Performance Measurement and Analysis of Heterogeneous Parallel Systems: Tasks and GPU Accelerators

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Outline

- What's all this about heterogeneous systems?
- Heterogeneity and performance tools
- Beating up on TAU
- Task performance abstraction and good 'ol master/worker
- What's all this about GPGPU's?
  - Accelerator performance measurement in PGI compiler
  - TAU CUDA performance measurement
- Final thoughts

Heterogeneous Parallel Systems

- What does it mean to be heterogenous?
  - New Oxford America, 2nd Edition:
    diverse in character or content
  - Prof. Dr. Felix Wolf, Sage of Research Centre Juelich:
    not homogeneous
- Diversity in what?
  - Hardware
    - processors/cores, memory, interconnection, …
    - different in computing elements and how they are used
  - Software (hybrid)
    - how the hardware is programmed
    - different software models, libraries, frameworks, …
- Diversity when? Heterogeneous implies combining together

Why Do We Care?

- Heterogeneity has been around for a long time
  - Have different programmable components in computer systems
  - Long history of specialized hardware
- Heterogeneous (computing) technology more accessible
  - Multicore processors
  - Manycore accelerators (e.g., NVIDIA Tesla GPU)
  - High-performance processing engines (e.g., IBM Cell BE)
- Performance is the main driving concern
  - Heterogeneity is arguably the only path to extreme scale
- Heterogeneous (hybrid) software technology required
- Greater performance enables more powerful software
  - Will give rise to more sophisticated software environments

Implications for Performance Tools

- Tools should support parallel computation models
- Current status quo is comfortable
  - Mostly homogeneous parallel systems and software
  - Shared-memory multithreading – OpenMP
  - Distributed-memory message passing – MPI
- Parallel computational models are relatively stable (simple)
  - Corresponding performance models are relatively tractable
  - Parallel performance tools are just keeping up
- Heterogeneity creates richer computational potential
  - Results in greater performance diversity and complexity
- Performance tools have to support richer computation models and broader (less constrained) performance perspectives

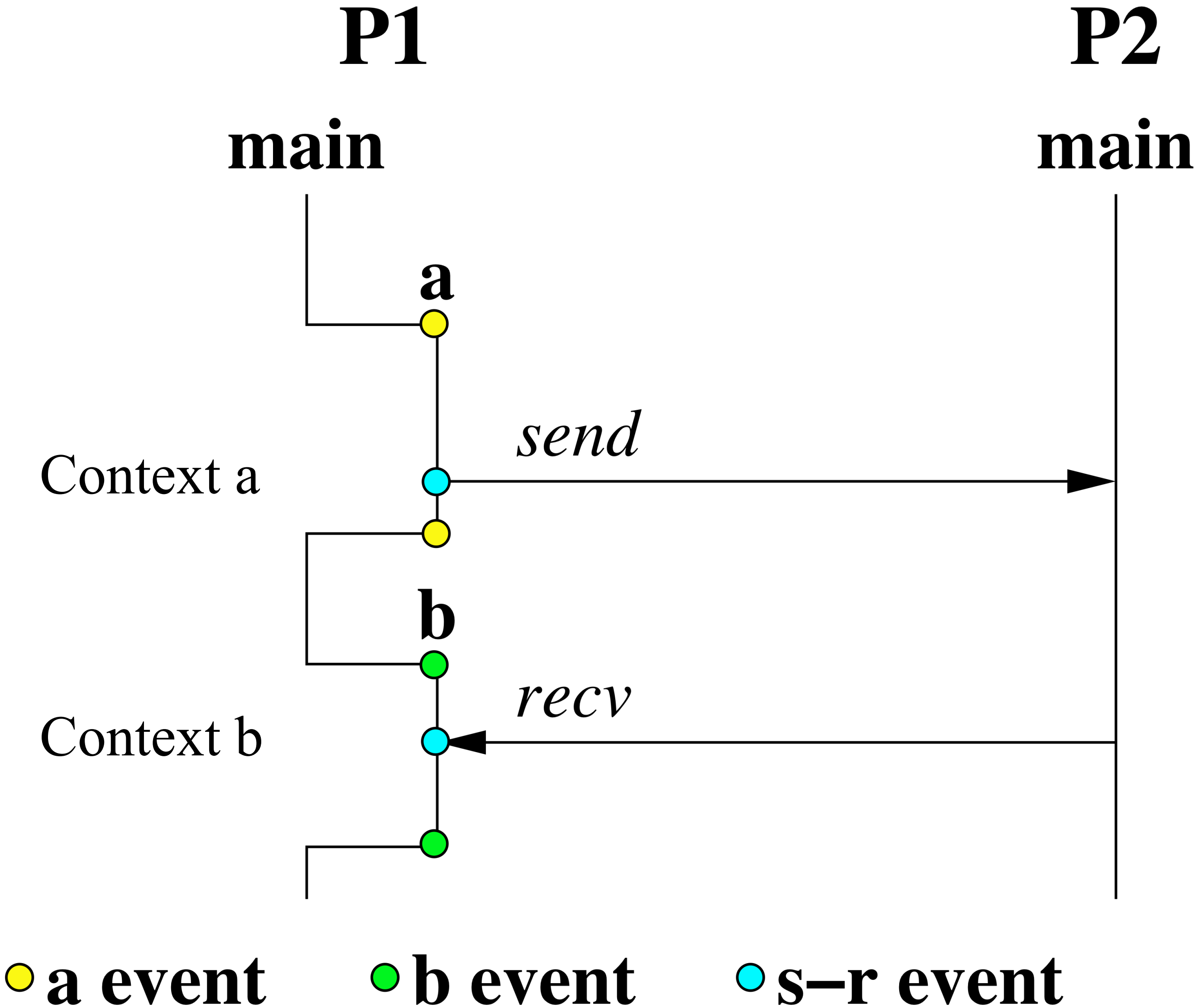
Current TAU Performance Perspective

- TAU is a direct measurement performance systems
  - Event stack performance perspective for “threads of execution”
  - Message communication performance
- TAU measures two general types of events
  - Interval event: coupled *begin* and *end* events
  - Atomic events
- TAU also maintains an *event stack* during execution
  - Events can be nested
  - Top of event stack the *event context*
  - Used to generate callpath performance measurements
  - Events can not overlap! (TAU enforces this requirement)
- What about events that are not event stack compatible?

MPI and Performance View

- TAU measures MPI events through the MPI interface
  - Standard PMPI approach (same as other tools)
  - Performance for interval events plus metadata
- Consider a paired message send/receive between P1 and P2
  - Suppose we want to measure the time on P1 from:
    - when P1 sends a message to P2
    - to when P1 receives a message from P2
  - TAU MPI events will not do this
  - Can create a TAU user-level interval event (*s*-*r*)
    - *s*-*r* begin and *s*-*r* end must have the same event context
    - no other events can overlap (nested events are ok)
  - What if these requirements can not be maintained?

Conflicting Contexts in Send-Receive MPI Scenario



Supporting Multiple Performance Perspectives

- Need to support alternative performance views
  - Reflect execution logic beyond standard actions
  - Capture performance semantics at multiple levels
  - Allow for compatible perspectives that do not conflict
- TAU event stack (nesting) perspective somewhat limited
- TAU's performance mapping can partially address need
- Some frameworks have own performance (timing) packages
  - Cactus, SAMRAI, PETSc, Charm++
  - Want to leverage/integrate/layer on TAU infrastructure
- Need also to incorporate views of external performance

TAU ProfilerCreate API

- Exposes TAU measurement infrastructure
- Software packages can easily access TAU profiler objects
  - Control completely determined by package
  - Can use to translate performance measures
  - Can access and set any part of the profiler information
- Goal of simplicity
  - API had to be easy to integrate in existing packages!
- Allows for multiple, layered performance measurements
  - Simultaneous to TAU (internal) measurement system

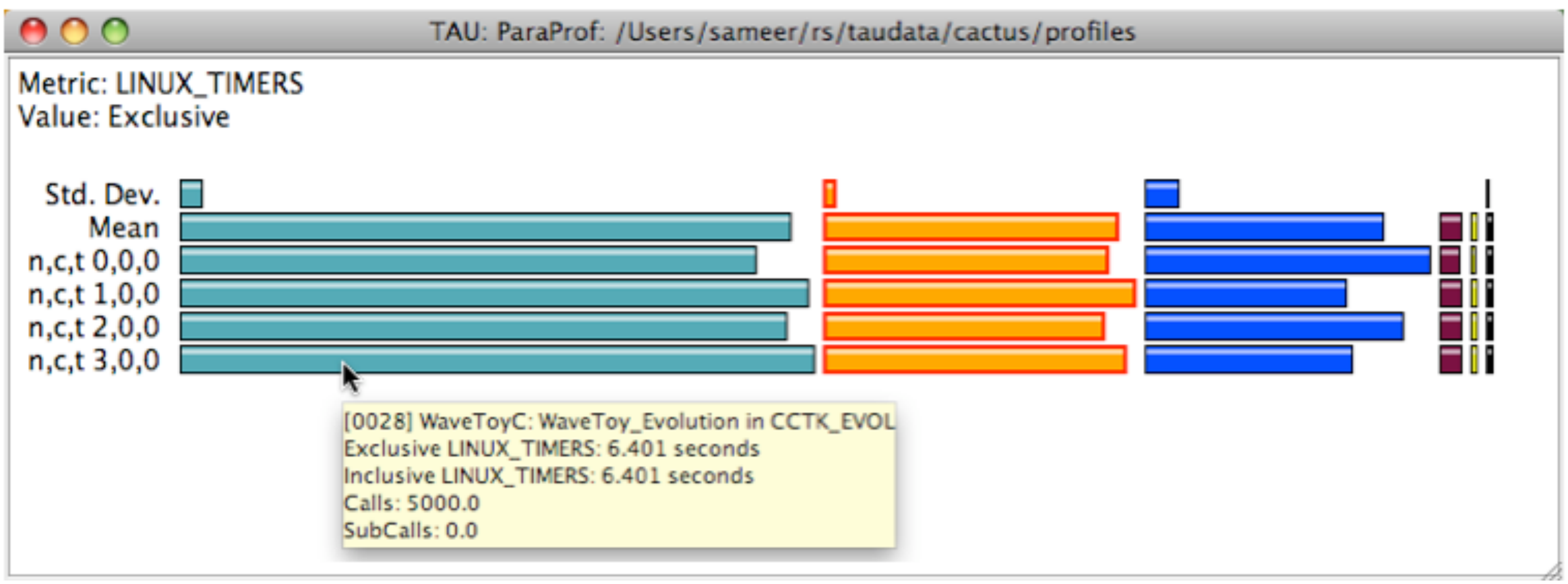
ProfilerCreate API

```
#include <TAU.h>

//TAU_PROFILER_CREATE(void *ptr, char *name, char *type,
   TauGroup_t tau_group);

TAU_PROFILER_CREATE(ptr, “main”, “int (int, char**)”,
   TAU_USER);

TAU_PROFILER_START(ptr);
// work
TAU_PROFILER_STOP(ptr);
```

```
#include <TAU.h>

TAU_PROFILER_GET_INCLUSIVE_VALUES(handle, data)
TAU_PROFILER_GET_EXCLUSIVE_VALUES(handle, data)
TAU_PROFILER_GET_CALLS(handle, data)
TAU_PROFILER_GET_CHILD_CALLS(handle, data)
TAU_PROFILER_GET_COUNTER_INFO(counters, numcounters)
```

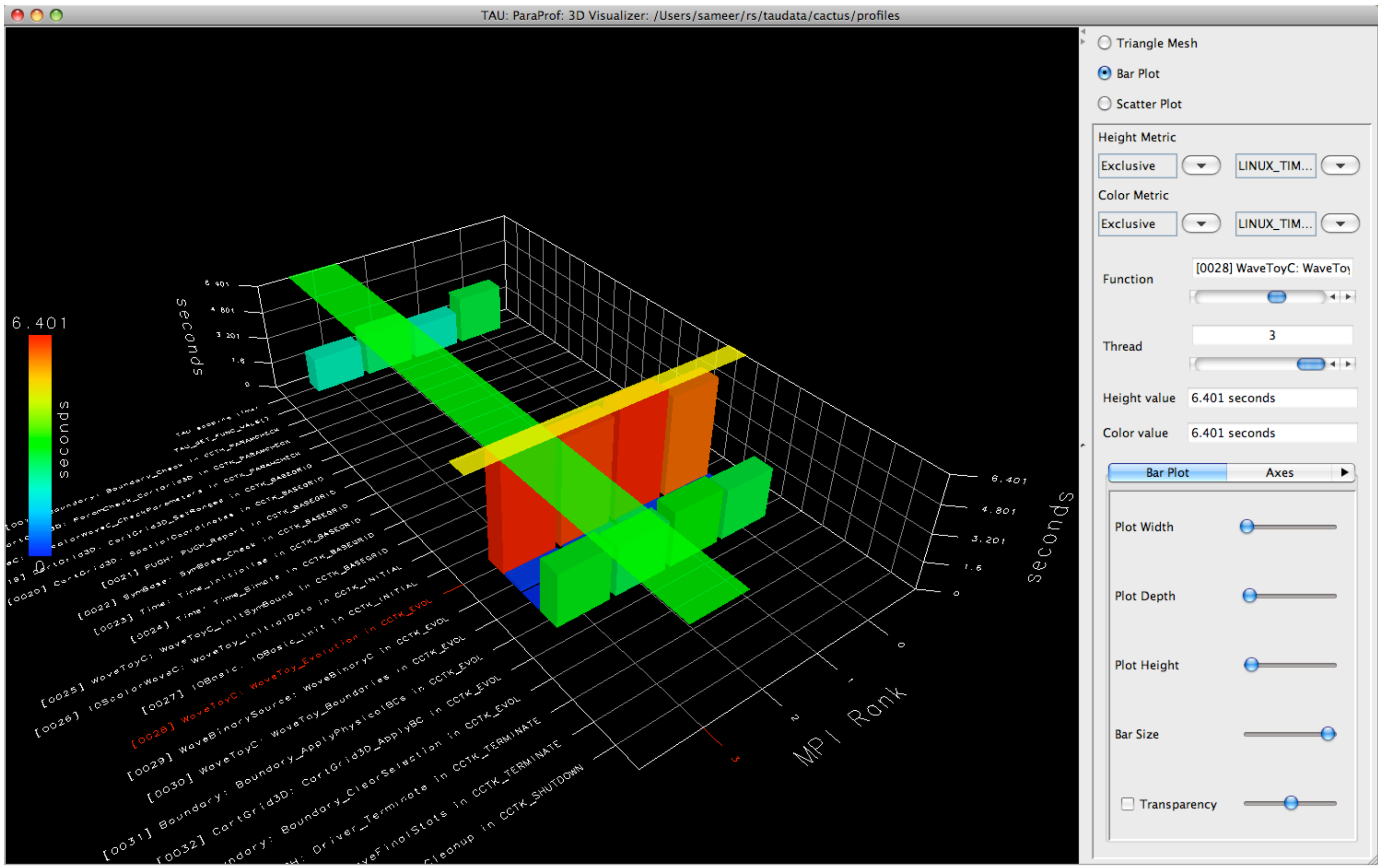
Use of TAU ProfilerCreate API in Cactus

- Cactus has its own performance evaluation interface
- Developers prefer to use TAU's interface
- Need a runtime performance assessment interface
- Layered Cactus API on top of new ProfilerCreate API
- Created a TAU scoping profiler for capturing top-level performance event (equivalent to main)



Cactus Performance (Full Profile)

- Events under Cactus control
- Use TAU to capture timing and hardware measures



Performance Views of External Execution

- Heterogeneous applications can have concurrent execution
  - Main “host” path and “external” external paths
  - Want to capture performance for all execution paths
  - External execution may be difficult or impossible to measure
- “Host” creates measurement view for external entity
  - Maintains local and remote performance data
  - External entity may provide performance data to the host
- What perspective does the host have of the external entity?
  - Determines the semantics of the measurement data
- Consider the “task” abstraction

Task-based Performance Views

- Host regards external execution as a task
  - Tasks operate concurrently with respect to the host
  - Requires support for tracking asynchronous execution
- Host keeps measurements for external task
  - Host-side measurements of task events
  - Performance data received external task
  - Tasks may have limited measurement support
  - May depend on host for performance data I/O
- Need an task performance API
  - Capture abstract (host-side) task events
  - Populate TAU's performance data structures for task
  - Derived from ProfilerCreate API to address these concerns

TAU Task API

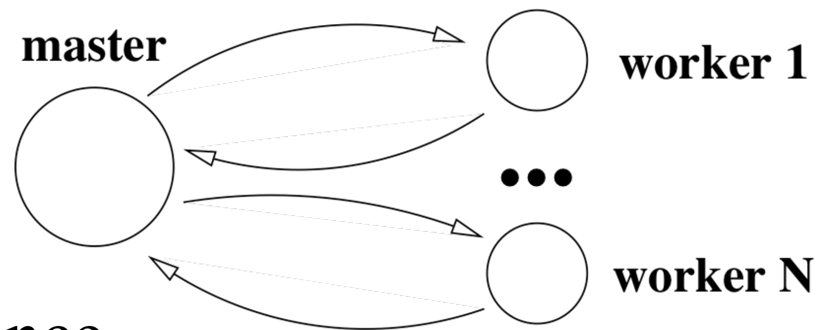
```
#include <TAU.h>

TAU_CREATE_TASK(taskid);

//TAU_PROFILER_CREATE(void *ptr, char *name, char *type,
  TauGroup_t tau_group);

TAU_PROFILER_CREATE(ptr, “main”, “int (int, char**)”,
  TAU_USER);

TAU_PROFILER_START_TASK(ptr, taskid);
// work
TAU_PROFILER_STOP_TASK(ptr, taskid);
```

TAU Task API (2)

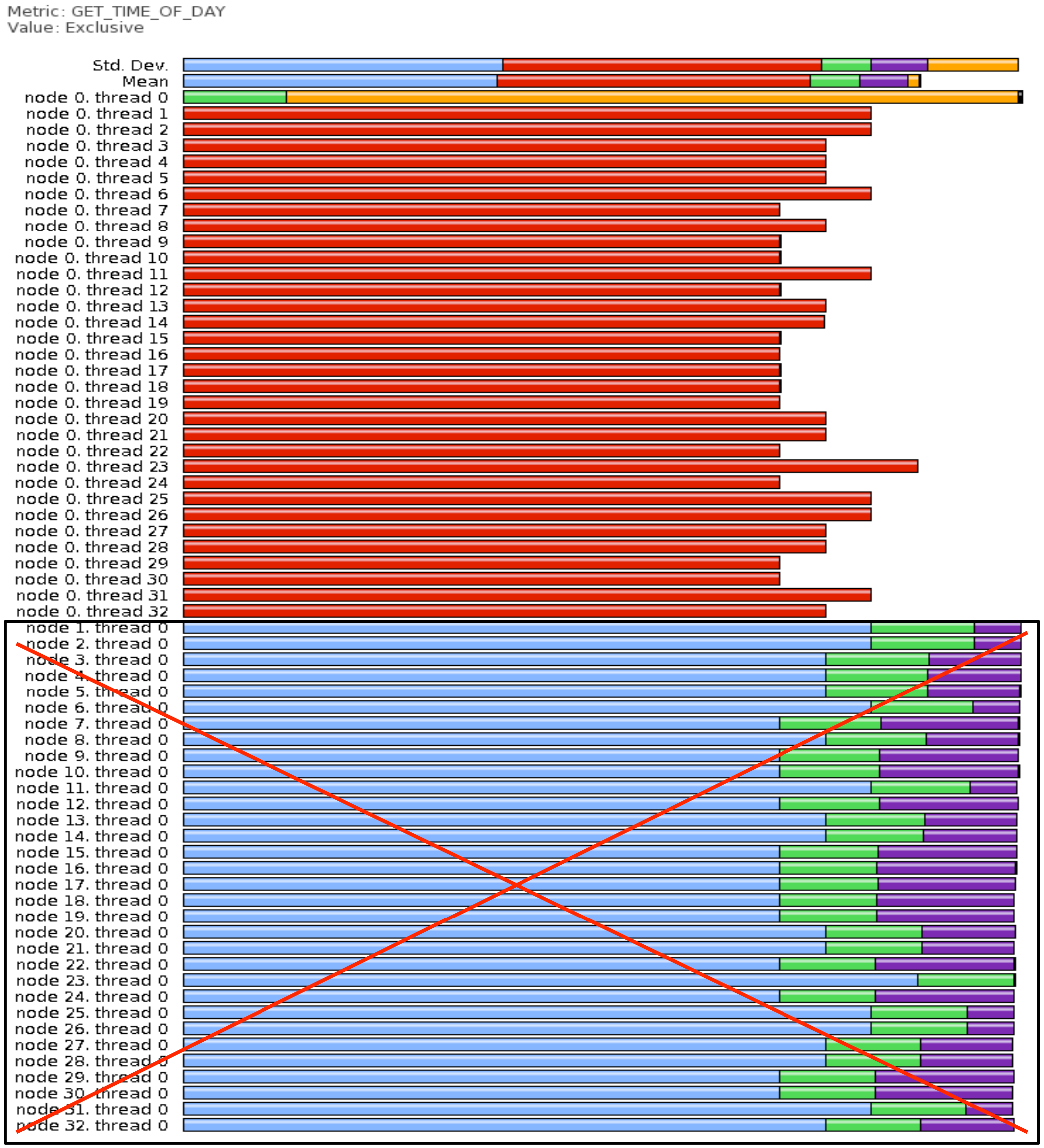
```
#include <TAU.h>

TAU_PROFILER_GET_INCLUSIVE_VALUES_TASK(ptr, data, taskid);
TAU_PROFILER_SET_INCLUSIVE_VALUES_TASK(ptr, data, taskid);

TAU_PROFILER_GET_EXCLUSIVE_VALUES_TASK(ptr, data, taskid);
TAU_PROFILER_SET_EXCLUSIVE_VALUES_TASK(ptr, data, taskid);

TAU_PROFILER_GET_CALLS_TASK(ptr, data, taskid);
TAU_PROFILER_SET_CALLS_TASK(ptr, data, taskid);

TAU_PROFILER_GET_CHILD_CALLS_TASK(ptr, data, taskid);
TAU_PROFILER_SET_CHILD_CALLS_TASK(ptr, data, taskid);
```

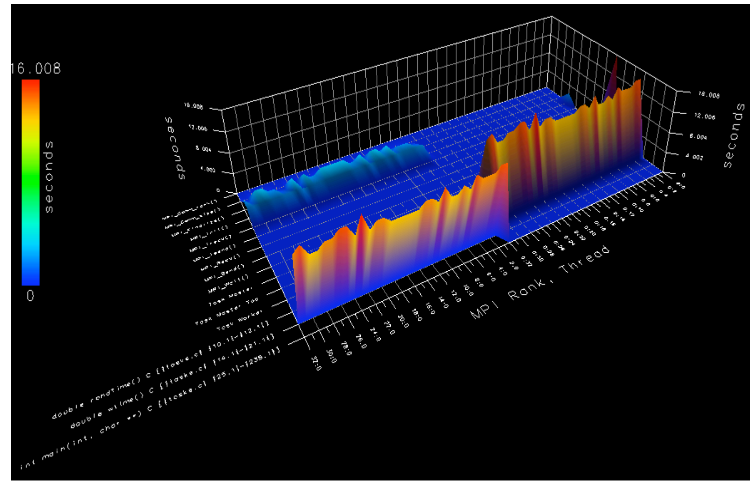
Master-Worker Scenario with TAU Task API

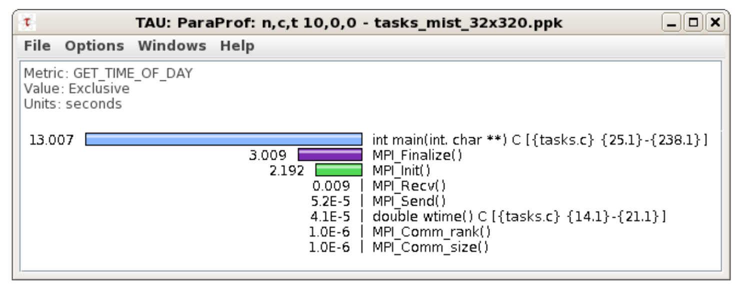
- Master sends tasks to *N* workers
- Workers report back their performance to master
  - Done for each piece of work
- Build a worker performance perspective in the master
- TAU will only output a performance profile from the master
  - Each work task will appear as a separate "thread" of the master
- In general, the external performance data can be arbitrary
  - Single time value
  - More complete representation of external performance

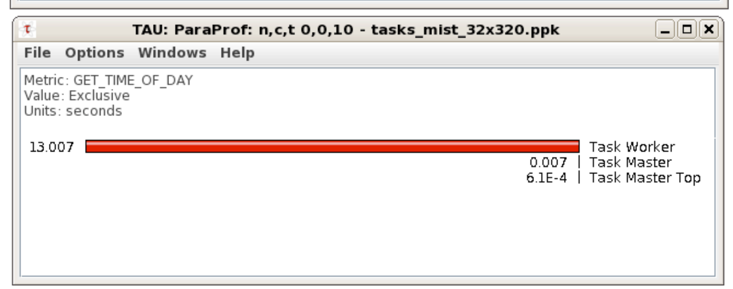


Master-Worker with Task API: 32 Workers

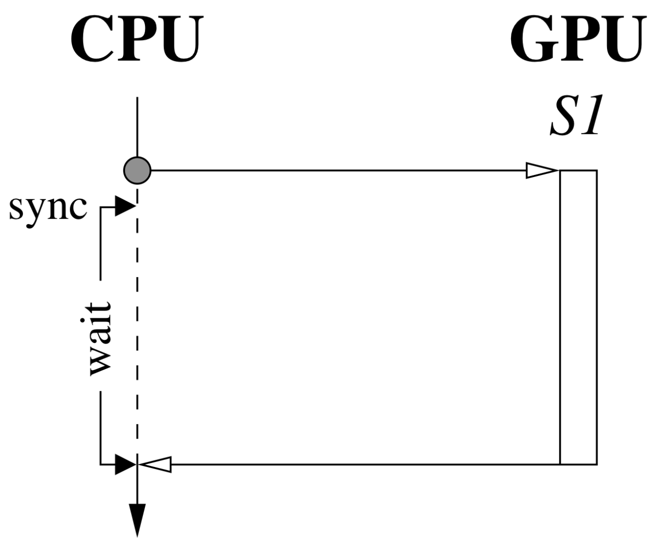


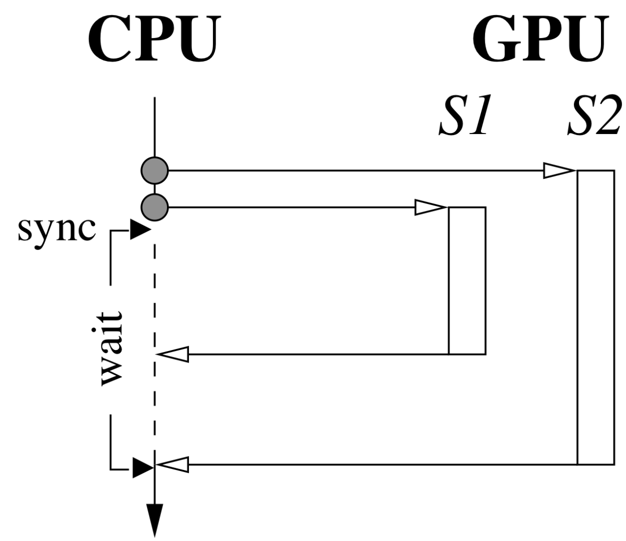


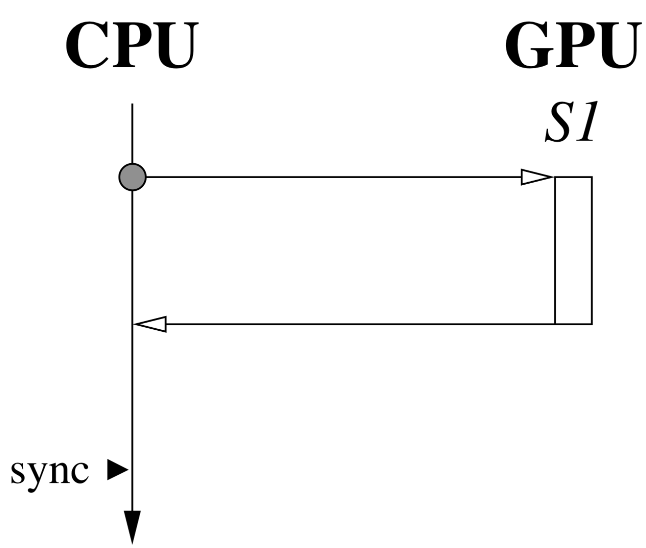


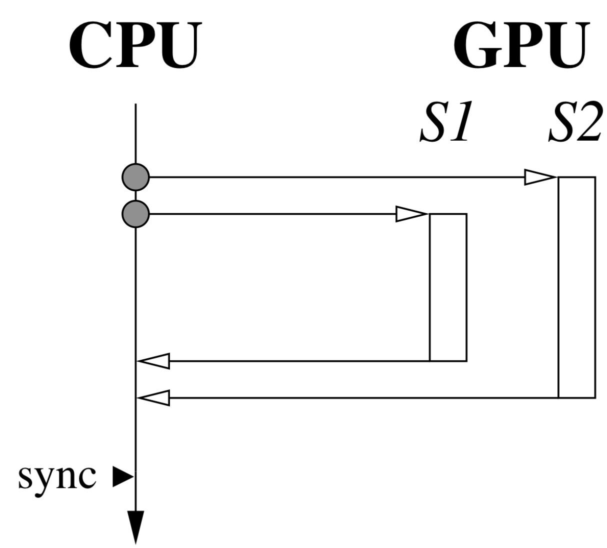


CPU – GPU Execution Scenarios









PGI Compiler for GPUs

- Accelerator programming support
  - Fortran and C
  - Directive-based programming
  - Loop parallelization for acceleration on GPUs
  - PGI 9.0 for x64-based Linux (preview release)
- Compiled program
  - CUDA target
  - Synchronous accelerator operations
- Profile interface support

TAU with PGI Accelerator Compiler

- Supports compiler-based instrumentation for PGI compilers
- Track runtime system events as seen from the host processor
- Show source information associated with events
  - Routine name
  - File name, source line number for kernel
  - Variable names in memory upload, download operations
  - Grid sizes
- Any configuration of TAU with PGI supports tracking of accelerator operations
  - Tested with PGI 8.0.3, 8.0.5, 8.0.6 compilers
  - Qualification and testing with PGI 9.0-1 complete

Wrapping PGI Accelerator Runtime System Calls

- Wrapping performed using *performance interface*
  - Append "_p" to runtime calls of interest to measure

```
void __pgi_cu_module_p(void *image);
void __pgi_cu_module(void *image) {
  TAU_PROFILE("__pgi_cu_module","",TAU_DEFAULT);
  __pgi_cu_module_p(image);
}
```

- Provided in calls for:
  - Init
  - Launching kernels (synchronous execution)
  - Upload and download

PGI Accelerator Runtime Measurement API

__pgi_cu_sync
__pgi_cu_fini
__pgi_cu_module
__pgi_cu_module_function
__pgi_cu_module_file
__pgi_cu_module_unload
__pgi_cu_paramset
__pgi_cu_launch
__pgi_cu_free
cuda_deviceptr __pgi_cu_alloc

__pgi_cu_download
__pgi_cu_download1
__pgi_cu_download2
__pgi_cu_download3
__pgi_cu_downloadp
__pgi_cu_upload
__pgi_cu_upload1
__pgi_cu_upload2
__pgi_cu_upload3
__pgi_cu_uploadc
__pgi_cu_uploadn

Matrix Multiply (MM) Example

- Test with simple matrix multiply
- Vary the matrix sizes
- Demonstrate TAU integration

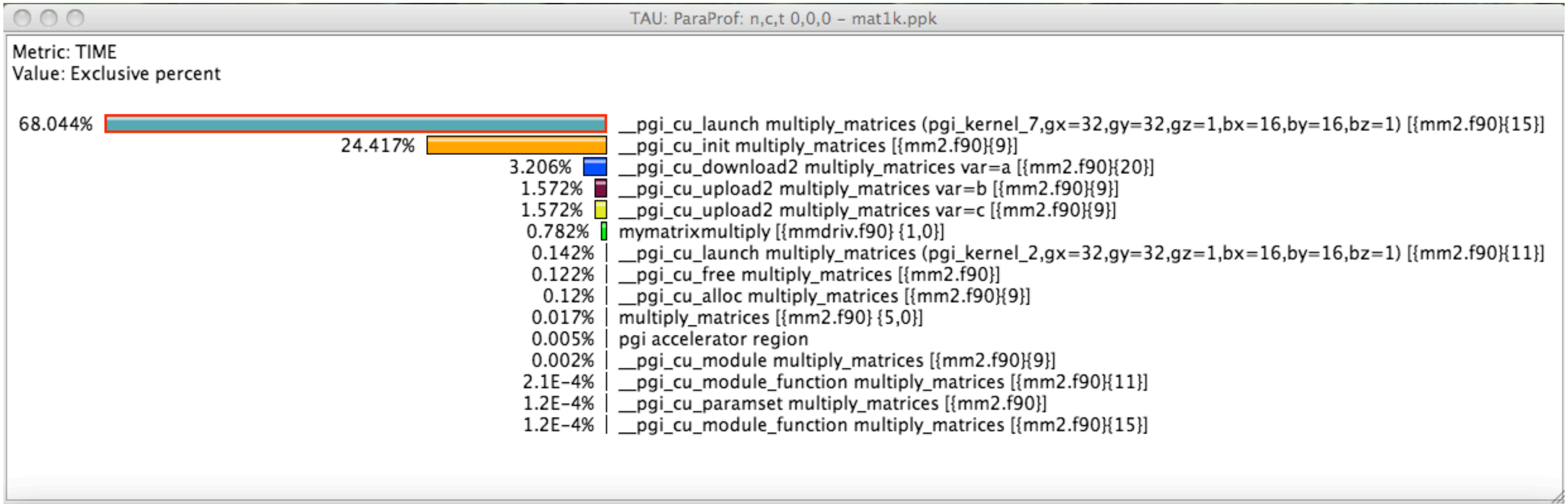
xterm

```
    module mymm
    contains
    subroutine multiply_matrices( a, b, c, m )
     real, dimension(:,:) :: a,b,c
     i = 0

!$acc region
     do j = 1,m
         do i = 1,m
          a(i,j) = 0.0
         enddo
       do k = 1,m
         do i = 1,m
          a(i,j) = a(i,j) + b(i,k) * c(k,j)
         enddo
       enddo
     enddo
!$acc end region
    end subroutine
    end module

"mm2.f90" 23 lines --95%--     22,5          Bot
```

Build with Compiler-based Instrumentation

```
[ ~/mm]$ export TAU_MAKEFILE=/opt/tau-2.18.2/x86_64/lib/Makefile.tau-pgi
[ ~/mm]$ export TAU_OPTIONS='-optCompInst -optVerbose'
[ ~/mm]$ export PATH=/opt/tau-2.18.2/x86_64/bin:$PATH
[ ~/mm]$ cat Makefile
#F90=pgf90
# To profile with TAU, set TAU_MAKEFILE, TAU_OPTIONS and use
# tau_f90.sh as the compiler
F90=tau_f90.sh

#FFLAGS=-O3
FFLAGS=-ta=nvidia

mm: mm2.o mmdriv.o
        $(F90) $(FFLAGS) mm2.o mmdriv.o -o mm $(LIBS)
%.o: %.f90
        $(F90) -c $< $(FFLAGS)
clean:
        /bin/rm -rf mm  *.o profile.* MULT* *.mod
[ ~/mm]$ make

                                                            20,0-1        All
```

MM Profile (3000 x 3000, ~22 Gflops)



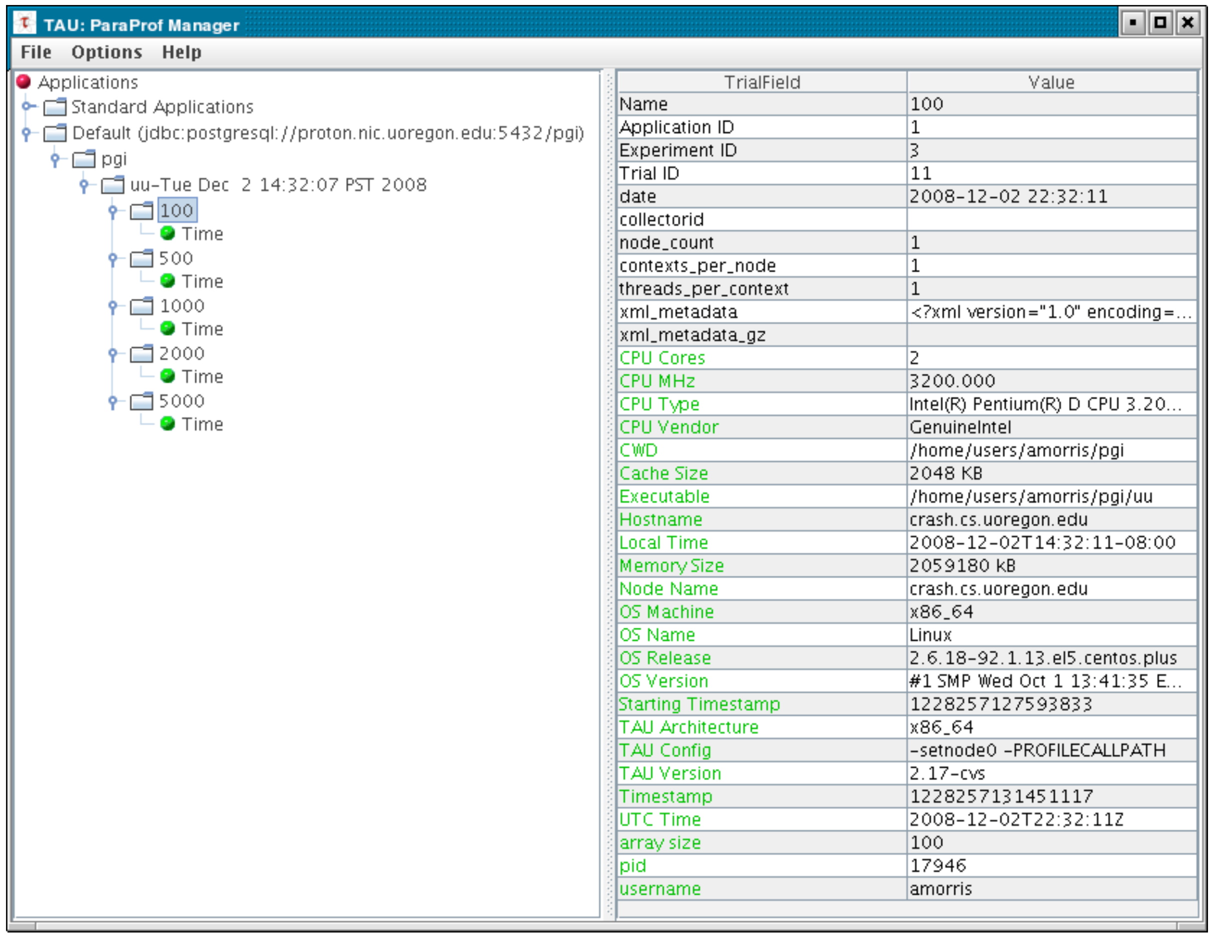
TAU: ParaProf: Thread Statistics: n,c,t, 0,0,0 – mat1k.ppk

Name	Exclusive TIME ▽	Inclusive TIME	Calls	Child Calls
__pgi_cu_launch multiply_matrices (pgi_kernel_7,gx=32,gy=32,gz=1,bx=16,by=16,bz=1) [{mm2.f90}{15}]	10.901	10.901	5	0
__pgi_cu_init multiply_matrices [{mm2.f90}{9}]	3.912	3.912	5	0
__pgi_cu_download2 multiply_matrices var=a [{mm2.f90}{20}]	0.514	0.514	5	0
__pgi_cu_upload2 multiply_matrices var=b [{mm2.f90}{9}]	0.252	0.252	5	0
__pgi_cu_upload2 multiply_matrices var=c [{mm2.f90}{9}]	0.252	0.252	5	0
mymatrixmultiply [{mmdriv.f90} {1,0}]	0.125	16.021	1	1
__pgi_cu_launch multiply_matrices (pgi_kernel_2,gx=32,gy=32,gz=1,bx=16,by=16,bz=1) [{mm2.f90}{11}]	0.023	0.023	5	0
__pgi_cu_free multiply_matrices [{mm2.f90}]	0.02	0.02	15	0
__pgi_cu_alloc multiply_matrices [{mm2.f90}{9}]	0.019	0.019	15	0
multiply_matrices [{mm2.f90} {5,0}]	0.003	15.895	5	9
pgi accelerator region	0.001	15.893	5	85
__pgi_cu_module multiply_matrices [{mm2.f90}{9}]	0	0	5	0
__pgi_cu_module_function multiply_matrices [{mm2.f90}{11}]	0	0	5	0
__pgi_cu_paramset multiply_matrices [{mm2.f90}]	0	0	10	0

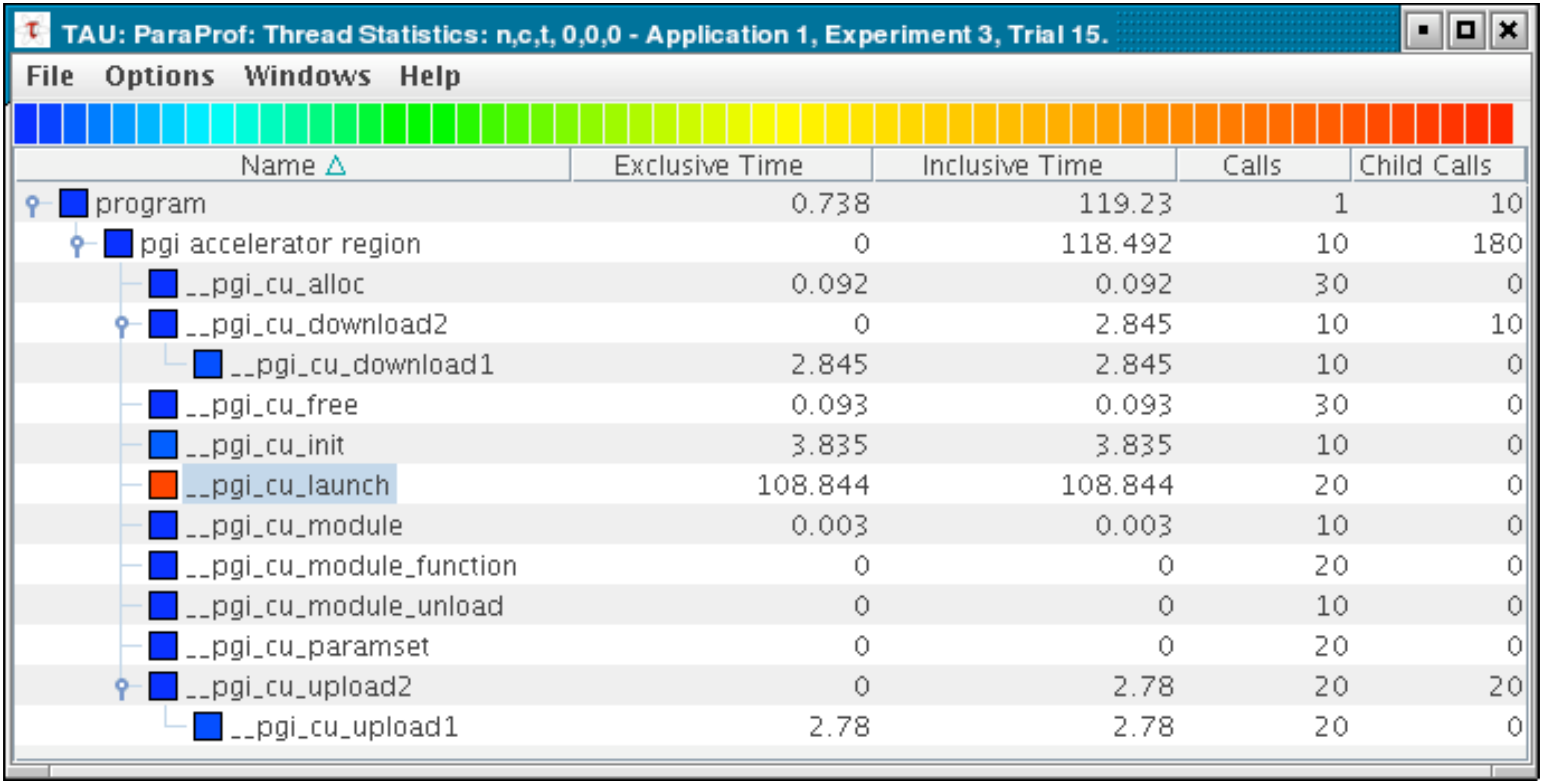
Show Source Code
Show Function Bar Chart
Show Function Histogram
Assign Function Color
Reset to Default Color

MM Program on Different Array Sizes

- Parameter study of MM to evaluate GPU
  - Array sizes: 100, 500, 1000, 2000, 5000
  - 10 iterations
  - Results uploaded to performance database
- Want to observe the effects on PGI accelerator runtime routines
  - __pgi_cu_launch



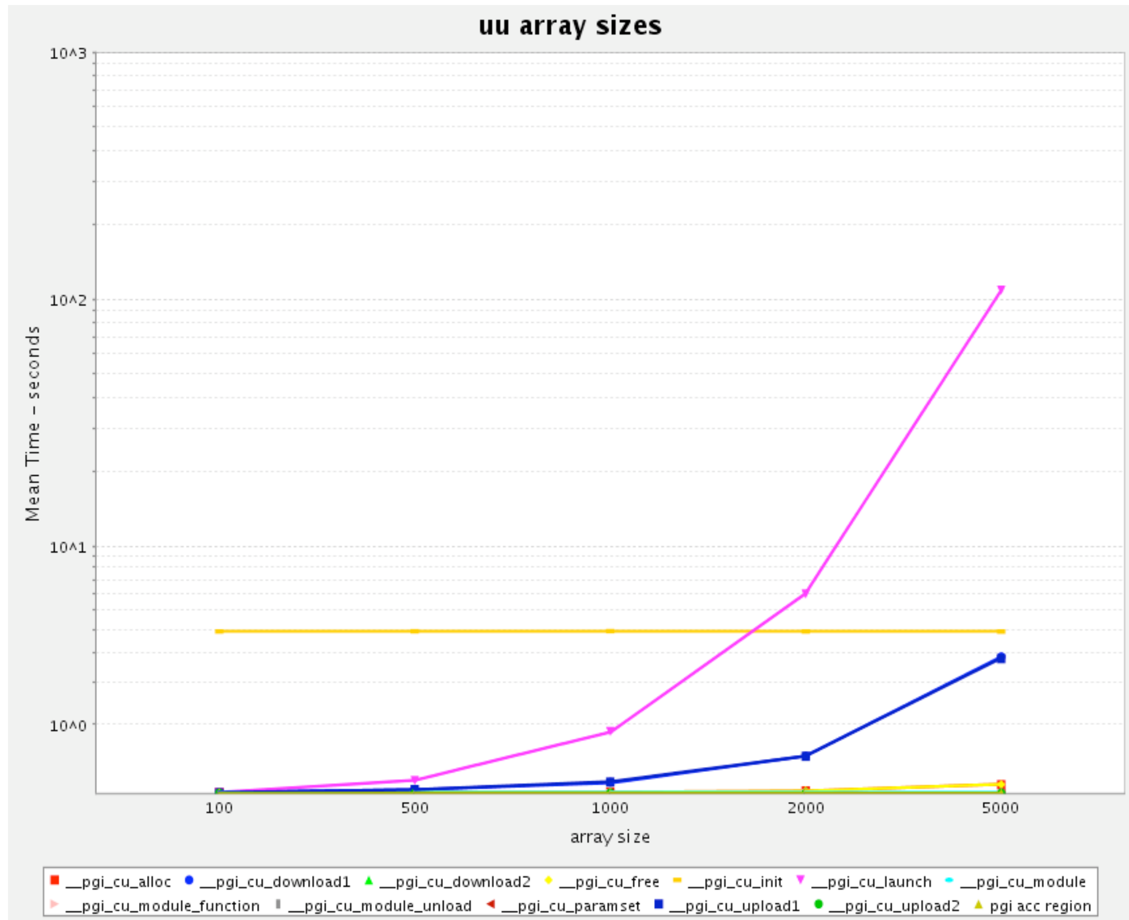
MM Callpath Profiling – Tree Table View



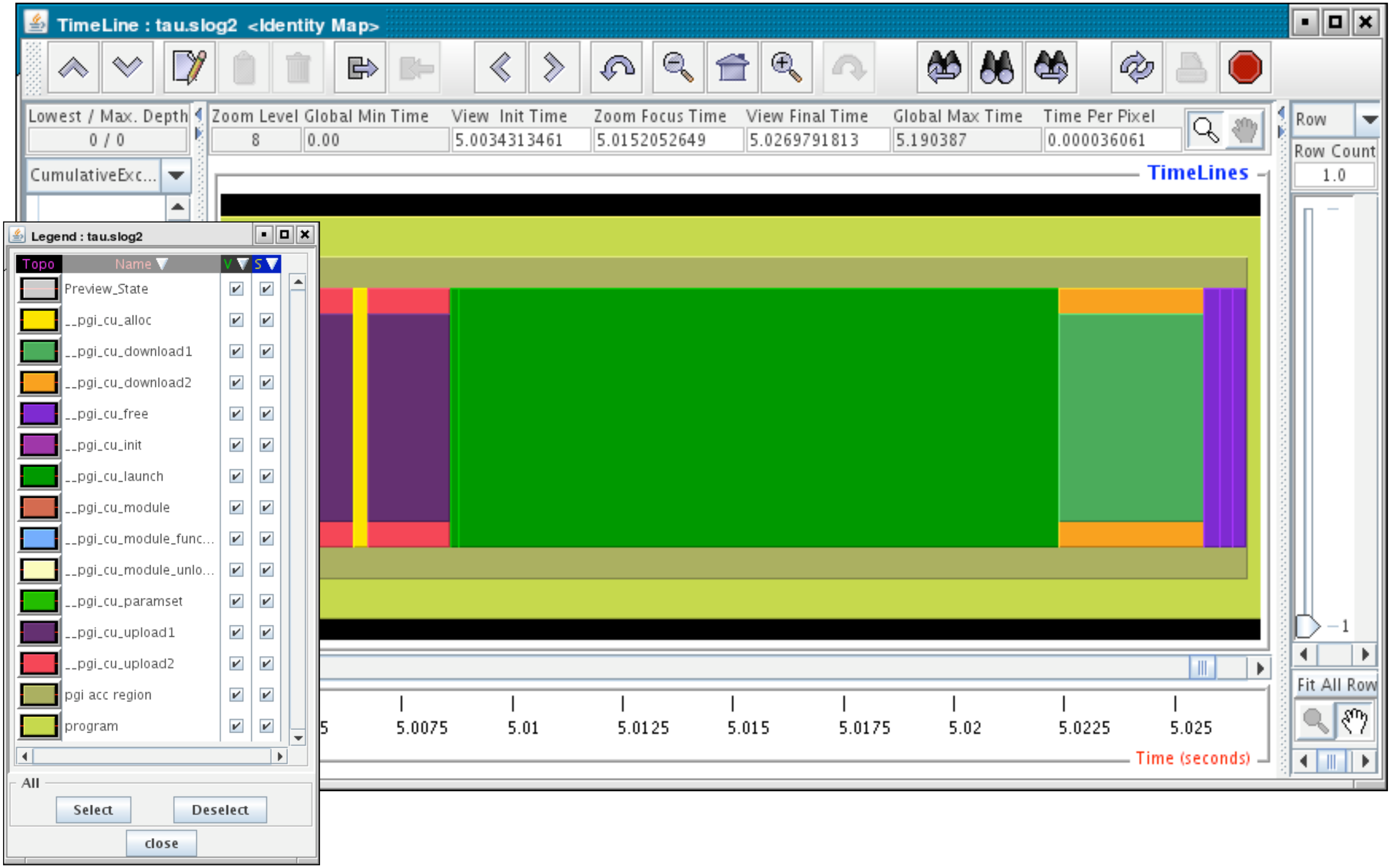
Name △	Exclusive Time	Inclusive Time	Calls	Child Calls
program	0.738	119.23	1	10
pgi accelerator region	0	118.492	10	180
__pgi_cu_alloc	0.092	0.092	30	0
__pgi_cu_download2	0	2.845	10	10
__pgi_cu_download1	2.845	2.845	10	0
__pgi_cu_free	0.093	0.093	30	0
__pgi_cu_init	3.835	3.835	10	0
__pgi_cu_launch	108.844	108.844	20	0
__pgi_cu_module	0.003	0.003	10	0
__pgi_cu_module_function	0	0	20	0
__pgi_cu_module_unload	0	0	10	0
__pgi_cu_paramset	0	0	20	0
__pgi_cu_upload2	0	2.78	20	20
__pgi_cu_upload1	2.78	2.78	20	0

MM Array Size Comparison with PerfExplorer

- Show effects of array size variation (log scale)
  - Init is significant, but constant
  - Launch grows with size because of computation
  - Upload and download do also, as determined by algorithm



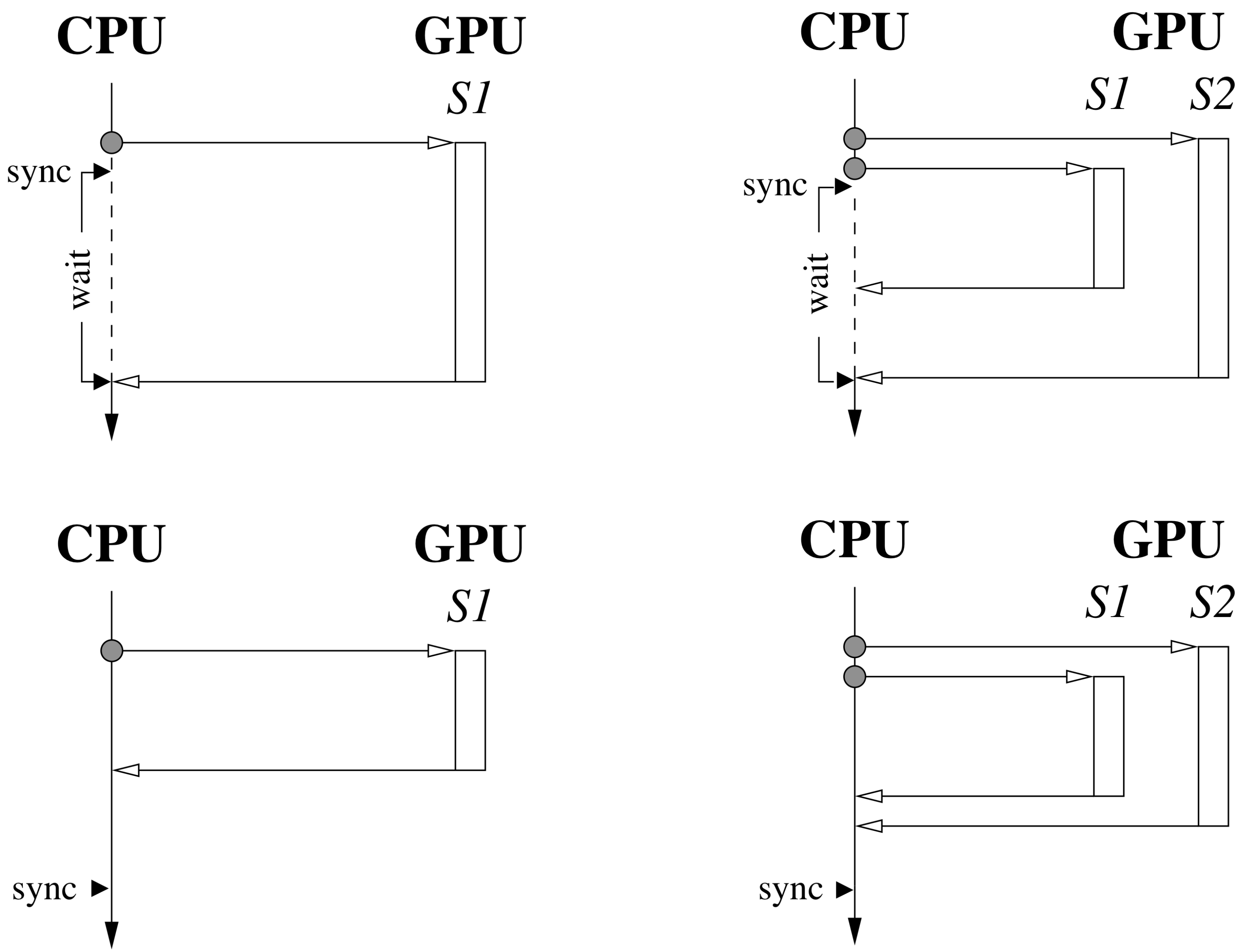
MM Trace View with Jumpshot



CUDA Programming for GPGPU

- PGI compiler represents GPGPU programming abstraction
  - Performance tool uses runtime system wrappers
    - essentially a synchronous call performance model!!!
- In general, programming of GPGPU devices is more complex
- CUDA environment
  - Programming of multiple streams and GPU devices
    - multiple streams execute concurrently
  - Programming of data transfers to/from GPU device
  - Programming of GPU kernel code
  - Synchronization with streams
  - Stream event interface
  - CUDA profiling tool

CPU – GPU Execution Scenarios



TAU CUDA Performance Measurement

- Build on CUDA event interface
  - Allow "events" to be placed in streams and processed
    - events are timestamped
  - CUDA runtime reports GPU timing in event structure
  - Events are reported back to CPU when requested
    - use begin and end events to calculate intervals
- Want to associate TAU event context with CUDA events
  - Get top of TAU event stack at begin
- CUDA kernel invocations are asynchronous
  - CPU does not see actual CUDA "end" event
  - CPU retrieves events in a non-blocking and blocking manner
- Want to capture "waiting time"

TAU CUDA Measurement API

void *tau_cuda_init*(int argc, char **argv);

- To be called when the application starts
- Initializes data structures and checks GPU status

void *tau_cuda_exit*()

- To be called before any thread exits at end of application
- All the CUDA profile data output for each thread of execution

void* *tau_cuda_stream_begin*(char *event, cudaStream_t stream);

- Called before CUDA statements to be measured
- Returns handle which should be used in the end call
- If *event* is new or the TAU context is new for the event, a new CUDA event profile object is created

void *tau_cuda_stream_end*(void * handle);

- Called immediately after CUDA statements to be measured
- Handle identifies the stream
- Inserts a CUDA event into the stream

TAU CUDA Measurement API (2)

vector<Event> *tau_cuda_update*();

- Checks for completed CUDA events on all streams
- Non-blocking and returns # completed on each stream

int *tau_cuda_update*(cudaStream_t stream);

- Same as *tau_cuda_update*() except for a particular stream
- Non-blocking and returns # completed on the stream

vector<Event> *tau_cuda_finalize*();

- Waits for all CUDA events to complete on all streams
- Blocking and returns # completed on each stream

int *tau_cuda_finalize*(cudaStream_t stream);

- Same as *tau_cuda_finalize*() except for a particular stream
- Blocking and returns # completed on the stream

Scenario Results – One and Two Streams

- Run simple CUDA experiments to test TAU CUDA
- Tesla S1070 test system

CPU Load	GPU Load	Event	Inclusive Time	Exclusive Time	Wait Time	Finalize Time
0	X	Interpolate (C-[main—]#D-0#S-0)	75222.4922	75222.4922	75134.7656	87.8906
0	2X	Interpolate (C-[main—]#D-0#S-0)	150097.7031	150097.7031	149995.6094	102.0508
0	3X	Interpolate (C-[main—]#D-0#S-0)	225034.2031	225034.2031	224915.5312	118.6523
Y	X	Interpolate (C-[main—]#D-0#S-0)	74985.6953	74985.6953	64097.1680	10888.6719
2Y	X	Interpolate (C-[main—]#D-0#S-0)	75058.5234	75058.5234	42563.9648	32494.6289
10Y	X	Interpolate (C-[main—]#D-0#S-0)	75032.9609	75032.9609	0.0000	108114.7500

Table 1: TAUCUDA Profiles for a single stream (Time measured in microseconds)

	GPU Load		Time Measured in Miliseconds				
CPU Load	S-1	S-2	Event	Inclusive Time	Exclusive Time	Wait Time	Finalize Time
0	2X	X	Interpolate (C-[main—]#D-0#S-1)	149982.8750	149982.8750	149858.8906	124.0234
0	2X	X	Interpolate (C-[main—]#D-0#S-2)	74929.6953	74929.6953	74909.6719	20.0195
0	X	2X	Interpolate (C-[main—]#D-0#S-1)	74993.2188	74993.2188	74869.6250	123.5352
0	X	2X	Interpolate (C-[main—]#D-0#S-2)	150055.8750	150055.8750	150019.0469	36.6211
Y	X	X	Interpolate (C-[main—]#D-0#S-1)	75054.0156	75054.0156	53687.0117	21367.1875
Y	X	X	Interpolate (C-[main—]#D-0#S-2)	74989.4688	74989.4688	53708.9844	21280.2734
2Y	X	X	Interpolate (C-[main—]#D-0#S-1)	74899.1406	74899.1406	32293.9453	42604.9805
2Y	X	X	Interpolate (C-[main—]#D-0#S-2)	74948.7344	74948.7344	32429.6875	42519.0430
5Y	X	X	Interpolate (C-[main—]#D-0#S-1)	75007.4219	75007.4219	0.0000	106393.0625
5Y	X	X	Interpolate (C-[main—]#D-0#S-2)	75008.5469	75008.5469	0.0000	106305.6641

Table 2: TAUCUDA Profiles for two streams

Scenario Results – Two Devices, Two Contexts

CPU Load		GPU Load		Time Measured in Miliseconds				
D-0	D-1	D-0	D-1	Event	Inclusive Time	Exclusive Time	Wait Time	Finalize Time
0	0	X	2X	Interpolate (C-[main—]#D-0#S-0)	75068.2500	75068.2500	74855.4688	212.8906
0	0	X	2X	Interpolate (C-[main—]#D-1#S-0)	149795.0156	149795.0156	149698.7344	96.1914
0	0	2X	X	Interpolate (C-[main—]#D-0#S-0)	150171.8750	150171.8750	150054.6875	117.1875
0	0	2X	X	Interpolate (C-[main—]#D-1#S-0)	74969.5625	74969.5625	74892.5781	77.1484
2Y	Y	X	X	Interpolate (C-[main—]#D-0#S-0)	75121.7266	75121.7266	53530.7617	21590.8203
2Y	Y	X	X	Interpolate (C-[main—]#D-1#S-0)	75864.0938	75864.0938	18769.0430	57095.2148
Y	2Y	X	X	Interpolate (C-[main—]#D-0#S-0)	75119.8750	75119.8750	53557.1289	21562.9883
Y	2Y	X	X	Interpolate (C-[main—]#D-1#S-0)	75123.8984	75123.8984	18204.1016	56919.9219

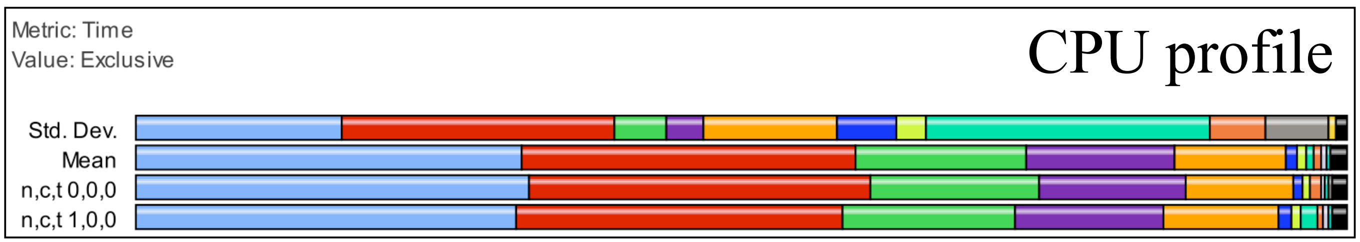
Table 3: TAUCUDA Profiles for two Devices

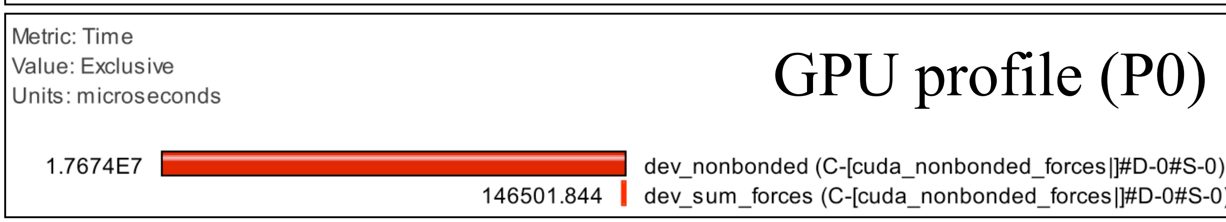
Event	calls	Inclusive Time	Exclusive Time	Wait Time	Finalize Time
All-Interpolate (C-[FirstWarepper—]#D-0#S-0)	1	300019.9375	65.3992	0.0000	8380799
InterpolateA (C-[FirstWarepper—]#D-0#S-0)	10	150013.6250	150013.6250	0.0000	83806752
InterpolateB (C-[FirstWarepper—]#D-0#S-0)	10	149940.8750	149940.8750	0.0000	83806616
All-Interpolate (C-[SecondWarepper—]#D-0#S-0)	1	300111.6250	65.0635	0.0000	467571.2812
InterpolateA (C-[SecondWarepper—]#D-0#S-0)	10	150018.1719	150018.1719	0.0000	4674823
InterpolateB (C-[SecondWarepper—]#D-0#S-0)	10	150028.3750	150028.3750	0.0000	4674740

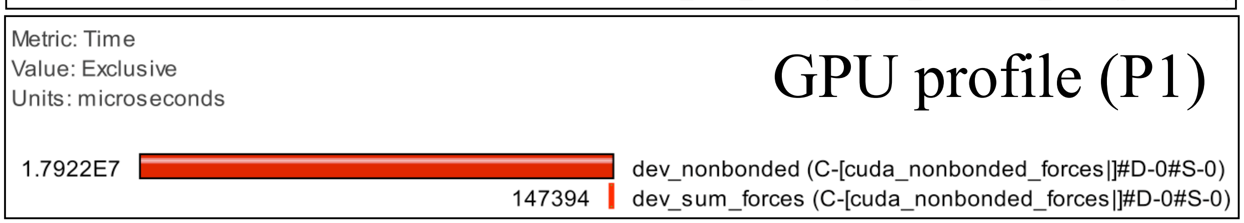
Table 4: TAUCUDA Profiles With Two TAU Contexts and Nested Events

TAU CUDA in NAMD

- TAU integrated in Charm++ (another talk)
- NAMD is a molecular dynamics application using Charm++
- NAMD has been accelerated with CUDA
- Test out TAU CUDA with NAMD
  - Two processes with one Tesla GPU for each







Conclusions

- Heterogeneous parallel computing will challenge parallel performance technology
  - Must deal with diversity in hardware and software
  - Must deal with richer parallelism and concurrency
- Performance tools should support parallel execution and computation models
  - Understanding of “performance” interactions
    - between integrated components
    - control and data interactions
  - Might not be able to see full parallel (concurrent) detail
- Need to support multiple performance perspectives
  - Layers of performance abstraction