Performance Measurement Support for Asynchronous Multi-Tasking with APEX

Kevin Huck, Allen Malony, Sameer Shende

khuck@cs.uoregon.edu

https://github.com/UO-OACISS/apex

RAPIDS

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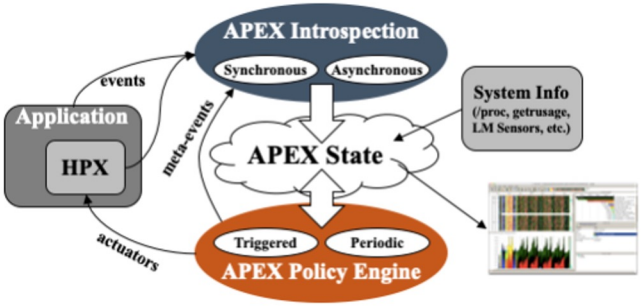
APEX Introduction

- Autonomic Performance Environment for eXascale
- **Performance Measurement**
- **Runtime Adaptation**
- Designed for AMT runtimes (HPX)
  - But works with conventional parallel models



- Focus on **task dependency** graph, not calling context graph
- Supports HPX, C/C++ threads, OpenMP, OpenACC, Kokkos, Raja, CUDA, HIP, (OneAPI, StarPU in dev)...
- https://github.com/UO-OACISS/apex
- Active Harmony* (Nelder Mead), Simulated Annealing, hill climbing for parametric search methods

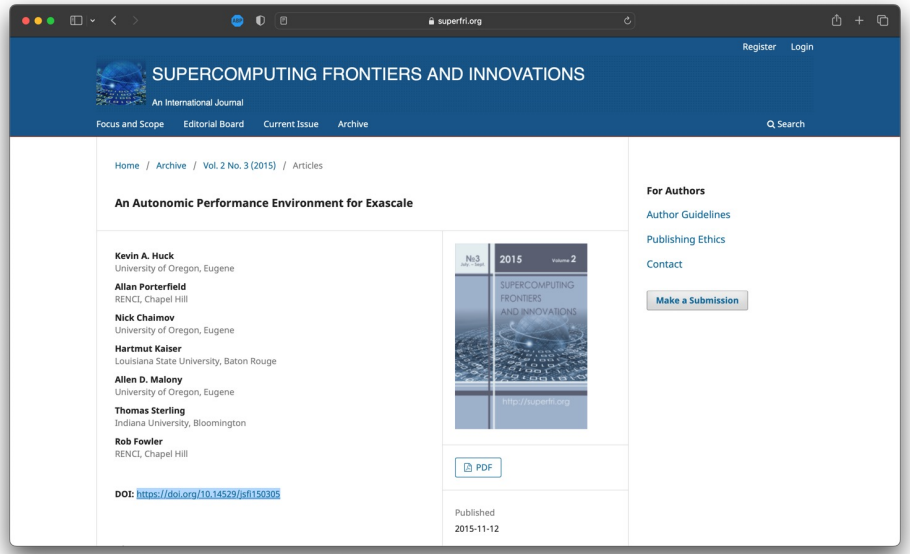
APEX

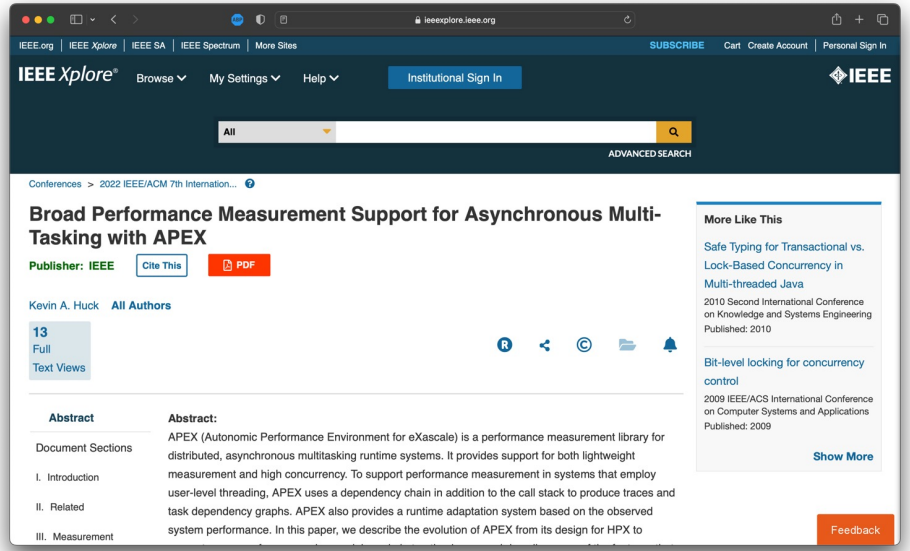
*https://www.dyninst.org/harmony

APEX Publications

https://doi.org/10.14529/jsfi150305 2015

https://doi.org/10.1109/ESPM256814.2022.00008 2022

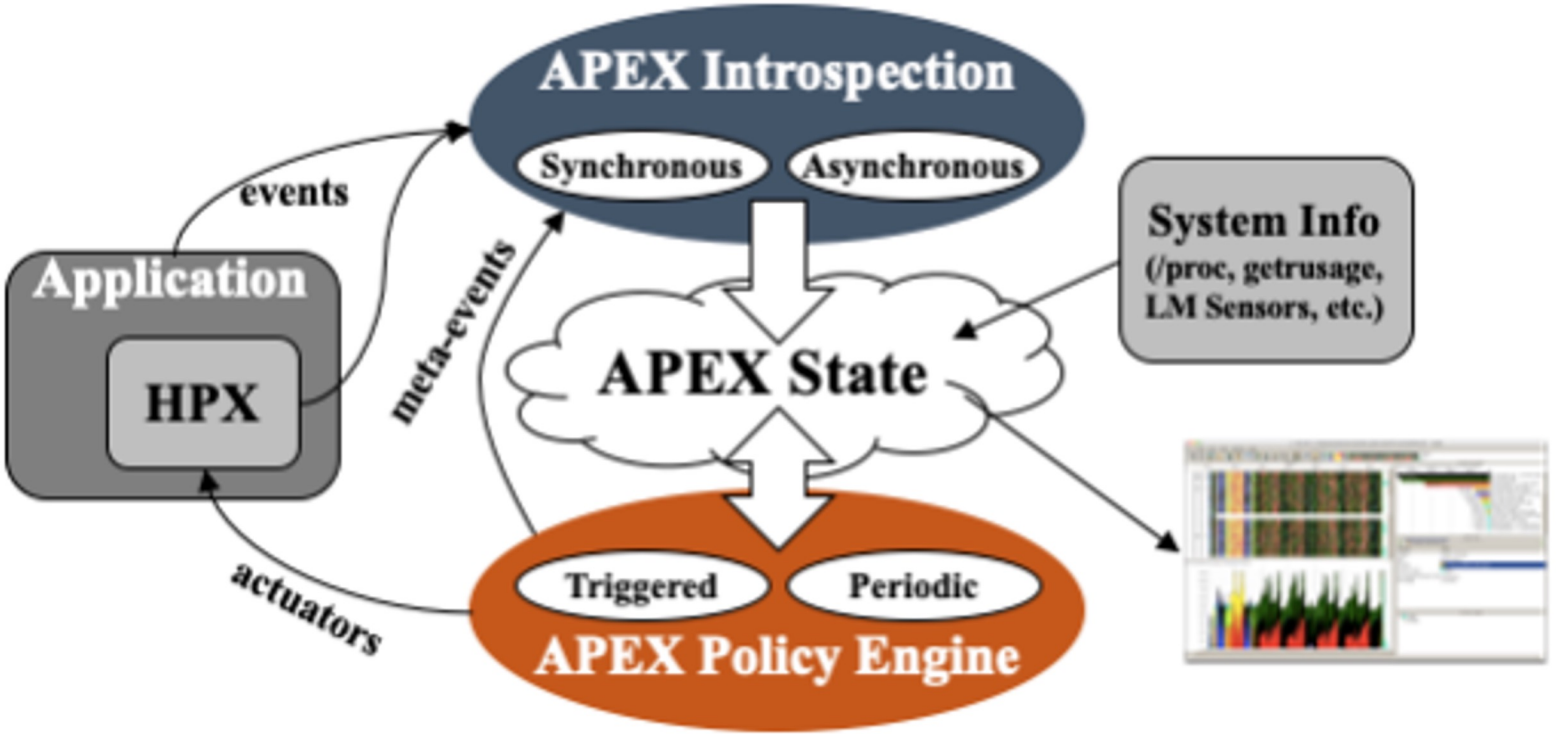




How is APEX different?

- No shortage of existing performance measurement tools
  - Primarily designed for post-mortem analysis
  - First-person measurement of tied tasks/functions on an OS thread – not untied tasks, runtime thread control, third-person measurement, runtime control
  - Not designed for permanent integration into applications
  - OS-thread context can be limiting
  - Vendor tools are great, but limited to each vendors' architecture – can't do cross-platform analysis
- APEX helps address these needs

APEX system diagram



Performance Measurement

- Timers designed for asynchronous tasking runtimes
  - Task creation
  - Start task
  - Create dependent tasks
  - Yield task
  - Resume task
  - Stop task

- "First-person" measurement – what is this runtime thread doing?

Performance Measurement

- Synchronous counters associated with timers
  - Bytes sent
  - Bytes received
  - GPU kernel data
  - Memory allocated
  - Memory freed

- "First-person" measurement – what is this runtime thread doing?

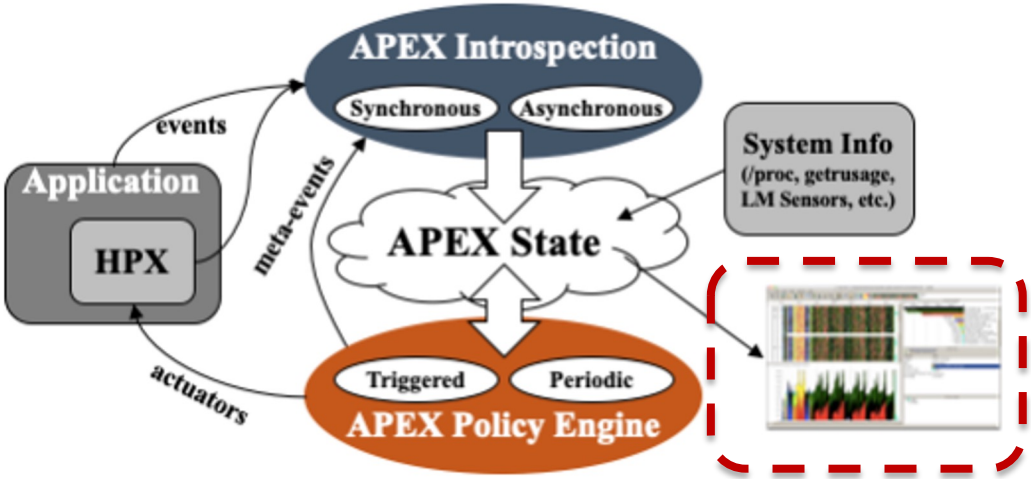
System Monitoring

- Asynchronous counters collected periodically to measure system health
  - Memory usage
  - Runtime data
  - CPU utilization
  - GPU utilization
  - Temperature
  - Energy/Power
  - PAPI metrics

- "Third-person" measurements – not directly related to what the application / runtime is doing

Performance Analysis

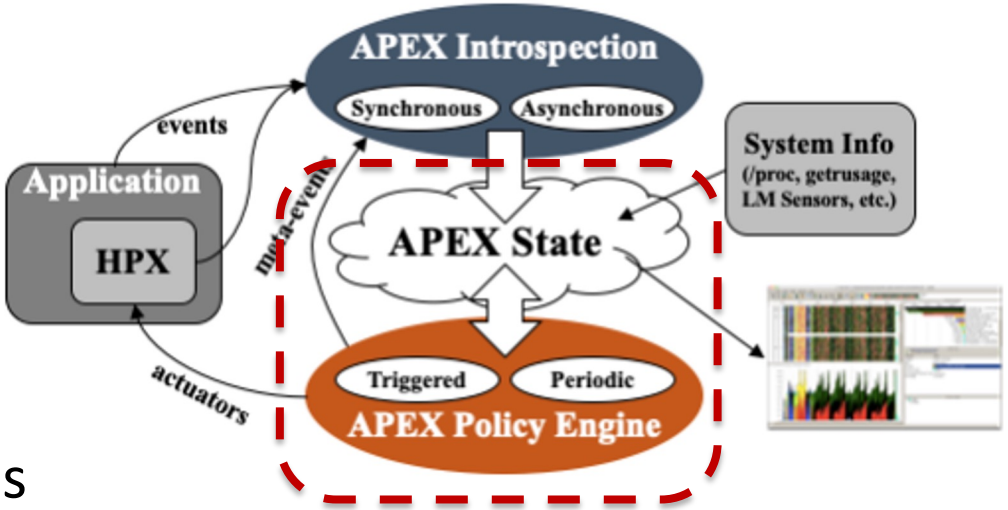
- Performance data is saved for post-mortem analysis
  - Profile data
  - Concurrency reports
  - Scatterplot data
  - Task dependency graph
  - Task dependency tree
  - OTF2 traces (Vampir)
  - Perfetto traces



- Any online analysis/policy *should* be done offline first

Policy Engine

- Performance data is used to control parametric values
  - “Magic numbers”
  - Timeouts
  - Queue depths
  - Max worker threads
  - Tiling parameters
  - Colaescing parameters
  - When to switch algorithms
  - Power/energy management



- Computational steering based on performance state

Asynchronous Tasking Models

- Lots of examples – C++ std::async, OpenMP tasks, HPX, StarPU, Charm++, …even CUDA/HIP/OneAPI
- …With lots of complications:
  - How to track task dependencies?
  - What about “untied” tasks?
  - How to track dependencies across OS threads?
  - What about task migration?
  - What about yielding for dependencies?
  - What about futures? Continuations? …

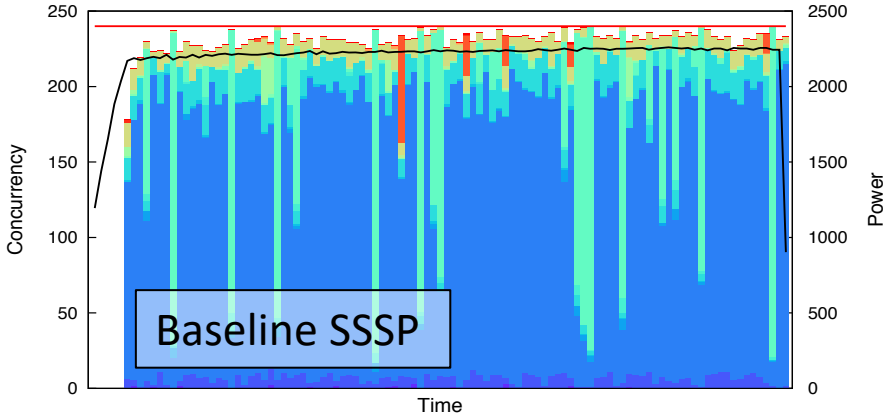
APEX and HPX

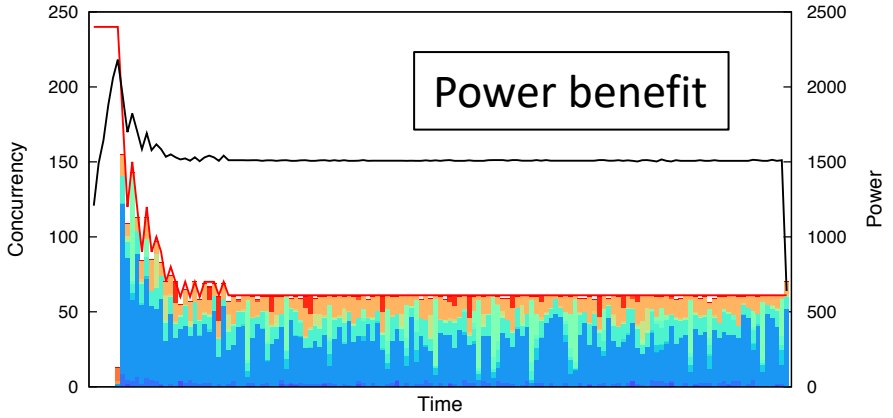
- HPX: Asynchronous Many-Task Runtime system in C++
- https://hpx.stellar-group.org
- Data and task dependencies can be expressed with HPX **futures** and **continuations**, chained together in an **execution graph**.
- The graph can be built asynchronously
- HPX tasks are created, scheduled, executed, and usually yielded and resumed by the runtime system scheduler
- This is particularly challenging because many different OS threads may have participated in the execution of the HPX task during its lifetime, and the calling context tree is meaningless to the application developer because it consists of runtime system functions, not application tasks

APEX and HPX

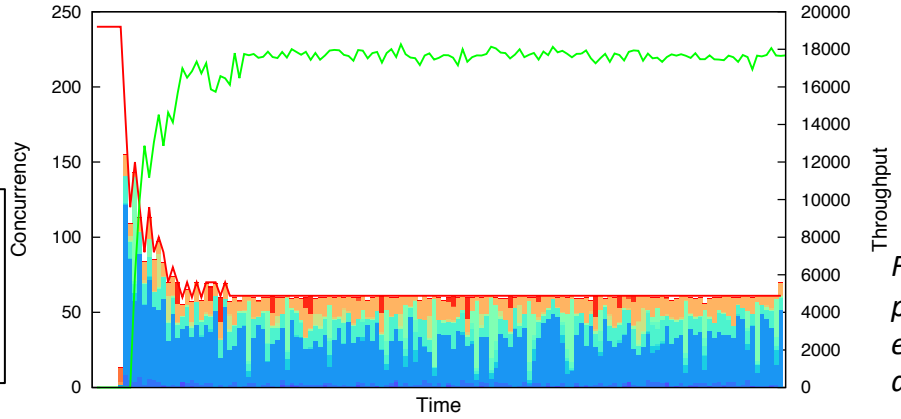
- APEX is integrated into the HPX thread scheduler, uniquely identifies each task with a GUID, and tracks all state transitions for a given task.
- HPX performance counters are also passed to APEX
- If HPX is configured with MPI support, the MPI functions are also captured (MPI_Isend, MPI_Irecv, MPI_Wait*)
- Policy Engine used for tuning heuristic control knobs in HPX thread scheduler, networking
  - Soft power caps, maximize throughput, reduce network latency, …

APEX and HPX





Throttled to maximize throughput



Figures: Huck, et al. "An autonomic performance environment for exascale." Supercomputing frontiers and innovations 2.3 (2015): 49-66.

Measurement Capabilities

- Timers – “per-process” aggregation for all timers
  - Start, stop, **yield, resume**
  - All times are *inclusive* (unless yielded/resumed)
- Counters
  - Can be associated with timed regions, e.g. MPI_Send #bytes
  - Can be periodically captured and aggregated, e.g. power, utilization, hardware counters, OS counters
- Task dependency chains
  - Each task has a unique parent
  - APEX builds graphs/trees of dependencies at runtime

HPX Example – Fibonacci (5)

```
std::uint64_t fibonacci(std::uint64_t n) {
    if (n < 2)  return n;
    // execute the Fibonacci function locally.
    hpx::id_type const locality_id = hpx::find_here();
    fibonacci_action fib;
    hpx::future<std::uint64_t> n1 = hpx::async(fib, locality_id, n -
1);
    hpx::future<std::uint64_t> n2 = hpx::async(fib, locality_id, n -
2);
    // wait for the Futures to return their values
    return n1.get() + n2.get();
}
int hpx_main(hpx::program_options::variables_map& vm) {
    // extract command line argument, i.e. fib(N)
    std::uint64_t n = vm["n-value"].as<std::uint64_t>();
    {
        // Keep track of the time required to execute.
        hpx::chrono::high_resolution_timer t;
        // Wait for fib() to return the value
        fibonacci_action fib;
        std::uint64_t r = fib(hpx::find_here(), n);
        char const* fmt =
            "fibonacci({1}) == {2}\nelapsed time: {3} [s]\n";
        hpx::util::format_to(std::cout, fmt, n, r, t.elapsed());
    }
    return hpx::finalize();     // Handles HPX shutdown
}
```

```
int main(int argc, char* argv[])
{
    // Set some APEX options
    apex::apex_options::use_screen_output(true);
    // Configure application-specific options
    hpx::program_options::options_description
desc_commandline(
        "Usage: " HPX_APPLICATION_STRING " [options]");

    desc_commandline.add_options()("n-value",
        hpx::program_options::value<std::uint64_t>()-
>default_value(10),
        "n value for the Fibonacci function");

    // Initialize and run HPX
    hpx::init_params init_args;
    init_args.desc_cmdline = desc_commandline;

    int status = hpx::init(argc, argv, init_args);

    return hpx::util::report_errors();
}
```

```
apex_exec --apex:tasktree ./bin/apex_action_count_test \
      --hpx:threads=8 --n-value 5
```

HPX Example – screen output

```
Elapsed time: 0.00760714 seconds
Total processes detected: 1
HW Threads detected on rank 0: 96
Worker Threads observed on rank 0: 8
Available CPU time on rank 0: 0.0608571 seconds
Available CPU time on all ranks: 0.0608571 seconds
Counter                                            : #samp |   mean   |  max
--------------------------------------------------------------------------------
                                   status:Threads  :      1      9.00      9.00
                                   status:VmHWM kB :      1  1.92e+04  1.92e+04
                                   status:VmRSS kB :      1  1.92e+04  1.92e+04
                 status:nonvoluntary_ctxt_switches :      1     97.00     97.00
                    status:voluntary_ctxt_switches :      1     29.00     29.00
--------------------------------------------------------------------------------
CPU Timers                                         : #calls|   mean |    total
--------------------------------------------------------------------------------
                                         APEX MAIN :      1      0.01      0.01
                            load_components_action :      1      0.00      0.00
                                        run_helper :      1      0.00      0.00
                                  fibonacci_action :     14      0.00      0.00
                               shutdown_all_action :      1      0.00      0.00
                       call_startup_functions_action :      2      0.00      0.00
--------------------------------------------------------------------------------
```

Counters sampled from OS/Hardware

HPX events/tasks

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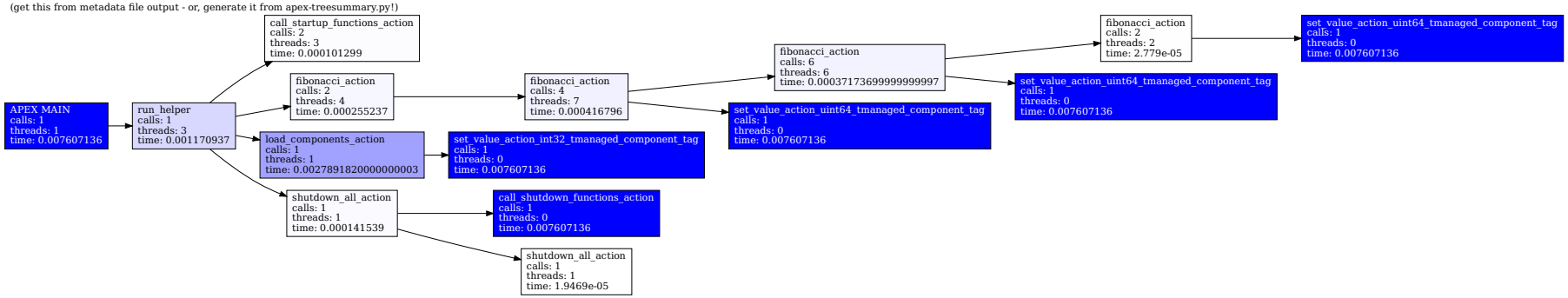
HPX Example – task tree (ASCII)

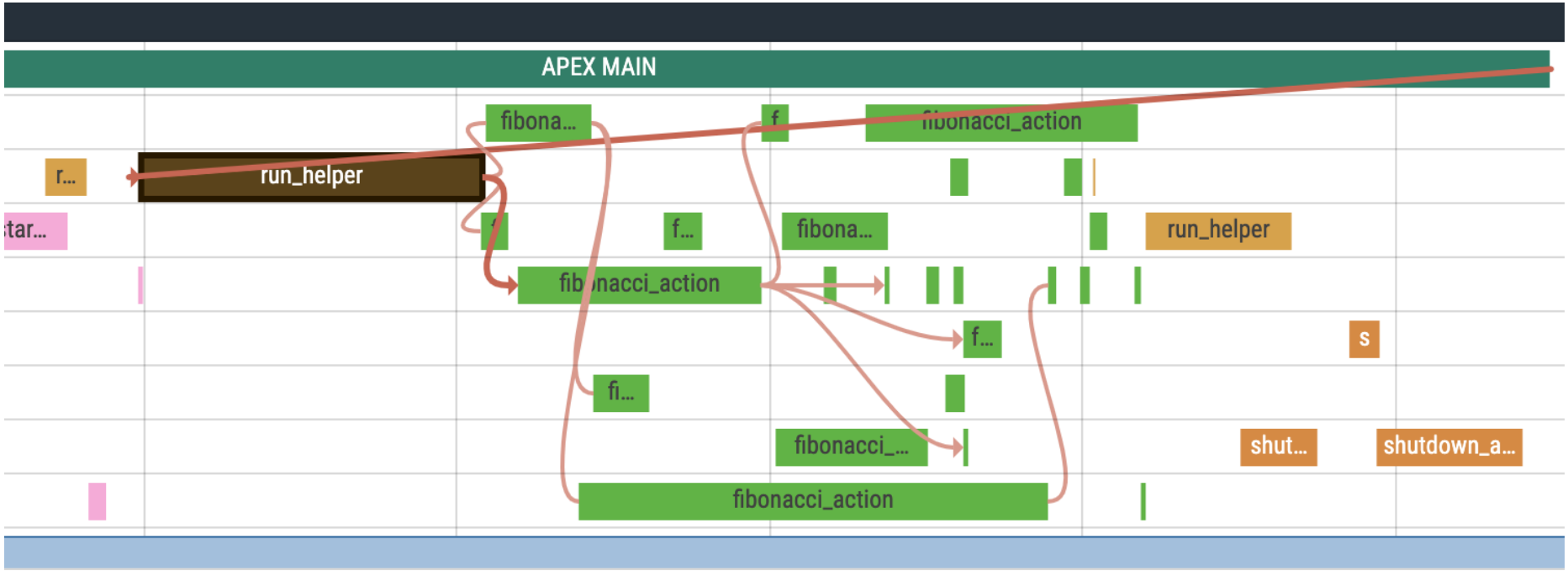
```
[khuck@gilgamesh build]$ /home/users/khuck/src/xpress-apex/install_gilgamesh_5.2.0/bin/apex-treesummary.py --dot --ascii
Reading tasktree...
Read 15 rows
Found 0 ranks, with max graph node index of 14 and depth of 6
building common tree...
Rank 0 ...
1-> 0.008 - 100.000% [1] {min=0.008, max=0.008, mean=0.008, threads=1} APEX MAIN
1 |-> 0.001 - 15.393% [1] {min=0.001, max=0.001, mean=0.001, threads=3} run_helper
1 | |-> 0.003 - 36.665% [1] {min=0.003, max=0.003, mean=0.003, threads=1} load_components_action
1 | | |-> 0.008 - 100.000% [1] {min=0.008, max=0.008, mean=0.008, threads=0} set_value_action_int32_tmanaged_component_tag
1 | |-> 0.000 - 3.355% [2] {min=0.000, max=0.000, mean=0.000, threads=4} fibonacci_action
1 | | |-> 0.000 - 5.479% [4] {min=0.000, max=0.000, mean=0.000, threads=7} fibonacci_action
1 | | | |-> 0.008 - 100.000% [1] {min=0.008, max=0.008, mean=0.008, threads=0} set_value_action_uint64_tmanaged_component_tag
1 | | | |-> 0.000 - 4.887% [6] {min=0.000, max=0.000, mean=0.000, threads=6} fibonacci_action
1 | | | | |-> 0.008 - 100.000% [1] {min=0.008, max=0.008, mean=0.008, threads=0}
set_value_action_uint64_tmanaged_component_tag
1 | | | | |-> 0.000 - 0.365% [2] {min=0.000, max=0.000, mean=0.000, threads=2} fibonacci_action
1 | | | | | |-> 0.008 - 100.000% [1] {min=0.008, max=0.008, mean=0.008, threads=0}
set_value_action_uint64_tmanaged_component_tag
1 | |-> 0.000 - 1.861% [1] {min=0.000, max=0.000, mean=0.000, threads=1} shutdown_all_action
1 | | |-> 0.008 - 100.000% [1] {min=0.008, max=0.008, mean=0.008, threads=0} call_shutdown_functions_action
1 | | |-> 0.000 - 0.256% [1] {min=0.000, max=0.000, mean=0.000, threads=1} shutdown_all_action
1 | |-> 0.000 - 1.332% [2] {min=0.000, max=0.000, mean=0.000, threads=3} call_startup_functions_action
16 total graph nodes

Task tree also written to tasktree.txt.
Computing new stats...
Building dot file
done.
```

HPX STE||AR GROUP

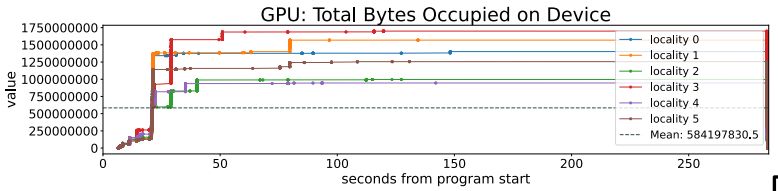
HPX Example – tasktree (DOT)

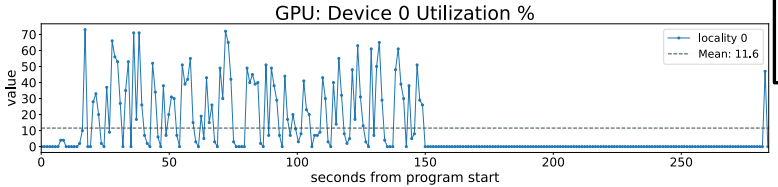


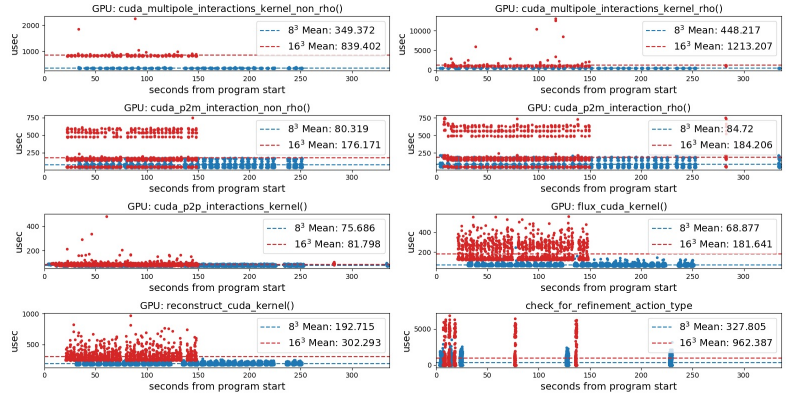
HPX Example – Perfetto trace



APEX example – Octo-Tiger (HPX)

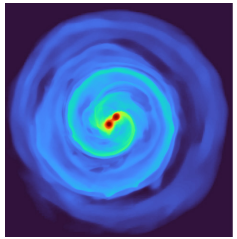




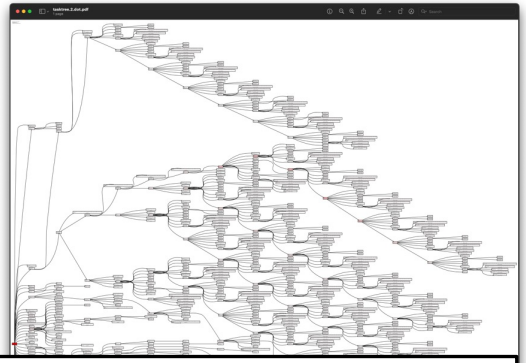


Tracking GPU memory usage with CUPTI

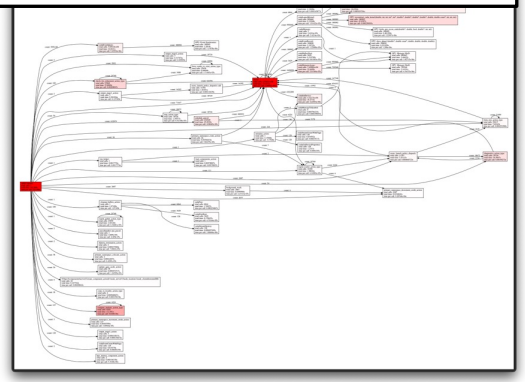
Monitoring GPU utilization with NVML library



Comparing subgrid sizes and relative kernel performance with CUPTI device activity



Full task tree (above) and task graph (below) showing task dependencies

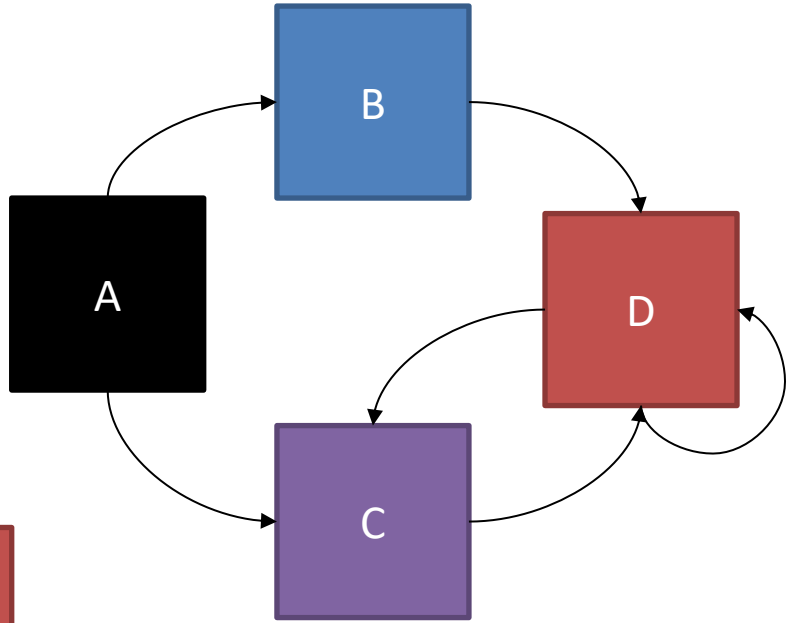


https://github.com/STEllAR-GROUP/octotiger
https://github.com/STEllAR-GROUP/hpx

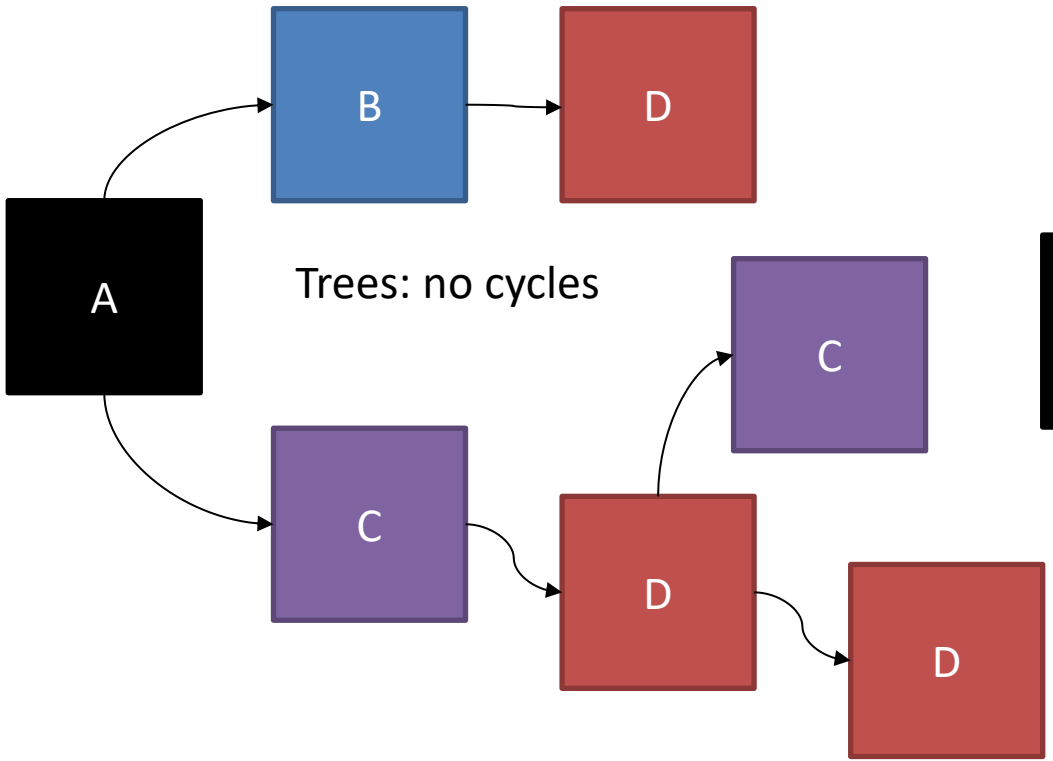
Diehl, Patrick, et al. "Octo-Tiger's New Hydro Module and Performance Using HPX+CUDA on ORNL's Summit." *2021 IEEE International Conference on Cluster Computing (CLUSTER)*. IEEE, 2021.

Task Dependencies: Trees & Graphs

Graphs: cycles, each node appears only once

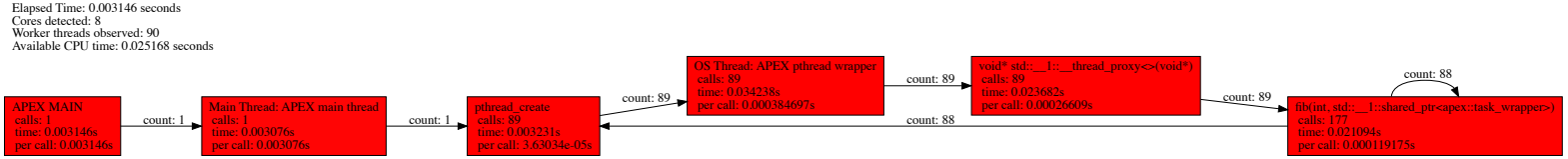


Trees: no cycles



Task Dependencies: C++ fib(10)

Task Graph: aggregated, contains cycles

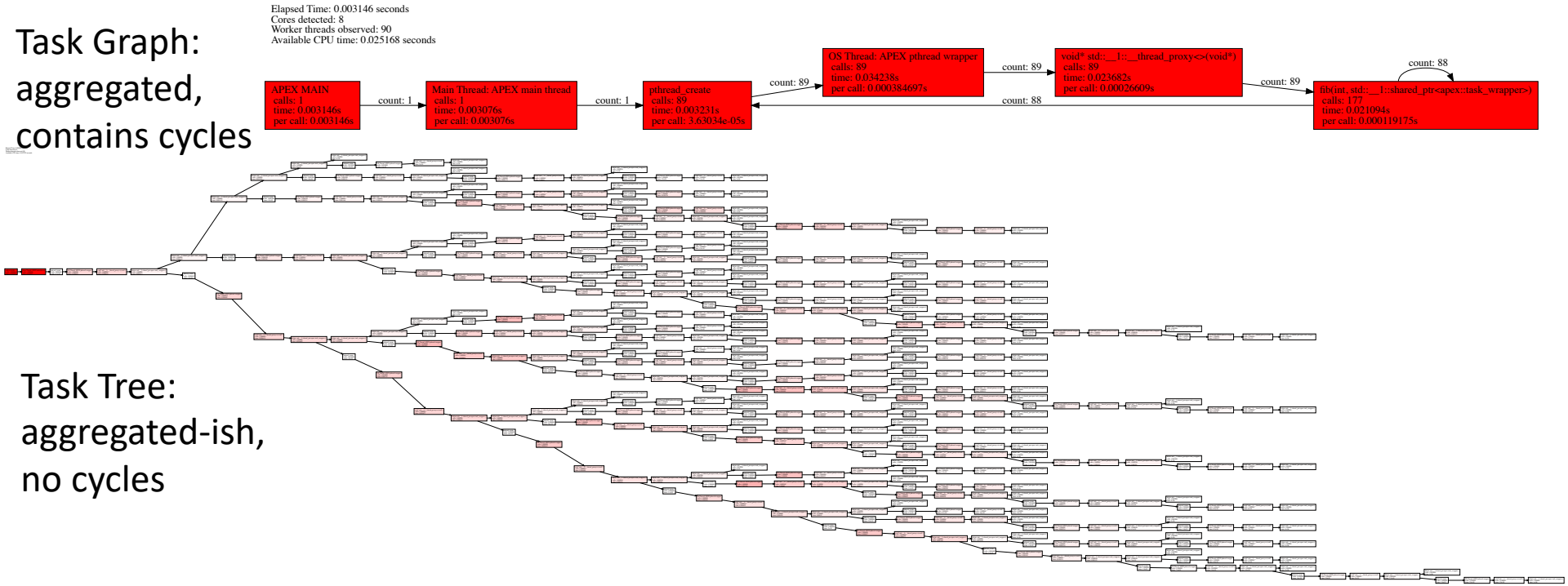



```
int fib (int in, std::shared_ptr<apex::task_wrapper> parent) {
    apex::scoped_thread st("fib thread");
    apex::scoped_timer ast((uint64_t)&fib,
        apex::apex_options::top_level_os_threads() ? nullptr : parent);
    if (in == 0) { return 0; }
    else if (in == 1) { return 1; }
    int a = in-1;
    int b = in-2;
    auto future_a = std::async(std::launch::async, fib, a,
        ast.get_task_wrapper());
    //ast.yield();
    int result_b = fib(b, ast.get_task_wrapper());
    int result_a = future_a.get();
    //ast.start();
    int result = result_a + result_b;
    return result;
}
```

```
int main(int argc, char *argv[]) {
    apex::init(argv[0], 0, 1);
    int i = 10;

    if (argc != 2) {
        std::cerr << "usage: " << argv[0] << " <integer value>" << std::endl;
        std::cerr << "Using default value of 10" << std::endl;
    } else {
        i = atol(argv[1]);
    }

    if (i < 1) {
        std::cerr << i << " must be>= 1" << std::endl;
        return -1;
    }

    std::shared_ptr<apex::task_wrapper> parent = nullptr;
    auto future = std::async(fib, i, parent);
    int result = future.get();
    std::cout << "fib of " << i << " is " << result
        << " (valid value: " << fib_results[i] << ")" << std::endl;
    apex::finalize();
    return 0;
}
```

Task Dependencies: fib(10)

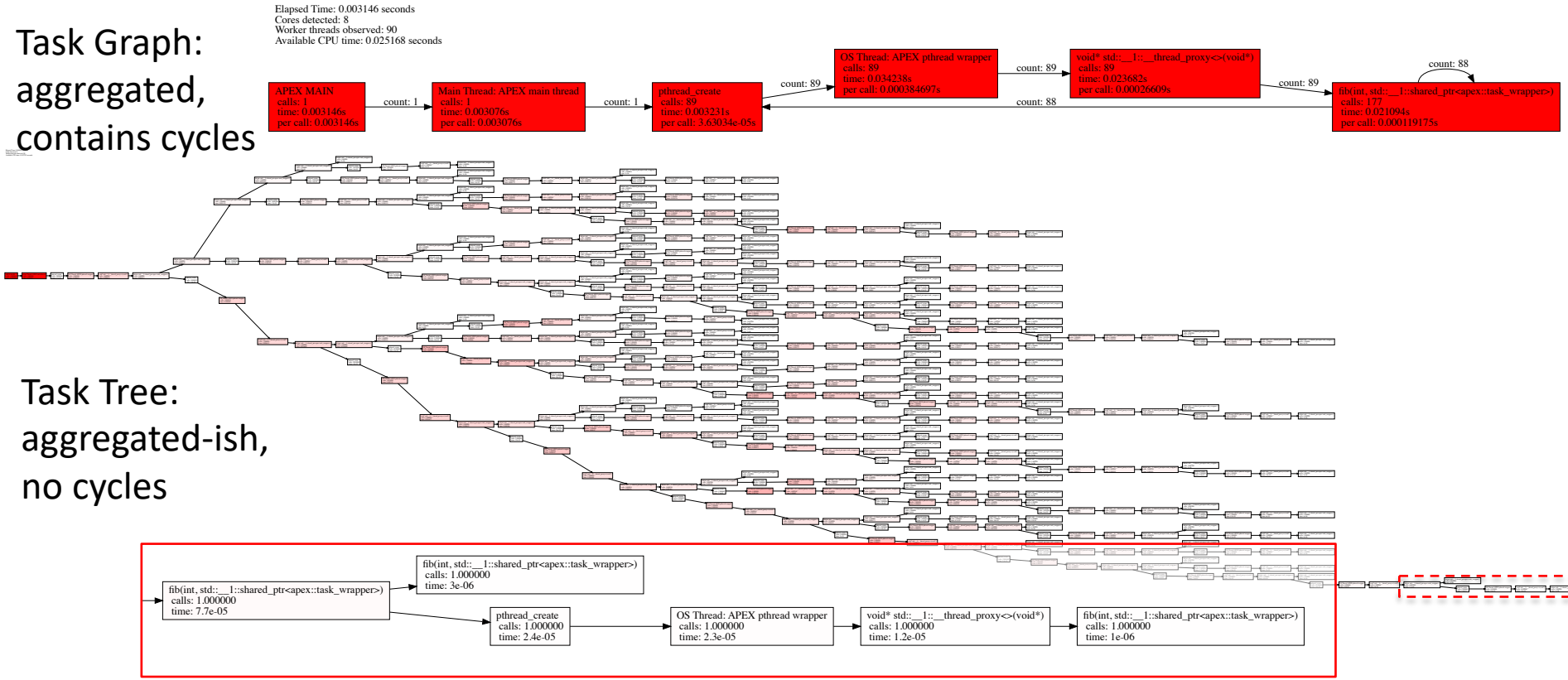
Task Graph:
aggregated,
contains cycles



Task Tree:
aggregated-ish,
no cycles

Task Dependencies: fib(10)

Task Graph: aggregated, contains cycles



Task Tree: aggregated-ish, no cycles

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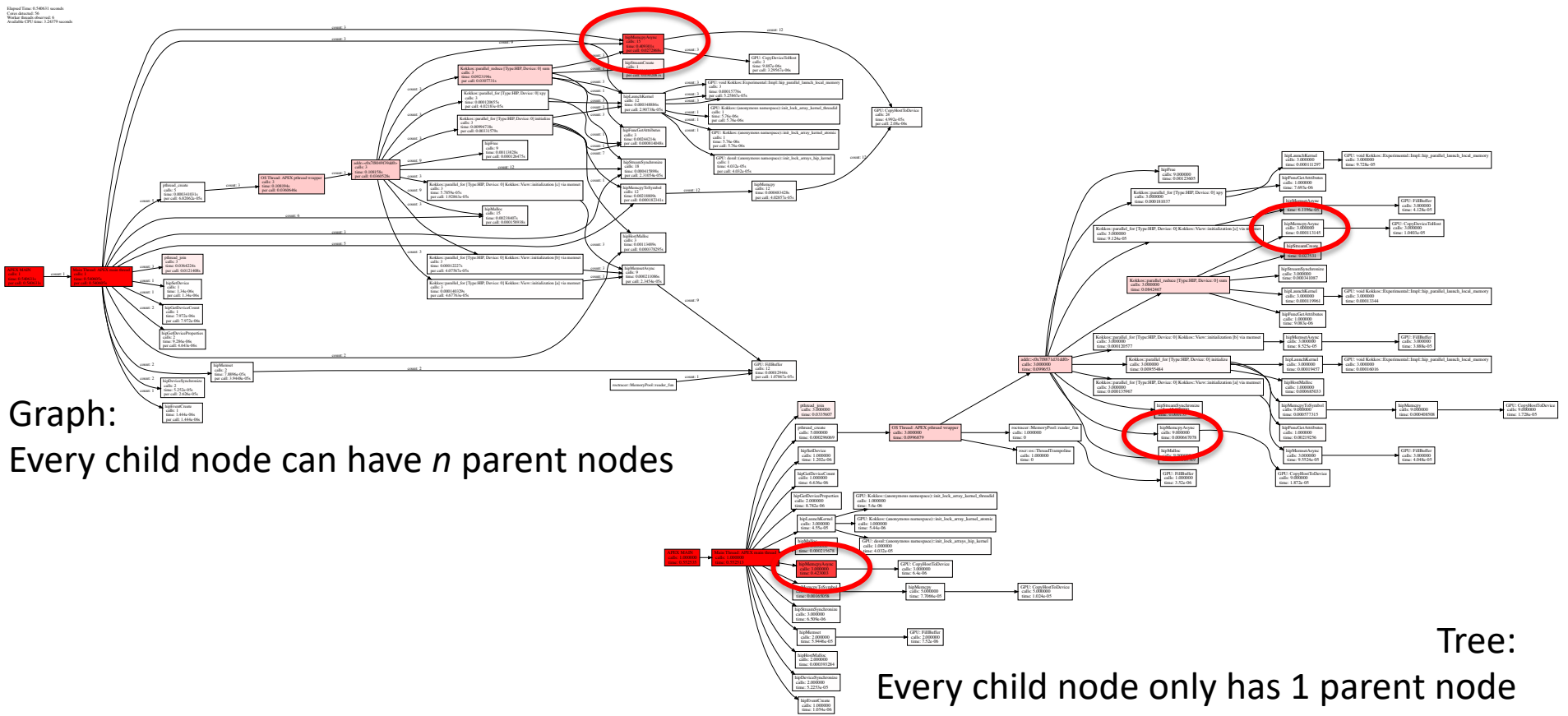
Better Example



Graph:

Every child node can have *n* parent nodes

Tree:

Every child node only has 1 parent node

Hardware Counters

- APEX is integrated with PAPI (Performance Application Programming Interface) https://icl.utk.edu/papi/
- Portable access to native hardware counters
  - CPU
  - GPU
  - Off-core (permission dependent)
  - Node/OS health
  - Power/energy
  - Filesystems
- HW counters collected with timers, or periodically

PAPI timer example

```
APEX_SCREEN_OUTPUT_DETAIL=1 APEX_PAPI_METRICS="PAPI_TOT_INS PAPI_BR_MSP"
srun ../apex/install/bin/apex_exec --apex:cuda build/bin/multiGpuThread_cu

CPU Timers                                                    : #calls| #yields|
#thread|      mean |     total |   tot/thr | %total | %wall | TOT_INS | BR_MSP
-------------------------------------------------------------------------------
-----------------------------------------------
                                        APEX MAIN :       1         0
1       0.13        0.13        0.13   100.0   100.0   7.52e+07   1.47e+05
          int apex_preload_main(int, char**, char**) :       1         0
1       0.13        0.13        0.13    19.6    98.2   7.04e+07   1.36e+05
                                      cudaMalloc :       2         0
1       0.05        0.09        0.09    13.9    69.3   6.32e+07   1.04e+05
                                      cudaMemcpy :      80         0
4       0.00        0.01        0.00     0.9     1.2   5.01e+06   2.98e+04
                                  cudaLaunchKernel :      40         0
4       0.00        0.00        0.00     0.2     0.2   1.01e+06   1.69e+04
```

PAPI periodic example

```
APEX_PAPI_COMPONENTS="perf perf_event"
APEX_PAPI_COMPONENT_METRICS="perf::INSTRUCTIONS:u=0" srun
../apex/install/bin/apex_exec --apex:cuda build/bin/multiGpuThread_cu --
apex:period 10000

Counter                                         : #samp |   mean   |  max
--------------------------------------------------------------------------------
                                  CPU Guest % :      20      0.00      0.00
                                CPU I/O Wait % :      20      0.00      0.00
                                    CPU IRQ % :      20      0.02      0.37
                                   CPU Idle % :      20     99.73    100.00
                                   CPU Nice % :      20      0.00      0.00
                                  CPU Steal % :      20      0.00      0.00
                                 CPU System % :      20      0.21      0.73
                                   CPU User % :      20      0.04      0.37
                               CPU soft IRQ % :      20      0.01      0.16
…(they should show up here. Didn’t work on mahti ☹ )
```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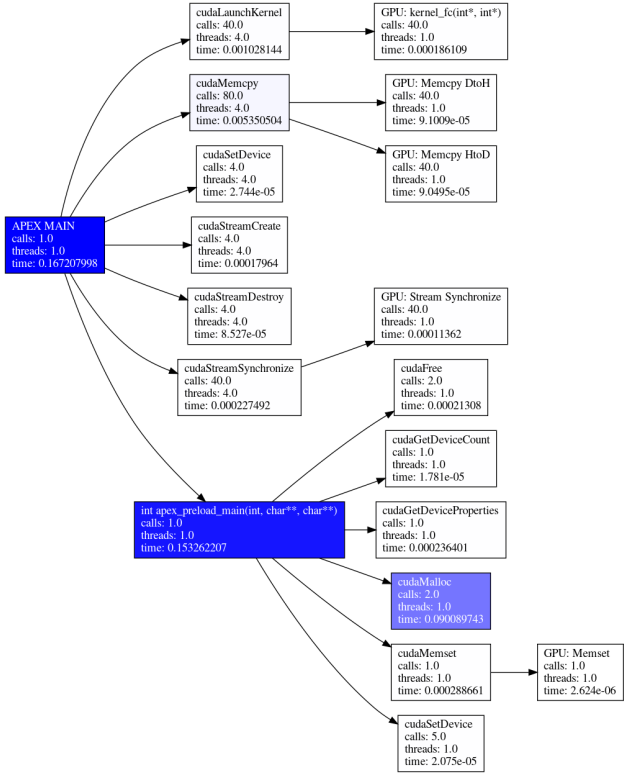
CUDA Measurement

- Support provided with NVIDIA **CUPTI** library
- Monitoring support provided with NVIDIA **NVML** library
- Hardware counters provided from **CUPTI**, indirectly through **PAPI**
- Host callback and device activity dependencies linked **using correlation IDs**
- Some kernel counters optionally captured (register usage, occupancy, block sizes, grid sizes, …)

CUDA example

```
[kehuck1@mahti-login11 apex-tutorial]$ srun
../apex/install/bin/apex_exec --apex:cuda build/bin/multiGpuThread_cu
--apex:monitor_gpu --apex:tasktree
[kehuck1@mahti-login11 apex-tutorial]$
$HOME/src/apex/install/bin/apex-treesummary.py --ascii --dot
Reading tasktree...
Read 19 rows
Found 0 ranks, with max graph node index of 18 and depth of 3
building common tree...
Rank 0 ...
…
Task tree also written to tasktree.txt.
Computing new stats...
Building dot file
done.
[kehuck1@mahti-login11 apex-tutorial]$ graphviz -Tpng -O tasktree.dot
```

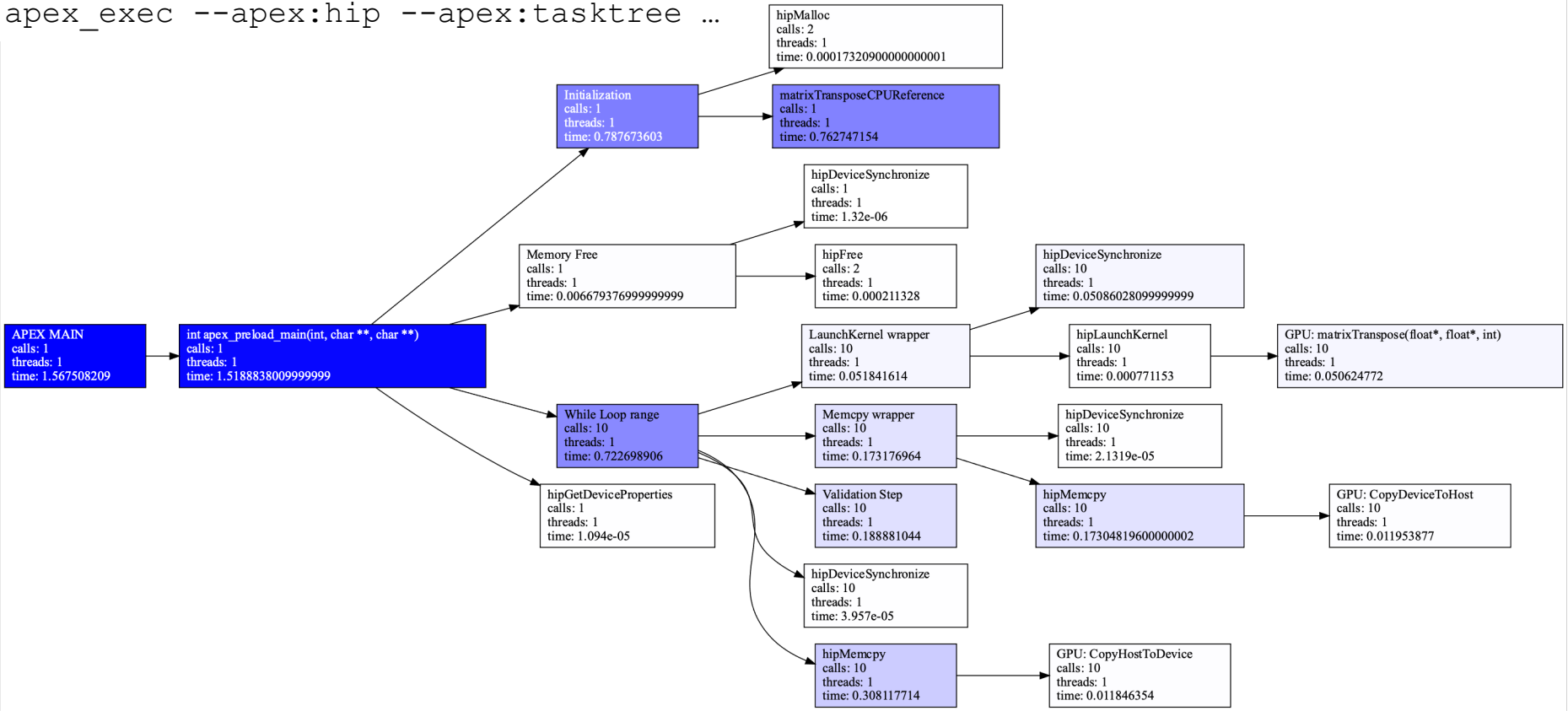


HIP/ROCm Measurement

- Support provided by AMD **Roctracer** and **Rocprofiler** libraries (deprecated, soon to be replaced)
- Monitoring support provided by AMD **rocm-smi** library
- Hardware counters provided through **PAPI**
- Host callback and device activity dependencies linked using **correlation IDs**
- Some kernel counters optionally captured (block sizes, grid sizes)

HIP example

```
apex_exec --apex:hip --apex:tasktree …
```



GPU Monitoring

Adding --apex:monitor_gpu will enable NVML or ROCM-SMI support

Counter	:	#samp	mean	max
GPU: Device 0 Clock Memory (MHz)	:	2	1215.00	1215.00
GPU: Device 0 Clock SM (MHz)	:	2	210.00	210.00
GPU: Device 0 Memory Free (GB)	:	2	42.47	42.48
GPU: Device 0 Memory Total (GB)	:	1	42.95	42.95
GPU: Device 0 Memory Used (GB)	:	2	0.48	0.48
GPU: Device 0 Memory Utilization %	:	2	0.00	0.00
GPU: Device 0 NvLink Link Count	:	1	12.00	12.00
GPU: Device 0 NvLink Speed (GB/s)	:	1	25.00	25.00
GPU: Device 0 NvLink Throughput Data RX	:	2	1.06e+11	1.06e+11
GPU: Device 0 NvLink Throughput Data TX	:	2	1.04e+11	1.04e+11
GPU: Device 0 NvLink Throughput Raw RX	:	2	1.68e+11	1.68e+11
GPU: Device 0 NvLink Throughput Raw TX	:	2	1.67e+11	1.67e+11
GPU: Device 0 PCIe RX Throughput (MB/s)	:	2	76.50	137.00
GPU: Device 0 PCIe TX Throughput (MB/s)	:	2	2.50	5.00
GPU: Device 0 Power (W)	:	2	55.87	57.49
GPU: Device 0 Temperature (C)	:	2	37.00	37.00
GPU: Device 0 Utilization %	:	2	0.00	0.00

…

OneAPI Measurement

- Support provided with Intel **Level0** library
- Monitoring support not yet provided
- Hardware counters not yet provided
- Host callback and device activity dependencies linked using **correlation IDs** – generated by APEX
- Very early stages of support

GPU Memory Tracking

- For both CUDA and HIP, when memory is allocated or freed through the cuda and hip *runtime* APIs, APEX captures:
  - Allocation type (host/gpu)
  - Bytes allocated
  - thread ID that requested it
  - Address of allocated memory
  - Backtrace from when allocation happened
- At application exit, any leaked allocations are reported to the user, similar to **`cuda-memcheck`**
- …but finds leaks that it doesn't
- Counters also saved by APEX (bytes allocated/freed/total)

Motivating paper: Wei, Weile, et al. "*Memory Reduction Using a Ring Abstraction Over GPU RDMA for Distributed Quantum Monte Carlo Solver*." Proceedings of the Platform for Advanced Scientific Computing Conference, 2021.

(b) Distributed G_t^d method with sub-ring size of three.

Example Program: memory error

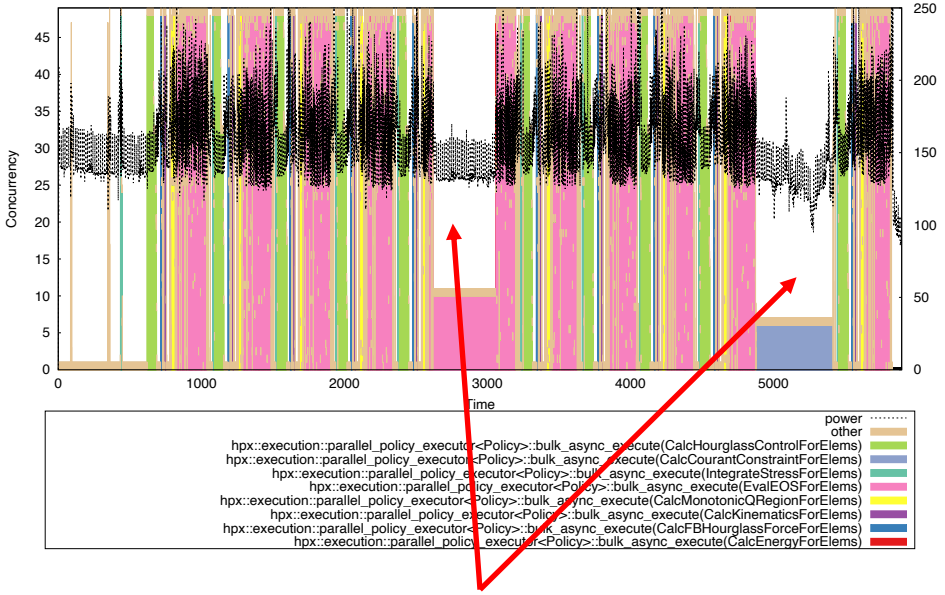
apex_exec --apex:gpu_memory …

```
1  #include <Kokkos_Core.hpp>
2  #include <cmath>
3
4  int main(int argc, char* argv[]) {
5    Kokkos::initialize(argc, argv);
6    {
7      void * ptr;
8      // This memory will leak
9      cudaMalloc(&ptr, 1024);
10     int N = argc > 1 ? atoi(argv[1]) : 1000000;
11     int R = argc > 2 ? atoi(argv[2]) : 10;
12     double result;
13     Kokkos::parallel_reduce(N, KOKKOS_LAMBDA(int i, double& r) {
14       r+=i;
15     },result);
16     printf("%lf\n",result);
17   }
18   Kokkos::finalize();
19 }
```

```
CUDA-MEMCHECK version 11.6.124 ID:(46)
========= CUDA-MEMCHECK
========= ERROR SUMMARY: 0 errors
```

```
1024 bytes leaked at 0x1465937ea400 from task cudaMalloc on tid 0 with backtrace:
gpu_device_malloc
addr=<0x1465fa0f409b> [{(unknown)} {0x1465fa0f409b}]
addr=<0x1465fa0f43b7> [{(unknown)} {0x1465fa0f43b7}]
addr=<0x1465fa0f6c1c> [{(unknown)} {0x1465fa0f6c1c}]
addr=<0x1465fe5e3143> [{(unknown)} {0x1465fe5e3143}]
addr=<0x1465fdfb247b> [{(unknown)} {0x1465fdfb247b}]
main [{/home/khuck/polaris/test/test.cpp} {9,0}]
__libc_start_main [{/lib64/libc-2.31.so} {0x1465fb4e434d}]
_start [{/home/abuild/rpmbuild/BUILD/glibc-2.31/csu/../sysdeps/x86_64/start.S} {122,0}]
```

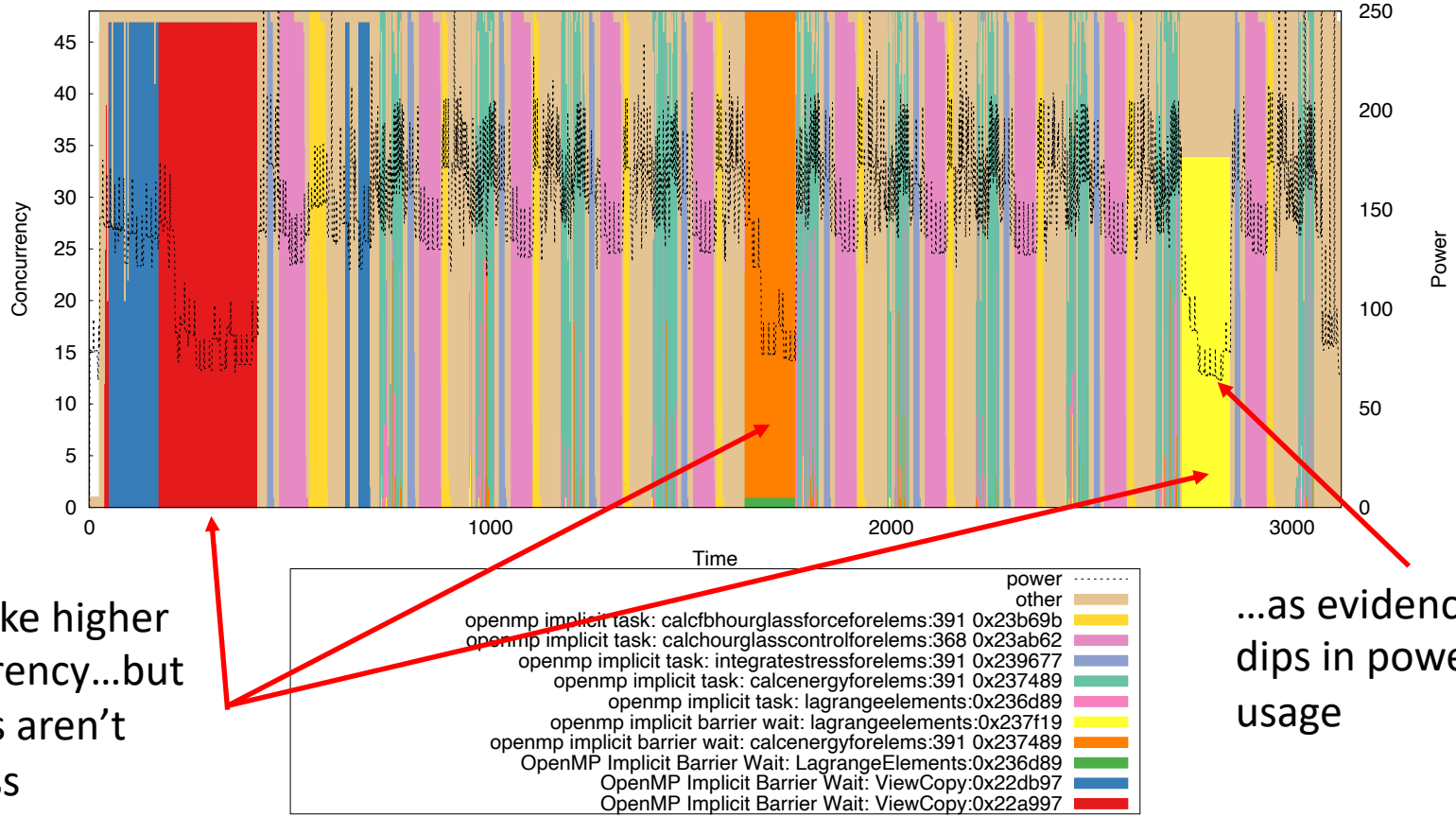
Concurrency Tracking



Helps identify regions of low concurrency

- Periodically sample all the currently executing tasks
- Aggregate across N timers
- Example shown:
  - Kokkos Lulesh with HPX back end
  - Sampled 200 times per second
  - 10 iterations, size 256

Concurrency: OpenMP back end

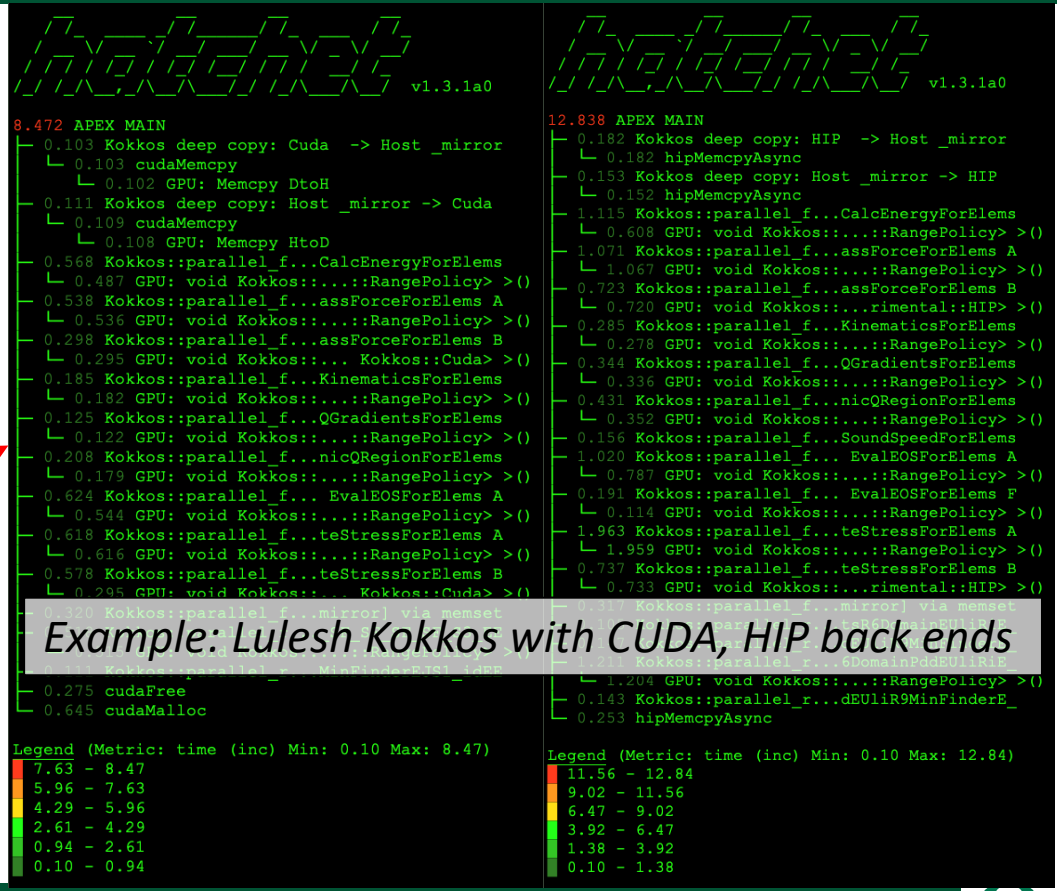


Looks like higher concurrency…but barriers aren't progress

…as evidenced by dips in power usage

Profile Formats

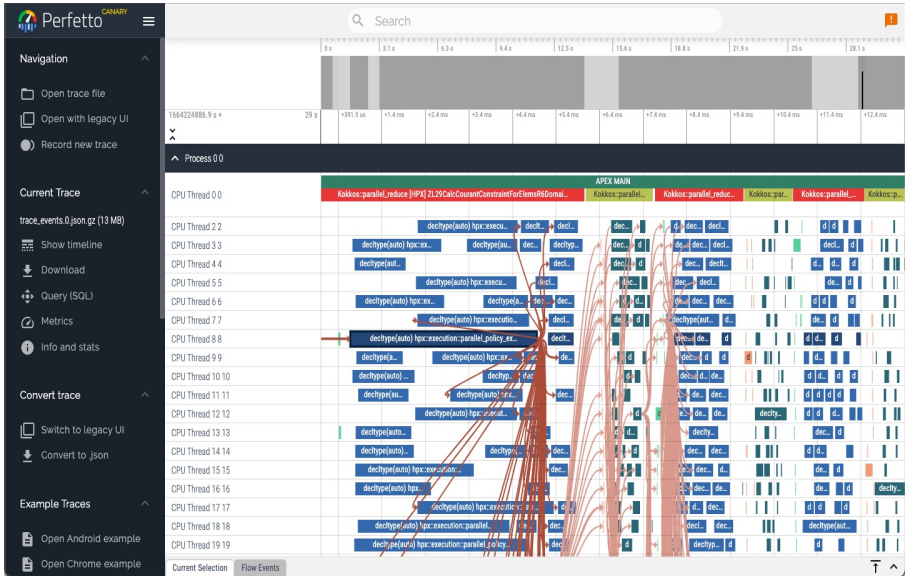
- All timer & counter data
- **Flat profile:**
  - Text summary to screen – all ranks merged with MPI or HPX at end of execution
  - CSV (for Python ingestion)
  - TAU Profiles (ParaProf)
- **Task graphs/trees:**
  - Hatchet-like JSON (still working on importer library for Hatchet) https://hatchet.readthedocs.io
  - ~~Graphviz dot files~~
  - ~~Txt files (similar to Trilinos profiler output)~~
  - … these are now replaced by single CSV file that is post-processed.



Example: Lulesh Kokkos with CUDA, HIP back ends

Trace Formats

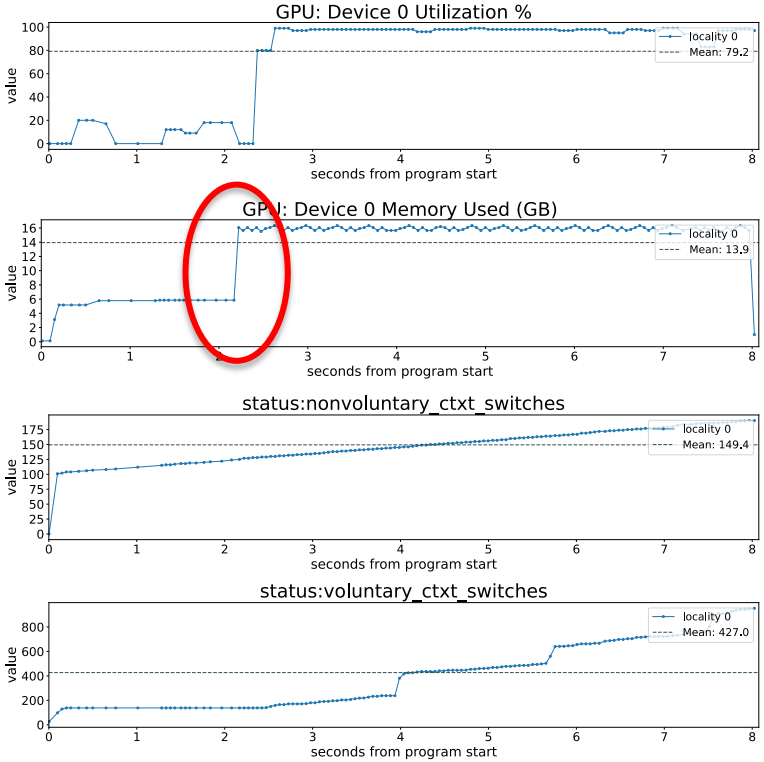
- OTF2 up to v 2.3
  - 3.0 has API changes, haven't been incorporated yet
  - Visualized with Vampir or Traveler / JetLag
- Google Trace Events Format
  - JSON support
  - Perfetto native support
  - Visualized with Perfetto
  - Some scaling issues (memory limit of web browser)



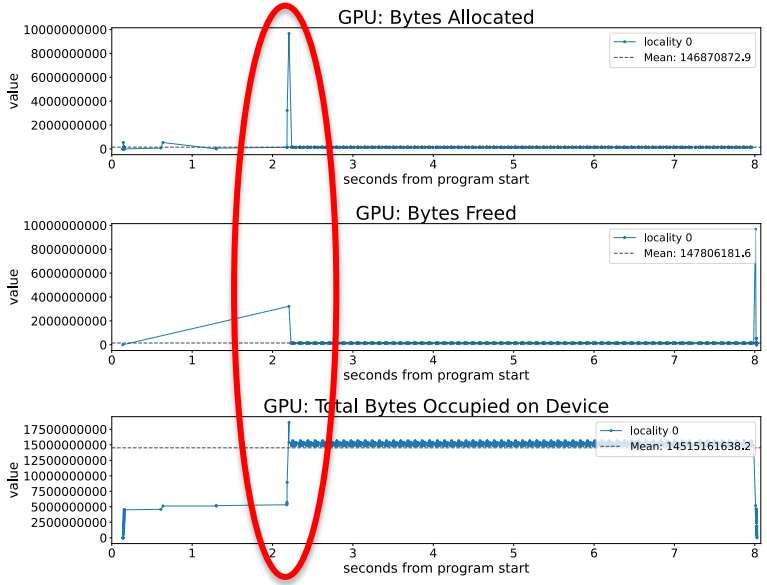
Example: Lulesh Kokkos with HPX back end

Scatterplots

Monitoring Data (periodic)



Progress Data (events)



Example: Lulesh Kokkos with CUDA back end

Supported Programming Models

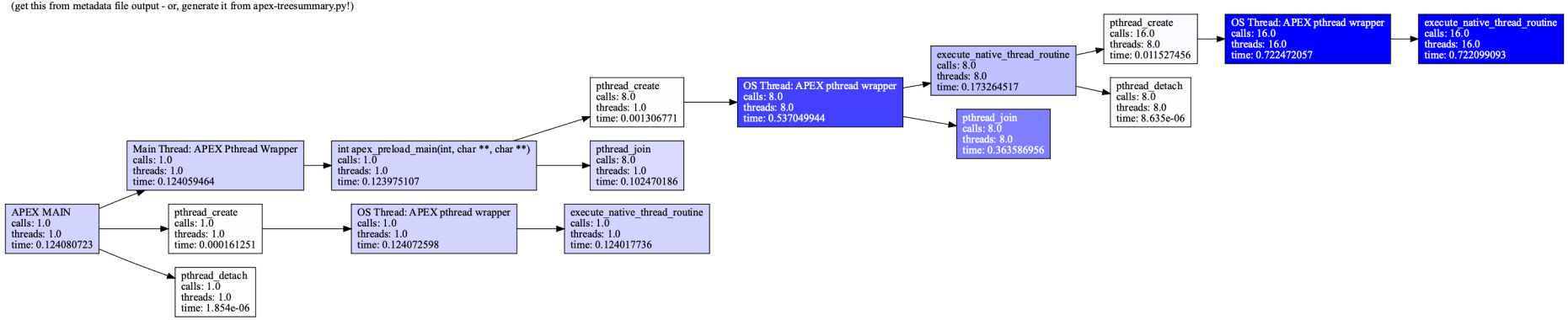
- HPX
- POSIX / C++ threads
- OpenMP/OpenACC
- GPU offload: CUDA, HIP, OneAPI, OpenMP target
- Abstractions: Kokkos (SNL), Raja (LLNL)
- MPI (subset)
- In development / experimental: StarPU (?), Iris (ORNL)

POSIX / C++ Threads

- APEX wraps the pthread_create() call:
  - Wraps target function with a proxy function
  - Times target function
  - Captures task dependency hierarchy between parent, child
- Provides support for C++ thread activity too
  - std::thread
  - std::async
  - Detached threads

Thread example

(get this from metadata file output - or, generate it from apex-treesummary.py!)

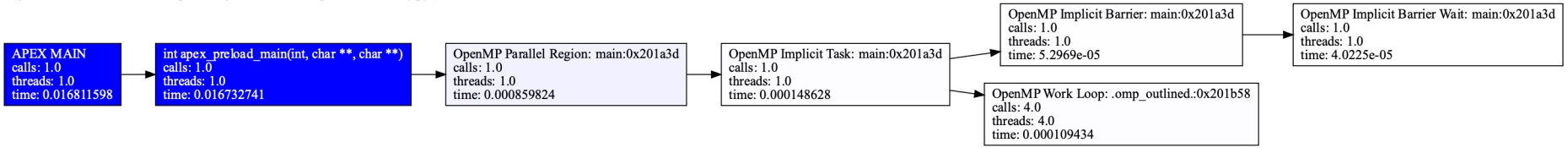


OpenMP and OpenACC

- OpenMP 5.0 included OMP-Tools (OMPT) API
  - Callbacks, query functions, sampling states
  - Buffer processing for **target offload** asynchronous activity
  - Tested with AMD Clang 5.0+, NVHPC 22.7+, Intel OneAPI 2022
- OpenACC profiling callbacks to intercept entry/exit of all OpenACC routines
  - CUDA/CUPTI provides support for device activity (see next slide)

OpenMP example

(get this from metadata file output - or, generate it from apex-treesummary.py!)



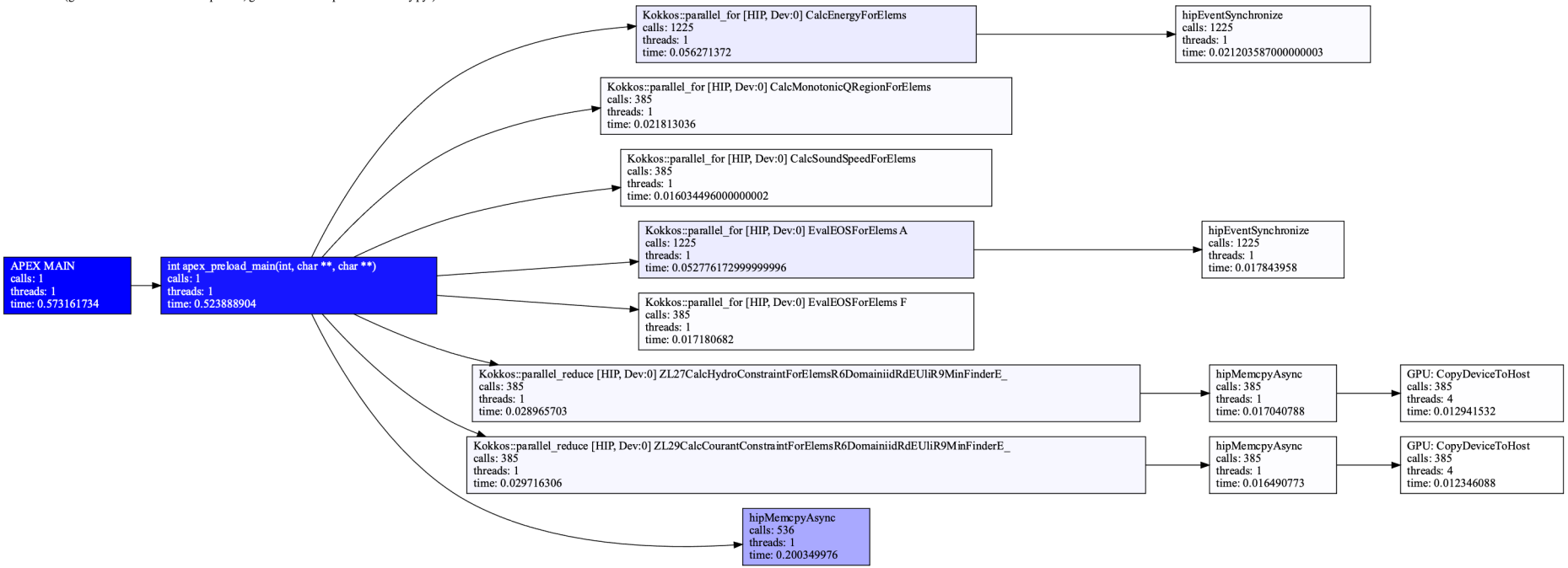
Kokkos and Raja

RAJA

- C++ Abstraction models for performance portability
- 1 source code implementation to target different architectural / model back ends
  - Serial, Pthreads, OpenMP, OpenACC, CUDA, HIP, SYCL, etc.
- Both provide profiling callbacks for tool support
- Kokkos includes a prototype “tuning” interface for tools to hook utilize at runtime
  - APEX has implemented tuning policies and tested with CUDA back end tuning Range, MDRange, Team policies

Kokkos Example

(get this from metadata file output - or, generate it from apex-treesummary.py!)



Lulesh w/ Kokkos Experiments

- https://github.com/kokkos/kokkos-miniapps
- Tested lulesh-2.0 mini-app (https://asc.llnl.gov/codes/proxy-apps/lulesh)
  - HPX
  - OpenMP
  - CUDA
  - HIP

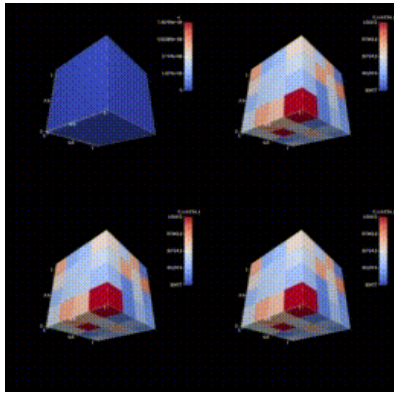
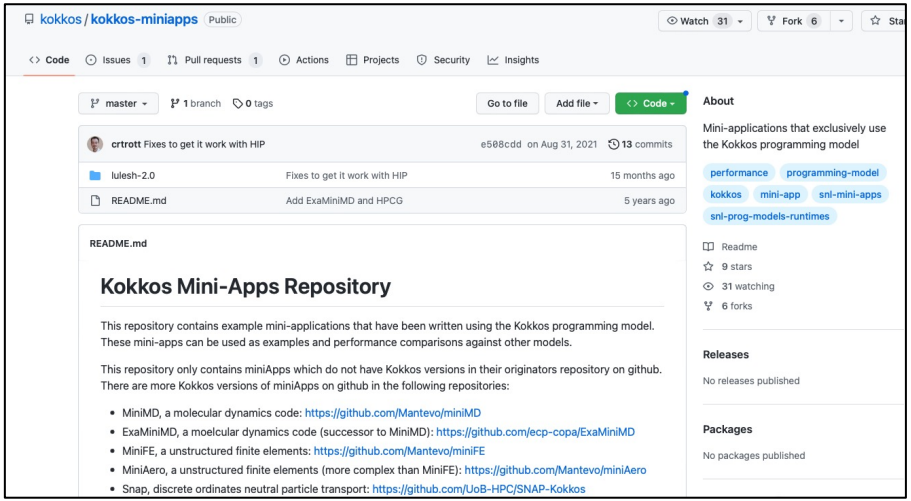


Figure: LULESH 2.0.3 executed with 64 MPI ranks, measured by TAU. Time spent in main loop rendered every 100 timesteps by Alpine-Ascent. Clockwise from upper left: Computed energy, accumulated time in main loop, time in main loop during last 100 timesteps, Δ time in main loop from previous 100 time steps. Source: Malony, et al. "When Parallel Performance Measurement and Analysis Meets In Situ Analytics and Visualization." Parallel Computing: Technology Trends. IOS Press, 2020. 521-530.



Lulesh: CUDA back end

```
Elapsed time: 8.96729 seconds
Total processes detected: 1
HW Threads detected on rank 0: 96
Worker Threads observed on rank 0: 1
Available CPU time on rank 0: 8.96729 seconds
Available CPU time on all ranks: 8.96729 seconds

Counter                                  : #samples | minimum |    mean    |  maximum |  stddev
------------------------------------------------------------------------------------------------
                    1 Minute Load average :      161     14.680     15.717     16.640     0.641
                              CPU Guest % :      160      0.000      0.000      0.000     0.000
                           CPU I/O Wait % :      160      0.000      0.001      0.192     0.015
                                CPU IRQ % :      160      0.000      0.054      0.200     0.086
                               CPU Idle % :      160     67.331     95.424     97.679     2.670
                               CPU Nice % :      160      0.000      0.000      0.000     0.000
                              C
                             CP

                           CPU
                              D
                      GPU: Bytes
                          GPU: E
          GPU: Device 0 Clock Me
              GPU: Device 0 Cloc
            GPU: Device 0 Memory
```

```
CPU Timers                                          : #calls  | #yields |   mean   |  total   | % total
--------------------------------------------------------------------------------------------------------
                                        APEX MAIN :        1         0      8.967      8.967    100.000
                           cudaDeviceSynchronize :    22901         0      0.000      4.004     44.647
                           cudaStreamSynchronize :     4398         0      0.000      0.767      8.550
                                      cudaMalloc :      946         0      0.001      0.727      8.106
Kokkos::parallel_for [Cuda, Dev:0] IntegrateStressF… :   64         0      0.010      0.632      7.048
Kokkos::parallel_for [Cuda, Dev:0] EvalEOSForElems A : 2240         0      0.000      0.630      7.031
Kokkos::parallel_for [Cuda, Dev:0] CalcEnergyForEle… : 2240         0      0.000      0.577      6.433
Kokkos::parallel_for [Cuda
Kokkos::parallel_for [Cuda
Kokkos::parallel_reduce [C
```

```
GPU Timers                                              : #calls  |   mean   |  total   | % total
---------------------------------------------------------------------------------------------------
                            GPU: Context Synchronize :    22901      0.000      3.705     41.318
                             GPU: Stream Synchronize :     4398      0.000      0.756      8.429
GPU: void Kokkos::Impl::cuda_parallel_launch_consta… :       64      0.010      0.628      7.000
GPU: void Kokkos::Impl::cuda_parallel_launch_consta… :     2240      0.000      0.543      6.051
GPU: void Kokkos::Impl::cuda_parallel_launch_consta… :       64      0.008      0.542      6.043
GPU: void Kokkos::Impl::cuda_parallel_launch_consta… :       64      0.008      0.524      5.846
GPU: void Kokkos::Impl::cuda_parallel_launch_consta… :     2240      0.000      0.487      5.432
GPU: void Kokkos::Impl::cuda_parallel_launch_consta… :       64      0.005      0.299      3.331
GPU: void Kokkos::Impl::cuda_parallel_launch_consta… :       64      0.005      0.298      3.322
GPU: void Kokkos::Impl::cuda_parallel_launch_consta… :       64      0.003      0.185      2.066
GPU: void Kokkos::Impl::cuda_parallel_launch_consta… :      704      0.000      0.178      1.990
                                GPU: Memcpy HtoD :    10261      0.000      0.170      1.892
```

apex_exec **--apex:kokkos_fence --apex:cuda** \
--apex:monitor_gpu --apex:period 5000 \
${builddir}/lulesh-cuda/lulesh.cuda -s 256

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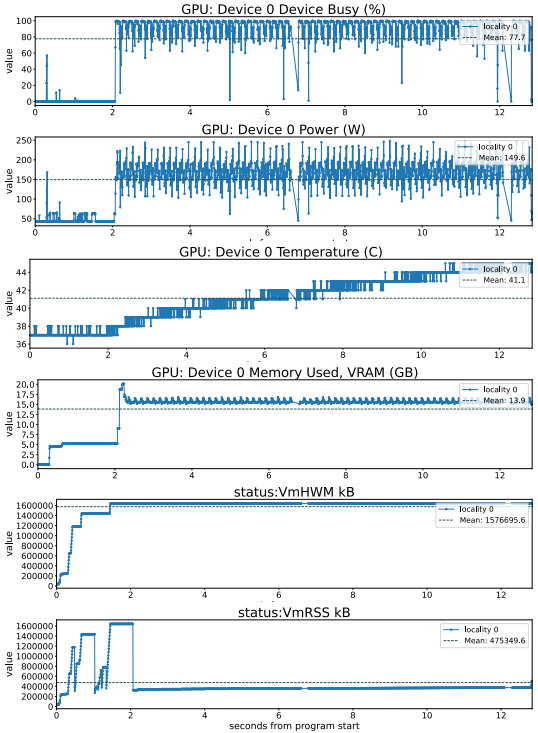
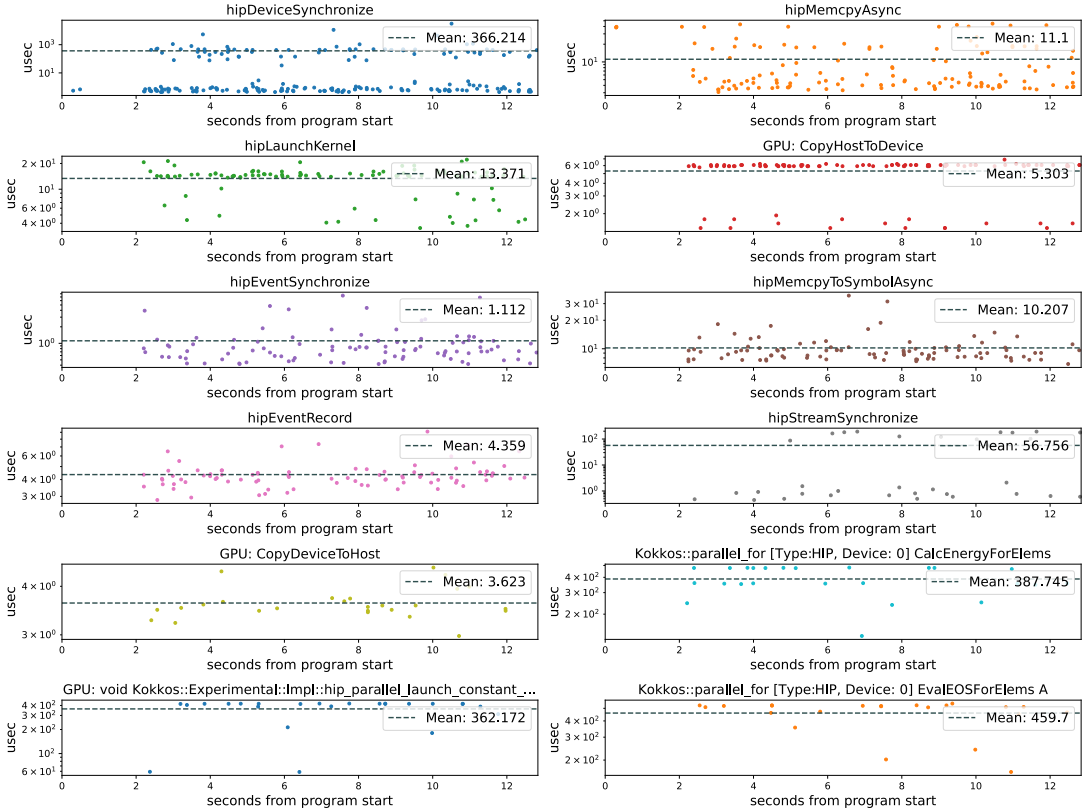
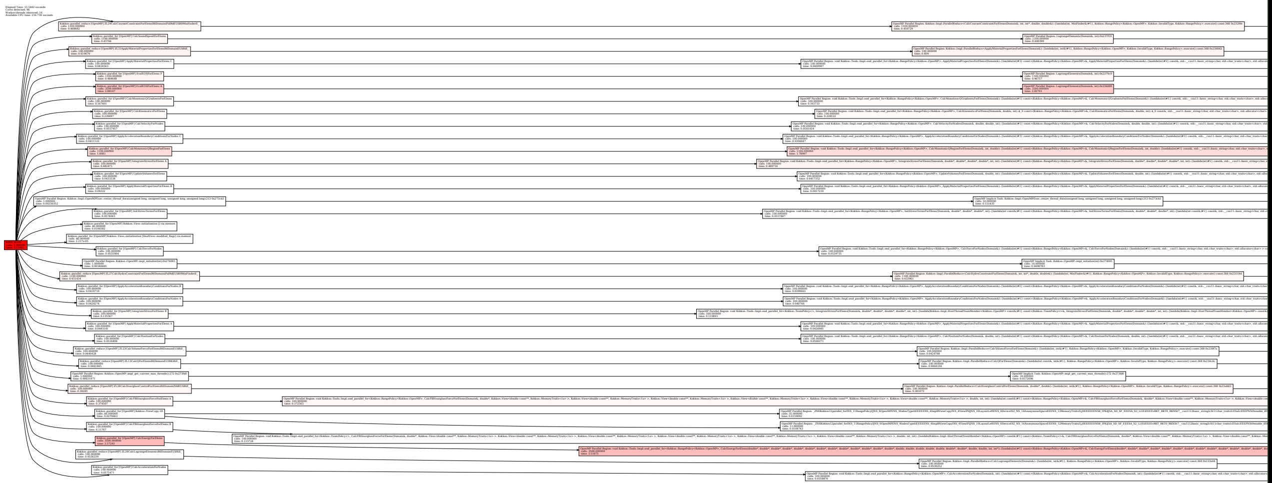
Lulesh: HIP back end

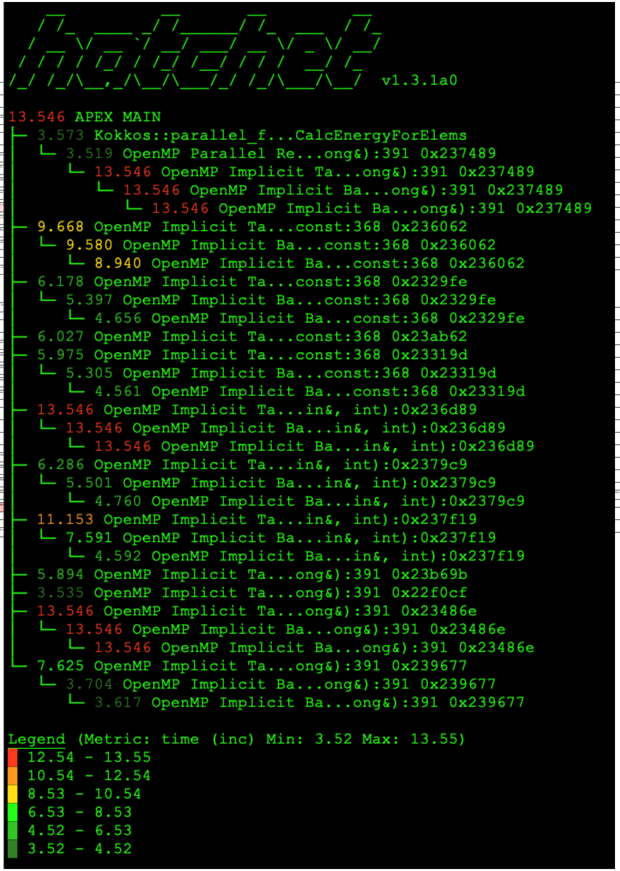




apex_exec **--apex:kokkos_fence --apex:scatter** \
--apex:hip --apex:monitor_gpu \
--apex:period 5000 ${builddir}/lulesh-hip/lulesh.hip -s 256

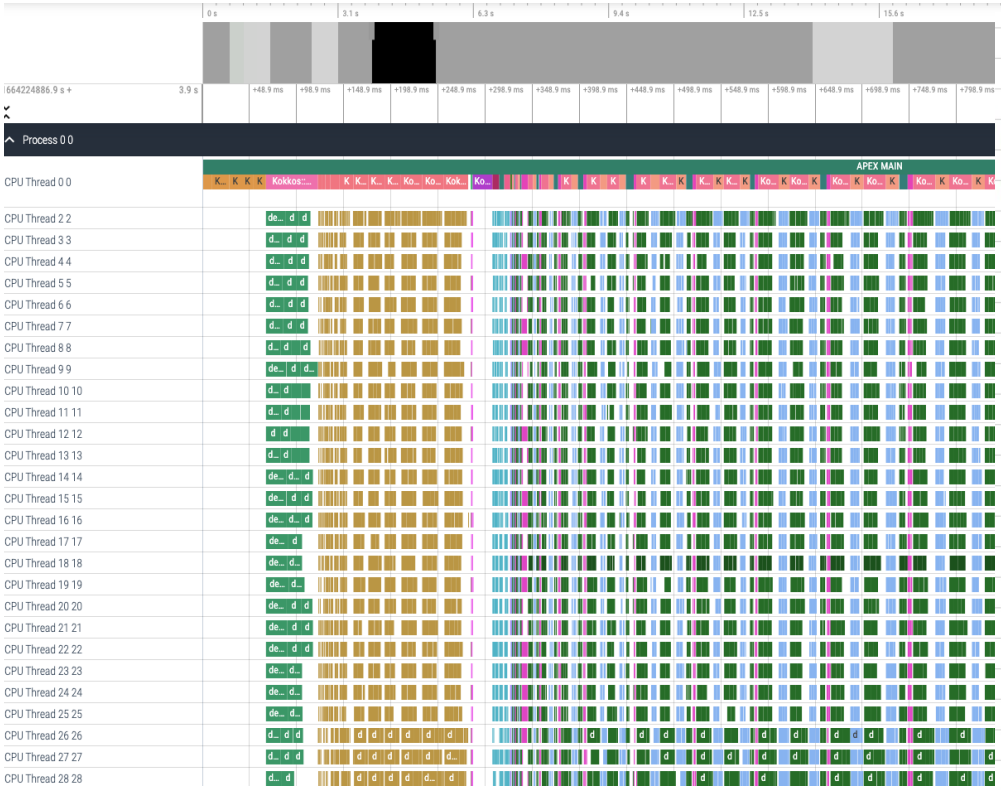
Lulesh: OpenMP back end

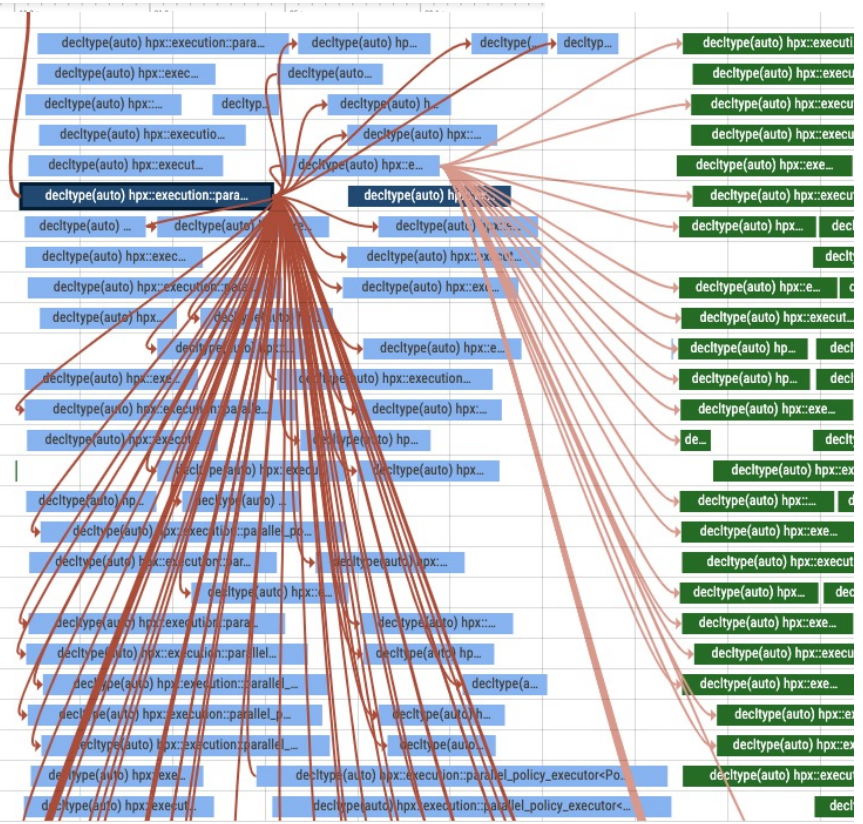




apex_exec **--apex:kokkos_fence --apex:ompt --apex:ompt_details** \
--apex:tasktree ${builddir}/lulesh-openmp/lulesh.host -s 256 -p -i 10

Lulesh: HPX back end





apex_exec **--apex:kokkos_fence --apex:gtrace** \
${builddir}/lulesh-hpx/lulesh.kk -p -i 10 -s 256

Policy Handling in APEX

- APEX has different methods for tuning: Active Harmony (Nelder Mead search), hill climbing, simulated annealing
- API:
  - setup_power_cap_throttling(), setup_timer_throttling(),
  - setup_throughput_tuning(), setup_custom_tuning(),
  - shutdown_throttling(), get_thread_cap(),
  - has_session_converged(), get_best_values()
- Policies are executed at an event, or periodically

Notes About Policies

- "Autotuning" any algorithm/model/feature/function has some pre-requisites:
  - Reconfigurable, parameterized problem with finite search space
  - Have to account for all causes of variability
    - Noise will influence the search
  - Have to have an observable, quantifiable affect
  - Single objective (no multi-objective tuning support yet)
- Not a magic solution

Typical Policy Example

```
int num_inputs = 3; // 2 for threads, block size; 3 for threads, block size, method
long * inputs[3] = {0L,0L,0L};
/* Set the minimum values */
long mins[3] = {2,128,DIVIDE_METHOD};
/* We'll set these later */
long maxs[3] = {0,0,0};    // we'll set these later
/* Set the step sizes */
long steps[3] = {2,128,1};
/* Active Harmony will update the values in these addresses */
inputs[0] = &active_threads;
inputs[1] = &block_size;
inputs[2] = &method;
/* Set the true max values */
maxs[0] = active_threads;
maxs[1] = num_cells/omp_get_max_threads();
maxs[2] = MULTIPLY_METHOD;
/* Register a custom event when we'll update the inputs */
my_custom_event = apex::register_custom_event("Perform Re-block");
/* Set up the tuning session */
apex::setup_throughput_tuning((apex_function_address)solve_iteration,
                APEX_MINIMIZE_ACCUMULATED, my_custom_event, num_inputs,
                inputs, mins, maxs, steps);
```

Custom Policy – use tuning request

```
enum class apex_param_type : int {NONE, LONG, DOUBLE, ENUM};
enum class apex_ah_tuning_strategy : int {EXHAUSTIVE, RANDOM, NELDER_MEAD,
PARALLEL_RANK_ORDER, SIMULATED_ANNEALING, APEX_EXHAUSTIVE, APEX_RANDOM};

class apex_tuning_request {
    protected:
        std::string name;
        std::function<double()> metric;
        std::map<std::string, std::shared_ptr<apex_param>> params;
        apex_event_type trigger;
        apex_tuning_session_handle tuning_session_handle;
        bool running;
        apex_ah_tuning_strategy strategy;
        double radius;
        int aggregation_times;
        std::string aggregation_function;
        …
```

Future Work

- ~~Intel Level0/OneAPI support has been prototyped, but not yet merged~~ ✅
- ~~StarPU support added by Camille Coti, needs additional testing and tighter integration~~ ✅
- ~~Perfetto native trace output~~ ✅
- PowerAPI integration for broader power/energy support
- Kokkos runtime autotuning development – in progress

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