::str(boost::format("%u,") % num
_localities);
    std::string const threads_str = boost::str(boost::format("%lu,") %
 num_os_threads);
    std::string const nx_str = boost::str(boost::format("%lu,") % nx);
    std::string const np_str = boost::str(boost::format("%lu,") % np);
    std::string const nt_str = boost::str(boost::format("%lu ") % nt);

    std::cout << ( boost::format("%-6s %-6s %.14g, %-21s %-21s %-21s\n
")
            % locs_str % threads_str % (elapsed / 1e9) %nx_str % np_st
r
            % nt_str) << std::flush;
}

////////////////////////////////////////////////////////////////////////

void print_time_results(
    std::uint64_t num_os_threads
  , std::uint64_t elapsed
  , std::uint64_t nx
  , std::uint64_t np
  , std::uint64_t nt
  , bool header
    )
{
    if (header)
        std::cout << "OS_Threads,Execution_Time_sec,"
                "Points_per_Partition,Partitions,Time_Steps\n"
             << std::flush;

    std::string const threads_str = boost::str(boost::format("%lu,") %
 num_os_threads);
    std::string const nx_str = boost::str(boost::format("%lu,") % nx);
    std::string const np_str = boost::str(boost::format("%lu,") % np);
    std::string const nt_str = boost::str(boost::format("%lu ") % nt);

    std::cout << ( boost::format("%-21s %.14g, %-21s %-21s %-21s\n")
            % threads_str % (elapsed / 1e9) %nx_str % np_str
            % nt_str) << std::flush;
}

void print_time_results(
    std::uint64_t num_os_threads
  , std::uint64_t elapsed
  , std::uint64_t nx
  , std::uint64_t nt
  , bool header
    )
{
    if (header)
        std::cout << "OS_Threads,Execution_Time_sec,"
                "Grid_Points,Time_Steps\n"
```

```
            << std::flush;

    std::string const threads_str = boost::str(boost::format("%lu,") %
 num_os_threads);
    std::string const nx_str = boost::str(boost::format("%lu,") % nx);
    std::string const nt_str = boost::str(boost::format("%lu ") % nt);

    std::cout << ( boost::format("%-21s %10.12s, %-21s %-21s\n")
            % threads_str % (elapsed / 1e9) %nx_str % nt_str) << std::
flush;
}

////////////////////////////////////////////////////////////////////////

// Command-line variables
bool header = true; // print csv heading
double k = 0.5;     // heat transfer coefficient
double dt = 1.;     // time step
double dx = 1.;     // grid spacing

inline std::size_t idx(std::size_t i, int dir, std::size_t size)
{
    if(i == 0 && dir == -1)
        return size-1;
    if(i == size-1 && dir == +1)
        return 0;

    HPX_ASSERT((i + dir) < size);

    return i + dir;
}

////////////////////////////////////////////////////////////////////////

// Our partition data type
struct partition_data
{
public:
    partition_data(std::size_t size)
      : data_(new double[size]), size_(size)
    {}

    partition_data(std::size_t size, double initial_value)
      : data_(new double[size]),
        size_(size)
    {
        double base_value = double(initial_value * size);
        for (std::size_t i = 0; i != size; ++i)
            data_[i] = base_value + double(i);
    }

    partition_data(partition_data && other)
      : data_(std::move(other.data_))
      , size_(other.size_)
    {}

    double& operator[](std::size_t idx) { return data_[idx]; }
```

```
    double operator[](std::size_t idx) const { return data_[idx]; }

    std::size_t size() const { return size_; }

private:
    std::unique_ptr<double[]> data_;
    std::size_t size_;
};

std::ostream& operator<<(std::ostream& os, partition_data const& c)
{
    os << "{";
    for (std::size_t i = 0; i != c.size(); ++i)
    {
        if (i != 0)
            os << ", ";
        os << c[i];
    }
    os << "}";
    return os;
}

///////////////////////////////////////////////////////////////////////

struct stepper
{
    // Our data for one time step
    typedef hpx::shared_future<partition_data> partition;
    typedef std::vector<partition> space;

    // Our operator
    static double heat(double left, double middle, double right)
    {
        return middle + (k*dt/(dx*dx)) * (left - 2*middle + right);
    }

    // The partitioned operator, it invokes the heat operator above on
 all
    // elements of a partition.
    static partition_data heat_part(partition_data const& left,
        partition_data const& middle, partition_data const& right)
    {
        apex_wrapper profiler("partition_data::heat_part", 0L);
        std::size_t size = middle.size();
        partition_data next(size);

        next[0] = heat(left[size-1], middle[0], middle[1]);

        for(std::size_t i = 1; i != size-1; ++i)
        {
            next[i] = heat(middle[i-1], middle[i], middle[i+1]);
        }

        next[size-1] = heat(middle[size-2], middle[size-1], right[0]);

        return next;
    }
```

```
    // do all the work on 'np' partitions, 'nx' data points each, for
 'nt'
    // time steps, limit depth of dependency tree to 'nd'
    hpx::future<space> do_work(std::size_t np, std::size_t nx, std::si
ze_t nt,
        std::uint64_t nd)
    {
        using hpx::dataflow;
        using hpx::util::unwrapping;

        // U[t][i] is the state of position i at time t.
        std::vector<space> U(2);
        for (space& s: U)
            s.resize(np);

        // Initial conditions: f(0, i) = i
        std::size_t b = 0;
        auto range = boost::irange(b, np);
        using hpx::parallel::execution::par;
        hpx::parallel::for_each(par, std::begin(range), std::end(range
),
            [&U, nx](std::size_t i)
            {
                U[0][i] = hpx::make_ready_future(partition_data(nx, do
uble(i)));
            }
        );

        // limit depth of dependency tree
        hpx::lcos::local::sliding_semaphore sem(nd);

        auto Op = hpx::util::annotated_function(unwrapping(&stepper::h
eat_part),
                                                "stepper::heat_part");

        // Actual time step loop
        for (std::size_t t = 0; t != nt; ++t)
        {
            space const& current = U[t % 2];
            space& next = U[(t + 1) % 2];

            for (std::size_t i = 0; i != np; ++i)
            {
                next[i] = dataflow(
                    Op, current[idx(i, -1, np)], current[i], current[i
dx(i, +1, np)]);
            }

            // every nd time steps, attach additional continuation whi
ch will
            // trigger the semaphore once computation has reached this
 point
            if ((t % nd) == 0)
            {
                next[0].then(
                    [&sem, t](partition &&)
```

```
                    {
                        // inform semaphore about new lower limit
                        sem.signal(t);
                    });
            }

            // suspend if the tree has become too deep, the continuati
on above
            // will resume this thread once the computation has caught
 up
            sem.wait(t);
        }

        // Return the solution at time-step 'nt'.
        return hpx::when_all(U[nt % 2]);
    }
};

///////////////////////////////////////////////////////////////////////

/*
    std::uint64_t np{10};   // Number of partitions.
    std::uint64_t nx{10};   // Number of grid points. (local x dimensi
on of each partition)
    std::uint64_t nt{45};   // Number of steps.
    std::uint64_t nd{10};   // Max depth of dep tree.
*/
void do_1d_solve(std::uint64_t np, std::uint64_t nx,
                 std::uint64_t nt, std::uint64_t nd, bool results)
{
    header = false;

    // Create the stepper object
    stepper step;

    // Measure execution time.
    std::uint64_t t = hpx::util::high_resolution_clock::now();

    // Execute nt time steps on nx grid points and print the final sol
ution.
    hpx::future<stepper::space> result = step.do_work(np, nx, nt, nd);

    stepper::space solution = result.get();
    hpx::wait_all(solution);

    std::uint64_t elapsed = hpx::util::high_resolution_clock::now() -
t;

    // Print the final solution
    if (results)
    {
        for (std::size_t i = 0; i != np; ++i)
            std::cout << "U[" << i << "] = " << solution[i].get() << s
td::endl;
    }

    std::uint64_t const os_thread_count = hpx::get_os_thread_count();
```

```
    print_time_results(os_thread_count, elapsed, nx, np, nt, header);

    return;
}
```

In [ ]:
```
.expr
apex::reset(0L);
do_1d_solve(100, 100, 450, 100, false);
apex::dump(true);
```

Heat Equation with an APEX policy

In [ ]:
```
#include <hpx/hpx_init.hpp>
#include <hpx/hpx.hpp>

#include <hpx/include/parallel_algorithm.hpp>
#include <hpx/include/performance_counters.hpp>

#include <boost/range/irange.hpp>
#include <boost/format.hpp>

#include <algorithm>
#include <cstddef>
#include <cstdint>
#include <iostream>
#include <limits>
#include <memory>
#include <string>
#include <utility>
#include <vector>

#include <apex_api.hpp>

#include <boost/shared_array.hpp>

using hpx::naming::id_type;
using hpx::performance_counters::get_counter;
using hpx::performance_counters::stubs::performance_counter;
using hpx::performance_counters::counter_value;
using hpx::performance_counters::status_is_valid;

static bool counters_initialized = false;
static std::string counter_name = "/threads{locality#0/total}/idle-rat
e";
static apex_event_type end_iteration_event = APEX_CUSTOM_EVENT_1;
static hpx::naming::id_type counter_id;

void setup_counters() {
    try {
        id_type id = get_counter(counter_name);
        // We need to explicitly start all counters before we can use
 them. For
```

```
        // certain counters this could be a no-op, in which case start
 will return
        // 'false'.
        performance_counter::start(hpx::launch::sync, id);
        std::cout << "Counter " << counter_name << " initialized " <<
id << std::endl;
        counter_value value = performance_counter::get_value(hpx::laun
ch::sync, id);
        std::cout << "Counter value " << value.get_value<std::int64_t>
() << std::endl;
        counter_id = id;
        end_iteration_event = apex::register_custom_event("Repartitio
n");
        counters_initialized = true;
    }
    catch(hpx::exception const& e) {
        std::cerr << "1d_stencil_4_repart: caught exception: "
            << e.what() << std::endl;
        counter_id = hpx::naming::invalid_id;
        return;
    }
}

double get_counter_value() {
    if (!counters_initialized) {
        std::cerr << "get_counter_value(): ERROR: counter was not init
ialized"
            << std::endl;
        return false;
    }
    try {
        counter_value value1 =
            performance_counter::get_value(hpx::launch::sync, counter_
id, true);
        std::int64_t counter_value = value1.get_value<std::int64_t>();

        std::cout << "counter_value " << counter_value << std::endl;
        return (double)(counter_value);
    }
    catch(hpx::exception const& e) {
        std::cout << "get_counter_value(): caught exception: " << e.wh
at()
            << std::endl;
        return (std::numeric_limits<double>::max)();
    }
}

////////////////////////////////////////////////////////////////////

// Our partition data type
struct partition_data2
{
public:
    partition_data2(std::size_t size)
      : data_(new double[size]), size_(size)
    {}
```

```
    partition_data2(std::size_t size, double initial_value)
      : data_(new double[size]),
        size_(size)
    {
        double base_value = double(initial_value * size);
        for (std::size_t i = 0; i != size; ++i)
            data_[i] = base_value + double(i);
    }

    partition_data2(std::size_t size, const double * other)
         : data_(new double[size]),
         size_(size)
    {
        for(std::size_t i = 0; i != size; ++i) {
            data_[i] = other[i];
        }
    }

    partition_data2(partition_data2 && other)
      : data_(std::move(other.data_))
      , size_(other.size_)
    {}

    double& operator[](std::size_t idx) { return data_[idx]; }
    double operator[](std::size_t idx) const { return data_[idx]; }

    void copy_into_array(double * a) const
    {
        for(std::size_t i = 0; i != size(); ++i) {
            a[i] = data_[i];
        }
    }

    std::size_t size() const { return size_; }

private:
    std::unique_ptr<double[]> data_;
    std::size_t size_;

};

std::ostream& operator<<(std::ostream& os, partition_data2 const& c)
{
    os << "{";
    for (std::size_t i = 0; i != c.size(); ++i)
    {
        if (i != 0)
            os << ", ";
        os << c[i];
    }
    os << "}";
    return os;
}


////////////////////////////////////////////////////////////////////
```

```
struct stepper2
{
    // Our data for one time step
    typedef hpx::shared_future<partition_data2> partition;
    typedef std::vector<partition> space;

    // Our operator
    static inline double heat(double left, double middle, double right
)
    {
        return middle + (k*dt/dx*dx) * (left - 2*middle + right);
    }

    // The partitioned operator, it invokes the heat operator above on
 all
    // elements of a partition.
    static partition_data2 heat_part(partition_data2 const& left,
        partition_data2 const& middle, partition_data2 const& right)
    {
        std::size_t size = middle.size();
        partition_data2 next(size);

        if(size == 1) {
            next[0] = heat(left[0], middle[0], right[0]);
            return next;
        }

        next[0] = heat(left[size-1], middle[0], middle[1]);

        for(std::size_t i = 1; i < size-1; ++i)
        {
            next[i] = heat(middle[i-1], middle[i], middle[i+1]);
        }

        next[size-1] = heat(middle[size-2], middle[size-1], right[0]);

        return next;
    }

    // do all the work on 'np' partitions, 'nx' data points each, for
 'nt'
    // time steps
    hpx::future<space> do_work(std::size_t np, std::size_t nx, std::si
ze_t nt,
        boost::shared_array<double> data)
    {
        using hpx::dataflow;
        using hpx::util::unwrapping;

        // U[t][i] is the state of position i at time t.
        std::vector<space> U(2);
        for (space& s: U)
            s.resize(np);

        if (!data) {
            // Initial conditions: f(0, i) = i
            std::size_t b = 0;
```

```
            auto range = boost::irange(b, np);
            using hpx::parallel::execution::par;
            hpx::parallel::for_each(
                par, std::begin(range), std::end(range),
                [&U, nx](std::size_t i)
                {
                    U[0][i] = hpx::make_ready_future(
                        partition_data2(nx, double(i)));
                }
            );
        }
        else {
            // Initialize from existing data
            std::size_t b = 0;
            auto range = boost::irange(b, np);
            using hpx::parallel::execution::par;
            hpx::parallel::for_each(
                par, std::begin(range), std::end(range),
                [&U, nx, data](std::size_t i)
                {
                    U[0][i] = hpx::make_ready_future(
                        partition_data2(nx, data.get()+(i*nx)));
                }
            );
        }

        auto Op =  hpx::util::annotated_function(unwrapping(&stepper2
::heat_part),
                                                 "stepper2::heat_part"
);

        // Actual time step loop
        for (std::size_t t = 0; t != nt; ++t)
        {
            space const& current = U[t % 2];
            space& next = U[(t + 1) % 2];

            for (std::size_t i = 0; i != np; ++i)
            {
                next[i] = dataflow(
                        hpx::launch::async, Op,
                        current[idx(i, -1, np)], current[i], current[i
dx(i, +1, np)]
                    );
            }
        }

        // Return the solution at time-step 'nt'.
        return hpx::when_all(U[nt % 2]);
    }
};

////////////////////////////////////////////////////////////////////

/*
    std::uint64_t np{10};   // Number of partitions.
    std::uint64_t nx{10};   // Number of grid points. (local x dimensi
```

```
on of each partition)
    std::uint64_t nt{45};   // Number of steps.
    std::uint64_t nr{10};   // Number of runs to tune
*/
void do_1d_solve_repart(std::uint64_t nx,
                std::uint64_t nt, std::uint64_t nr, bool results)
{
    setup_counters();

    /* Number of partitions dynamically determined    */
    header = false;

    std::uint64_t const os_thread_count = hpx::get_os_thread_count();

    // Find divisors of nx
    std::vector<std::uint64_t> divisors;
    // Start with os_thread_count so we have at least as many
    // partitions as we have HPX threads.
    for(std::uint64_t i = os_thread_count; i < std::sqrt(nx); ++i) {
        if(nx % i == 0) {
            divisors.push_back(i);
            divisors.push_back(nx/i);
        }
    }
    // This is not necessarily correct (sqrt(x) does not always evenly
 divide x)
    // and leads to partition size = 1 which we want to avoid
    //divisors.push_back(static_cast<std::uint64_t>(std::sqrt(nx)));
    std::sort(divisors.begin(), divisors.end());

    if(divisors.size() == 0) {
        std::cerr << "ERROR: No possible divisors for " << nx
            << " data elements with at least " << os_thread_count
            << " partitions and at least two elements per partition."
            << std::endl;
        return hpx::finalize();
    }

    //std::cerr << "Divisors: ";
    //for(std::uint64_t d : divisors) {
    //    std::cerr << d << " ";
    //}
    //std::cerr << std::endl;

    // Set up APEX tuning
    // The tunable parameter -- how many partitions to divide data int
o
    long np_index = 1;
    long * tune_params[1] = { 0L };
    long num_params = 1;
    long mins[1]  = { 0 };
    long maxs[1]  = { (long)divisors.size() };
    long steps[1] = { 1 };
    tune_params[0] = &np_index;
    apex::setup_custom_tuning(get_counter_value, end_iteration_event,
num_params,
            tune_params, mins, maxs, steps);
```