Performance Analysis of HPX using APEX and the TAU Performance System®

Sameer Shende, Kevin Huck

sameer@cs.uoregon.edu, khuck@cs.uoregon.edu

http://tau.uoregon.edu

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Outline

- Introduction to TAU
- Instrumentation: PDT, MPI, OpenMP, **tau_exec**
- I/O and Memory evaluation
- PAPI
- Demonstration of analysis tools: ParaProf, TAUdb and PerfExplorer, Vampir and Jumpshot
- Introduction to APEX
- Building HPX with APEX & TAU
- Program Examples

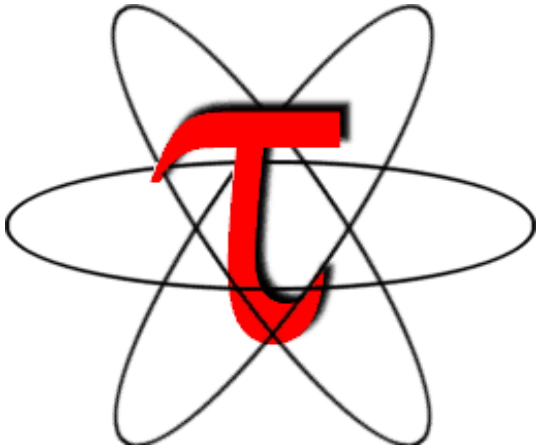
Tutorial Goals

This tutorial is an introduction to portable performance evaluation tools. You should leave here with a better understanding of…

- Concepts and steps involved in performance evaluation
- Understanding key concepts in understanding code performance
- How to collect and analyze data from hardware performance counters (PAPI)
- How to instrument your programs with TAU
- Measurement options provided by TAU
- Environment variables used for choosing metrics, generating performance data
- How to use ParaProf, TAU's profile browser
- General familiarity with TAU use for Fortran, C++, C, and mixed language
- How to generate trace data in different formats

TAU Performance System®

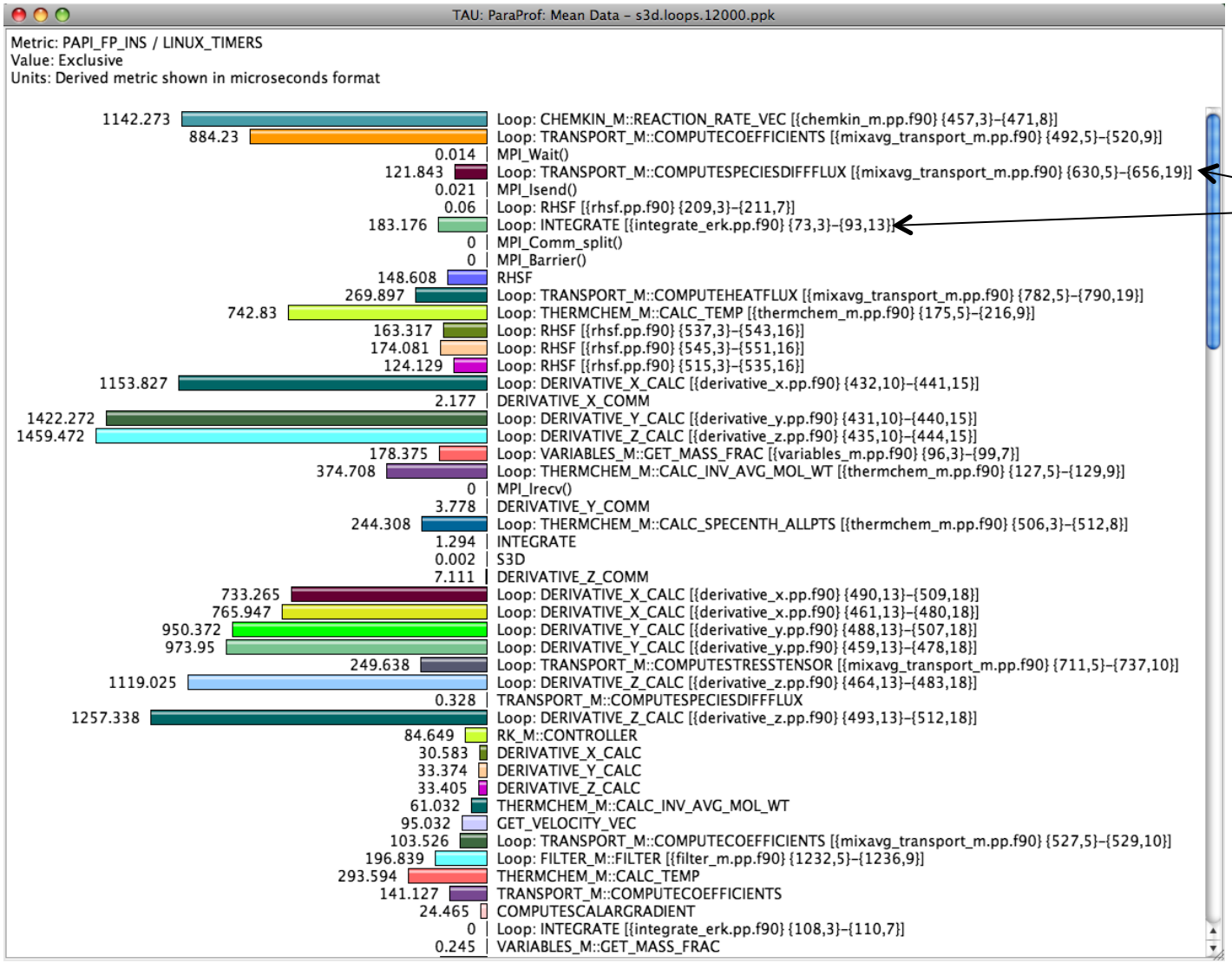
- **Tuning and Analysis Utilities (20+ year project)**
- **Comprehensive performance profiling and tracing**
  - Integrated, scalable, flexible, portable
  - Targets all parallel programming/execution paradigms
- **Integrated performance toolkit**
  - Instrumentation, measurement, analysis, visualization
  - Widely-ported performance profiling / tracing system
  - Performance data management and data mining
  - Open source (BSD-style license)
- **Integrates with application frameworks**



Understanding Application Performance using TAU

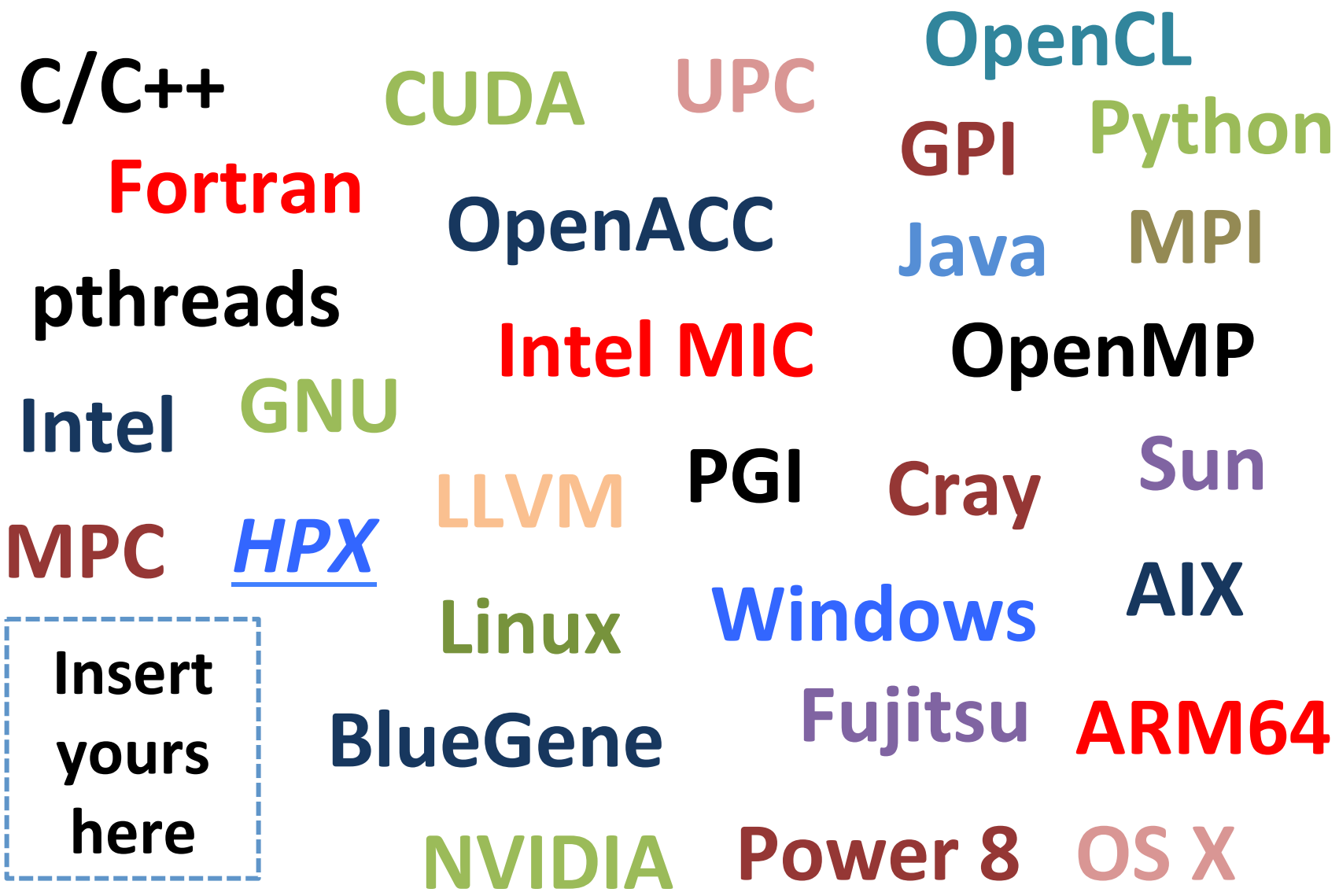
- **How much time** is spent in each application routine and outer loops? Within loops, what is the contribution of each *statement*?
- **How many instructions** are executed in these code regions? Floating point, Level 1 and 2 *data cache misses*, hits, branches taken?
- **What is the memory usage** of the code? When and where is memory allocated/de-allocated? Are there any memory leaks?
- **What are the I/O characteristics** of the code? What is the peak read and write *bandwidth* of individual calls, total volume?
- **What is the contribution of each *phase*** of the program? What is the time wasted/spent waiting for collectives, and I/O operations in Initialization, Computation, I/O phases?
- **How does the application *scale*?** What is the efficiency, runtime breakdown of performance across different core counts?

Identifying Potential Bottlenecks



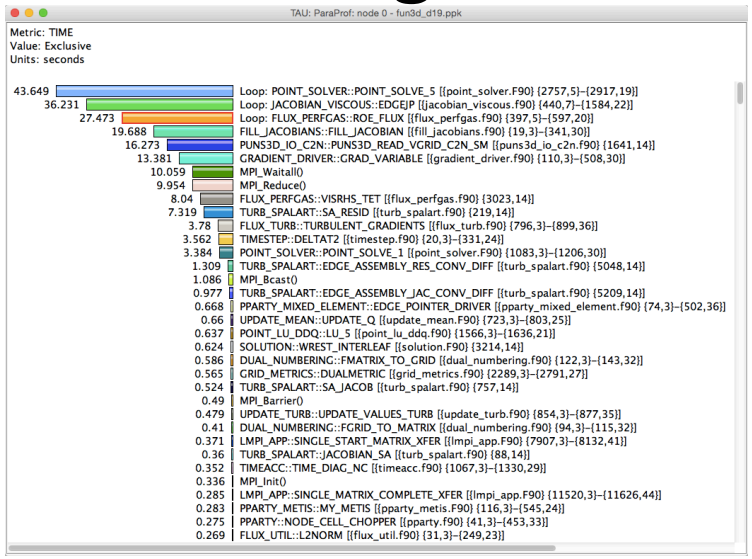
low mflops in loops?

What does TAU support?

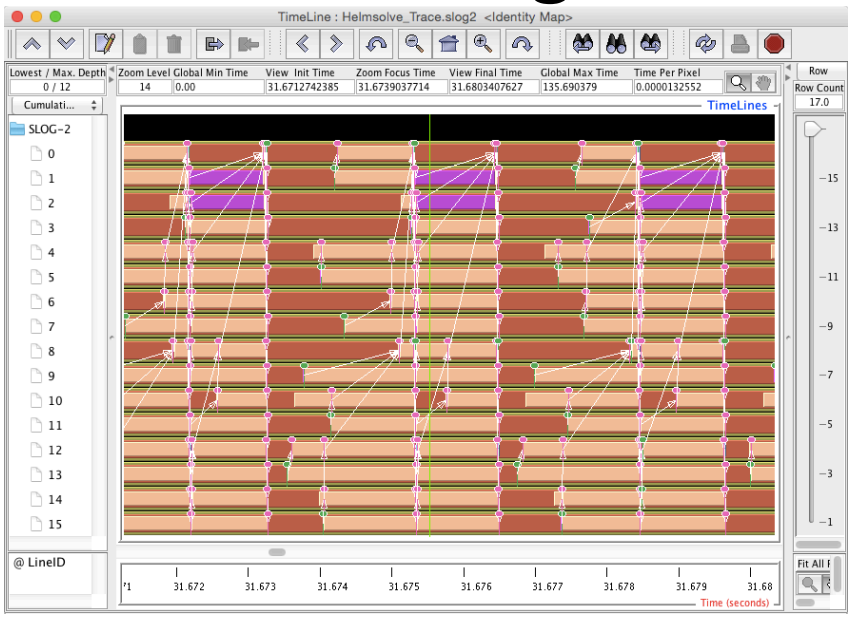


Profiling and Tracing

Profiling



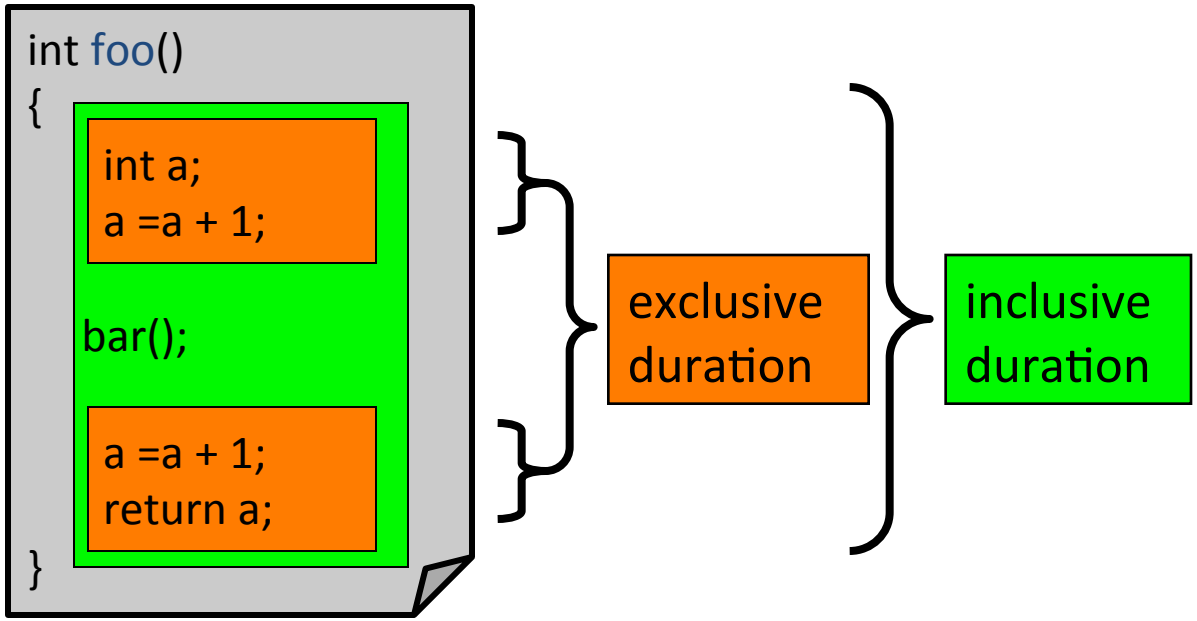
Tracing



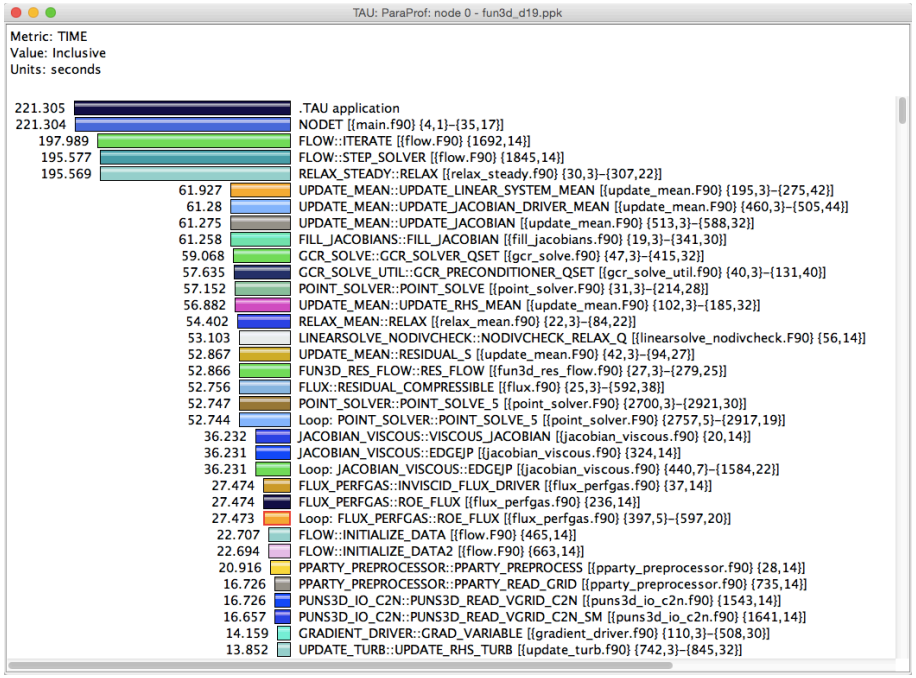
- Profiling and tracing
  - **Profiling** shows you **how much** (total) time was spent in each routine
  - **Tracing** shows you **when** the events take place on a timeline

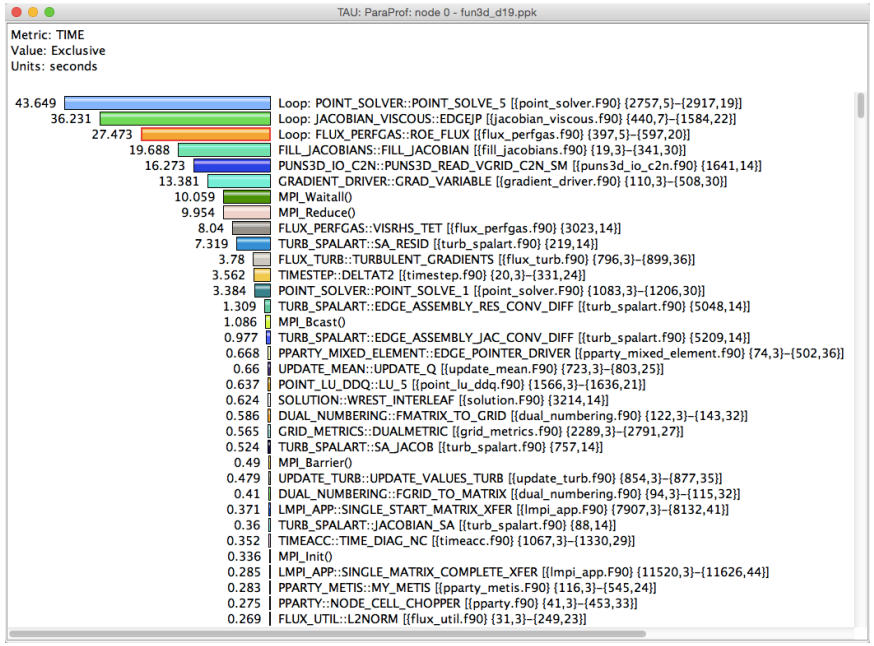
Inclusive vs. Exclusive Measurements

- Performance with respect to code regions
- Exclusive measurements for region only
- Inclusive measurements includes child regions



Inclusive vs. Exclusive Measurements

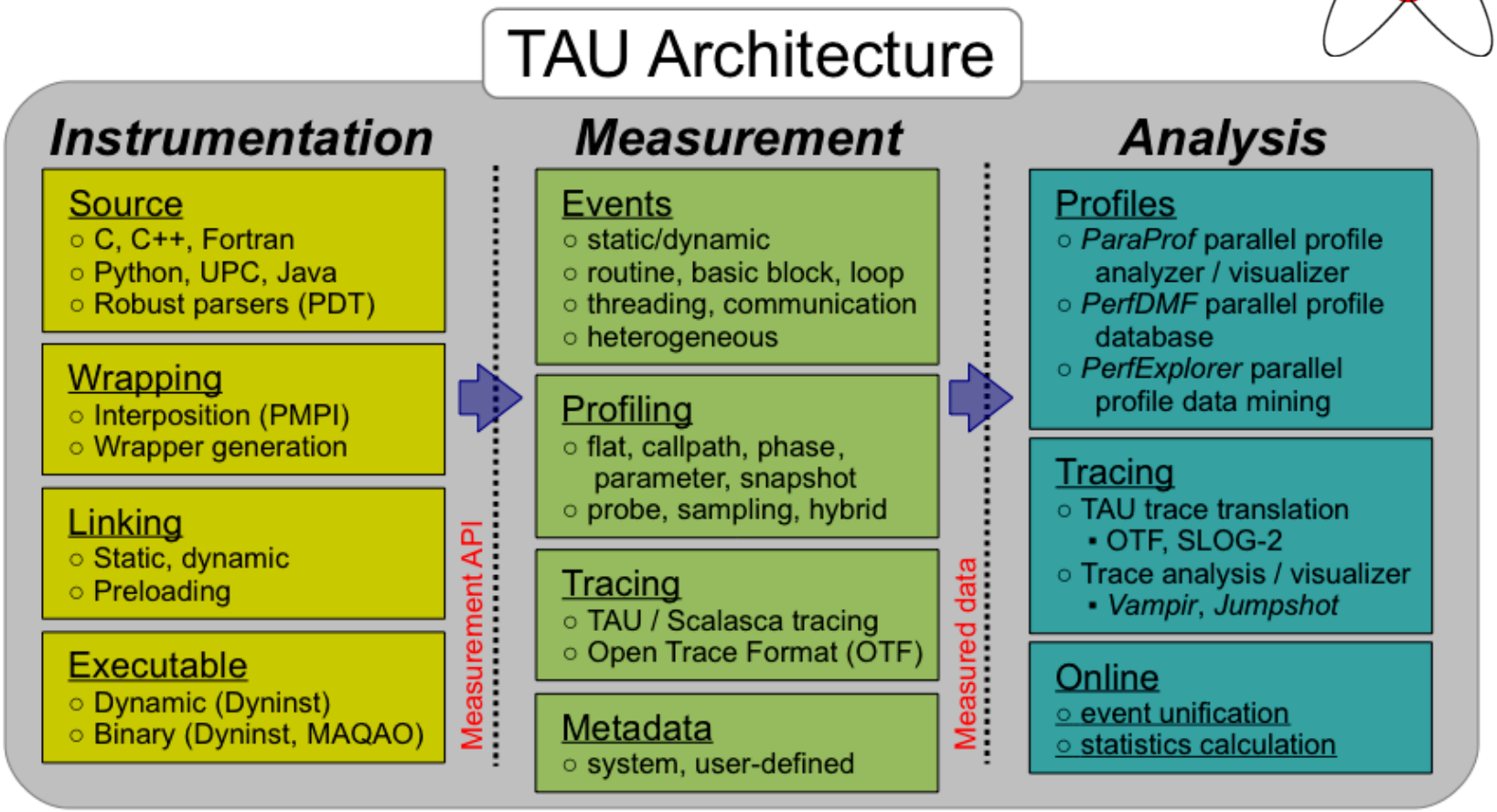




Inclusive time

Exclusive time

TAU Architecture and Workflow



TAU Architecture and Workflow

- **Instrumentation: Add probes to perform measurements**
  - Source code instrumentation using pre-processors and compiler scripts
  - Wrapping external libraries (I/O, MPI, Memory, CUDA, OpenCL, pthread)
  - Rewriting the binary executable

- **Measurement: Profiling or tracing using various metrics**
  - Direct instrumentation (Interval events measure exclusive or inclusive duration)
  - Indirect instrumentation (Sampling measures statement level contribution)
  - Throttling and runtime control of low-level events that execute frequently
  - Per-thread storage of performance data
  - Interface with external packages (e.g. PAPI hw performance counter library)

- **Analysis: Visualization of profiles and traces**
  - 3D visualization of profile data in paraprof or perfexplorer tools
  - Trace conversion & display in external visualizers (Vampir, Jumpshot, ParaVer)

Instrumentation

- **Direct and indirect performance observation**
  - Instrumentation invokes performance measurement
  - Direct measurement with *probes*
  - Indirect measurement with periodic sampling or hardware performance counter overflow interrupts
  - Events measure performance data, metadata, context, etc.

- **User-defined events**
  - **Interval** (start/stop) events to measure exclusive & inclusive duration
  - **Atomic events** take measurements at a single point
    - Measures total, samples, min/max/mean/std. deviation statistics
  - **Context events** are atomic events with executing context
    - Measures above statistics for a given calling path

Direct Observation Events

- **Interval events (begin/end events)**
  - Measures exclusive & inclusive durations between events
  - Metrics monotonically increase
  - Example: Wall-clock timer
- **Atomic events (trigger with data value)**
  - Used to capture performance data state
  - Shows extent of variation of triggered values (min/max/mean)
  - Example: heap memory consumed at a particular point
- **Code events**
  - Routines, classes, templates
  - Statement-level blocks, loops
  - Example: for-loop begin/end

Direct Instrumentation Options in TAU

- **Source Code Instrumentation**
  - Automatic instrumentation using pre-processor based on static analysis of source code (PDT), creating an instrumented copy
  - Compiler generates instrumented object code
  - Manual instrumentation
- **Library Level Instrumentation**
  - Statically or dynamically linked wrapper libraries
  - MPI, I/O, memory, etc.
  - Wrapping external libraries where source is not available
- **Runtime pre-loading and interception of library calls**
- **Binary Code instrumentation**
  - Rewrite the binary, runtime instrumentation
- **Virtual Machine, Interpreter, OS level instrumentation**

TAU Execution Command (tau_exec)

Uninstrumented execution

- % mpirun -np 256 ./a.out

Track GPU operations

- % mpirun –np 256 tau_exec –cupti ./a.out
- % mpirun –np 256 tau_exec –cupti -um ./a.out (for Unified Memory)
- % mpirun –np 256 tau_exec –opencl ./a.out
- % mpirun –np 256 tau_exec –openacc ./a.out

Track MPI performance

- % mpirun -np 256 tau_exec ./a.out
- Track OpenMP, I/O, and MPI performance (MPI enabled by default)
- % mpirun -np 256 tau_exec –ompt -io ./a.out

Track memory operations

- % export TAU_TRACK_MEMORY_LEAKS=1
- % mpirun –np 256 tau_exec –memory_debug ./a.out (bounds check)

Use event based sampling (compile with –g)

- % mpirun –np 256 tau_exec –ebs ./a.out
- Also –ebs_source=<PAPI_COUNTER> -ebs_period=<overflow_count>

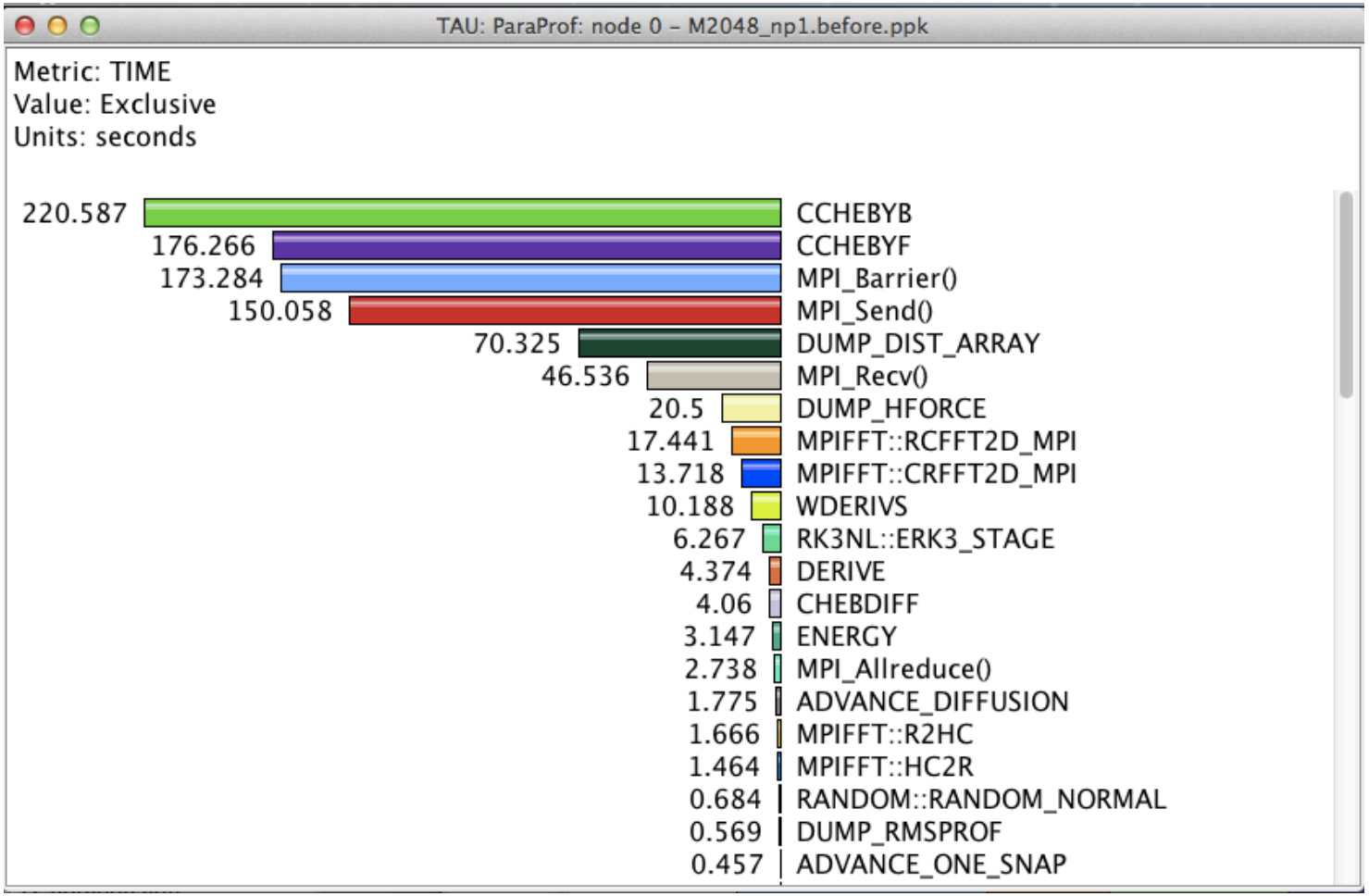
Configuration Tags for tau_exec

```
% ./configure -pdt=<dir> -mpi -papi=<dir>; make install
```
Creates in $TAU:
```
Makefile.tau-papi-mpi-pdt(Configuration parameters in stub makefile)
shared-papi-mpi-pdt/libTAU.so

% ./configure -pdt=<dir> -mpi; make install
```
creates
```
Makefile.tau-mpi-pdt
shared-mpi-pdt/libTAU.so
```
To explicitly choose preloading of shared-<options>/libTAU.so change:
```
% mpirun -np 256 ./a.out      to
% mpirun -np 256  tau_exec -T <comma_separated_options> ./a.out

% mpirun -np 256  tau_exec -T papi,mpi,pdt ./a.out
```
Preloads `$TAU/shared-papi-mpi-pdt/libTAU.so`
```
% mpirun -np 256  tau_exec -T papi ./a.out
```
Preloads `$TAU/shared-papi-mpi-pdt/libTAU.so by matching.`
```
% mpirun -np 256 tau_exec -T papi,mpi,pdt -s ./a.out
```
Does not execute the program. Just displays the library that it will preload if executed without the –s option.

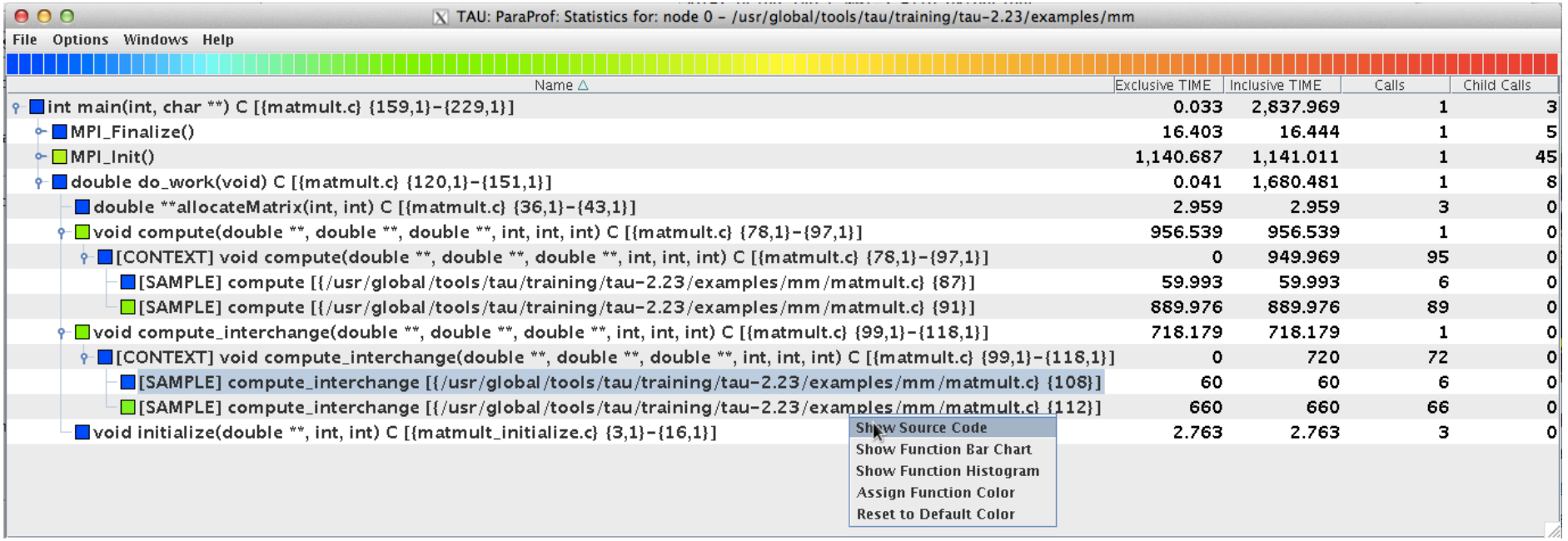
NOTE: -mpi configuration is selected by default. Use –T serial for Sequential programs.

Routine Level Profile

How much time is spent in each application routine?

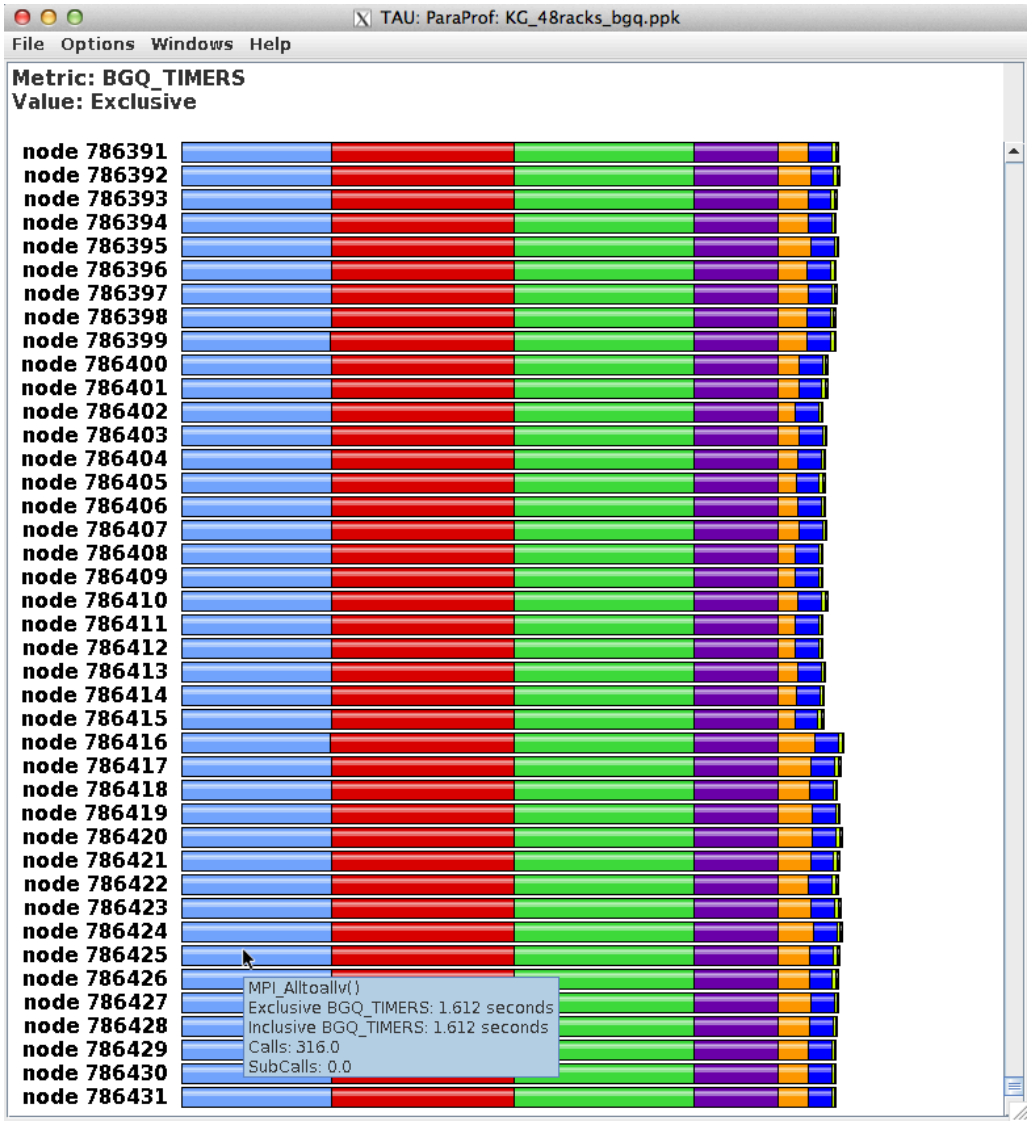


Event Based Sampling in TAU

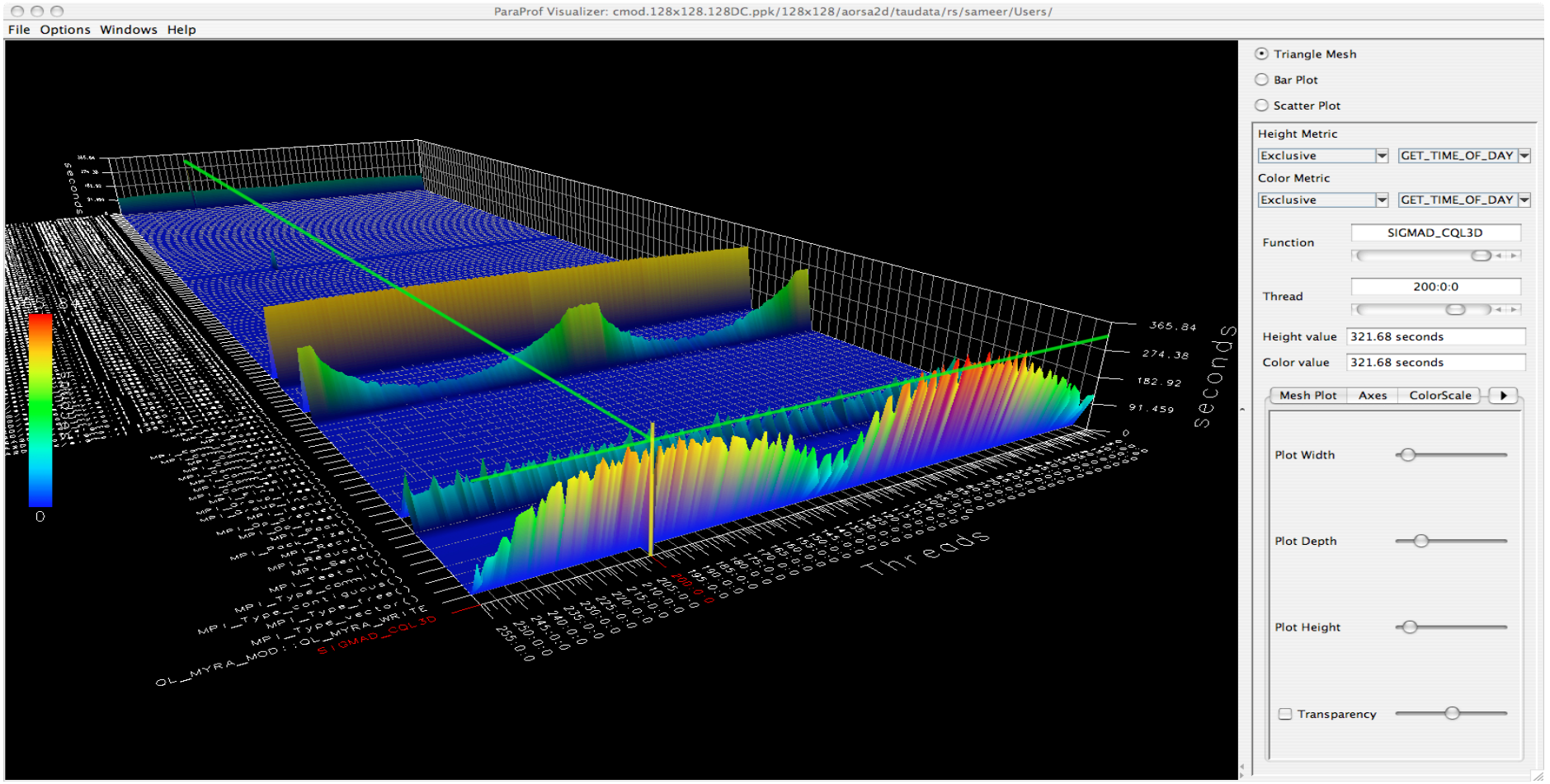



```
% export TAU_MAKEFILE=$TAU/Makefile.tau-icpc-papi-mpi-pdt
% make CC=tau_cc.sh CXX=tau_cxx.sh
% export TAU_SAMPLING=1
% mpirun –np 256 ./a.out
% paraprof
```

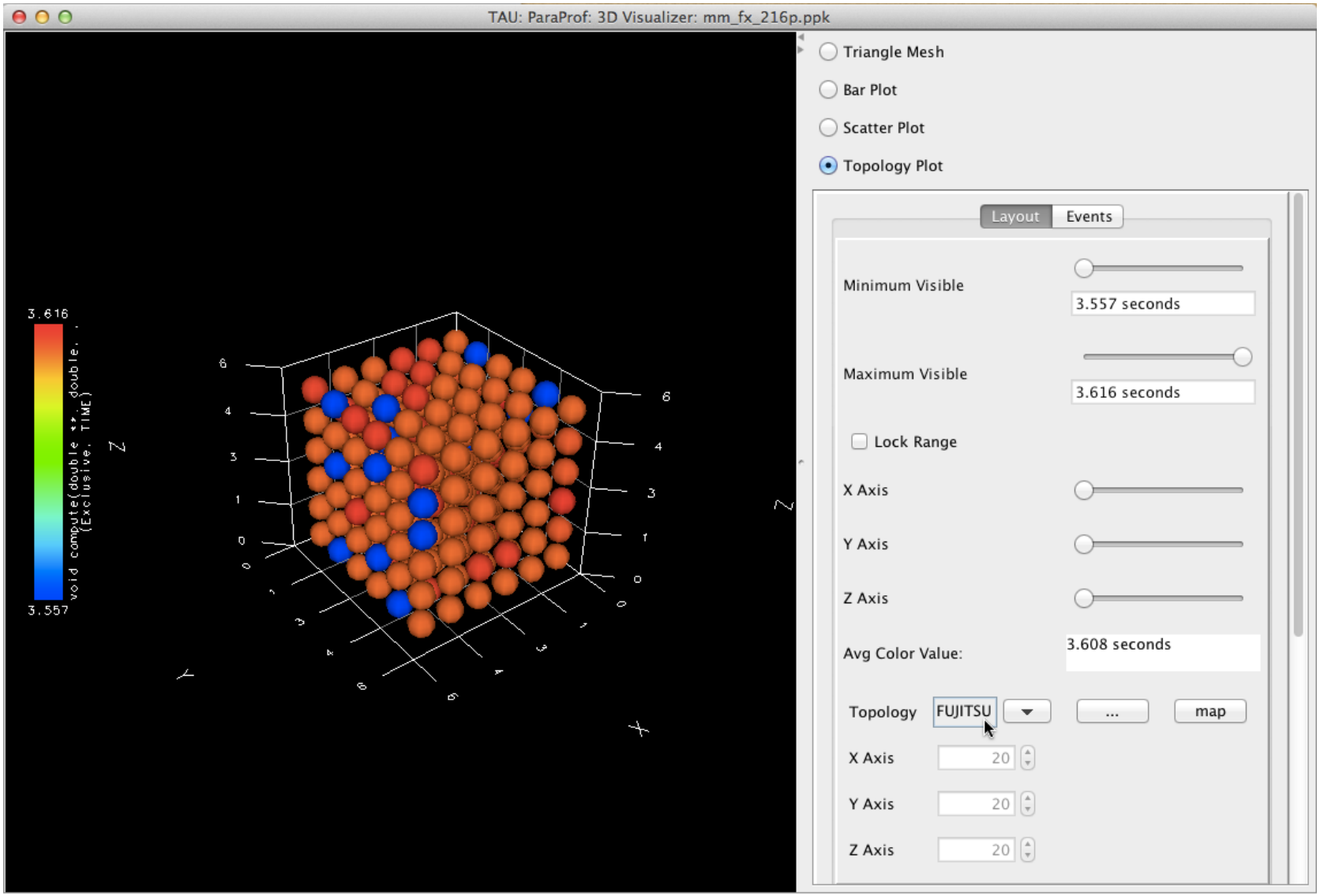
ParaProf Profile Browser



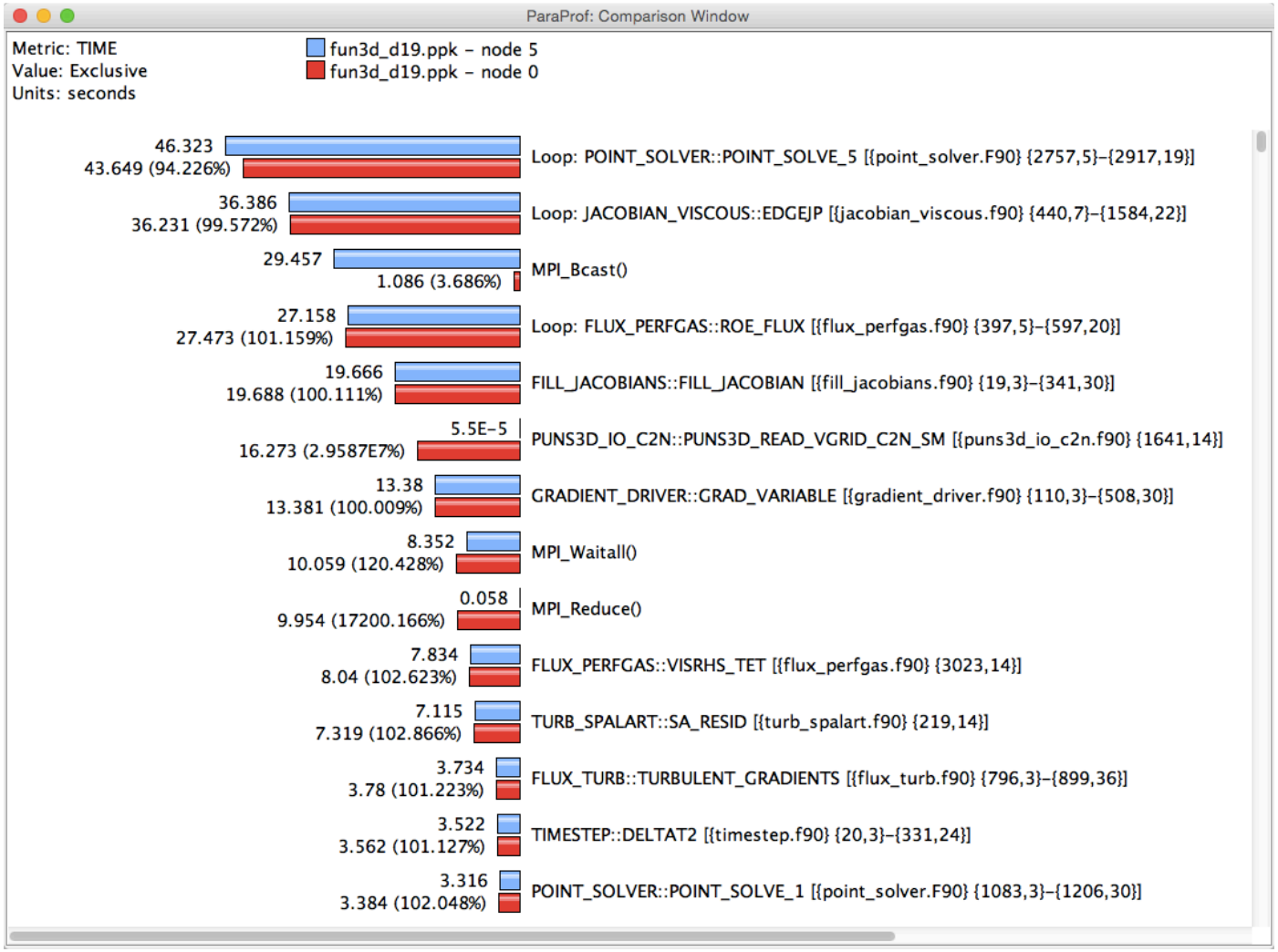
ParaProf 3D Profile Browser



ParaProf Topology Display



ParaProf Comparison Window



Comparing Rank 0 with 5 : Right click on “node 5” -> Add node to comparison window

Profiling with Multiple Counters

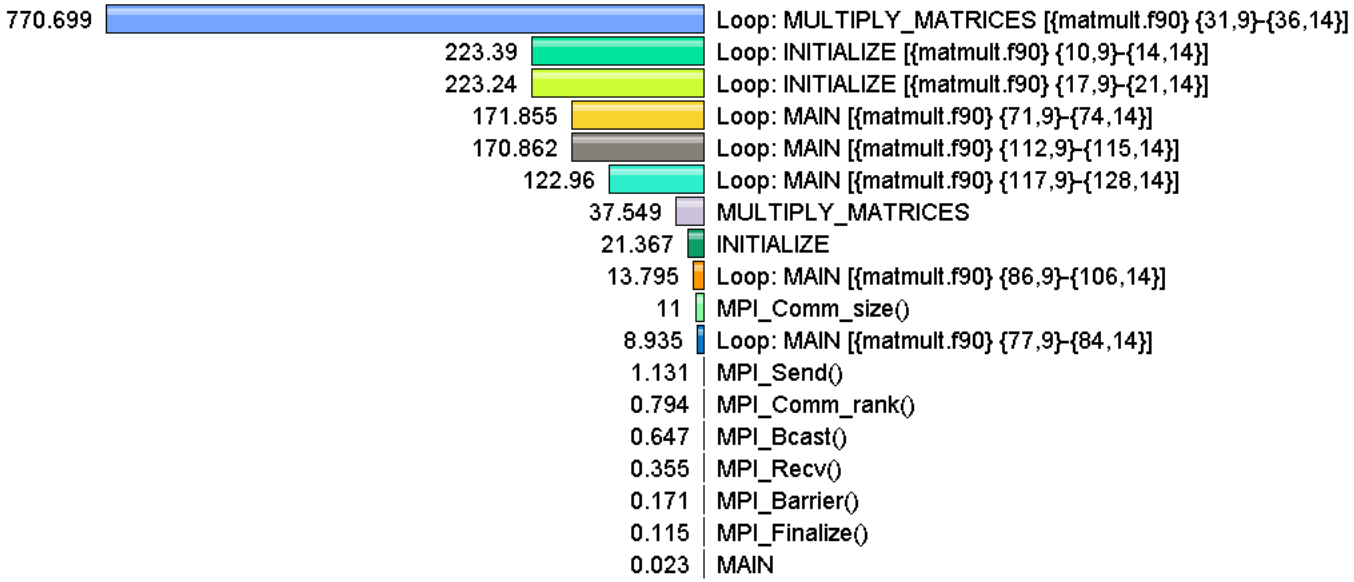
```
% source tau.bashrc
% export TAU_MAKEFILE=$TAU/Makefile.tau-icpc-papi-mpi-pdt
% export TAU_OPTIONS='-optTauSelectFile=select.tau -optVerbose'
% cat select.tau
  BEGIN_INSTRUMENT_SECTION
  loops routine="#"
  END_INSTRUMENT_SECTION
% make F90=tau_f90.sh
% mxterm 1 16 40
% export TAU_METRICS=TIME,PAPI_FP_INS,PAPI_L1_DCM
% mpirun -np 4  ./matmult
% paraprof --pack app.ppk
  Move the app.ppk file to your desktop.
% paraprof app.ppk
  Choose Options -> Show Derived Panel -> Click PAPI_FP_INS,
 Click "/",  Click TIME, Apply, Choose new metric by double
clicking.
```

Computing FLOPS

- Goal: What is the execution rate of my loops in MFLOPS?

- Flat profile with PAPI_FP_INS and time with loop instrumentation:

Metric: PAPI_FP_INS / GET_TIME_OF_DAY
Value: Exclusive
Units: Derived metric shown in microseconds format

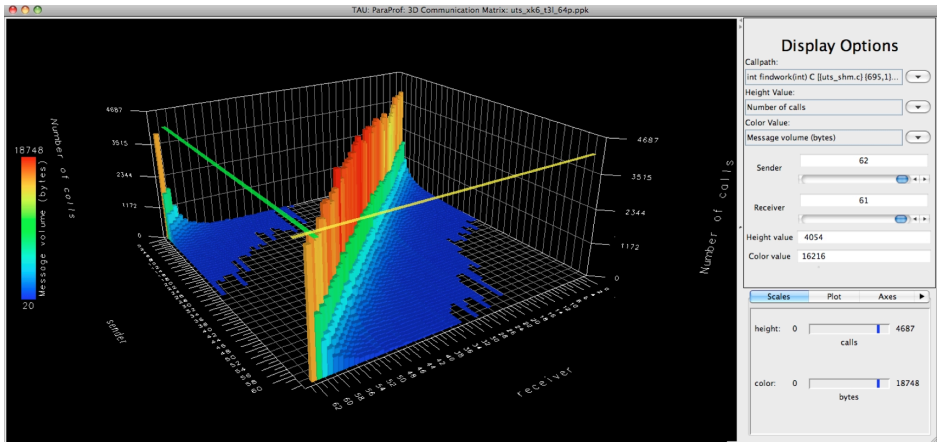


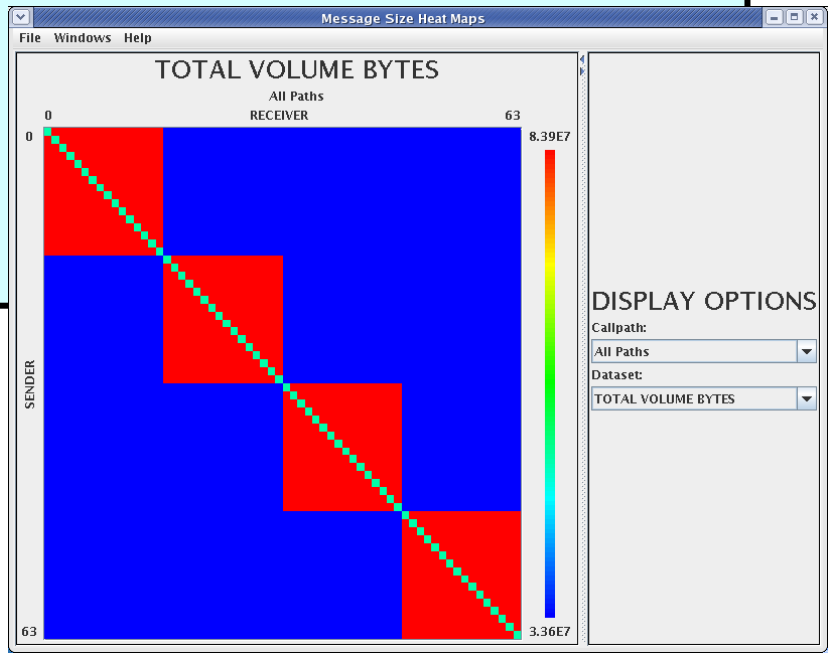
Callpath Profiles

```
% source tau.bashrc
% export TAU_MAKEFILE=$TAU/Makefile.tau-icpc-papi-mpi-pdt
% make F90=tau_f90.sh
(Or edit Makefile and change F90=tau_f90.sh)

% mxterm 1 16 40
% export TAU_CALLPATH=1
% export TAU_CALLPATH_DEPTH=100
(truncates all calling paths to a specified depth)
% mpirun -np 4   ./a.out
% paraprof --pack app.ppk
  Move the app.ppk file to your desktop.
% paraprof app.ppk
(Windows -> Thread -> Call Graph)
```

Comunication Matrix

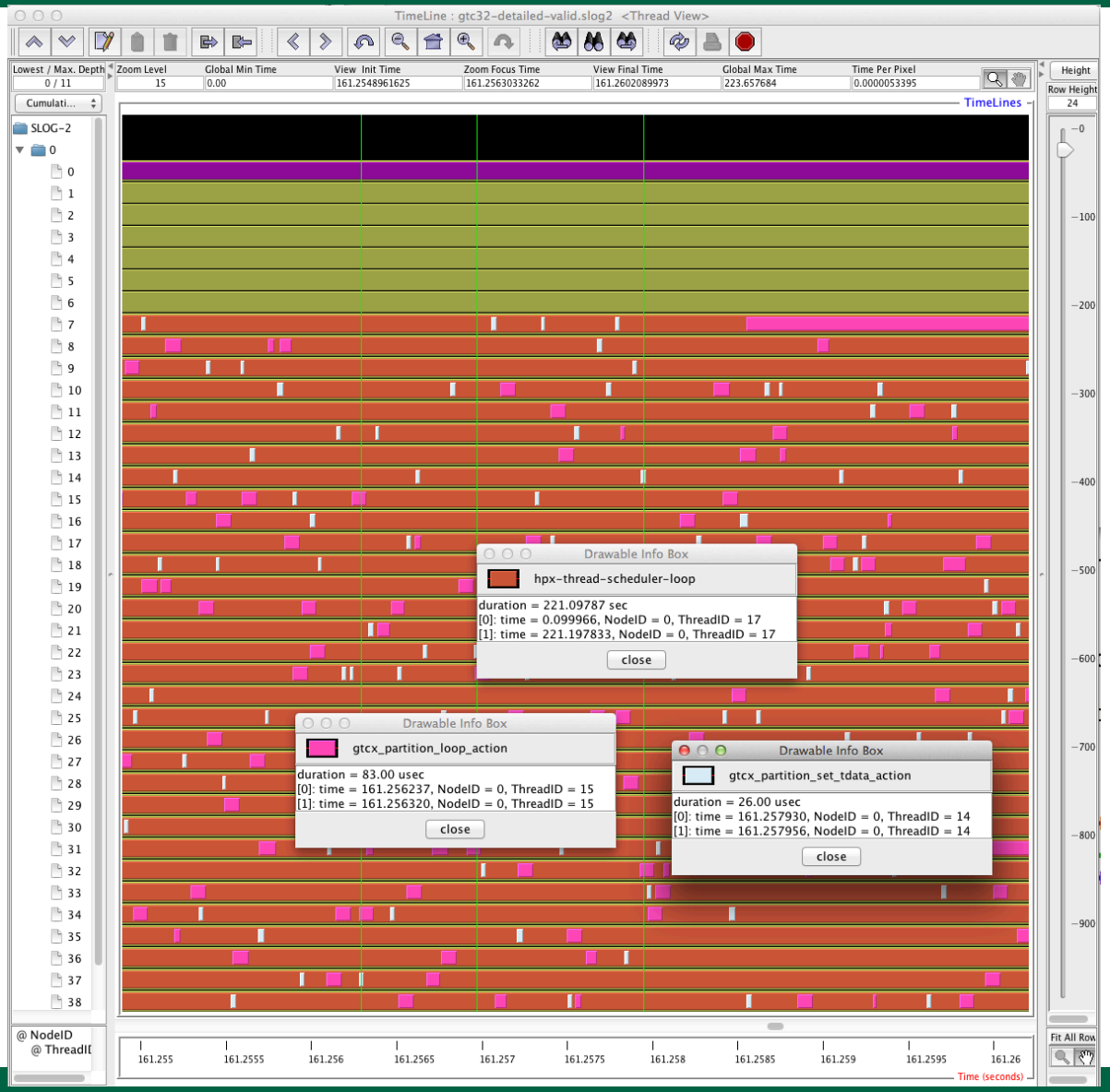
```
% source tau.bashrc
% export TAU_MAKEFILE=$TAU/Makefile.tau-icpc-papi-mpi-pdt
% make F90=tau_f90.sh
(Or edit Makefile and change F90=tau_f90.sh)

% mxterm 1 16 40
•    % export TAU_COMM_MATRIX=1
% mpirun -np 4    ./a.out

% paraprof
(Windows -> Communication Matrix)
(Windows -> 3D Communication Matrix)
```





Goal: What is the volume of inter-process communication? Along which calling path?

Jumpshot Trace Visualizer



Vampir Trace Visualizer

APEX

Autonomic Performance Environment for eXascale

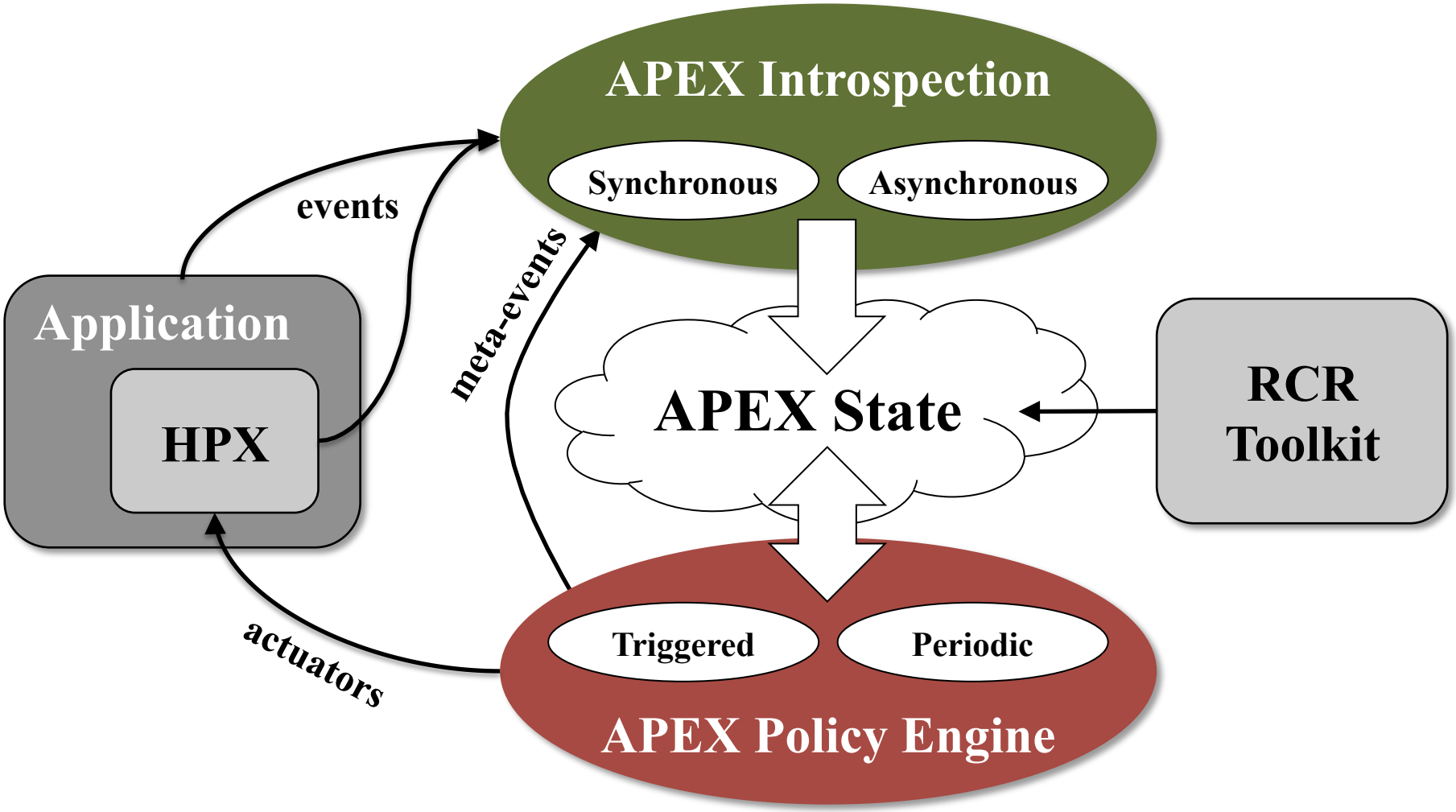
APEX Runtime Adaptation : Motivation

- **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

APEX architecture



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-5, HPX-3)
    - Custom events (meta-events)
  - *Asynchonous* do not rely on events, but occur periodically
- **APEX exploits access to performance data from lower stack components**
  - Reading from the RCR blackboard (i.e., power, energy)
  - "Health" data through other interfaces (/proc/stat, cpuinfo, meminfo, net/dev, self/status, lm_sensors, power*, etc.)

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-3, processed/scheduled as a thread/task)
- **TAU Listener (postmortem analysis)**
  - Synchronously passes all measurement events to TAU to build an offline profile
- **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
  - Engages actuators across stack layers
  - Could also be used to involve online auto-tuning support*

Building the tools…

- Building TAU pre-requisites
  - PDT
- Building TAU
- Building APEX pre-requisites
  - ActiveHarmony
- Building HPX with TAU+APEX support

Building PDT for use with TAU

```
$ wget http://tau.uoregon.edu/pdt_lite.tgz
$ tar –xzf pdt_lite.tgz
$ cd pdtoolkit-3.21
$ ./configure -GNU
    -prefix=$HOME/install/pdtoolkit/3.21
$ make
$ make install
```

Optional step – TAU with HPX doesn't require instrumentation

Building TAU for use with HPX

```
$ wget http://tau.uoregon.edu/tau.tgz
$ tar -xvzf tau.tgz
$ cd tau-2.25
$ wget http://tau.uoregon.edu/ext.tgz
$ tar -xvzf ext.tgz
# build for the host
$ ./configure -pthread -bfd=download
        -unwind=download -pdt=$HOME/install/pdtoolkit/3.21
$ make -j install
# build for the device
$ ./configure -pthread -cc=icc -c++=icpc -fortran=intel
        -arch=mic_linux -bfd=download -unwind=download
        -pdt=$HOME/install/pdtoolkit/3.21 -pdt_c++=g++
$ make -j install
```

Italics = optional – TAU with HPX doesn't require instrumentation, binutils or unwinding

Building ActiveHarmony for APEX

```
$ wget
http://www.dyninst.org/sites/default/files/downloads/
harmony/ah-4.5.tar.gz
$ tar -xvzf ah-4.5.tar.gz
$ cd activeharmony-4.5
$ make
$ make install PREFIX=$HOME/local/harmony-4.5
# for device:
$ make MPICC=mpicc_disabled CC=icc CXX=icpc
    CFLAGS="-mmic" CXXFLAGS="-mmic"
    LDFLAGS="-mmic"
$ make install PREFIX=$HOME/local/harmony-4.5-mic
```

Optional step – APEX in HPX will build its own version of ActiveHarmony if it isn't found

Building HPX with APEX & TAU

$ cmake <usual HPX settings>…

-DHPX_WITH_APEX=TRUE \

-DAPEX_WITH_ACTIVEHARMONY=TRUE \

-DACTIVEHARMONY_ROOT=<path-to-harmony> \

-DHPX_WITH_TAU=TRUE \

-DTAU_ROOT=<path-to-TAU> \

-DTAU_ARCH=<x86_64, craycnl, mic_linux…>

-DTAU_OPTIONS=<-icpc-pthread, -intel-pthread, …>

..

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

Runtime Environment Variables - APEX

Environment Variable	Default	Description
APEX_TAU	**0**	**Enable TAU profiling**
APEX_POLICY	1	Execute APEX policies
APEX_MEASURE_CONCURRENCY	0	Periodically sample thread activity
APEX_MEASURE_CONCURRENCY_PERIOD	1000000	Thread sampling period, microseconds
APEX_SCREEN_OUTPUT	**0**	**Output APEX summary at exit**
APEX_PROC_CPUINFO	0	Periodically read data from /proc/cpuinfo
APEX_PROC_MEMINFO	0	Periodically read data from /proc/meminfo
APEX_PROC_NET_DEV	0	Periodically read data from /proc/net/dev
APEX_PROC_SELF_STATUS	0	Periodically read data from /proc/self/status
APEX_PROC_STAT	**1**	**Periodically read data from /proc/stat**
APEX_THROTTLE_CONCURRENCY	**0**	**Deactivate/Activate threads for policies**
APEX_THROTTLING_MAX_THREADS	**48**	**Max threads allowed**
APEX_THROTTLING_MIN_THREADS	**1**	**Min threads allowed**
APEX_THROTTLE_ENERGY	0	Enable energy throttling
APEX_THROTTLING_MIN_WATTS	150	Minimum Watt threshold
APEX_THROTTLING_MAX_WATTS	300	Maximum Watt threshold

Runtime Environment Variables - TAU

Environment Variable	Default	Description
TAU_TRACE	**0**	**Setting to 1 turns on tracing**
TAU_CALLPATH	0	Setting to 1 turns on callpath profiling
TAU_TRACK_MEMORY_FOOTPRINT	0	Setting to 1 turns on tracking memory usage by sampling periodically the resident set size and high water mark of memory usage
TAU_TRACK_POWER	0	Tracks instantaneous power usage by sampling periodically.
TAU_CALLPATH_DEPTH	2	Specifies depth of callpath. Setting to 0 generates no callpath or routine information, setting to 1 generates flat profile and context events have just parent information (e.g., Heap Entry: foo)
TAU_SAMPLING	**0**	**Setting to 1 enables event-based sampling.**
TAU_TRACK_SIGNALS	0	Setting to 1 generate debugging callstack info when a program crashes
TAU_COMM_MATRIX	0	Setting to 1 generates communication matrix display using context events
TAU_THROTTLE	1	Setting to 0 turns off throttling. Enabled by default to remove instrumentation in lightweight routines that are called frequently
TAU_THROTTLE_NUMCALLS	100000	Specifies the number of calls before testing for throttling
TAU_THROTTLE_PERCALL	10	Specifies value in microseconds. Throttle a routine if it is called over 100000 times and takes less than 10 usec of inclusive time per call
TAU_COMPENSATE	0	Setting to 1 enables runtime compensation of instrumentation overhead
TAU_PROFILE_FORMAT	**Profile**	**Setting to "merged" generates a single file. "snapshot" generates xml format**
TAU_METRICS	TIME	Setting to a comma separated list generates other metrics. (e.g., TIME,ENERGY,PAPI_FP_INS,PAPI_NATIVE_<event>:<subevent>)

Runtime Environment Variables - TAU

Environment Variable	Default	Description
TAU_TRACK_MEMORY_LEAKS	0	Tracks allocates that were not de-allocated (needs –optMemDbg or tau_exec –memory)
TAU_EBS_SOURCE	TIME	Allows using PAPI hardware counters for periodic interrupts for EBS (e.g., TAU_EBS_SOURCE=PAPI_TOT_INS when TAU_SAMPLING=1)
TAU_EBS_PERIOD	100000	Specifies the overflow count for interrupts
TAU_MEMDBG_ALLOC_MIN/MAX	0	Byte size minimum and maximum subject to bounds checking (used with TAU_MEMDBG_PROTECT_*)
TAU_MEMDBG_OVERHEAD	0	Specifies the number of bytes for TAU's memory overhead for memory debugging.
TAU_MEMDBG_PROTECT_BELOW/ ABOVE	0	Setting to 1 enables tracking runtime bounds checking below or above the array bounds (requires –optMemDbg while building or tau_exec –memory)
TAU_MEMDBG_ZERO_MALLOC	0	Setting to 1 enables tracking zero byte allocations as invalid memory allocations.
TAU_MEMDBG_PROTECT_FREE	0	Setting to 1 detects invalid accesses to deallocated memory that should not be referenced until it is reallocated (requires –optMemDbg or tau_exec –memory)
TAU_MEMDBG_ATTEMPT_CONTINUE	0	Setting to 1 allows TAU to record and continue execution when a memory error occurs at runtime.
TAU_MEMDBG_FILL_GAP	Undefined	Initial value for gap bytes
TAU_MEMDBG_ALINGMENT	Sizeof(int)	Byte alignment for memory allocations
TAU_EVENT_THRESHOLD	0.5	Define a threshold value (e.g., .25 is 25%) to trigger marker events for min/max

Note about environment variables…

- mpirun.mic does not pass environment variables to the application without considerable effort (to me, anyway)
- TAU and APEX will read environment variables from $PWD/tau.conf or $PWD/apex.conf files, respectively
- When running on Babbage, this is sometimes necessary

Example 1: HPX+APEX

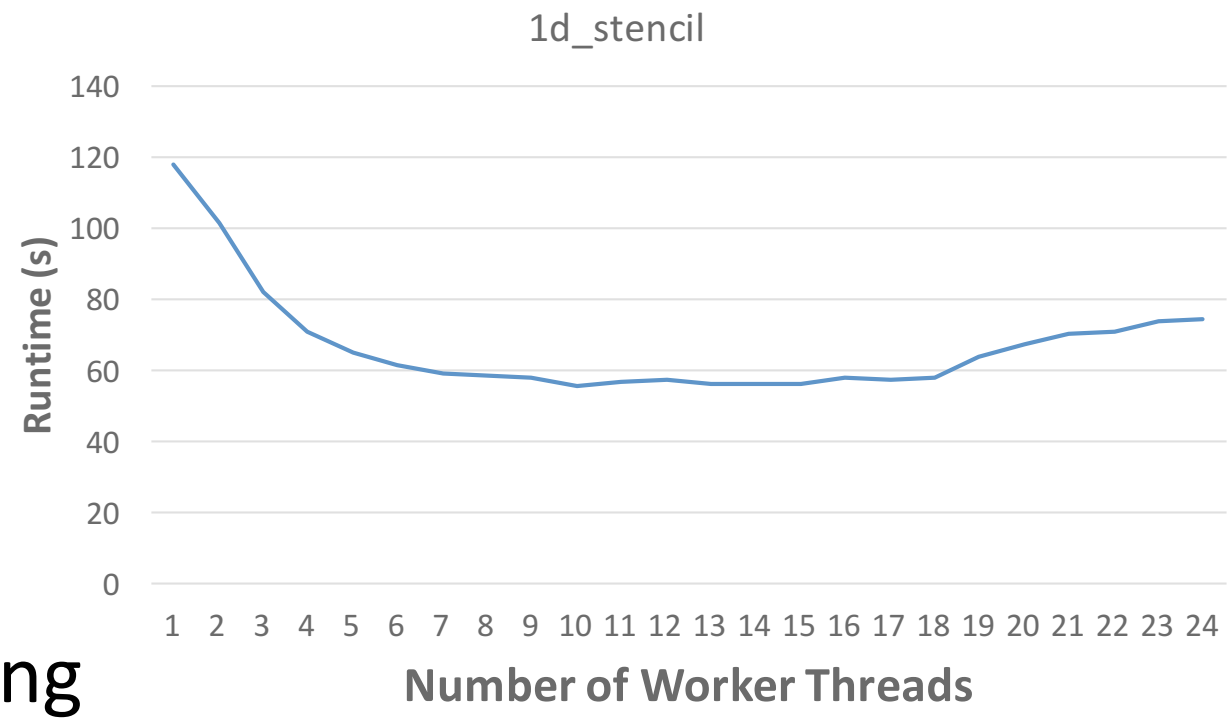
- Follow instructions found at http://github.com/khuck/SC15_APEX_tutorial

```
$ bash
$ source /usr/share/Modules/init/bash
$ source /project/projectdirs/training/SC15/
  HPX-SC15/hpx_install/env.sh
$ module load hpx/mic-0.9.11
$ ./scripts/configure-mic.sh
$ salloc --reservation=SC_Reservation -N 1 -p
  debug
# after the allocation is granted:
$ ./scripts/run_1d_stencil-mic.sh
```

…example will run and spit lots of verbose APEX output to confirm it is working

Example2 : HPX+APEX+TAU

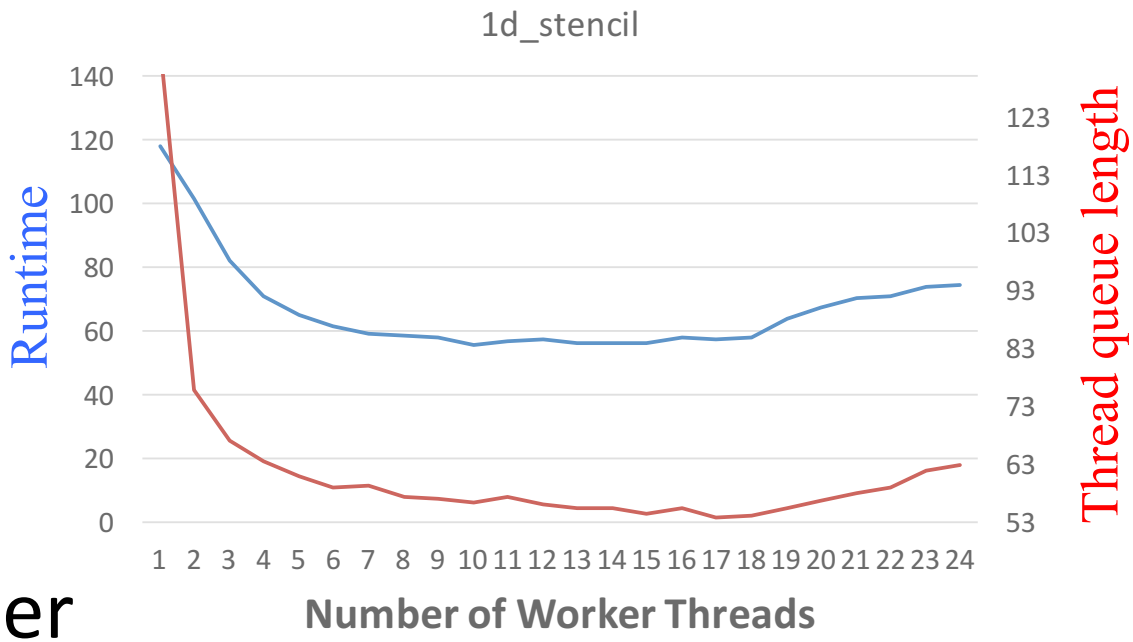
- Heat diffusion
- 1D stencil code
- Data array partitioned into chunks
- 1 node with no hyperthreading



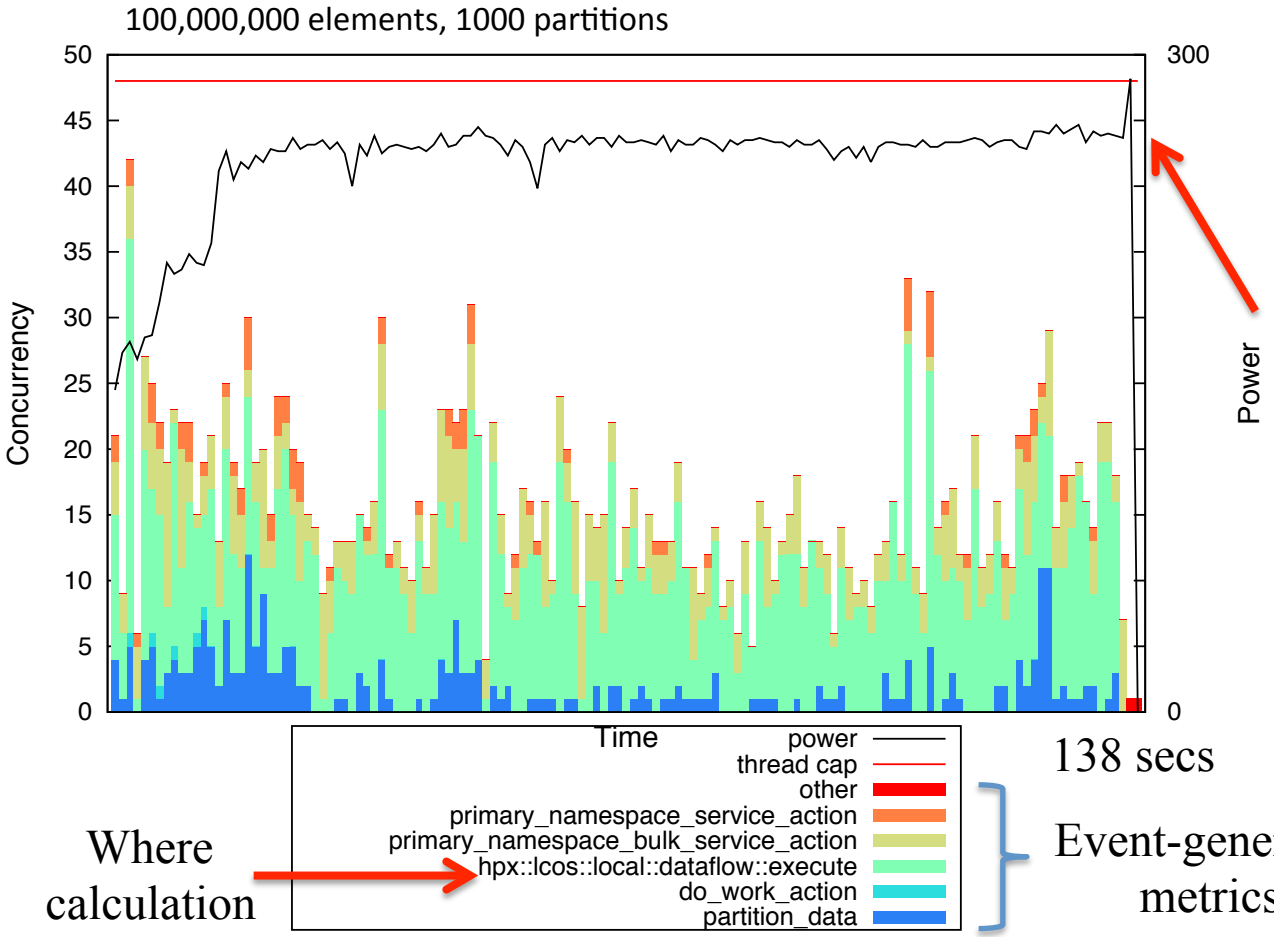
- Performance increases to a point with increasing worker threads, then decreases

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 example 3)

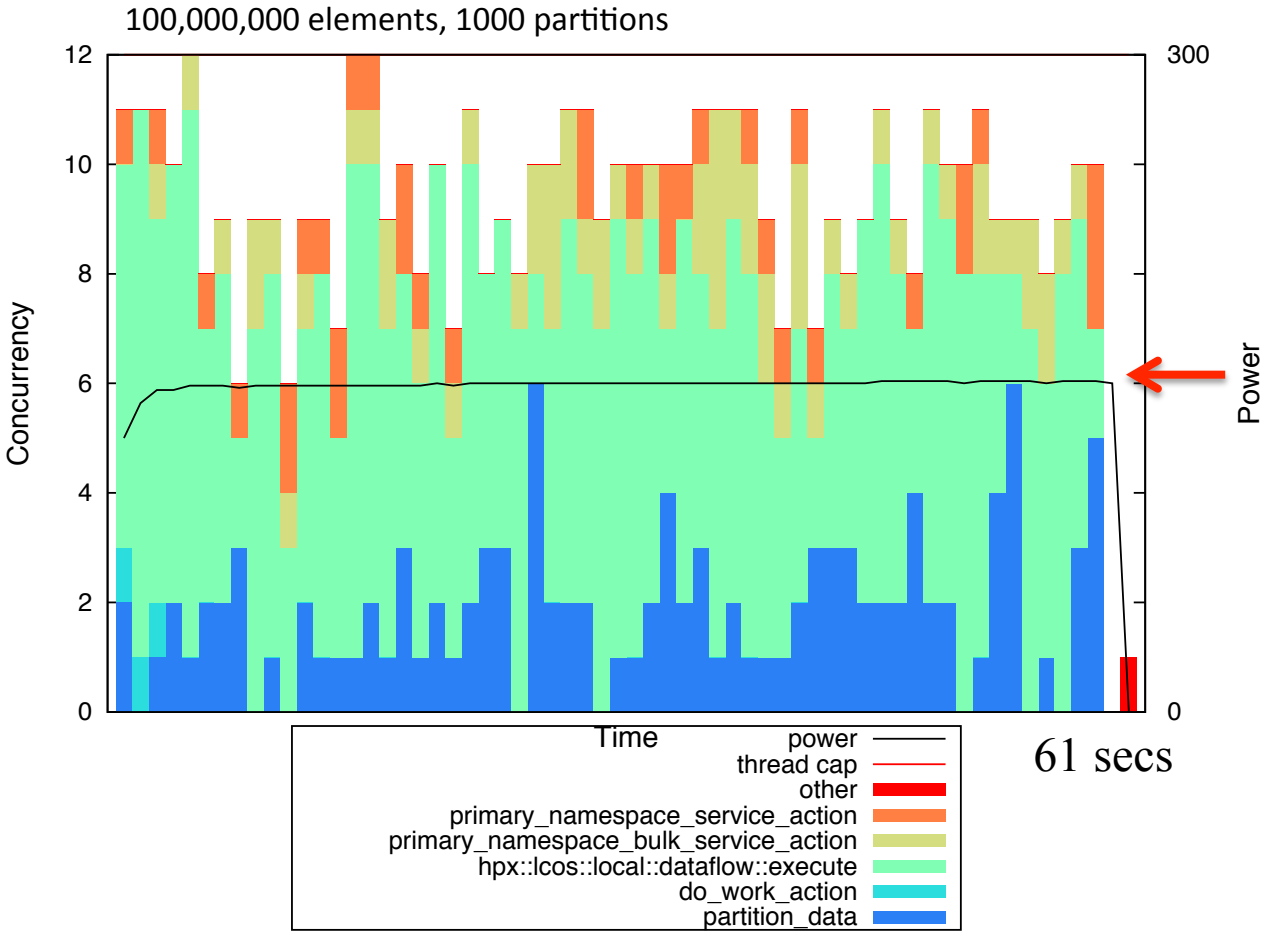


1d_stencil_4 Baseline



- 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

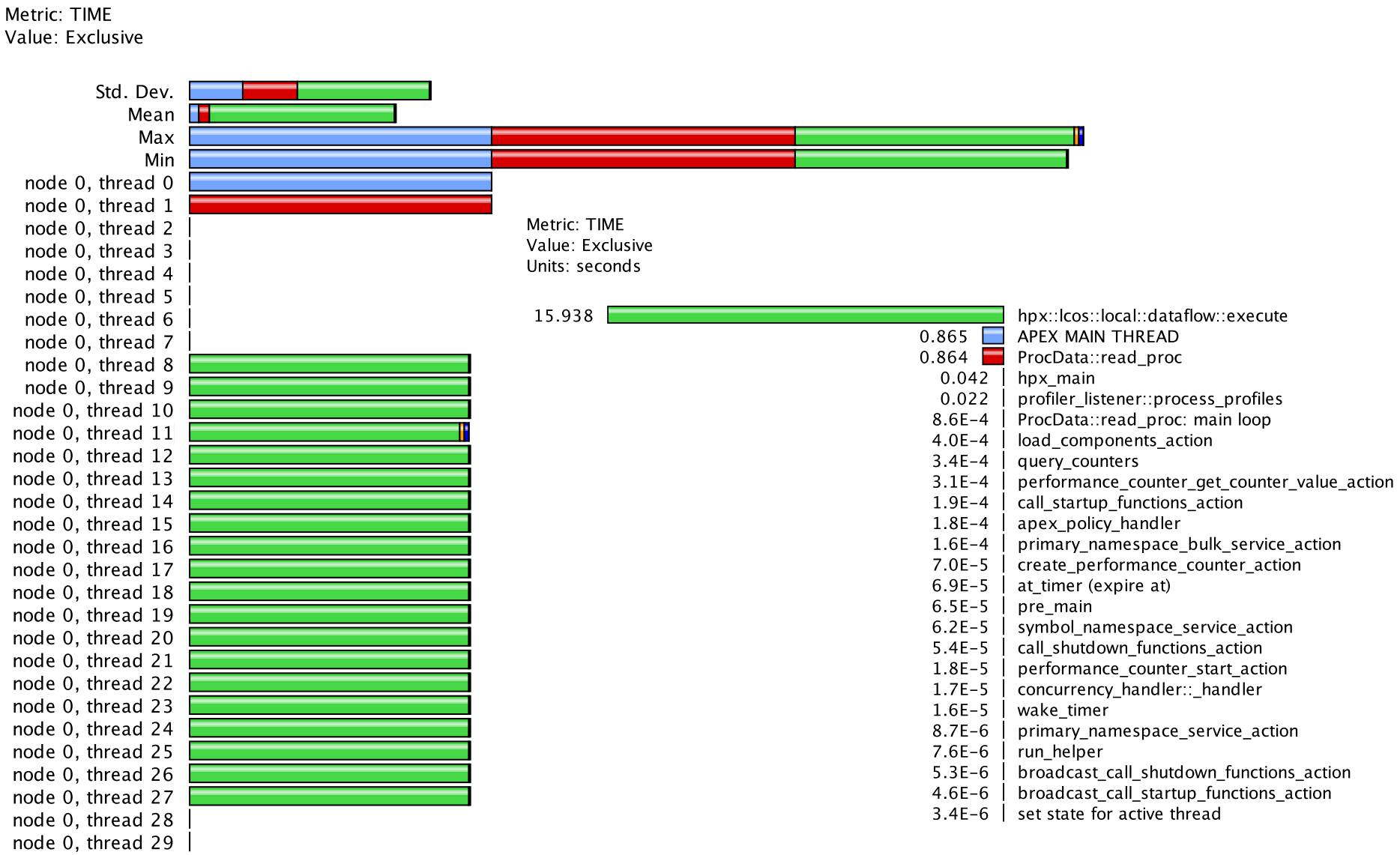


- 12 worker threads on Edison
- Greater proportion of threads kept busy
  - Less interference between active threads and threads waiting for memory
- Much faster
  - 61 sec. vs 138 sec.

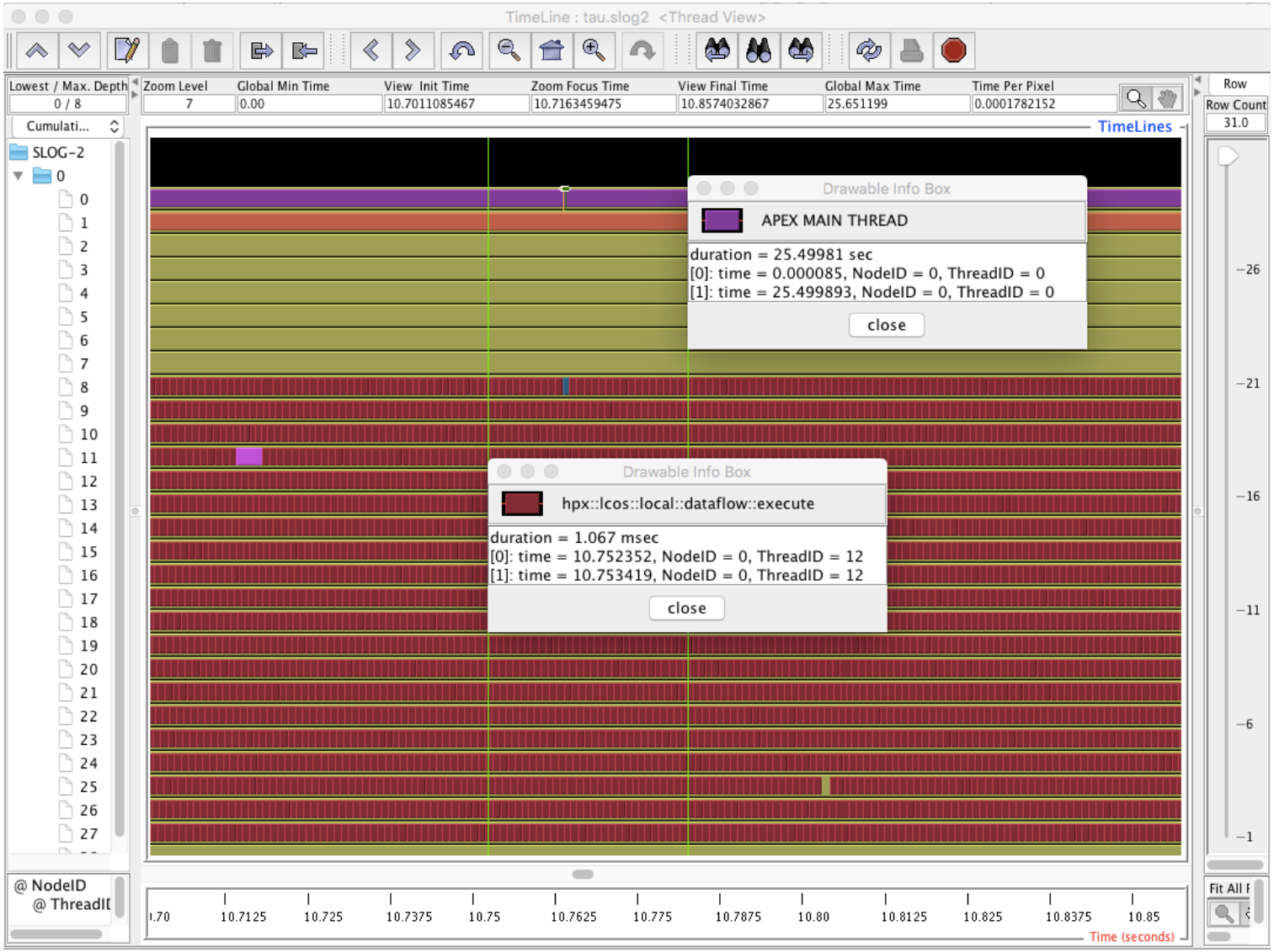
Run the example #2

```
$ ./scripts/run_1d_stencil-mic.sh
# which does:
$ export APEX_TAU=1
$ export TAU_TRACE=1 (to collect a trace, optional)
$ export APEX_PROFILE=1
# to run on device (babbage):
$ get_micfile ; srun mpirun.mic -n 1 -hostfile
    micfile.$SLURM_JOB_ID -ppn 1 ./build-mic/
    apex_examples/1d_stencil_4 --nx 100000 --np 1000
    --nt 45 --hpx:threads 60
# to view summary of TAU profiles:
$ pprof –s
# to merge trace:
$ tau_multimerge && tau2slog2 tau.trc tau.edf -o
    tau.slog2
```

Paraprof view of profile



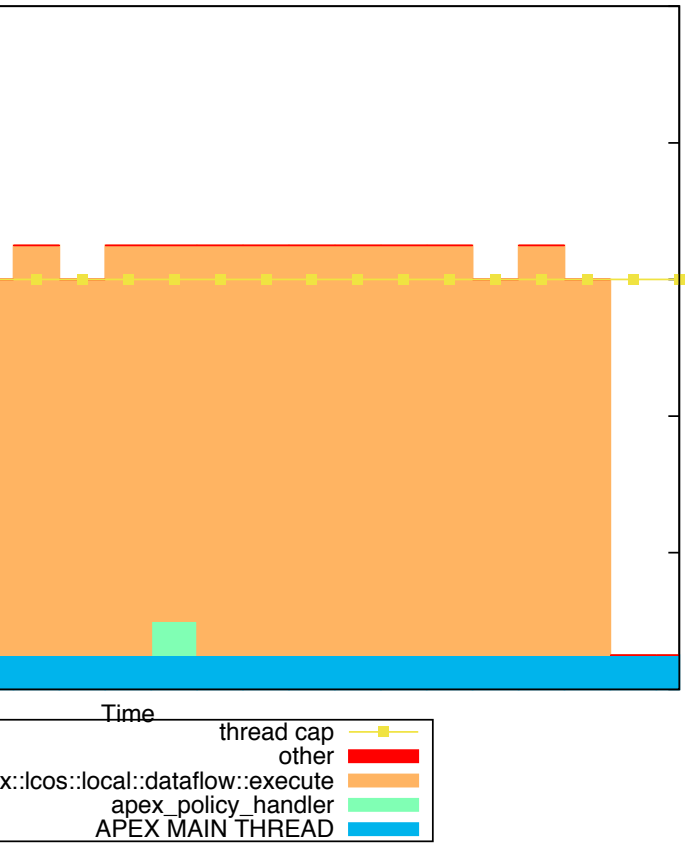
Jumpshot view of trace



Run the example #3:

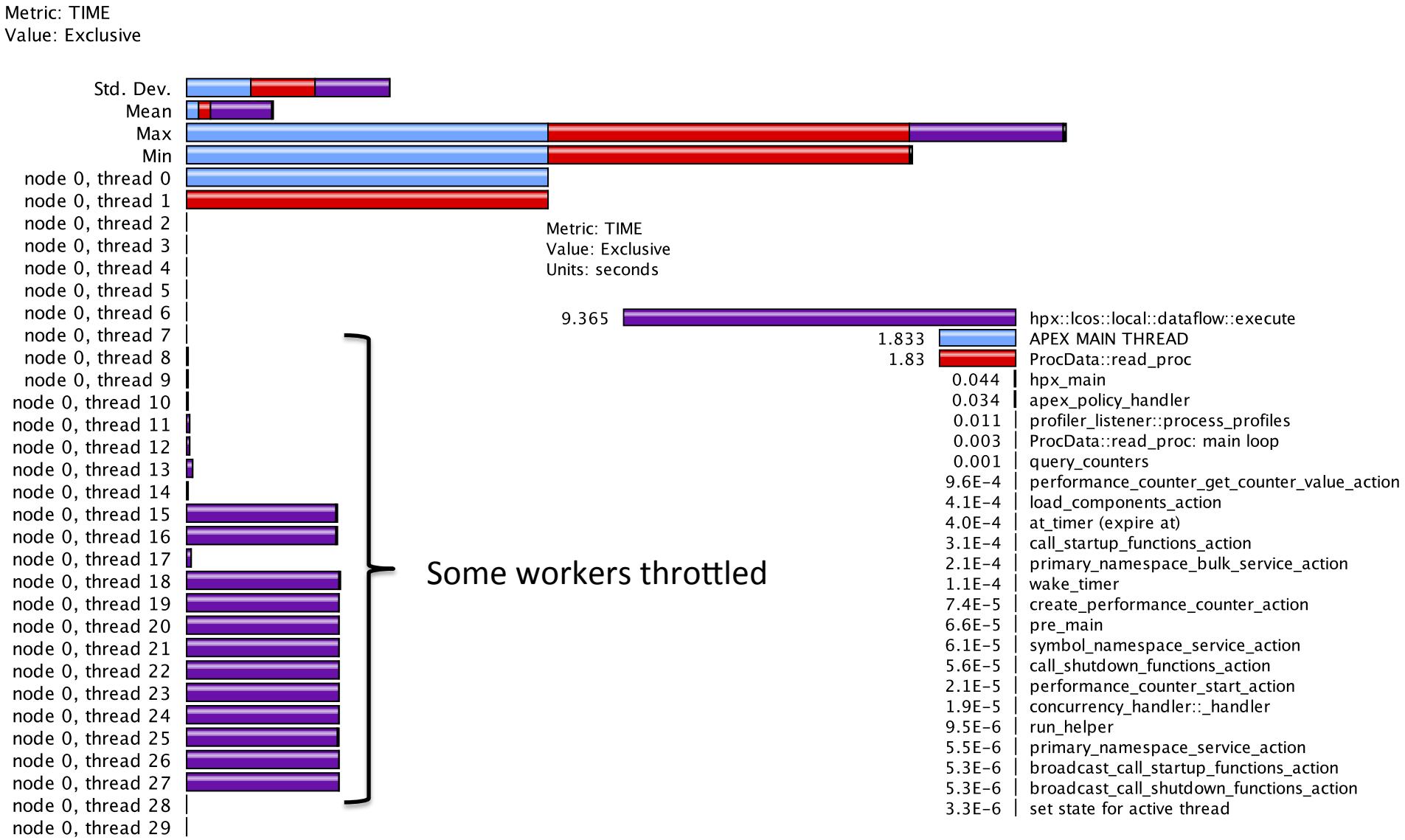
```
$ ./scripts/run_1d_stencil-host.sh
# which will:
$ export APEX_TAU=1
$ export TAU_TRACE=1
$ export TAU_PROFILE=1
$ export TAU_PROFILE_FORMAT=merged
$ export APEX_POLICY=1
$ export APEX_THROTTLE_CONCURRENCY=1
$ export APEX_THROTTLING_MIN_THREADS=8
$ export APEX_THROTTLING_MAX_THREADS=32
# note: nx is number of cells per partition, np is
    number of partitions, nt is number of timesteps
$ ./build-host/apex_examples/1d_stencil_4_throttle
    --nx 100000 --np 1000 --nt 450 --
    hpx:queuing=throttle --hpx:threads 32
```

1d_stencil Adaptation with APEX

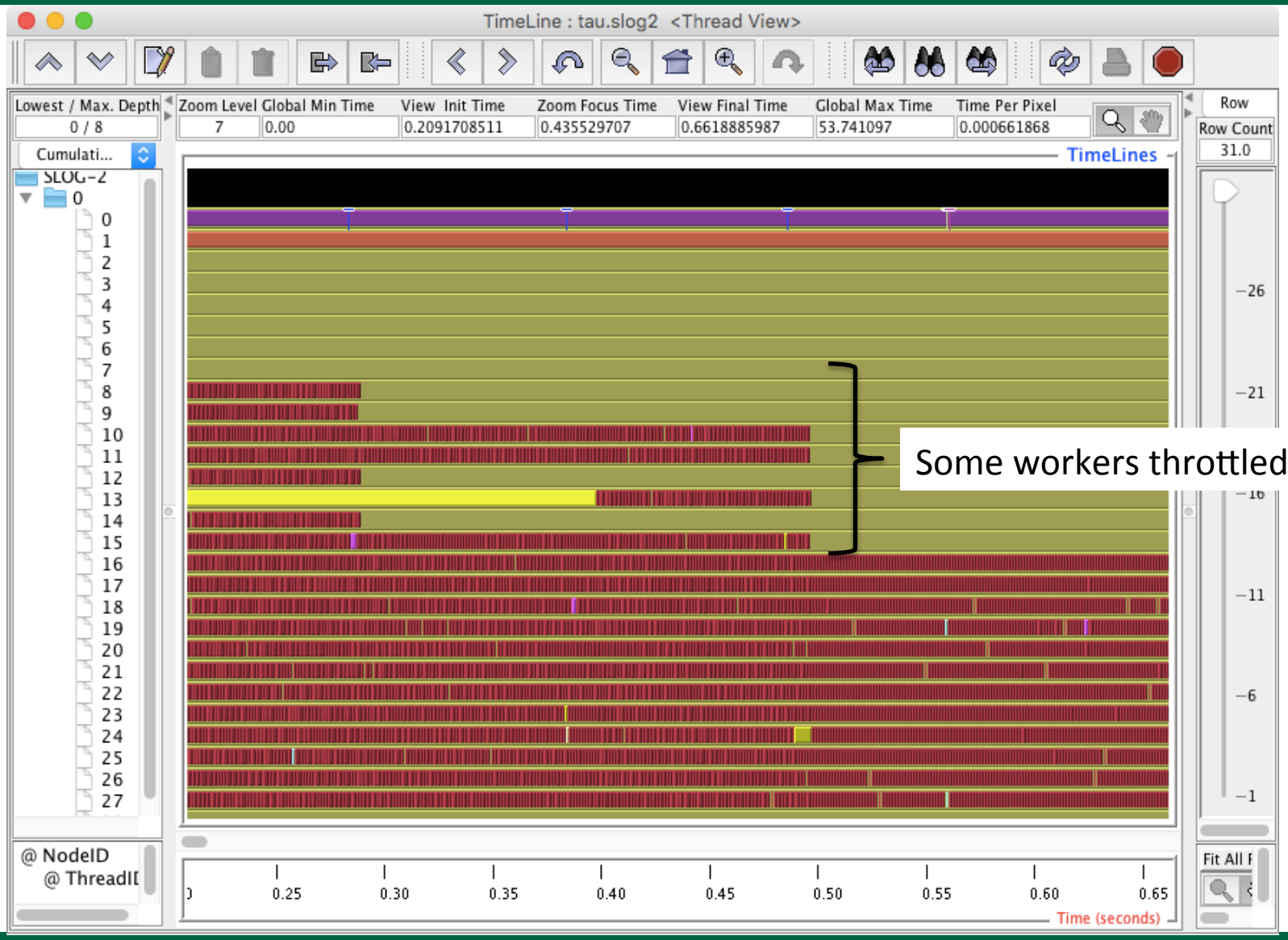


- Initially 32 worker threads
- ActiveHarmony searches for minimal thread queue length
- Quickly converges on 20

Profile of throttled execution



Trace of throttled execution



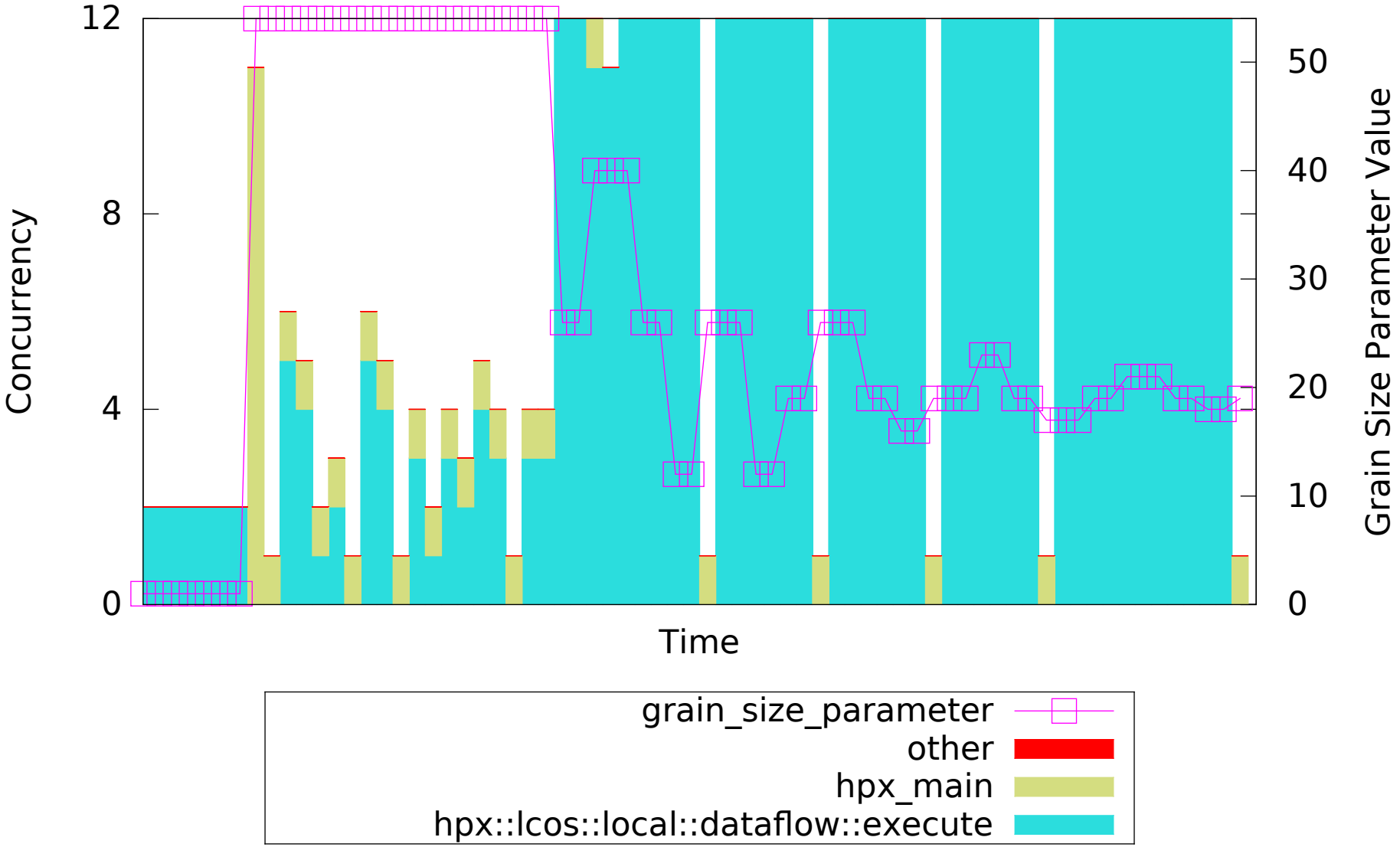
Adapting Block Size

- 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?

Run the example #4:

```
$ ./scripts/run_1d_stencil_repart-
    host.sh
# which will:
$ export APEX_POLICY=1
# note: nx is TOTAL elements, nt is
    timesteps between repetitions, nr
    is number of repetitions
$ ./build-host/apex_examples/
    1d_stencil_4_repart –nx 10000000
    –nr 50 --nt 50 --hpx:threads 12
```

1d_stencil: adapting block size



Wrap-up…

- Introduced TAU
- Instrumentation: PDT, MPI, OpenMP, **tau_exec**
- I/O and Memory evaluation
- PAPI
- Demonstration of analysis tools: ParaProf, TAUdb and PerfExplorer, Vampir and Jumpshot
- Introduced APEX
- Built HPX with APEX & TAU
- Ran Program Examples

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