Virtual Institute – High Productivity Supercomputing

TAU PERFORMANCE SYSTEM

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- Tuning and Analysis Utilities (18+ 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)
- Easy to integrate in application frameworks

http://tau.uoregon.edu

What is TAU?

- TAU is a performance evaluation tool
- It supports parallel profiling and tracing
- Profiling shows you how much (total) time was spent in each routine
- Tracing shows you *when* the events take place in each process along a timeline
- Profiling and tracing can measure time as well as hardware performance counters (cache misses, instructions) from your CPU
- TAU can automatically instrument your source code using a package called PDT for routines, loops, I/O, memory, phases, etc.
- TAU runs on most HPC platforms and it is free (BSD style license)
- TAU has instrumentation, measurement and analysis tools
  - paraprof is TAU's 3D profile browser
- To use TAU's automatic source instrumentation, you may set a couple of environment variables and substitute the name of your compiler with a TAU shell script

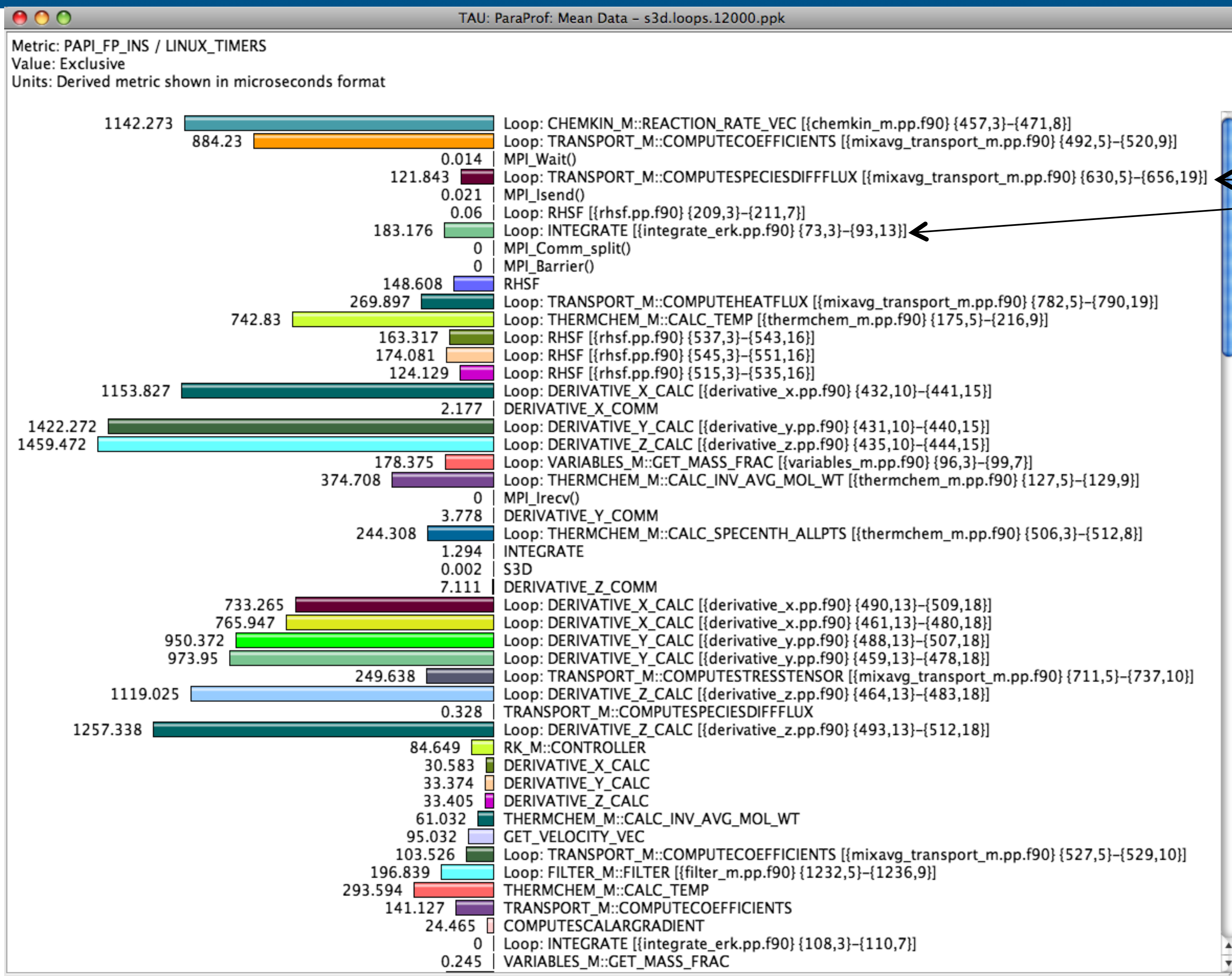
TAU: Usage Scenarios

- 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 ***peak heap memory*** usage of the code? When and where is memory allocated/de-allocated? Are there any memory leaks?
- How much time does the application spend performing ***I/O***? What is the peak read and write ***bandwidth*** of individual calls, total volume?
- What is the contribution of different ***phases*** 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?

Using TAU: Simplest Case

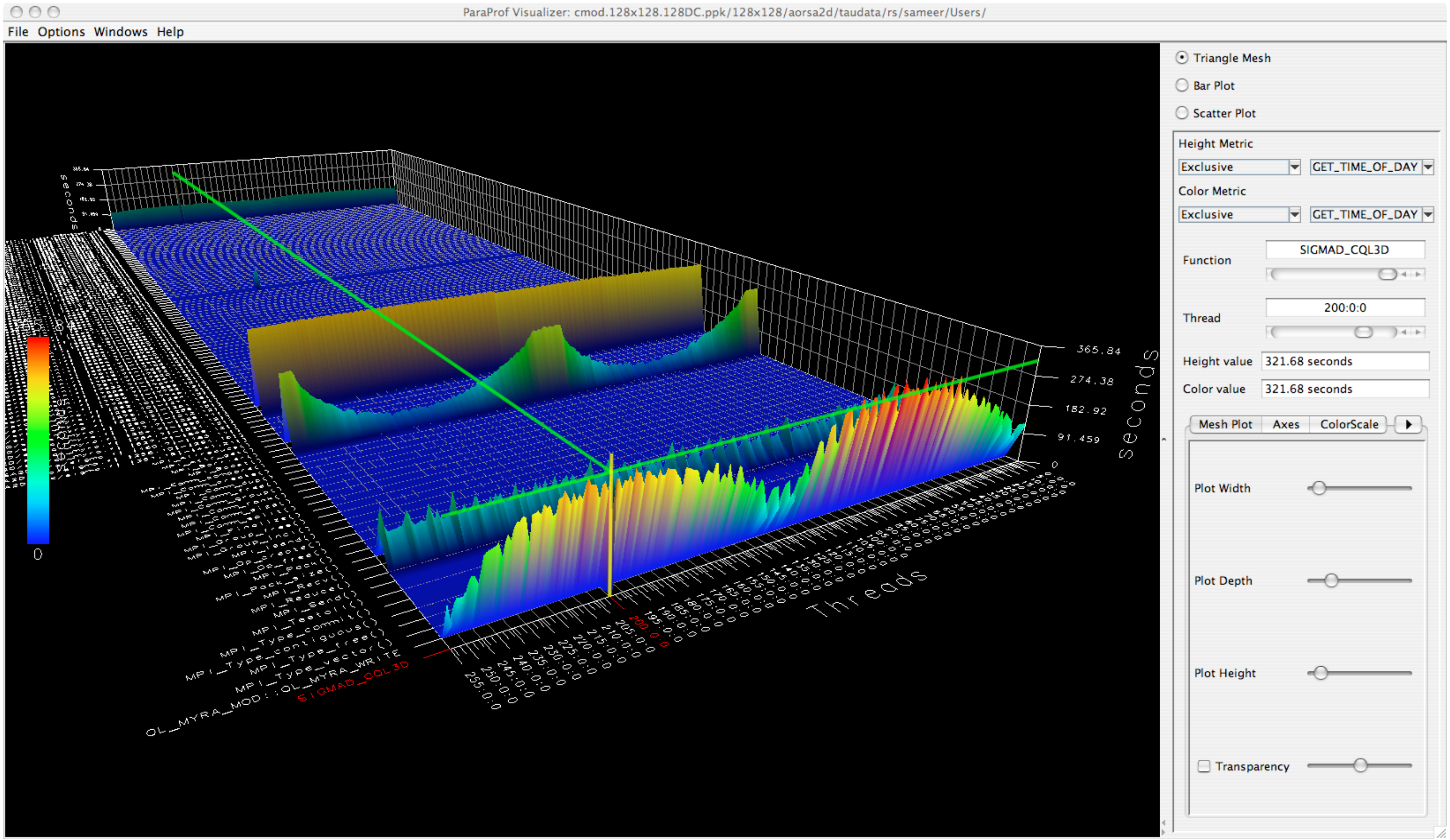
- Uninstrumented code:
  - % mpirun –np 8 ./a.out
- With TAU:
  - % mpirun –np 8 tau_exec ./a.out
  - % paraprof

ParaProf: Mflops Sorted by Exclusive Time



low mflops in loops?

Parallel Profile Visualization: ParaProf



How does TAU work?

- **Instrumentation**: Adds 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 wallclock time or hardware counters
  - 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 (Scalasca, VampirTrace, Score-P, PAPI)
- **Analysis**: Visualization of profiles and traces
  - 3D visualization of profile data in paraprof, perfexplorer tools
  - Trace conversion & display in external visualizers (Vampir, Jumpshot, ParaVer)

Using TAU: A Brief Introduction

- TAU supports several measurement and thread options
  - Phase profiling, profiling with hardware counters, trace with Score-P…
- Each measurement configuration of TAU corresponds to a unique stub makefile and library that is generated when you configure it
- To instrument source code automatically using PDT
  - Choose an appropriate TAU stub makefile in <arch>/lib:

  % export TAU_MAKEFILE=$TAU/Makefile.tau-mpi-pdt

  % export TAU_OPTIONS='-optVerbose …' (see tau_compiler.sh)

  Use tau_f90.sh, tau_cxx.sh or tau_cc.sh as F90, C++ or C compilers:

  % mpif90 foo.f90 **changes to**

  % tau_f90.sh foo.f90
- Set runtime environment variables, execute application and analyze performance data:

  % pprof (for text based profile display)

  % paraprof (for GUI)

Choosing an Appropriate TAU_MAKEFILE

```
% cd $TAUROOTDIR/<arch>/lib; ls Makefile.*
Makefile.tau-pdt
Makefile.tau-mpi-pdt
Makefile.tau-pthread-pdt
Makefile.tau-papi-mpi-pdt
Makefile.tau-mpi-pthread-pdt
Makefile.tau-papi-pthread-pdt
Makefile.tau-opari-openmp-mpi-pdt
Makefile.tau-papi-mpi-pdt-epilog-scalasca-trace
Makefile.tau-papi-mpi-pdt-vampirtrace-trace …
```

- For an MPI+F90 application, you may choose **Makefile.tau-mpi-pdt**
  - Supports MPI instrumentation & PDT for automatic source instrumentation
  - `% export TAU_MAKEFILE=$TAU/Makefile.tau-mpi-pdt`
  - `% tau_f90.sh matrix.f90 -o matrix`
  - `% mpirun -np 8 ./matrix`
  - `% paraprof`

TAU Instrumentation Approach

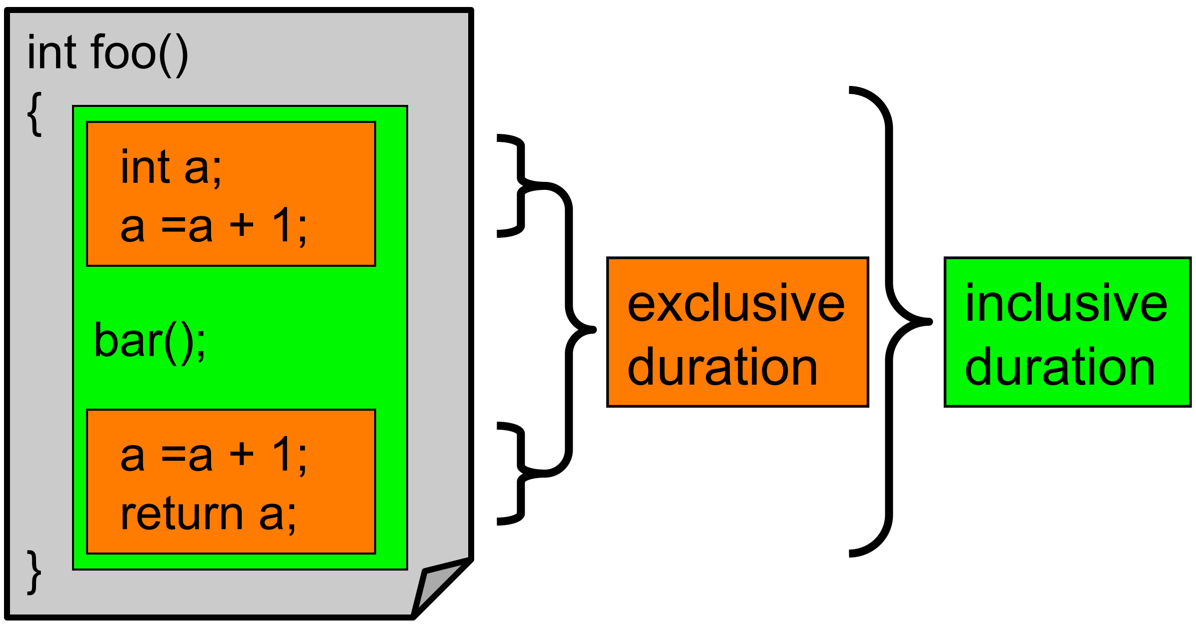
- Supports both direct and indirect performance observation
  - Direct instrumentation of program (system) code (probes)
  - Instrumentation invokes performance measurement
  - Event measurement: performance data, meta-data, context
  - Indirect mode supports sampling based on periodic timer or hardware performance counter overflow based interrupts
- Support for user-defined events
  - ***Interval*** (Start/Stop) events to measure exclusive & inclusive duration
  - ***Atomic events*** (Trigger at a single point with data, e.g., heap memory)
    - 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

- Event types
  - Interval events (begin/end events)
    - Measures exclusive & inclusive durations between events
    - Metrics monotonically increase
  - Atomic events (trigger with data value)
    - Used to capture performance data state
    - Shows extent of variation of triggered values (min/max/mean)
- Code events
  - Routines, classes, templates
  - Statement-level blocks, loops

Inclusive and Exclusive Profiles

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



Interval Events, Atomic Events in TAU

```
NODE 0;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                          usec/call
---------------------------------------------------------------------------------------
100.0        0.187        1,105           1          44    1105659 int main(int, char **) C
 93.2        1,030        1,030           1           0    1030654 MPI_Init()
  5.9        0.879           65          40         320       1637 void func(int, int) C
  4.6           51           51          40           0       1277 MPI_Barrier()
  1.2           13           13         120           0        111 MPI_Recv()
  0.8            9            9           1           0       9328 MPI_Finalize()
  0.0        0.137        0.137         120           0          1 MPI_Send()
  0.0        0.086        0.086          40           0          2 MPI_Bcast()
  0.0        0.002        0.002           1           0          2 MPI_Comm_size()
  0.0        0.001        0.001           1           0          1 MPI_Comm_rank()
---------------------------------------------------------------------------------------

USER EVENTS Profile :NODE 0, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------------
       365  5.138E+04      44.39   3.09E+04  1.234E+04  Heap Memory Used (KB) : Entry
       365  5.138E+04       2064  3.115E+04   1.21E+04  Heap Memory Used (KB) : Exit
        40         40         40         40          0  Message size for broadcast
---------------------------------------------------------------------------------------
                                                                 27,1          1%
```

Interval events e.g., routines (start/stop) show ***duration***

Atomic events (triggered with value) show ***extent of variation*** (min/max/mean)

% export TAU_CALLPATH_DEPTH=0
% export TAU_TRACK_HEAP=1

Atomic Events, Context Events

```
xterm
---------------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                          usec/call
---------------------------------------------------------------------------------------
100.0        0.253        1,106           1          44    1106701 int main(int, char **) C
 93.2        1,031        1,031           1           0    1031311 MPI_Init()
  6.0            1           66          40         320       1650 void func(int, int) C
  5.7           63           63          40           0       1588 MPI_Barrier()
  0.8            9            9           1           0       9119 MPI_Finalize()
  0.1            1            1         120           0         10 MPI_Recv()
  0.0        0.141        0.141         120           0          1 MPI_Send()
  0.0        0.085        0.085          40           0          2 MPI_Bcast()
  0.0        0.001        0.001           1           0          1 MPI_Comm_size()
  0.0            0            0           1           0          0 MPI_Comm_rank()
---------------------------------------------------------------------------------------

USER EVENTS Profile :NODE 0, CONTEXT 0, THREAD 0
---------------------------------------------------------------------------------------
NumSamples   MaxValue   MinValue  MeanValue  Std. Dev.  Event Name
---------------------------------------------------------------------------------------
        40         40         40         40          0  Message size for broadcast
       365  5.139E+04      44.39  3.091E+04  1.234E+04  Heap Memory Used (KB) : Entry
        40  5.139E+04       3097  3.114E+04  1.227E+04  Heap Memory Used (KB) : Entry : MPI_Barrier()
        40  5.139E+04   1.13E+04  3.134E+04  1.187E+04  Heap Memory Used (KB) : Entry : MPI_Bcast()
         1       2067       2067       2067          0  Heap Memory Used (KB) : Entry : MPI_Comm_rank()
         1       2066       2066       2066          0  Heap Memory Used (KB) : Entry : MPI_Comm_size()
         1  5.139E+04  5.139E+04  5.139E+04  0.0006905  Heap Memory Used (KB) : Entry : MPI_Finalize()
         1      57.56      57.56      57.56          0  Heap Memory Used (KB) : Entry : MPI_Init()
       120  5.139E+04   1.13E+04  3.134E+04  1.187E+04  Heap Memory Used (KB) : Entry : MPI_Recv()
       120  5.139E+04  1.129E+04  3.134E+04  1.187E+04  Heap Memory Used (KB) : Entry : MPI_Send()
         1      44.39      44.39      44.39          0  Heap Memory Used (KB) : Entry : int main(int, char **) C
        40  5.036E+04       2068  3.011E+04  1.227E+04  Heap Memory Used (KB) : Entry : void func(int, int) C
                                                                            4,9           1%
```

Atomic events

Context events =atomic event + executing context

% export TAU_CALLPATH_DEPTH=1

Controls depth of executing context shown in profiles

% export TAU_TRACK_HEAP=1

Context Events (Default)

VI-HPS

xterm

NODE 0;CONTEXT 0;THREAD 0:

%Time	Exclusive msec	Inclusive total msec	#Call	#Subrs	Inclusive usec/call	Name
100.0	0.357	1,114	1	44	1114040	int main(int, char **) C
92.6	1,031	1,031	1	0	1031066	MPI_Init()
6.7	72	74	40	320	1865	void func(int, int) C
0.7	8	8	1	0	8002	MPI_Finalize()
0.1	1	1	120	0	12	MPI_Recv()
0.1	0.608	0.608	40	0	15	MPI_Barrier()
0.0	0.136	0.136	120	0	1	MPI_Send()
0.0	0.095	0.095	40	0	2	MPI_Bcast()
0.0	0.001	0.001	1	0	1	MPI_Comm_size()
0.0	0	0	1	0	0	MPI_Comm_rank()

USER EVENTS Profile :NODE 0, CONTEXT 0, THREAD 0

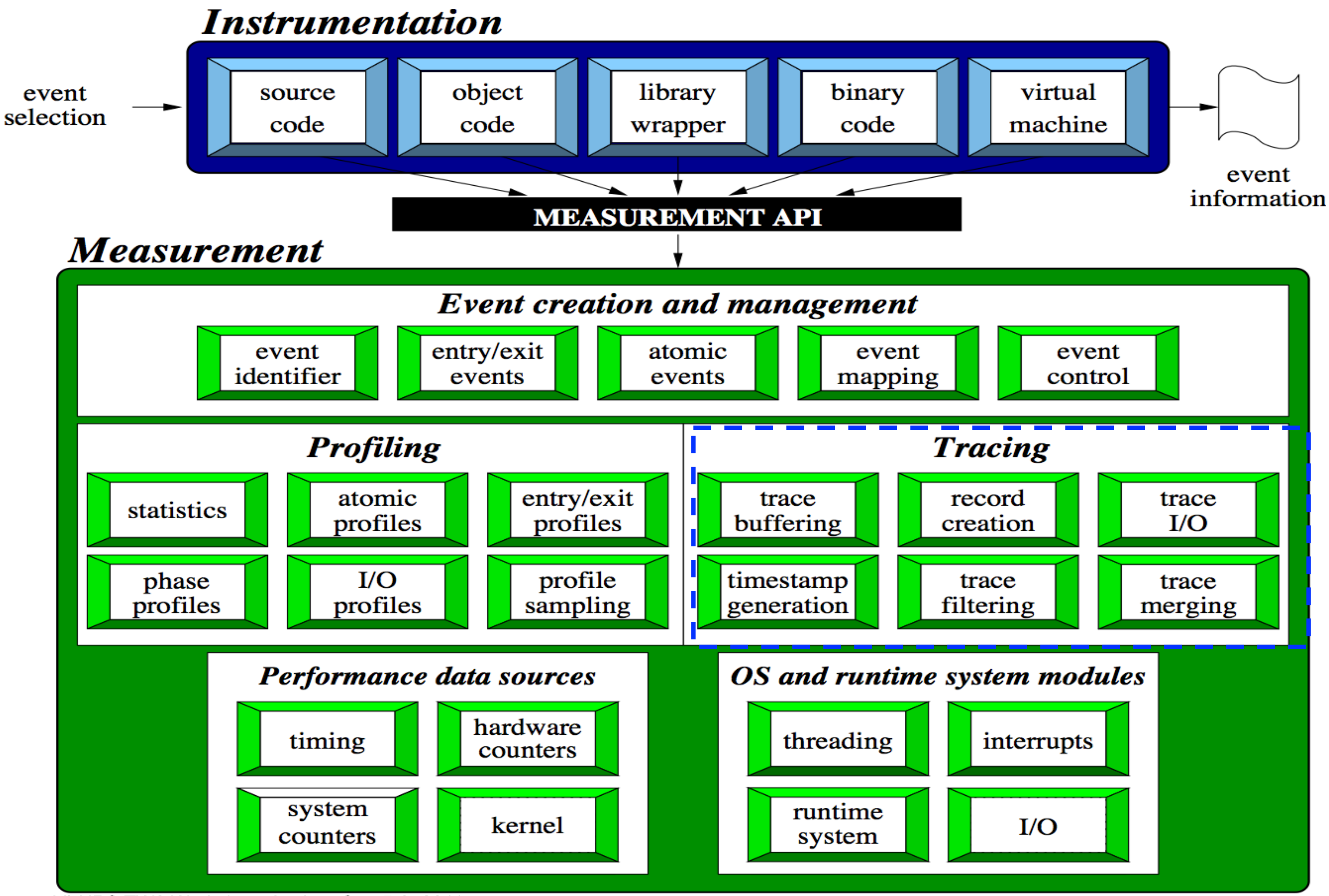
NumSamples	MaxValue	MinValue	MeanValue	Std. Dev.	Event Name
365	5.139E+04	44.39	3.091E+04	1.234E+04	Heap Memory Used (KB) : Entry
1	44.39	44.39	44.39	0	Heap Memory Used (KB) : Entry : int main(int, char **) C
1	2068	2068	2068	0	Heap Memory Used (KB) : Entry : int main(int, char **) C => MPI_Comm_rank()
1	2066	2066	2066	0	Heap Memory Used (KB) : Entry : int main(int, char **) C => MPI_Comm_size()
1	5.139E+04	5.139E+04	5.139E+04	0	Heap Memory Used (KB) : Entry : int main(int, char **) C => MPI_Finalize()
1	57.58	57.58	57.58	0	Heap Memory Used (KB) : Entry : int main(int, char **) C => MPI_Init()
40	5.036E+04	2069	3.011E+04	1.228E+04	Heap Memory Used (KB) : Entry : int main(int, char **) C => void func(int, int) C
40	5.139E+04	3098	3.114E+04	1.227E+04	Heap Memory Used (KB) : Entry : void func(int, int) C => MPI_Barrier()
40	5.139E+04	1.13E+04	3.134E+04	1.187E+04	Heap Memory Used (KB) : Entry : void func(int, int) C => MPI_Bcast()
120	5.139E+04	1.13E+04	3.134E+04	1.187E+04	Heap Memory Used (KB) : Entry : void func(int, int) C => MPI_Recv()
120	5.139E+04	1.13E+04	3.134E+04	1.187E+04	Heap Memory Used (KB) : Entry : void func(int, int) C => MPI_Send()
365	5.139E+04	2065	3.116E+04	1.21E+04	Heap Memory Used (KB) : Exit

3,7 1%

Context event =atomic event + executing context

```
% export TAU_CALLPATH_DEPTH=2
% export TAU_TRACK_HEAP=1
```

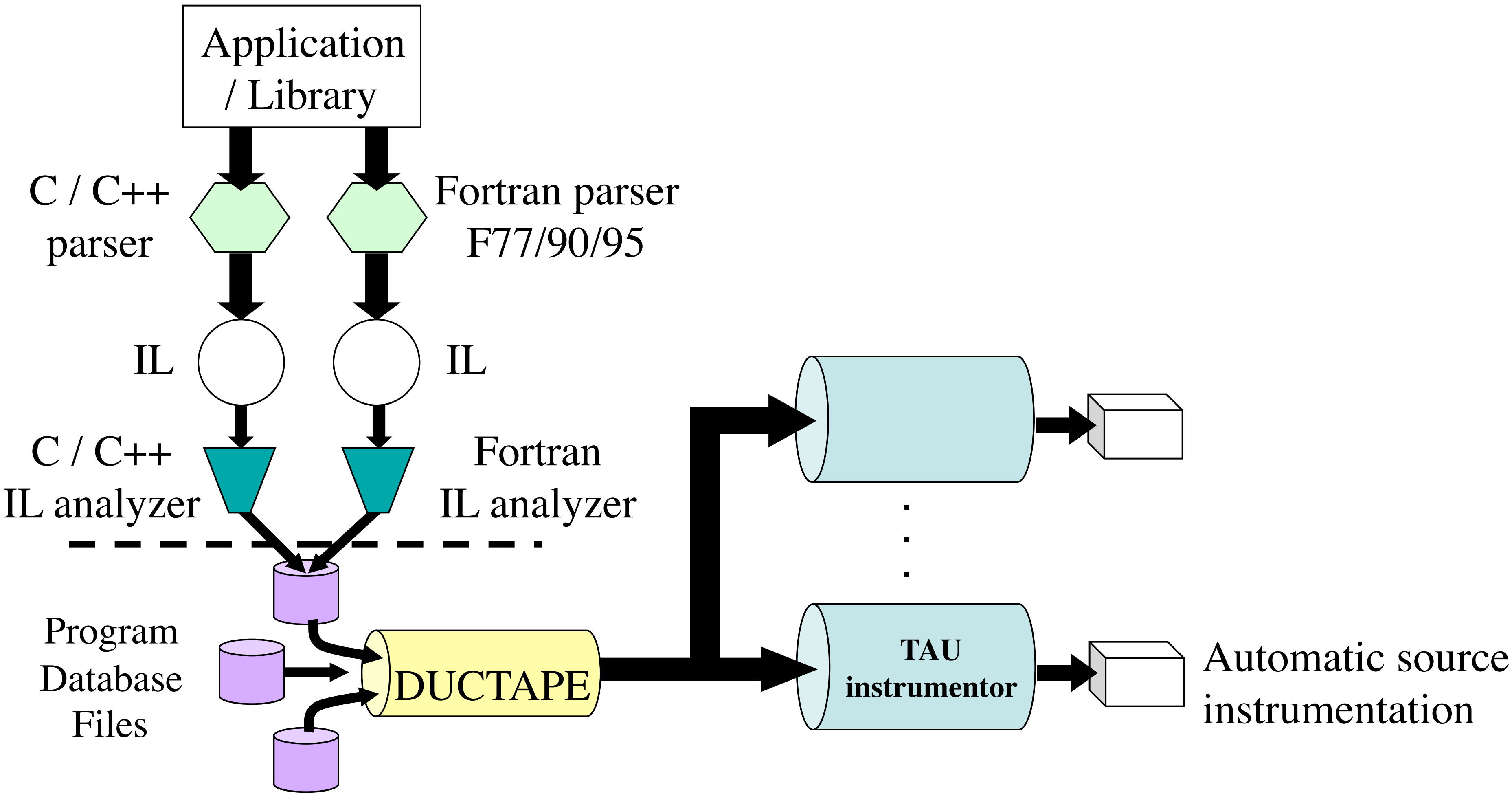
TAU Instrumentation / Measurement



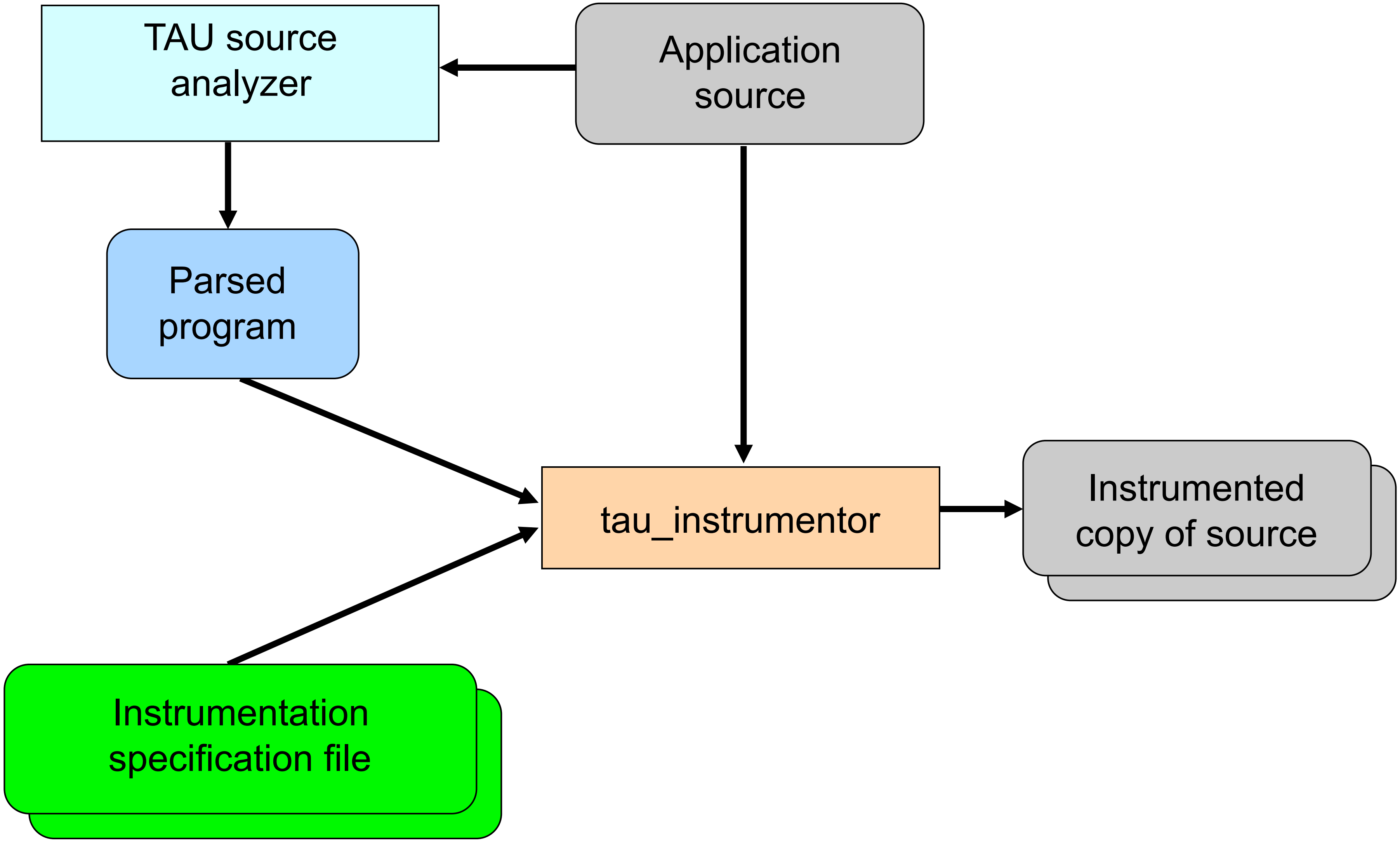
Direct Instrumentation Options in TAU

- Source Code Instrumentation
  - Manual instrumentation
  - Automatic instrumentation using pre-processor based on static analysis of source code (PDT), creating an instrumented copy
  - Compiler generates instrumented object code
- Library Level Instrumentation
  - Wrapper libraries for standard MPI libraries using PMPI interface
  - 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's Static Analysis System: Program Database Toolkit (PDT)



Automatic Source Instrumentation using PDT



PDT: Automatic Source Code Instrumentation

- To instrument source code using PDT
  - Choose an appropriate TAU stub makefile from <taudir>/<arch>/lib/Makefile.tau*:
    (typically, *arch*=i386_linux, x86_64, craycnl, bgp, cygwin … and *taudir*=/usr/local/packages/tau on LiveDVD)

  % export TAU_MAKEFILE=$TAU/Makefile.tau-mpi-pdt

  % make CC=tau_cc.sh CXX=tau_cxx.sh F90=tau_f90.sh

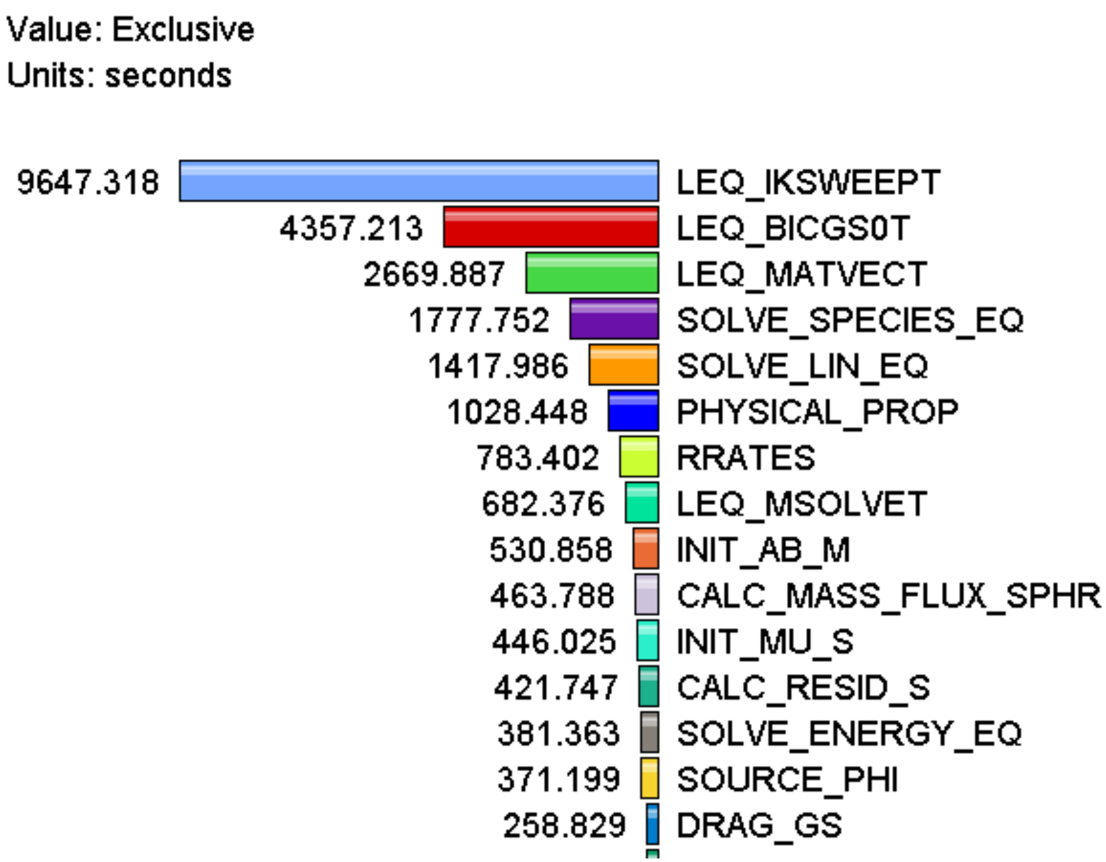
- Execute application and analyze performance data:

  % pprof   (for text based profile display)

  % paraprof (for GUI)

Usage Scenarios: Routine Level Profile

- How much time is spent in each application routine?



Solution: Generating a flat profile with MPI

```
% export TAU_MAKEFILE=<taudir>/<arch>/lib/Makefile.tau-mpi-pdt
% export PATH=<taudir>/<arch>/bin:$PATH
Or
% module load tau
% make F90=tau_f90.sh
Or
% tau_f90.sh matmult.f90
% mpirun –np 8 ./a.out
% paraprof
To view. To view the data locally on the workstation,
% paraprof --pack app.ppk
  Move the app.ppk file to your desktop.

% paraprof app.ppk

Click on the “node 0” label to see profile for that node. Right
click to see other options. Windows -> 3D Visualization for 3D
window.
```

Automatic Instrumentation

- We now provide compiler wrapper scripts
  - Simply replace `CC` with `tau_cxx.sh`
  - Automatically instruments C++ and C source code, links with TAU MPI Wrapper libraries.
- Use `tau_cc.sh` and `tau_f90.sh` for C and Fortran

Before

```
CXX = mpicxx
F90 = mpif90
CXXFLAGS =
LIBS = -lm
OBJS = f1.o f2.o f3.o … fn.o

app: $(OBJS)
      $(CXX) $(LDFLAGS) $(OBJS) -o $@
      $(LIBS)
.cpp.o:
      $(CXX) $(CXXFLAGS) -c $<
```

After

```
CXX = tau_cxx.sh
F90 = tau_f90.sh
CXXFLAGS =
LIBS = -lm
OBJS = f1.o f2.o f3.o … fn.o

app: $(OBJS)
      $(CXX) $(LDFLAGS) $(OBJS) -o $@
      $(LIBS)
.cpp.o:
      $(CXX) $(CXXFLAGS) -c $<
```

Passing Optional Parameters to TAU Compiler Scripts

- See `<taudir>/<arch>/bin/tau_compiler.sh –help`
- Compilation:

  ```
  % ftn -c foo.f90
  ```

  Changes to

  ```
  % gfparse foo.f90 $(OPT1)
  % tau_instrumentor foo.pdb foo.f90 –o foo.inst.f90 $(OPT2)
  % ftn –c foo.inst.f90 –o foo.o $(OPT3)
  ```

- Linking:

  ```
  % ftn foo.o bar.o –o app
  ```

  Changes to

  ```
  % ftn foo.o bar.o –o app <taulibs> $(OPT4)
  ```

- Where options OPT[1-4] default values may be overridden by the user:

  ```
  F90 = tau_f90.sh
  ```

Compile-Time Environment Variables

- Optional parameters for the TAU_OPTIONS environment variable:
  % tau_compiler.sh

-optVerbose	Turn on verbose debugging messages
-optCompInst	Use compiler based instrumentation
-optNoCompInst	Do not revert to compiler instrumentation if source instrumentation fails.
-optTrackIO	Wrap POSIX I/O call and calculates vol/bw of I/O operations (Requires TAU to be configured with *–iowrapper*)
-optKeepFiles	Does not remove intermediate .pdb and .inst.* files
-optPreProcess	Preprocess Fortran sources before instrumentation
-optTauSelectFile="<file>"	Specify selective instrumentation file for *tau_instrumentor*
-optTauWrapFile="<file>"	Specify path to *link_options.tau* generated by *tau_gen_wrapper*
-optHeaderInst	Enable Instrumentation of headers
-optLinking=""	Options passed to the linker. Typically $(TAU_MPI_FLIBS) $(TAU_LIBS) $(TAU_CXXLIBS)
-optCompile=""	Options passed to the compiler. Typically $(TAU_MPI_INCLUDE) $(TAU_INCLUDE) $(TAU_DEFS)
-optPdtF95Opts=""	Add options for Fortran parser in PDT (f95parse/gfparse)
-optPdtF95Reset=""	Reset options for Fortran parser in PDT (f95parse/gfparse)
-optPdtCOpts=""	Options for C parser in PDT (cparse). Typically $(TAU_MPI_INCLUDE) $(TAU_INCLUDE) $(TAU_DEFS)
-optPdtCxxOpts=""	Options for C++ parser in PDT (cxxparse). Typically $(TAU_MPI_INCLUDE) $(TAU_INCLUDE) $(TAU_DEFS) ...

Compiling Fortran Codes with TAU

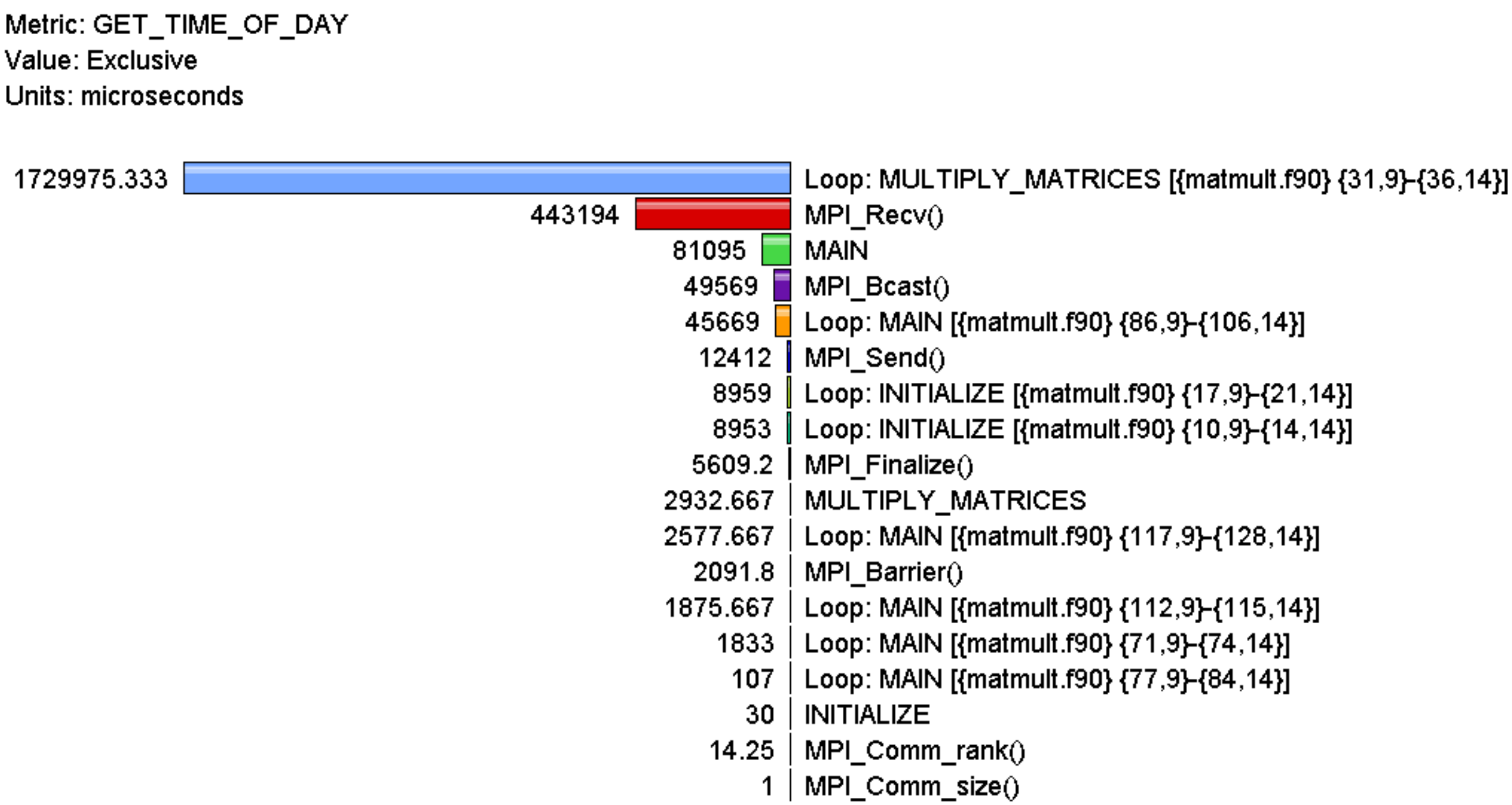
- If your Fortran code uses free format in .f files (fixed is default for .f), you may use:
  % export TAU_OPTIONS='-optPdtF95Opts="-R free" -optVerbose '
- To use the compiler based instrumentation instead of PDT (source-based):
  % export TAU_OPTIONS='-optCompInst -optVerbose'
- If your Fortran code uses C preprocessor directives (#include, #ifdef, #endif):
  % export TAU_OPTIONS='-optPreProcess -optVerbose -optDetectMemoryLeaks'
- To use an instrumentation specification file:
  % export TAU_OPTIONS='-optTauSelectFile=select.tau -optVerbose -optPreProcess'
  % cat select.tau
  BEGIN_INSTRUMENT_SECTION
  loops routine="#"
  # this statement instruments all outer loops in all routines. # is wildcard as well as comment in first column.
  END_INSTRUMENT_SECTION

Runtime Environment Variables in 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_LEAKS	0	Setting to 1 turns on leak detection (for use with tau_exec –memory ./a.out)
TAU_TRACK_HEAP or TAU_TRACK_HEADROOM	0	Setting to 1 turns on tracking heap memory/headroom at routine entry & exit using context events (e.g., Heap at Entry: main=>foo=>bar)
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_TRACK_IO_PARAMS	0	Setting to 1 with –optTrackIO or tau_exec –io captures arguments of I/O calls
TAU_SAMPLING	1	Generates sample based profiles
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:P_VIRTUAL_TIME:PAPI_FP_INS:PAPI_NATIVE_<event>\\:<subevent>)

Usage Scenarios: Loop Level Instrumentation

- Goal: What loops account for the most time? How much?
- Flat profile with wallclock time with loop instrumentation:

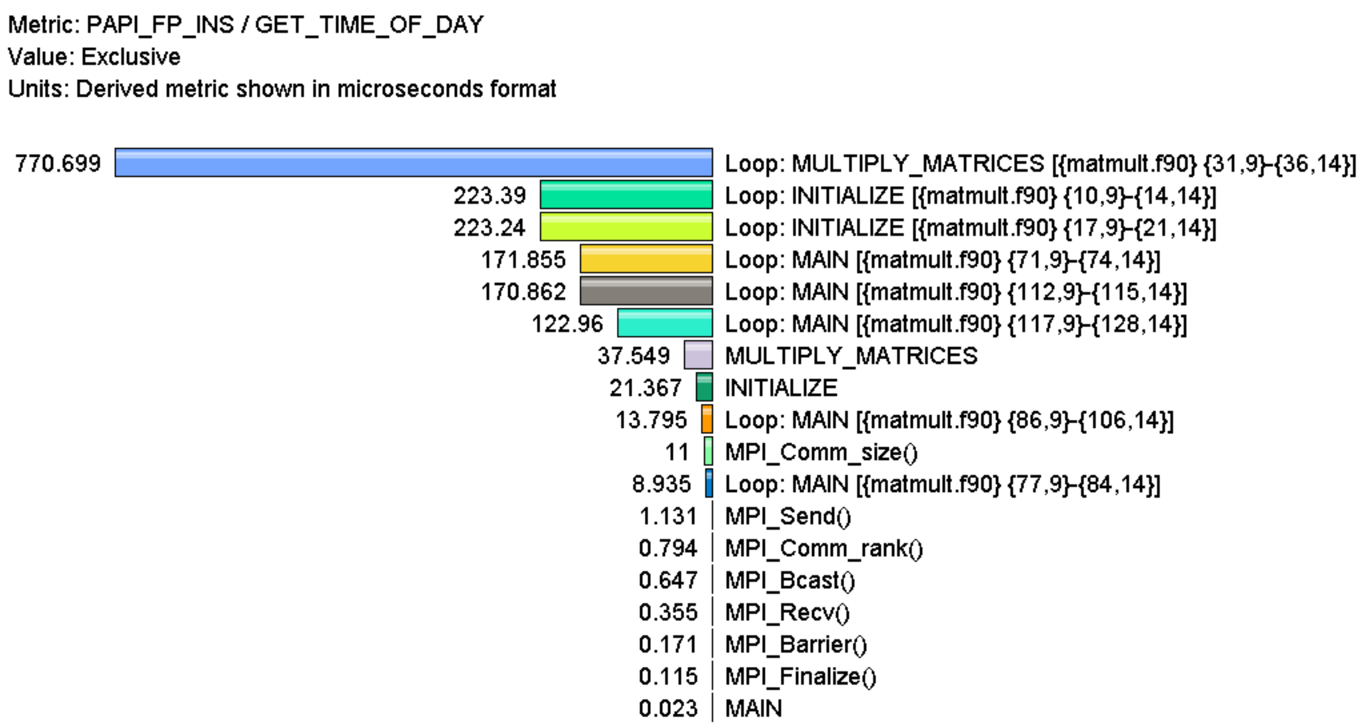


Solution: Generating a loop level profile

```
% export TAU_MAKEFILE=<taudir>/<arch>/lib/Makefile.tau-mpi-pdt
% export TAU_OPTIONS='-optTauSelectFile=select.tau -optVerbose'
% cat select.tau
  BEGIN_INSTRUMENT_SECTION
  loops routine="#"
  END_INSTRUMENT_SECTION

% module load tau
% make F90=tau_f90.sh
(Or edit Makefile and change F90=tau_f90.sh)
% mpirun -np 8 ./a.out
% paraprof --pack app.ppk
  Move the app.ppk file to your desktop.

% paraprof app.ppk
```

Computing Floating Point Instructions Executed Per Second in Loops

- Goal: What execution rate do my application loops get in mflops?
- Flat profile with PAPI_FP_INS and time with loop instrumentation:

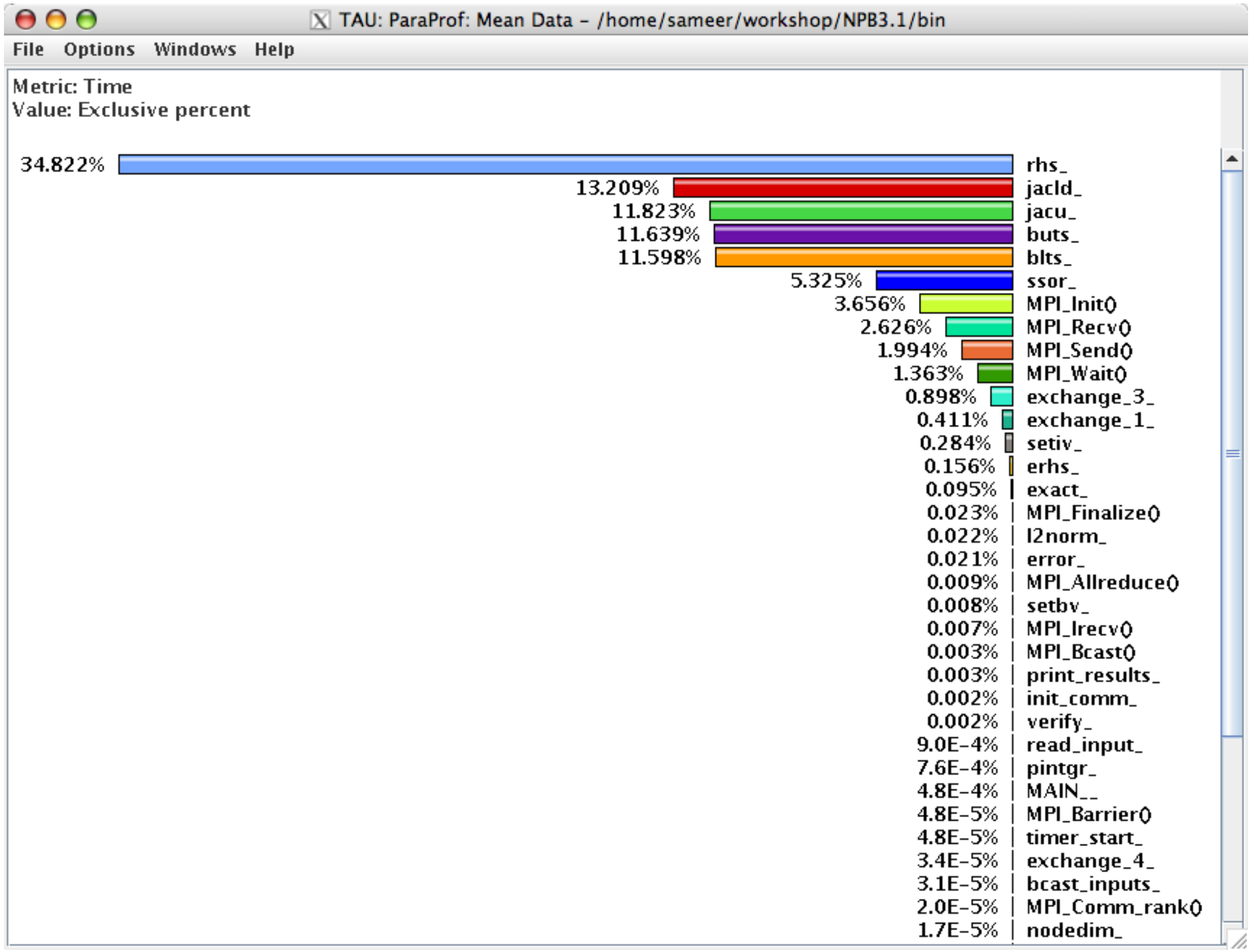


Generate a PAPI profile with 2 or more counters

```
% export TAU_MAKEFILE=<taudir>/<arch>/lib/Makefile.tau-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
(Or edit Makefile and change F90=tau_f90.sh)
% export TAU_METRICS=TIME:PAPI_FP_INS
% mpirun –np 8 ./a.out
% 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.
```

Usage Scenarios: Compiler-based Instrumentation

- Use the compiler to automatically emit instrumentation calls in the object code instead of parsing the source code using PDT.



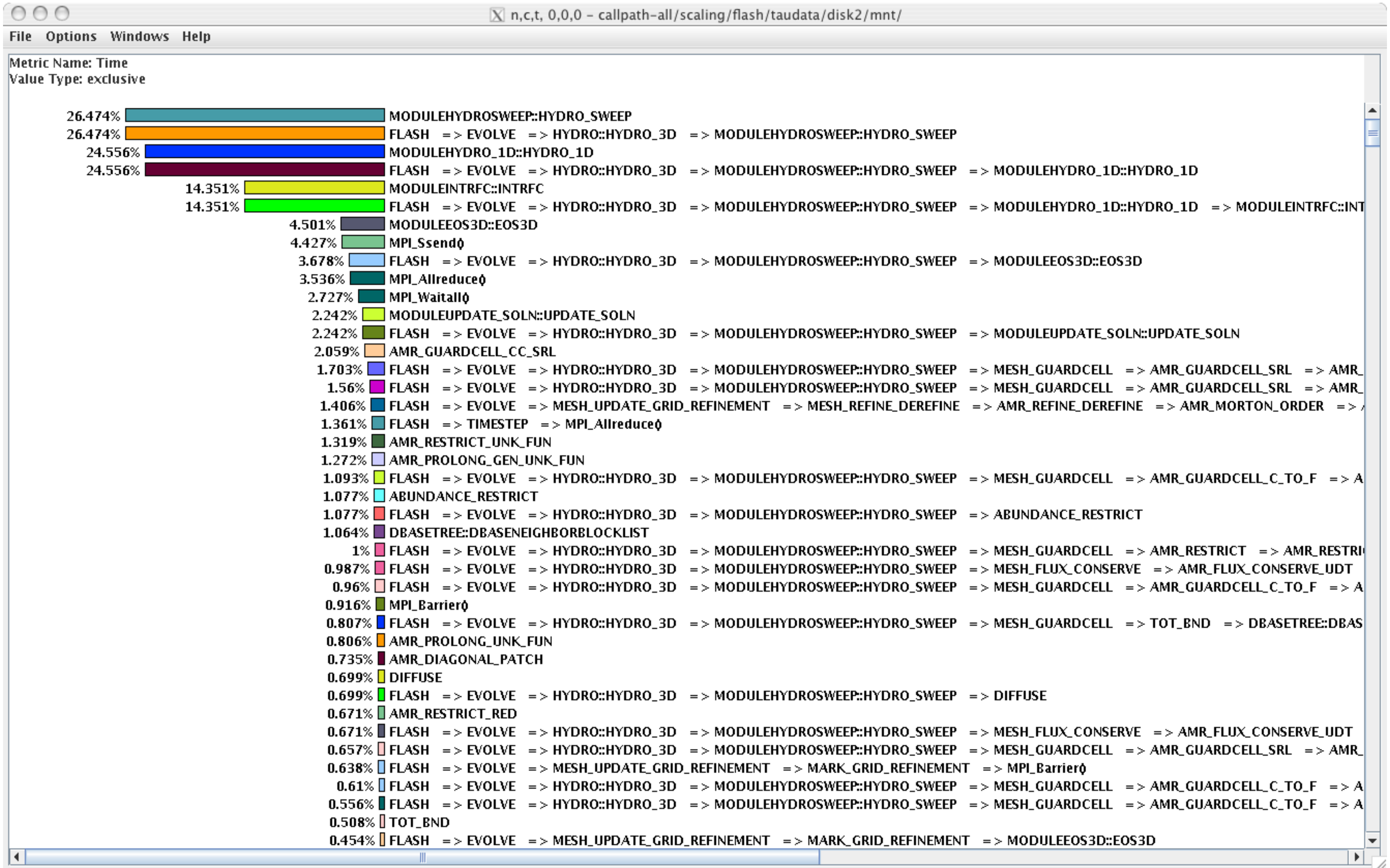
Use Compiler-Based Instrumentation

```
% export TAU_MAKEFILE=<taudir>/<arch>/lib/Makefile.tau-mpi-pdt
% export TAU_OPTIONS='-optCompInst -optQuiet'

% make CC=tau_cc.sh CXX=tau_cxx.sh F90=tau_f90.sh
```

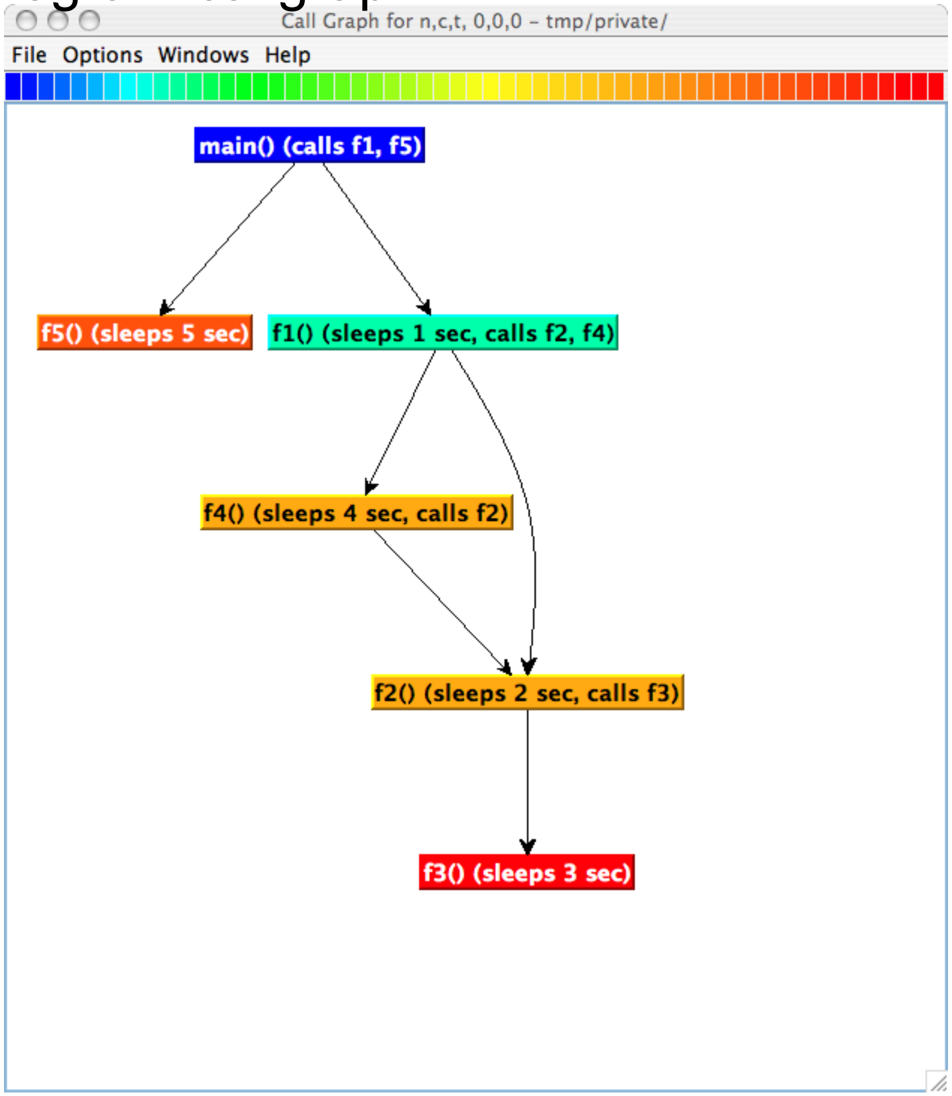
NOTE: You may also use the short-hand scripts taucc, tauf90, taucxx instead of specifying TAU_OPTIONS and using the traditional tau_<cc,cxx,f90>.sh scripts. These scripts use compiler-based instrumentation by default.

```
% make CC=taucc CXX=taucxx F90=tauf90
% mpirun -np 8 ./a.out
% paraprof --pack app.ppk
  Move the app.ppk file to your desktop.
% paraprof app.ppk
```

Generate a Callpath Profile



- Generates program callgraph

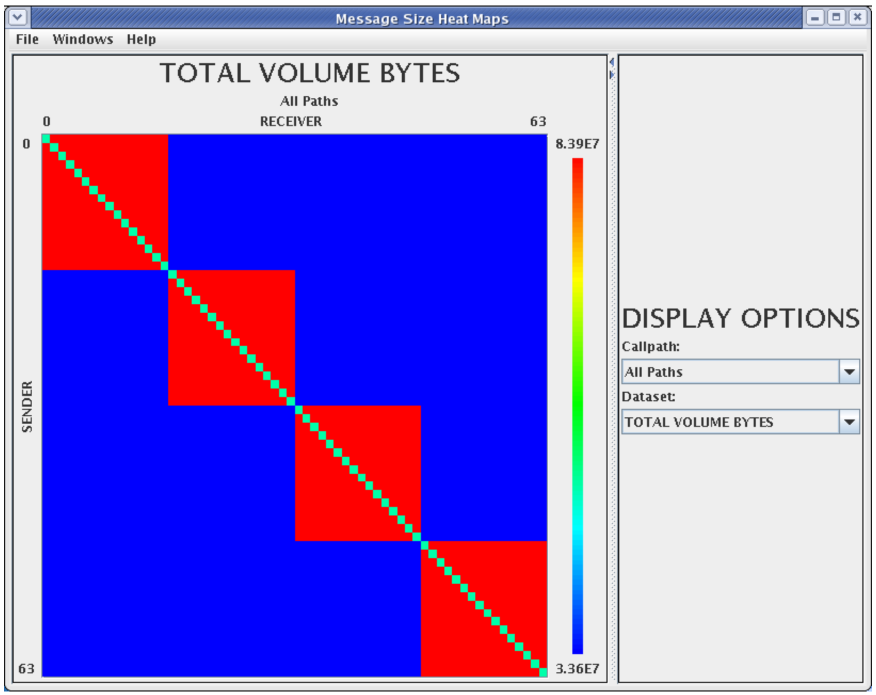


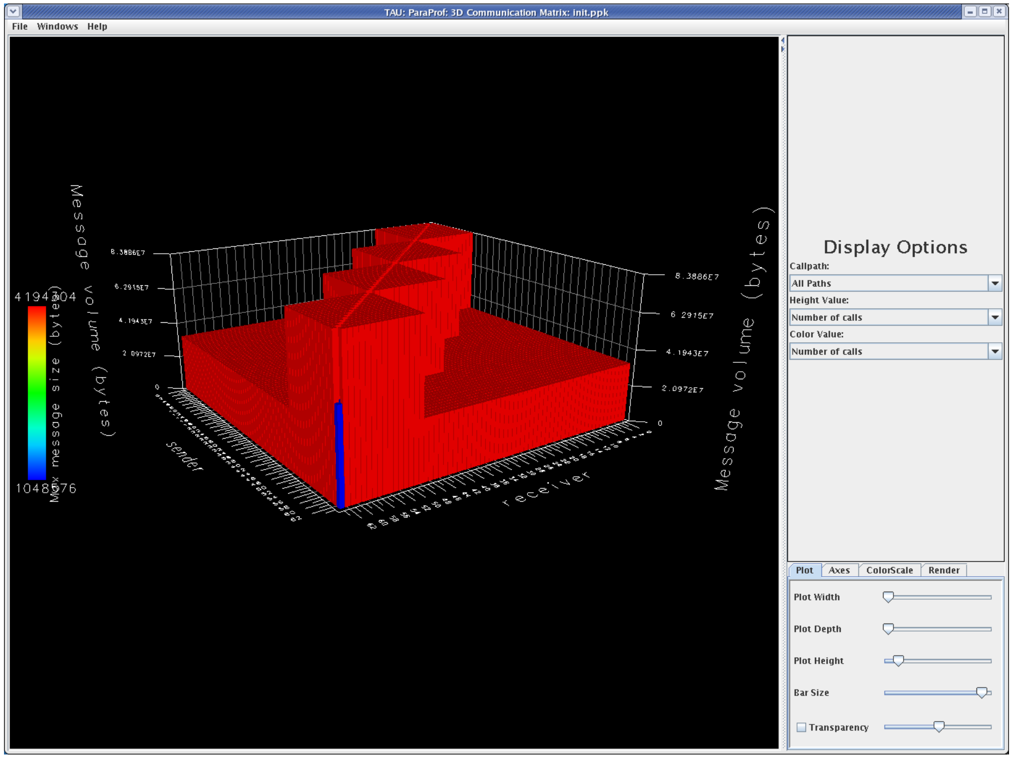
Generate a Callpath Profile

```
% export TAU_MAKEFILE=<taudir>/<arch>/lib/Makefile.tau-mpi-pdt
% export PATH=<taudir>/<arch>/bin:$PATH
% make F90=tau_f90.sh
(Or edit Makefile and change F90=tau_f90.sh)

% export TAU_CALLPATH=1
% export TAU_CALLPATH_DEPTH=100
(truncates all calling paths to a specified depth)


% mpirun -np 8 ./a.out
% paraprof --pack app.ppk
  Move the app.ppk file to your desktop.
% paraprof app.ppk
(Windows -> Thread -> Call Graph)
```

Communication Matrix Display

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





Evaluate Scalability using PerfExplorer Charts

```
% export TAU_MAKEFILE=$TAU/Makefile.tau-mpi-pdt
% export PATH=<taudir>/<arch>/bin:$PATH
% make F90=tau_f90.sh
(Or edit Makefile and change F90=tau_f90.sh)
% export TAU_COMM_MATRIX=1

% mpirun -np 8 ./a.out

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

Three Instrumentation Techniques for Wrapping External Libraries

- Pre-processor based substitution by re-defining a call (e.g., read)
  - Tool defined header file with same name <*unistd.h*> takes precedence
  - Header redefines a routine as a different routine using macros
  - Substitution: *read()* substituted by preprocessor as *tau_read()* at callsite
- Preloading a library at runtime
  - Library preloaded (*LD_PRELOAD* env var in Linux) in the address space of executing application intercepts calls from a given library
  - Tool's wrapper library defines *read(),* gets address of global *read()* symbol (dlsym), internally calls timing calls around call to global read
- Linker based substitution
  - Wrapper library defines *__wrap_read* which calls *__real_read* and linker is passed *-Wl,-wrap,read* to substitute all references to read from application's object code with the *__wrap_read* defined by the tool

Issues: Preprocessor based substitution

- Pre-processor based substitution by re-defining a call
  - Compiler replaces read() with tau_read() in the body of the source code
- Advantages:
  - Simple to instrument
    - Preprocessor based replacement
    - A header file redefines the calls
    - No special linker or runtime flags required
- Disadvantages
  - Only works for C & C++ for replacing calls in the body of the code.
  - Incomplete instrumentation: fails to capture calls in uninstrumented libraries (e.g., libhdf5.a)

Issues: Linker based substitution

- Linker based substitution
  – Wrapper library defines __wrap_read which calls __real_read and linker is passed -Wl,-wrap, read
- Advantages
  – Tool can intercept all references to a given call
  – Works with static as well as dynamic executables
  – No need to recompile the application source code, just re-link the application objects and libraries with the tool wrapper library
- Disadvantages
  – Wrapping an entire library can lengthen the linker command line with multiple –Wl,-wrap,<func> arguments. It is better to store these arguments in a file and pass the file to the linker
  – Approach does not work with un-instrumented binaries

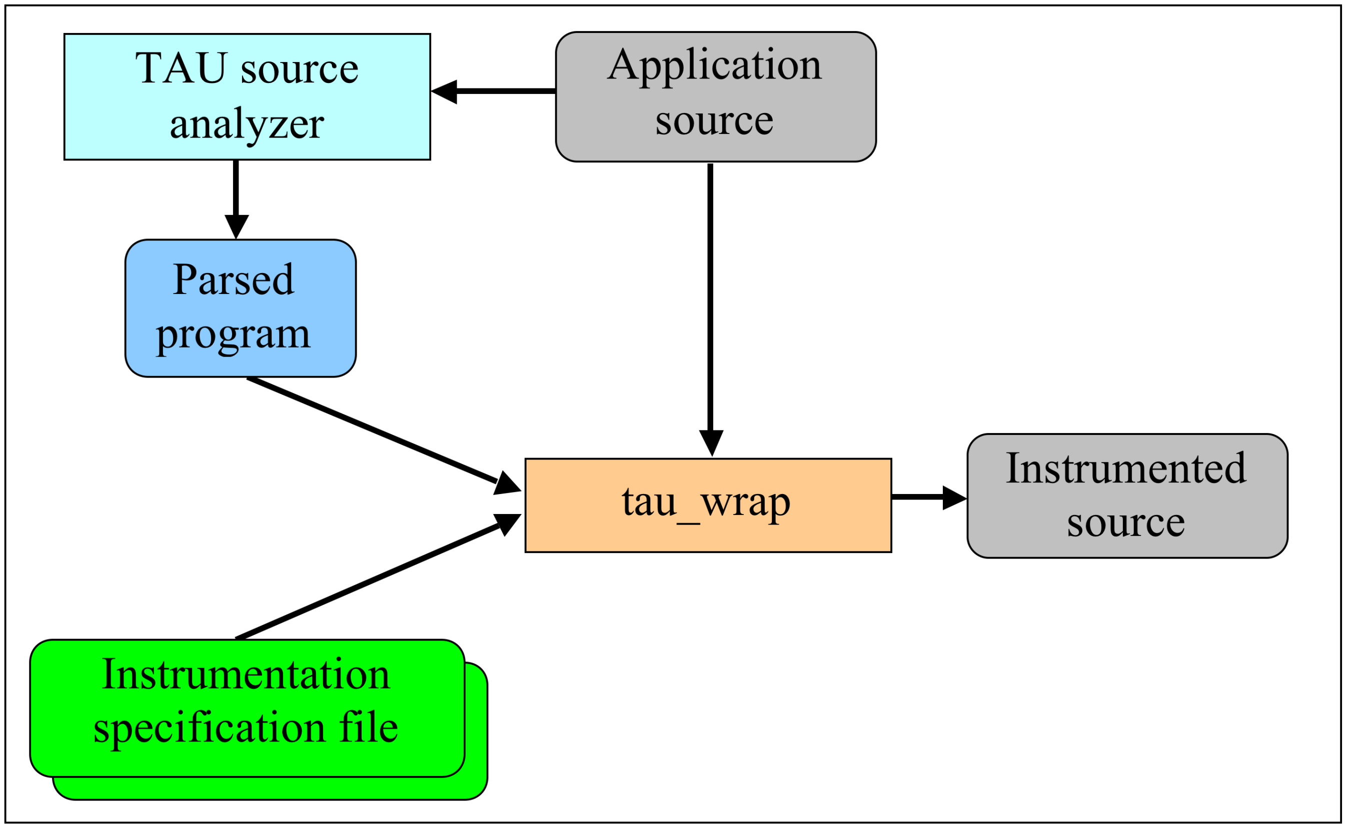
Solution: tau_gen_wrapper

- Automates creation of wrapper libraries using TAU
- Input:
  - header file (foo.h)
  - library to be wrapped (/path/to/libfoo.a)
  - technique for wrapping
    - Preprocessor based redefinition (-d)
    - Runtime preloading (-r)
    - Linker based substitution (-w: default)
  - Optional selective instrumentation file (-f select)
    - Exclude list of routines, or
    - Include list of routines
- Output:
  - wrapper library
  - optional *link_options.tau* file (-w), pass –optTauWrapFile=<file> in TAU_OPTIONS environment variable

Design of wrapper generator (tau_gen_wrapper)

- *tau_gen_wrapper* shell script:
  - parses source of header file using static analysis tool Program Database Toolkit (PDT)
  - Invokes *tau_wrap*, a tool that generates
    - instrumented wrapper code,
    - an optional *link_options.tau* file (for linker-based substitution, -w)
    - Makefile for compiling the wrapper interposition library
  - Builds the wrapper library using make
- Use TAU_OPTIONS environment variable to pass location of link_options.tau file using
  % export TAU_OPTIONS='-optTauWrapFile=<path/to/link_options.tau> -optVerbose'
- Use *tau_exec –loadlib=<wrapperlib.so>* to pass location of wrapper library for preloading based substitution

tau_wrap


TAU source analyzer
Application source
Parsed program
tau_wrap
Instrumented source
Instrumentation specification file

HDF5 Library Wrapping

```
[sameer@zorak]$ tau_gen_wrapper hdf5.h /usr/lib/libhdf5.a -f select.tau

Usage : tau_gen_wrapper <header> <library> [-r|-d|-w (default)] [-g groupname] [-i headerfile] [-c|-c++|-fortran] [-f <instr_spec_file> ]
• instruments using runtime preloading (-r), or -Wl,-wrap linker (-w), redirection of header file to redefine the wrapped routine (-d)
• instrumentation specification file (select.tau)
• group (hdf5)
• tau_exec loads libhdf5_wrap.so shared library using –loadlib=<libwrap_pkg.so>
• creates the wrapper/ directory

NODE 0;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                          usec/call
---------------------------------------------------------------------------------------
100.0        0.057            1           1          13       1236 .TAU Application
 70.8        0.875        0.875           1           0        875 hid_t H5Fcreate()
  9.7         0.12         0.12           1           0        120 herr_t H5Fclose()
  6.0        0.074        0.074           1           0         74 hid_t H5Dcreate()
  3.1        0.038        0.038           1           0         38 herr_t H5Dwrite()
  2.6        0.032        0.032           1           0         32 herr_t H5Dclose()
  2.1        0.026        0.026           1           0         26 herr_t H5check_version()
  0.6        0.008        0.008           1           0          8 hid_t H5Screate_simple()
  0.2        0.002        0.002           1           0          2 herr_t H5Tset_order()
  0.2        0.002        0.002           1           0          2 hid_t H5Tcopy()
  0.1        0.001        0.001           1           0          1 herr_t H5Sclose()
  0.1        0.001        0.001           2           0          0 herr_t H5open()
  0.0            0            0           1           0          0 herr_t H5Tclose()
```

Using POSIX I/O wrapper library in TAU

- Setting environment variable TAU_OPTIONS=-optTrackIO links in TAU's wrapper interposition library using linker-based substitution
- Instrumented application generates bandwidth, volume data
- Workflow:
  - % export TAU_OPTIONS='-optTrackIO –optVerbose'
  - % export TAU_MAKEFILE=/path/to/tau/x86_64/lib/Makefile.tau-mpi-pdt
  - % make CC=tau_cc.sh CXX=tau_cxx.sh F90=tau_f90.sh
  - % mpirun –np 8 ./a.out
  - % paraprof
- Get additional data regarding individual arguments by setting environment variable TAU_TRACK_IO_PARAMS=1 prior to running

Issues: Preloading a wrapper library at runtime

VI-HPS

- Preloading a library at runtime
  - Tool defines read(), gets address of global read() symbol (dlsym), internally calls timing calls around call to global read
  - *tau_exec* tool uses this mechanism to intercept library calls
- Advantages
  - No need to re-compile or re-link the application source code
  - Drop-in replacement library implemented using LD_PRELOAD environment variable under Linux, Cray CNL, IBM BG/P CNK, Solaris…
- Disadvantages
  - Only works with dynamic executables. Default compilation mode under Cray XE6 and IBM BG/P is to use static executables
  - Not all operating systems support preloading of dynamic shared objects (DSOs)

Runtime Preloading: tau_exec

- Runtime instrumentation by pre-loading the measurement library
- Works on dynamic executables (default under Linux)
- Can substitute I/O, MPI, SHMEM, CUDA, OpenCL, and memory allocation/deallocation routines with instrumented calls
- Track interval events (e.g., time spent in write()) as well as atomic events (e.g., how much memory was allocated) in wrappers
- Accurately measure I/O and memory usage
- Preload any wrapper interposition library in the context of the executing application

Preloading a Specific TAU Measurement Library

```
% ./configure -pdt=<dir> -mpi -papi=<dir>; make install
```

Creates in <taudir>/<arch>/lib:

```
Makefile.tau-papi-mpi-pdt
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 8 ./a.out      to
% mpirun -np 8 tau_exec -T <comma_separated_options> ./a.out
```

```
% mpirun -np 8 tau_exec -T papi,mpi,pdt ./a.out
```

Preloads `<taudir>/<arch>/shared-papi-mpi-pdt/libTAU.so`

```
% mpirun -np 8 tau_exec -T papi ./a.out
```

Preloads `<taudir>/<arch>/shared-papi-mpi-pdt/libTAU.so by matching.`

```
% mpirun -np 8 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.

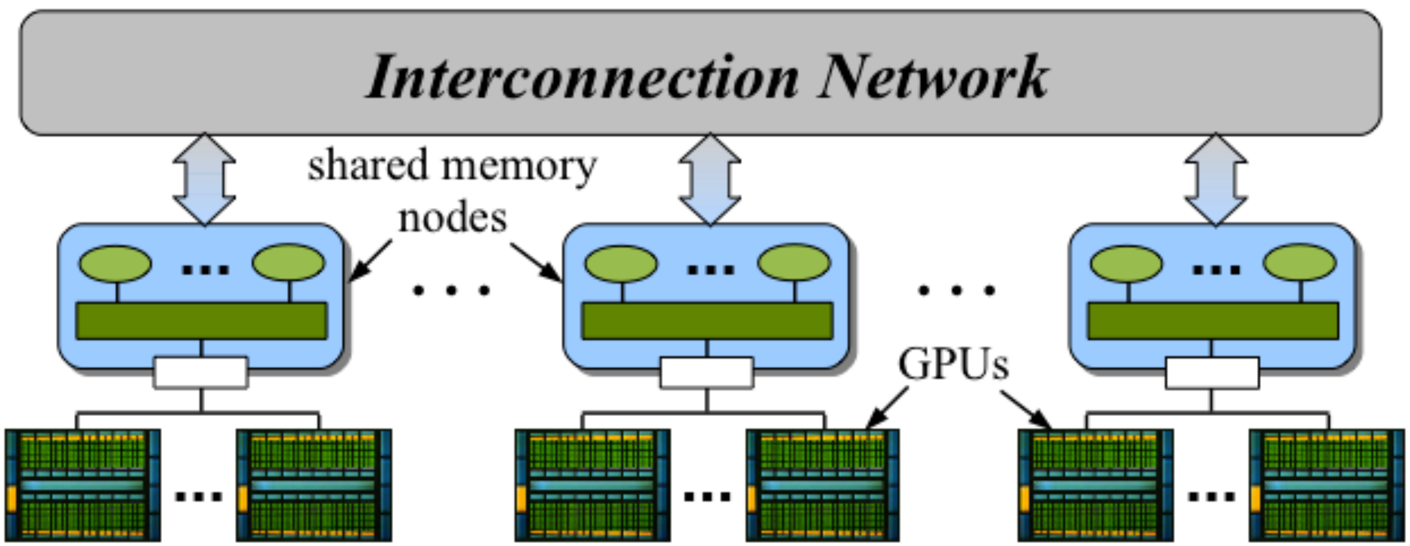
TAU Execution Command (tau_exec)

- Uninstrumented execution
  - % mpirun –np 8 ./a.out
- Track MPI performance
  - % mpirun –np 8 tau_exec ./a.out
- Track POSIX I/O and MPI performance (MPI enabled by default)
  - % mpirun –np 8 tau_exec –io ./a.out
- Track memory operations
  - % setenv TAU_TRACK_MEMORY_LEAKS   1
  - % mpirun –np 8 tau_exec –memory ./a.out
- Use event based sampling (compile with –g)
  - % mpirun –np 8 tau_exec –ebs ./a.out
  - Also –ebs_source=<PAPI_COUNTER> -ebs_period=<overflow_count>
- Load wrapper interposition library
  - % mpirun –np 8 tau_exec –loadlib=<path/libwrapper.so> ./a.out
- Track GPGPU operations
  - % mpirun –np 8 tau_exec –cuda ./a.out
  - % mpirun –np 8 tau_exec –opencl ./a.out

Profiling GPGPU Executions

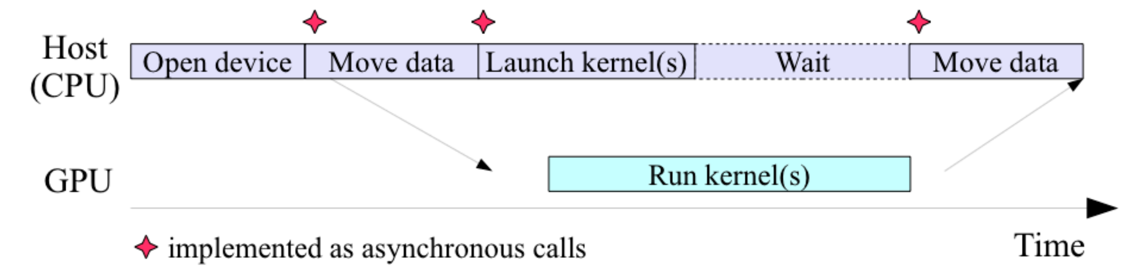
- GPGPU compilers (e.g., CAPS hmpp and PGI) can now automatically generate GPGPU code using manual annotation of loop-level constructs and routines (hmpp)
- The loops (and routines for HMPP) are transferred automatically to the GPGPU
- TAU intercepts the runtime library routines and examines the arguments
- Shows events as seen from the host
- Profiles and traces GPGPU execution

- Multi-CPU, multicore shared memory nodes
- GPU accelerators connected by high-BW I/O
- Cluster interconnection network

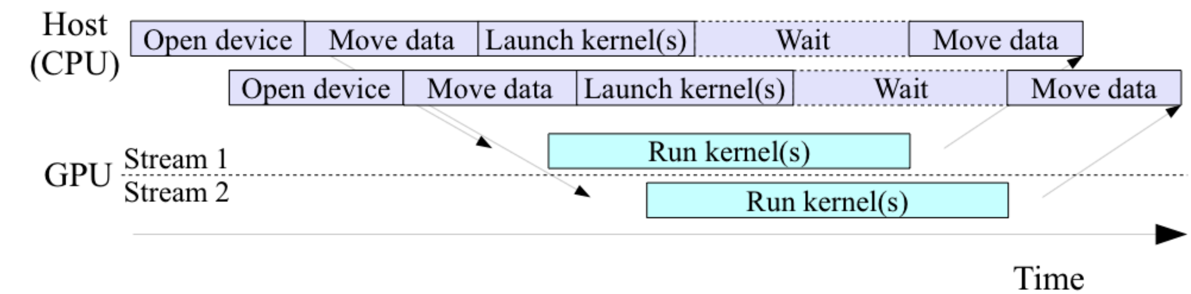


Host (CPU) - GPU Scenarios

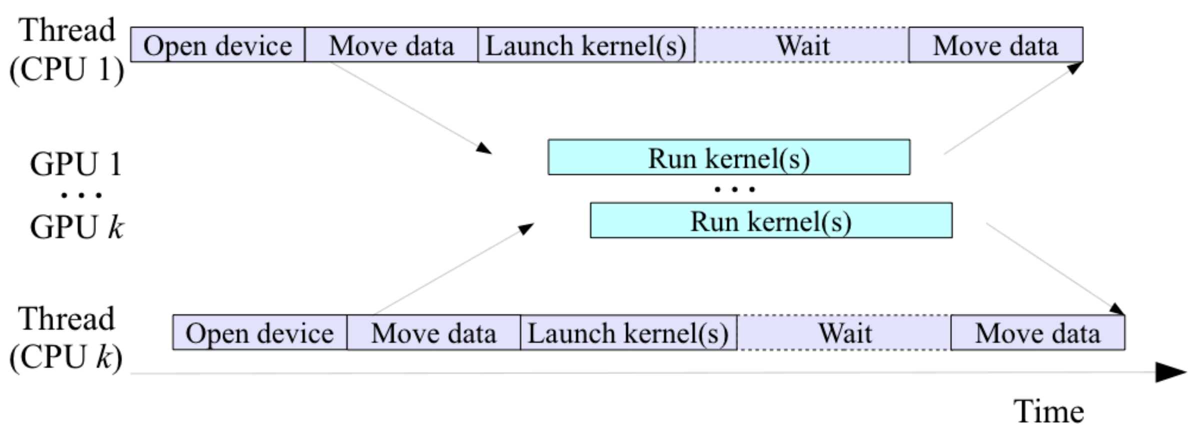
- Single GPU



- Multi-stream

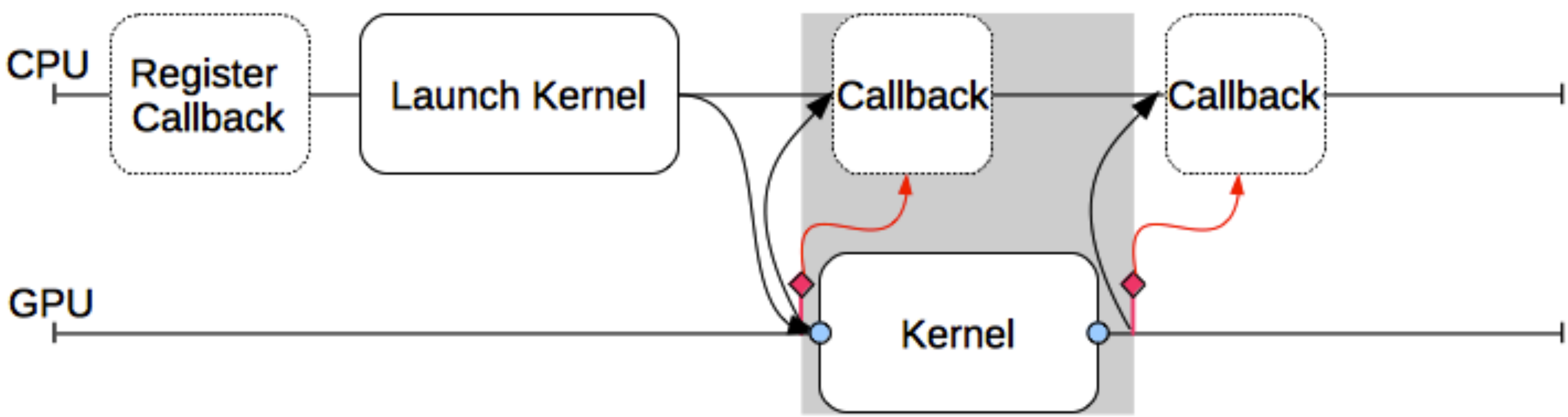


- Multi-CPU, Multi-GPU



Host-GPU Measurement – Callback Method

- GPU driver libraries provide callbacks for certain routines and captures measurements
- Measurement tool registers the callbacks and processes performance data
- Application code is not modified



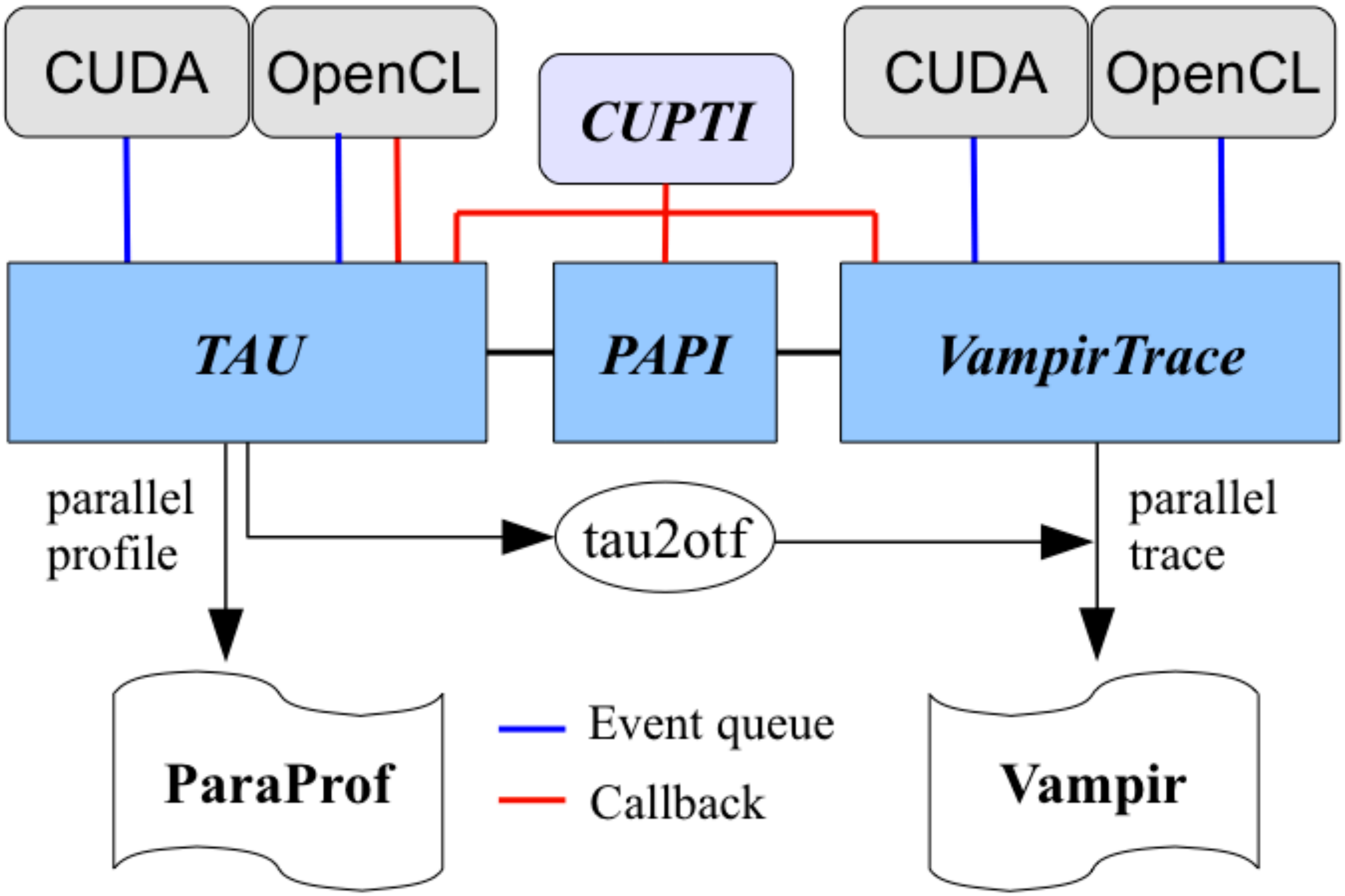
Method Support and Implementation

- Synchronous method
  - Place instrumentation appropriately around GPU calls (kernel launch, library routine, …)
  - Wrap (synchronous) library with performance tool
- Event queue method
  - Utilize CUDA and OpenCL event support
  - Again, need instrumentation to create and insert events in the streams with kernel launch and process events
  - Can be implemented with driver library wrapping
- Callback method
  - Utilize language-level callback support in OpenCL
  - Utilize NVIDIA CUDA Performance Tool Interface (CUPTI)
  - Need to appropriately register callbacks

GPU Performance Measurement Tools

- Support the Host-GPU performance perspective
- Provide integration with existing measurement system to facilitate tool use
- Utilize support in GPU driver library and device
- Tools
  - TAU performance system
  - Vampir
  - PAPI
  - NVIDIA CUPTI

GPU Performance Tool Interoperability



- NVIDIA is developing CUPTI to enable the creation of profiling and tracing tools
- Callback API
  - Interject tool code at the entry and exist to each CUDA runtime and driver API call
- Counter API
  - Query, configure, start, stop, and read the counters on CUDA-enabled devices
- CUPTI is delivered as a dynamic library
- CUPTI is released with CUDA 4.0

TAU for Heterogeneous Measurement

- Multiple performance perspectives
- Integrate Host-GPU support in TAU measurement framework
  - Enable use of each measurement approach
  - Include use of PAPI and CUPTI
  - Provide profiling and tracing support
- Tutorial
  - Use TAU library wrapping of libraries
  - Use `tau_exec` to work with binaries

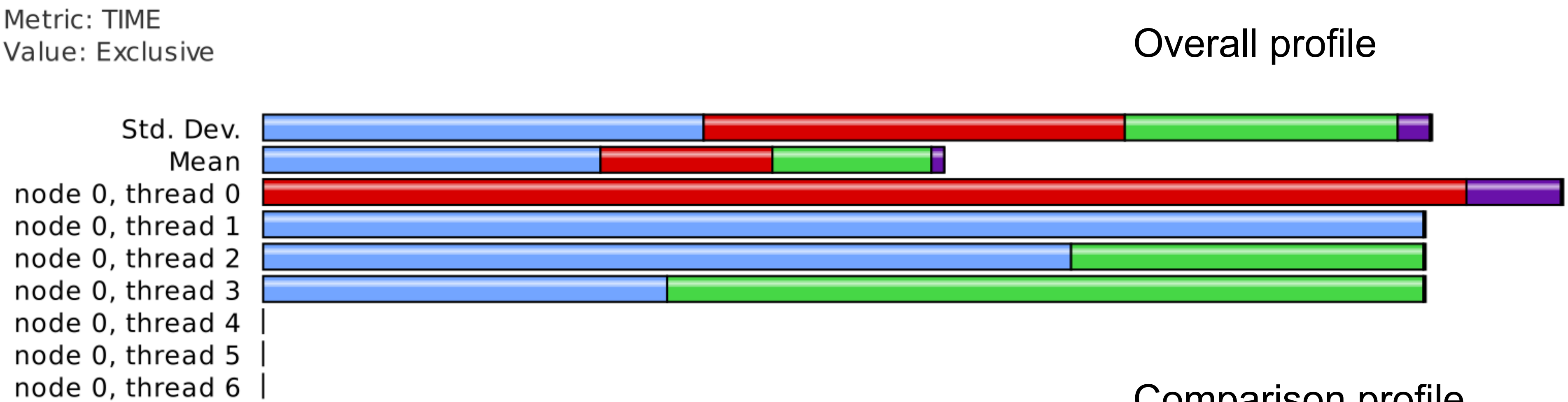
```
% ./a.out    (uninstrumented)
% tau_exec –T serial –cuda ./a.out
% paraprof
```

Example: SDK simpleMultiGPU

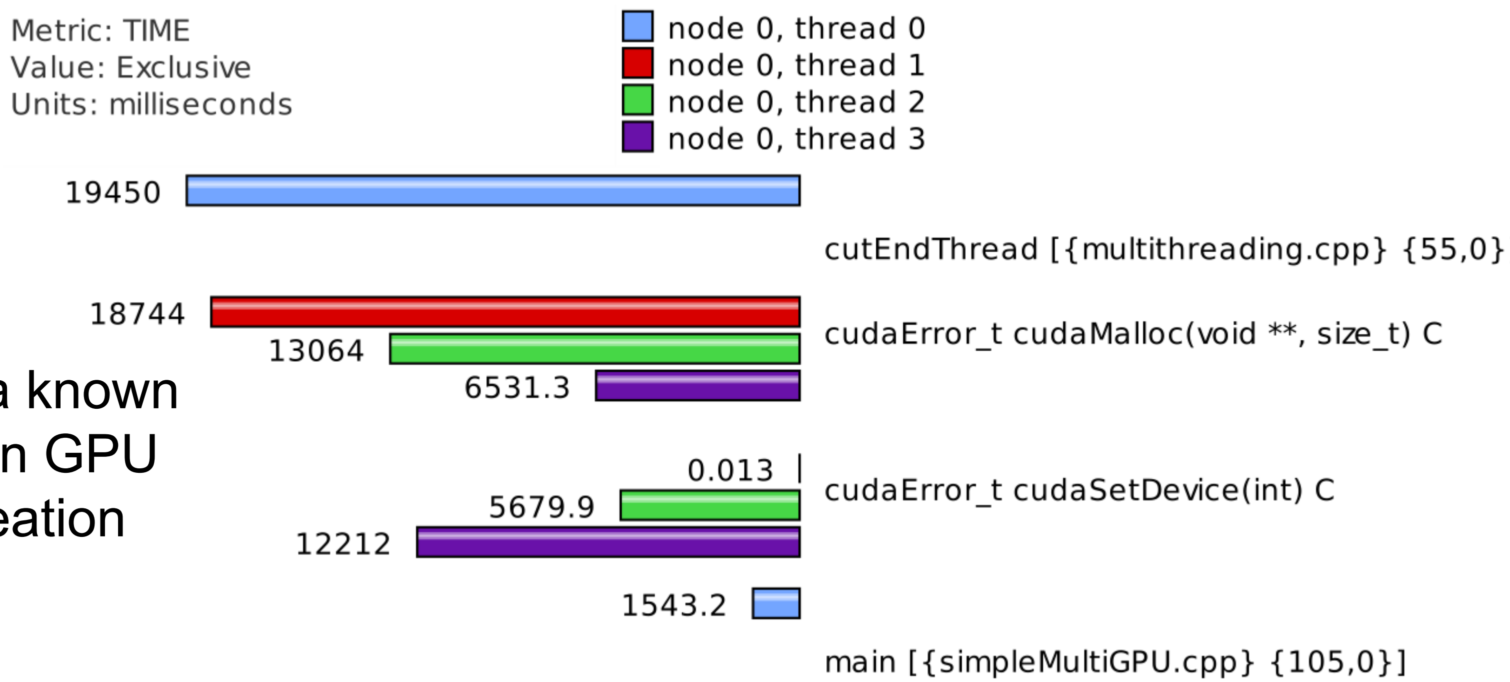
- Demonstration of multiple GPU device use
- *main* → *solverThread* → *reduceKernel*
- One Keeneland node with three GPUs
- Performance profile for:
  - One *main* thread
  - Three *solverThread* threads
  - Three *reduceKernel* "threads"

simpleMultiGPU Profile

Overall profile

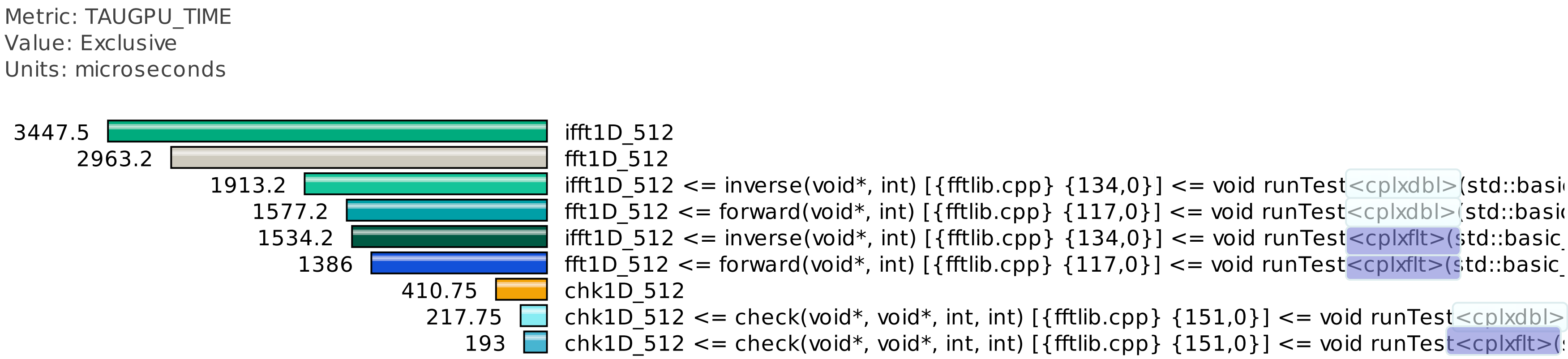


Comparison profile



Identified a known overhead in GPU context creation

- TAU is able to associate callsite context information with kernel launch so that different kernel calls can be distinguished

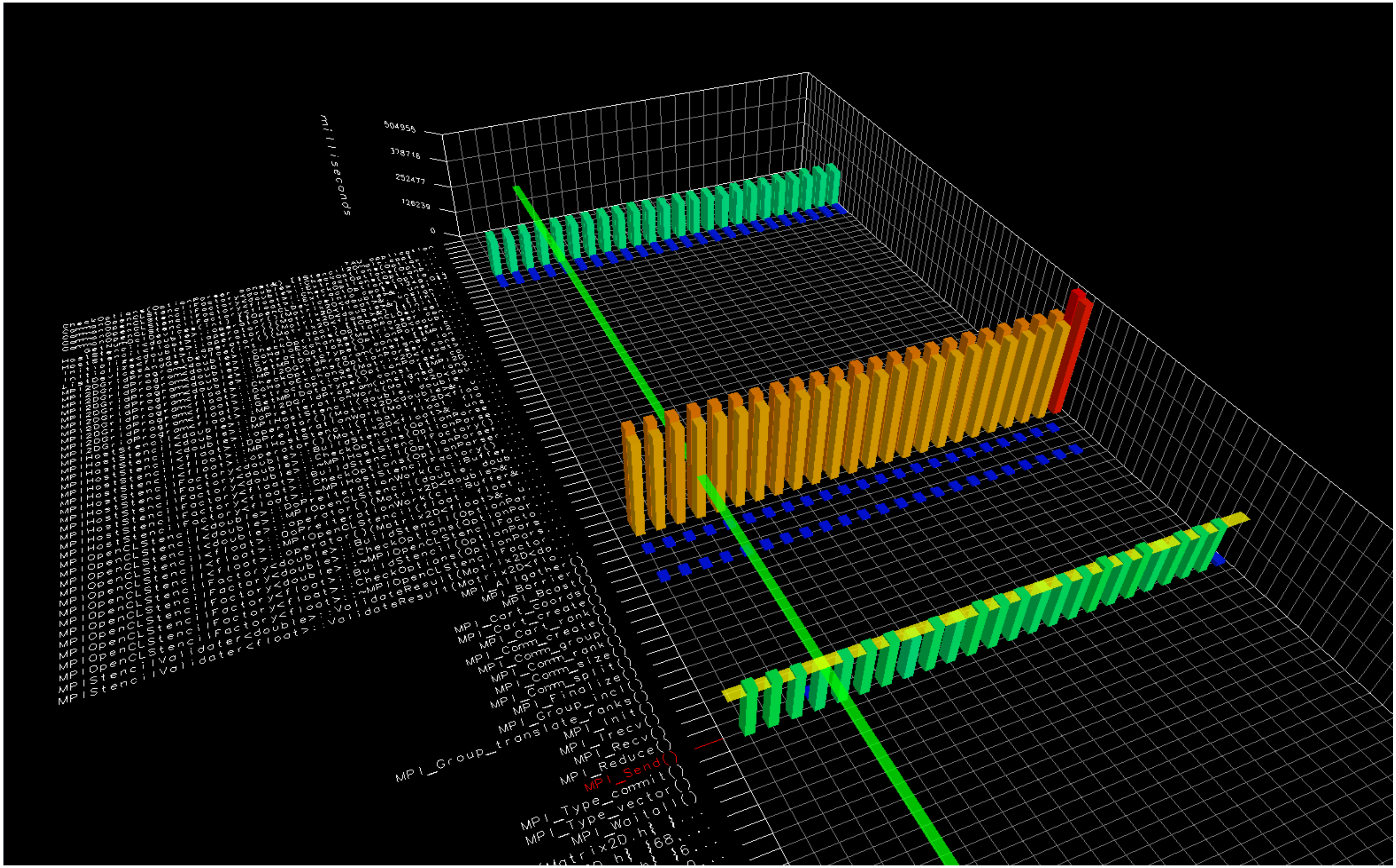


Each kernel (ifft1D_512, fft1D_512 and chk1D_512) is broken down by call-site, either during the single precession or double precession step.

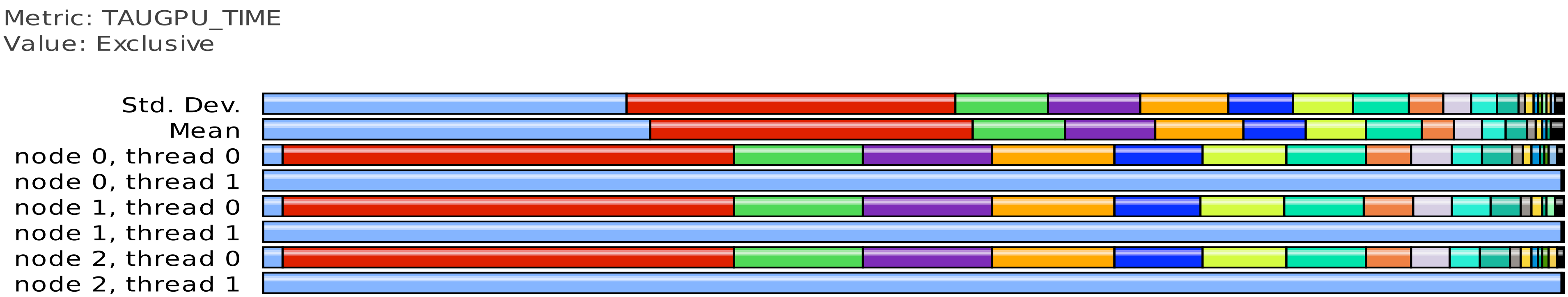
Example: SHOC Stencil2D

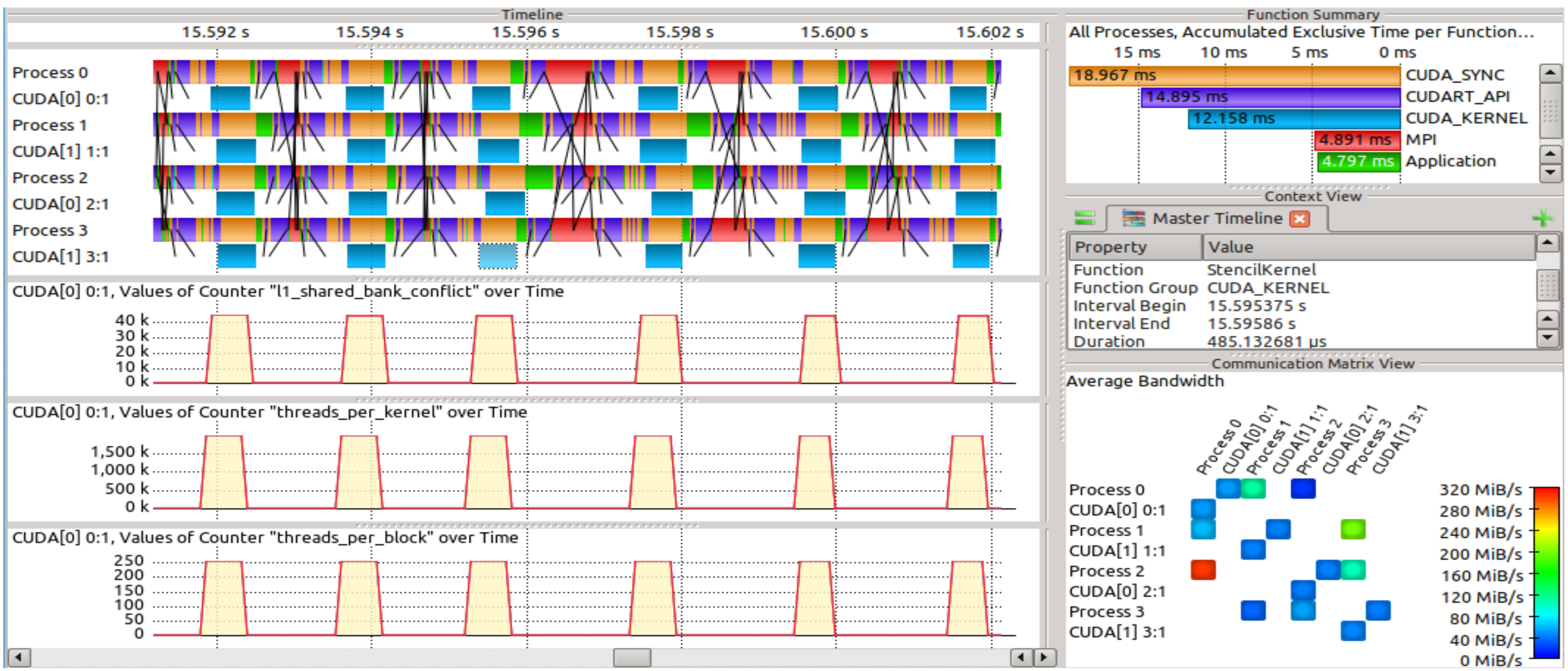
- Compute 2D, 9-point stencil
  - Multiple GPUs using MPI
  - CUDA and OpenCL versions
- One Keeneland node with 3 GPUs
- Eight Keeneland nodes with 24 GPUs
- Performance profile and trace
  - Application events
  - Communication events
  - Kernel execution

Stencil2D Parallel Profile

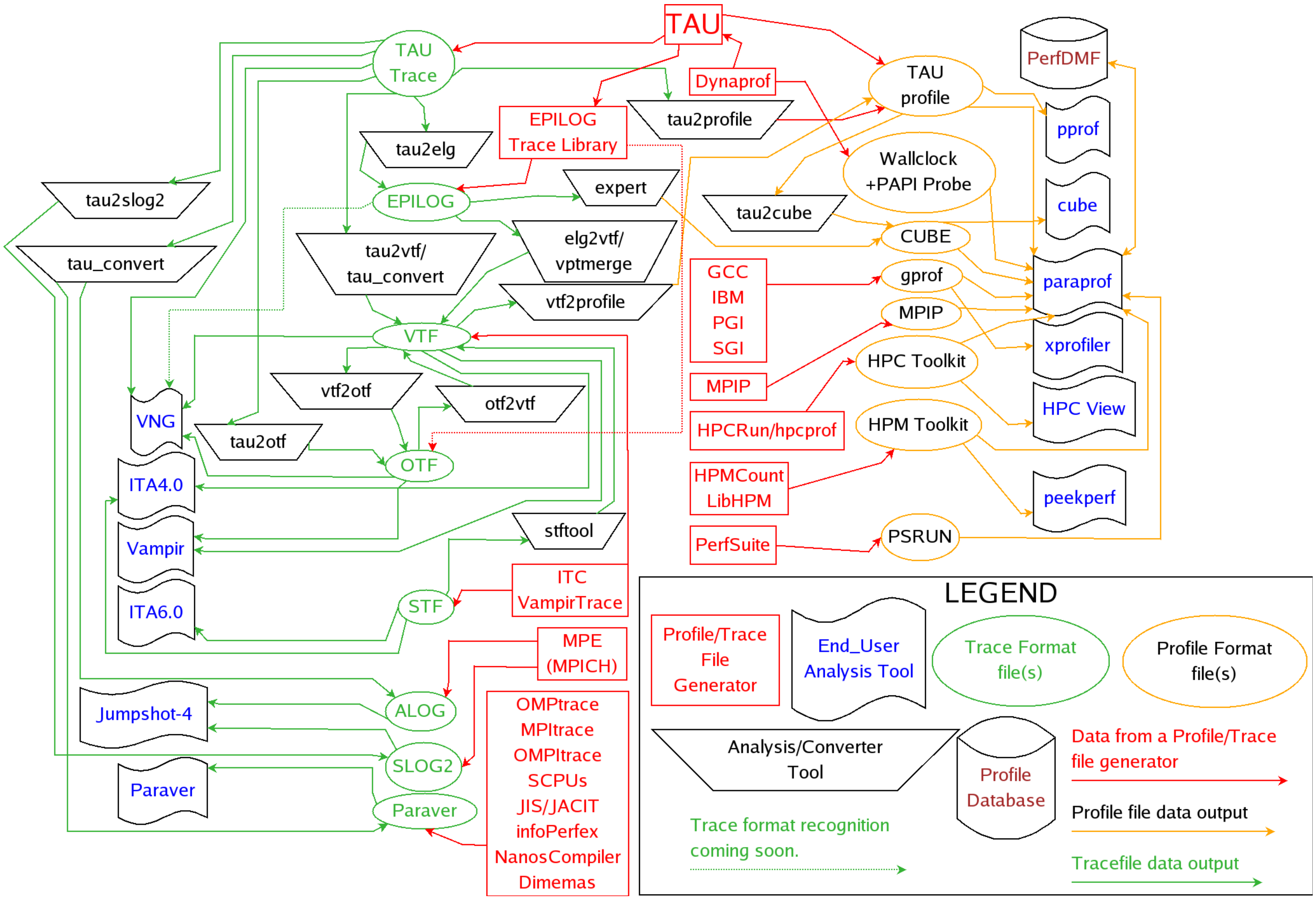


Stencil2D Parallel Profile / Trace in Vampir

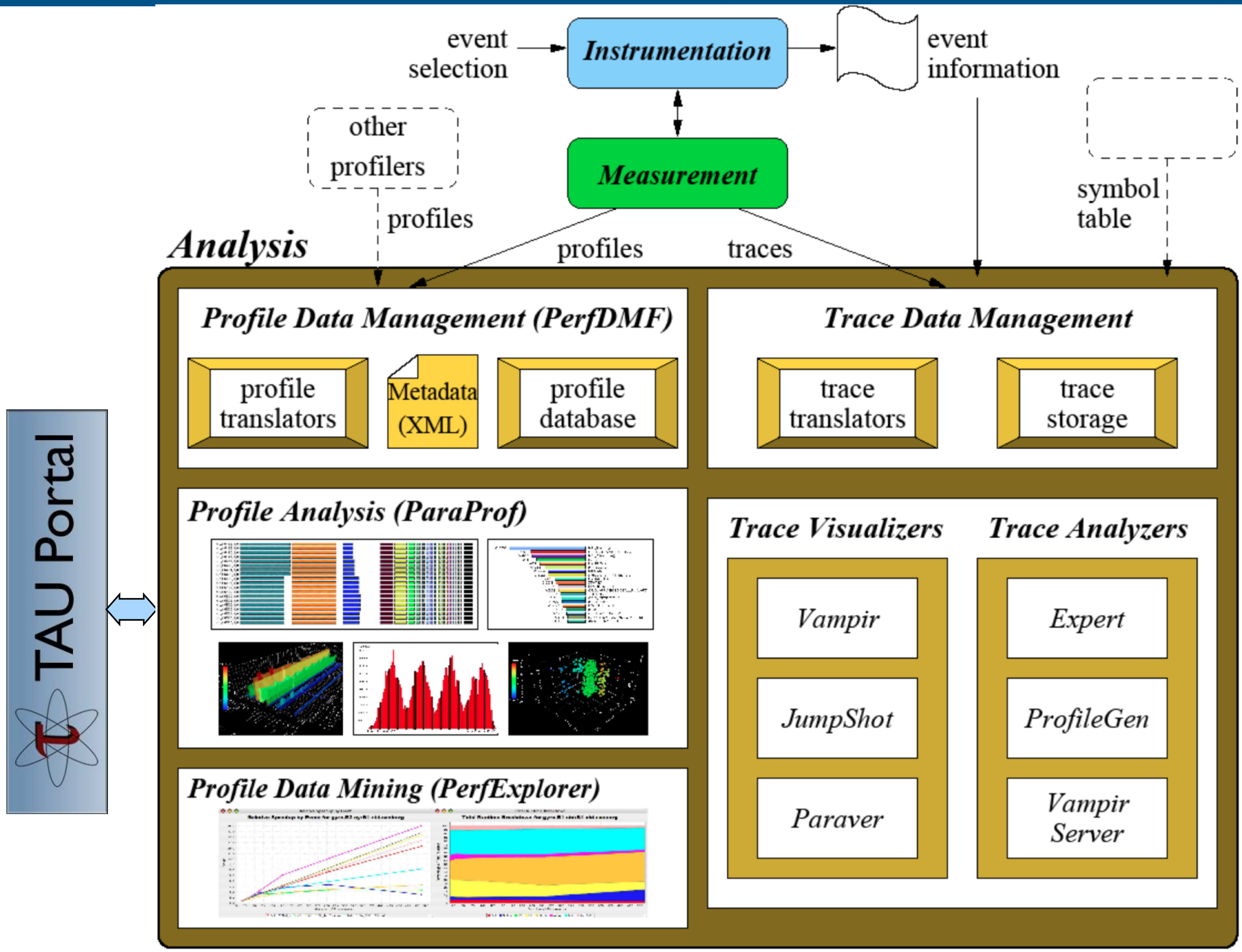




Building Bridges to Other Tools



TAU Analysis



Example: NAMD with CUPTI

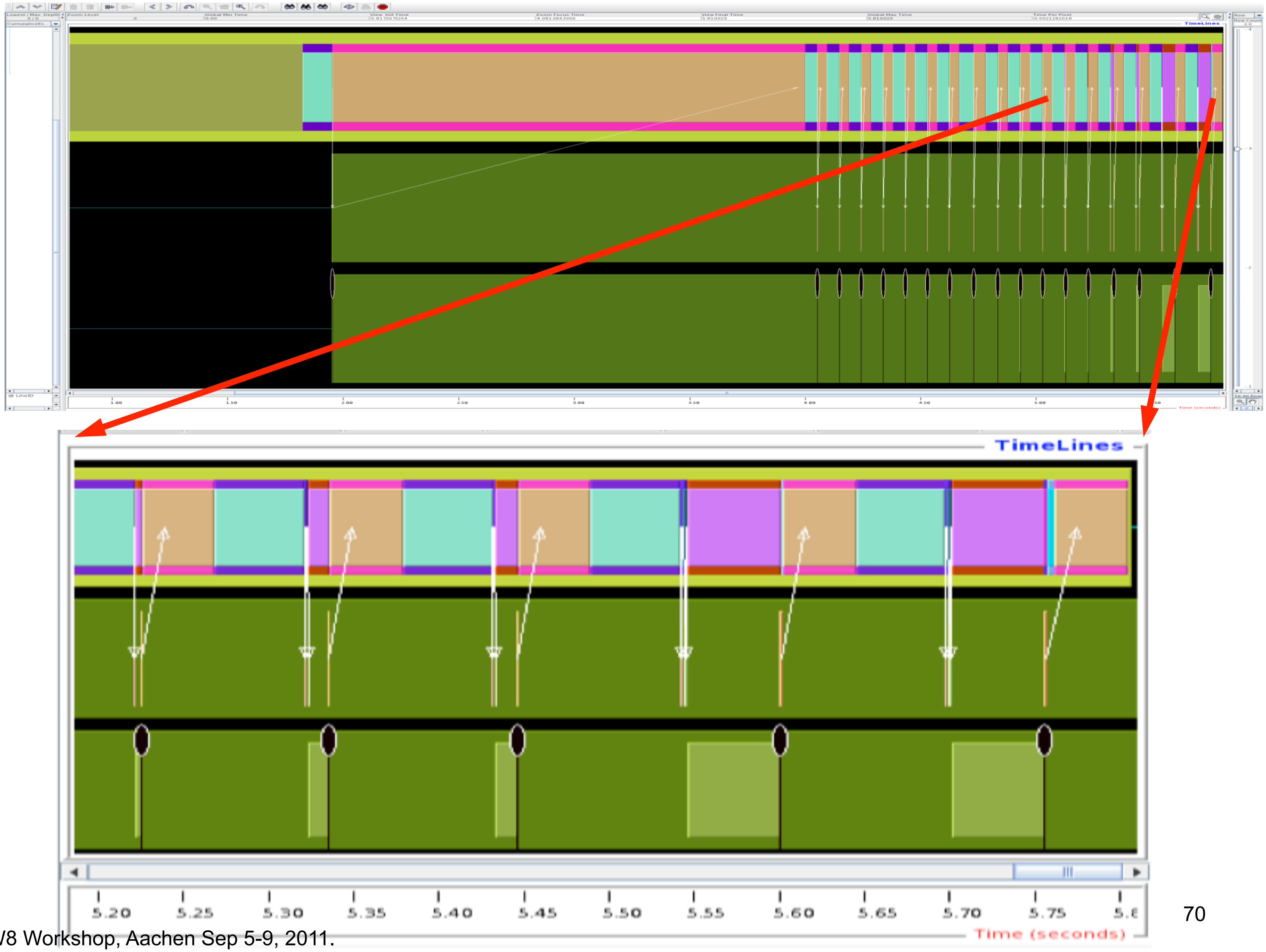
HMPP SGEMM (CAPS Entreprise)

VI-HPS

Host Process

Transfer Kernel

Compute Kernel



Host Process

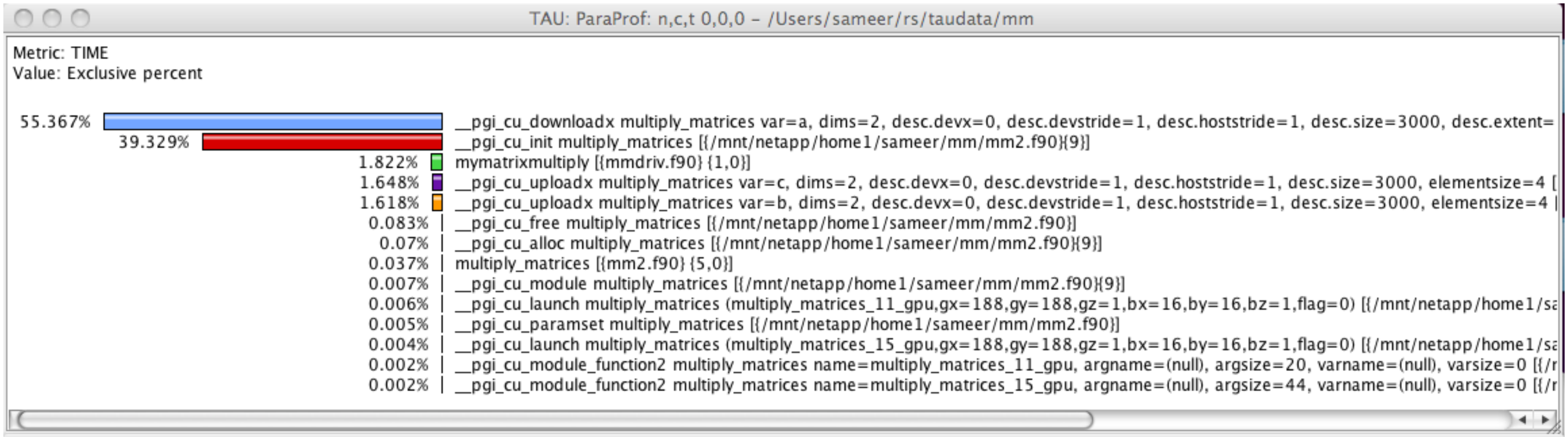
Transfer Kernel

Compute Kernel

Profiling PGI Accelerator Primitives

- PGI compiler allows users to annotate source code to identify loops that should be accelerated
- When a program is compiled with TAU, its measurement library intercepts the PGI runtime library layer to measure time spent in the runtime library routines and data transfers
- TAU also captures the arguments:
  - array data dimensions and sizes, strides, upload and download times, variable names, source file names, row and column information, and routines

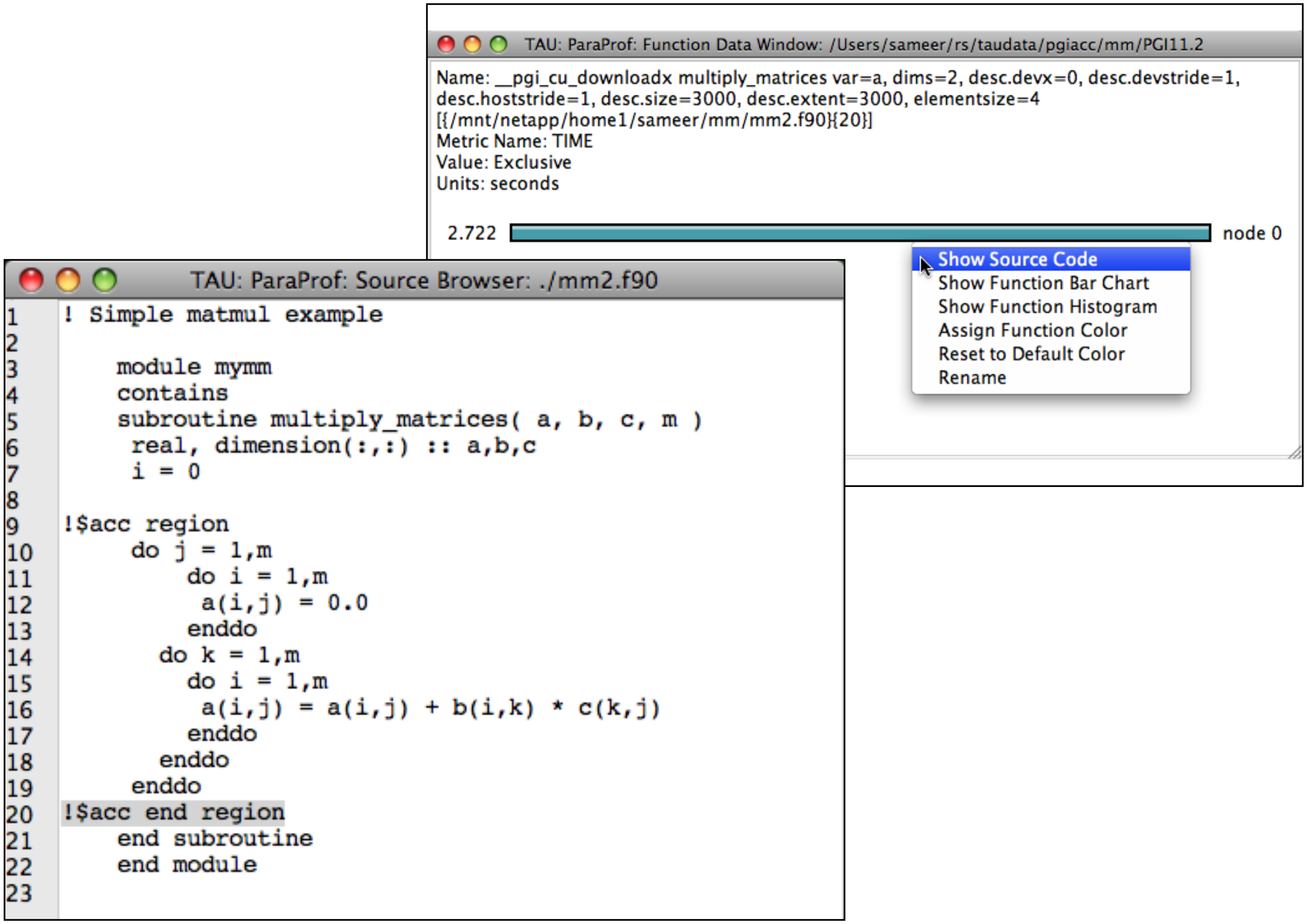
Example: PGI GPU-accelerated MM



TAU: ParaProf: Thread Statistics: n,c,t, 0,0,0 - /Users/sameer/rs/taudata/mm

Exclusive TIME %	Name	Exclusive TIME ▽	Inclusive TIME	Calls	Child Calls
55.4%	__pgi_cu_downloadx multiply_matrices var=a, dims=2, desc.devx=0, desc.devstride=1, desc.hostst	2.721	2.721	5	0
39.3%	__pgi_cu_init multiply_matrices [{/mnt/netapp/home1/sameer/mm/mm2.f90}{9}]	1.933	1.933	5	0
1.8%	mymatrixmultiply [{mmdriv.f90} {1,0}]	0.09	4.914	1	5
1.6%	__pgi_cu_uploadx multiply_matrices var=c, dims=2, desc.devx=0, desc.devstride=1, desc.hoststrid	0.081	0.081	5	0
1.6%	__pgi_cu_uploadx multiply_matrices var=b, dims=2, desc.devx=0, desc.devstride=1, desc.hoststrid	0.079	0.079	5	0
0.1%	__pgi_cu_free multiply_matrices [{/mnt/netapp/home1/sameer/mm/mm2.f90}]	0.004	0.004	15	0
0.1%	__pgi_cu_alloc multiply_matrices [{/mnt/netapp/home1/sameer/mm/mm2.f90}{9}]	0.003	0.003	15	0
0.0%	multiply_matrices [{mm2.f90} {5,0}]	0.002	4.825	5	85
0.0%	__pgi_cu_module multiply_matrices [{/mnt/netapp/home1/sameer/mm/mm2.f90}{9}]	0	0	5	0
0.0%	__pgi_cu_launch multiply_matrices (multiply_matrices_11_gpu,gx=188,gy=188,gz=1,bx=16,by=16	0	0	5	0
0.0%	__pgi_cu_paramset multiply_matrices [{/mnt/netapp/home1/sameer/mm/mm2.f90}]	0	0	10	0
0.0%	__pgi_cu_launch multiply_matrices (multiply_matrices_15_gpu,gx=188,gy=188,gz=1,bx=16,by=16	0	0	5	0
0.0%	__pgi_cu_module_function2 multiply_matrices name=multiply_matrices_11_gpu, argname=(null), arg:	0	0	5	0

PGI MM Computational Kernel



Instrumentation: Re-writing Binaries

- Support for both static and dynamic executables
- Specify the list of routines to instrument/exclude from instrumentation
- Specify the TAU measurement library to be injected
- Simplify the usage of TAU:
  - To instrument:

    ```
    % tau_run a.out -o a.inst
    ```
  - To perform measurements, execute the application:

    ```
    % mpirun -np 8 ./a.inst
    ```
  - To analyze the data:

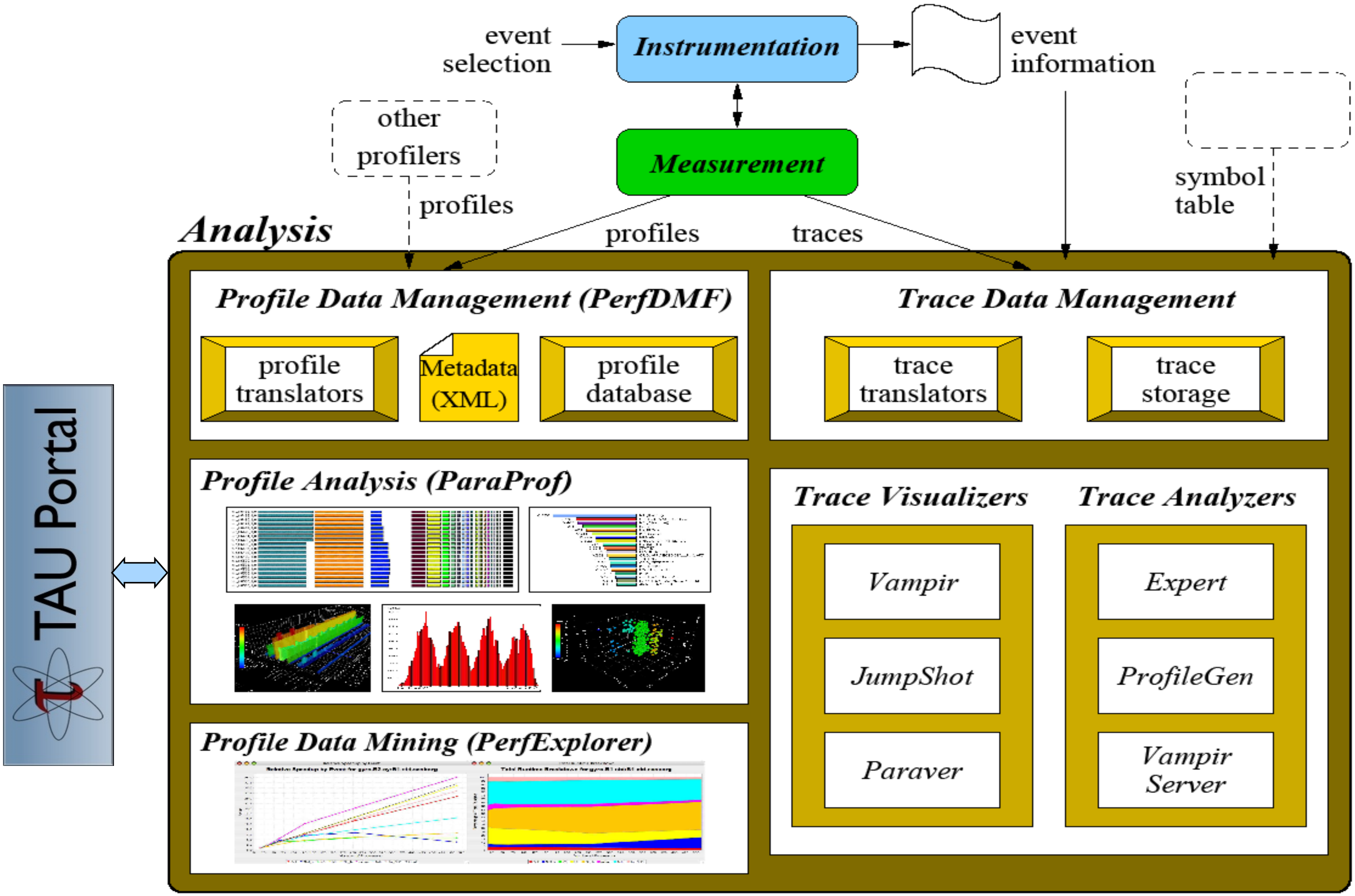
    ```
    % paraprof
    ```

tau_run with NAS PBS

livetau@paratools01:~

```
/home/livetau% cd ~/tutorial
/home/livetau/tutorial% # Build an uninstrumented bt NAS Parallel Benchmark
/home/livetau/tutorial% make bt CLASS=W NPROCS=4
/home/livetau/tutorial% cd bin
/home/livetau/tutorial/bin% # Run the instrumented code
/home/livetau/tutorial/bin% mpirun -np 4 ./bt_W.4
/home/livetau/tutorial/bin%
/home/livetau/tutorial/bin% # Instrument the executable using TAU with DyninstAPI
/home/livetau/tutorial/bin%
/home/livetau/tutorial/bin% tau_run ./bt_W.4 -o ./bt.i
/home/livetau/tutorial/bin% rm -rf profile.* MULT*
/home/livetau/tutorial/bin% mpirun -np 4 ./bt.i
/home/livetau/tutorial/bin% paraprof
/home/livetau/tutorial/bin%
/home/livetau/tutorial/bin% # Choose a different TAU configuration
/home/livetau/tutorial/bin% ls $TAU/libTAUsh
libTAUsh-depthlimit-mpi-pdt.so*           libTAUsh-papi-pdt.so*
libTAUsh-mpi-pdt.so*                      libTAUsh-papi-pthread-pdt.so*
libTAUsh-mpi-pdt-upc.so*                  libTAUsh-param-mpi-pdt.so*
libTAUsh-mpi-python-pdt.so*               libTAUsh-pdt.so*
libTAUsh-papi-mpi-pdt.so*                 libTAUsh-pdt-trace.so*
libTAUsh-papi-mpi-pdt-upc.so*             libTAUsh-phase-papi-mpi-pdt.so*
libTAUsh-papi-mpi-pdt-upc-udp.so*         libTAUsh-pthread-pdt.so*
libTAUsh-papi-mpi-pdt-vampirtrace-trace.so* libTAUsh-python-pdt.so*
libTAUsh-papi-mpi-python-pdt.so*
/home/livetau/tutorial/bin%
/home/livetau/tutorial/bin% tau_run -XrunTAUsh-papi-mpi-pdt-vampirtrace-trace bt_W.4 -o bt.vpt
/home/livetau/tutorial/bin% setenv VT_METRICS PAPI_FP_INS:PAPI_L1_DCM
/home/livetau/tutorial/bin% mpirun -np 4 ./bt.vpt
/home/livetau/tutorial/bin% vampir bt.vpt.otf &
```

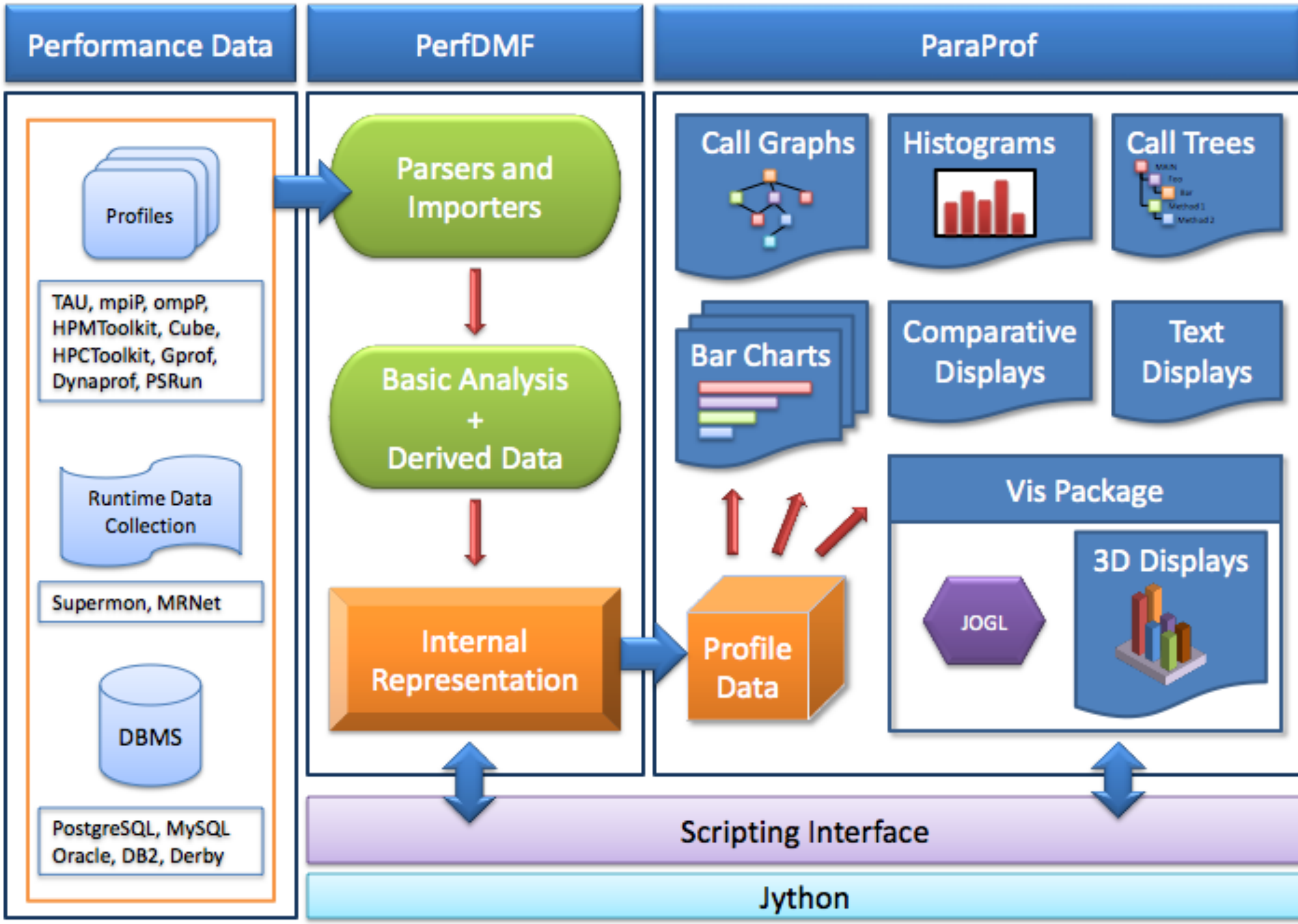
TAU Analysis



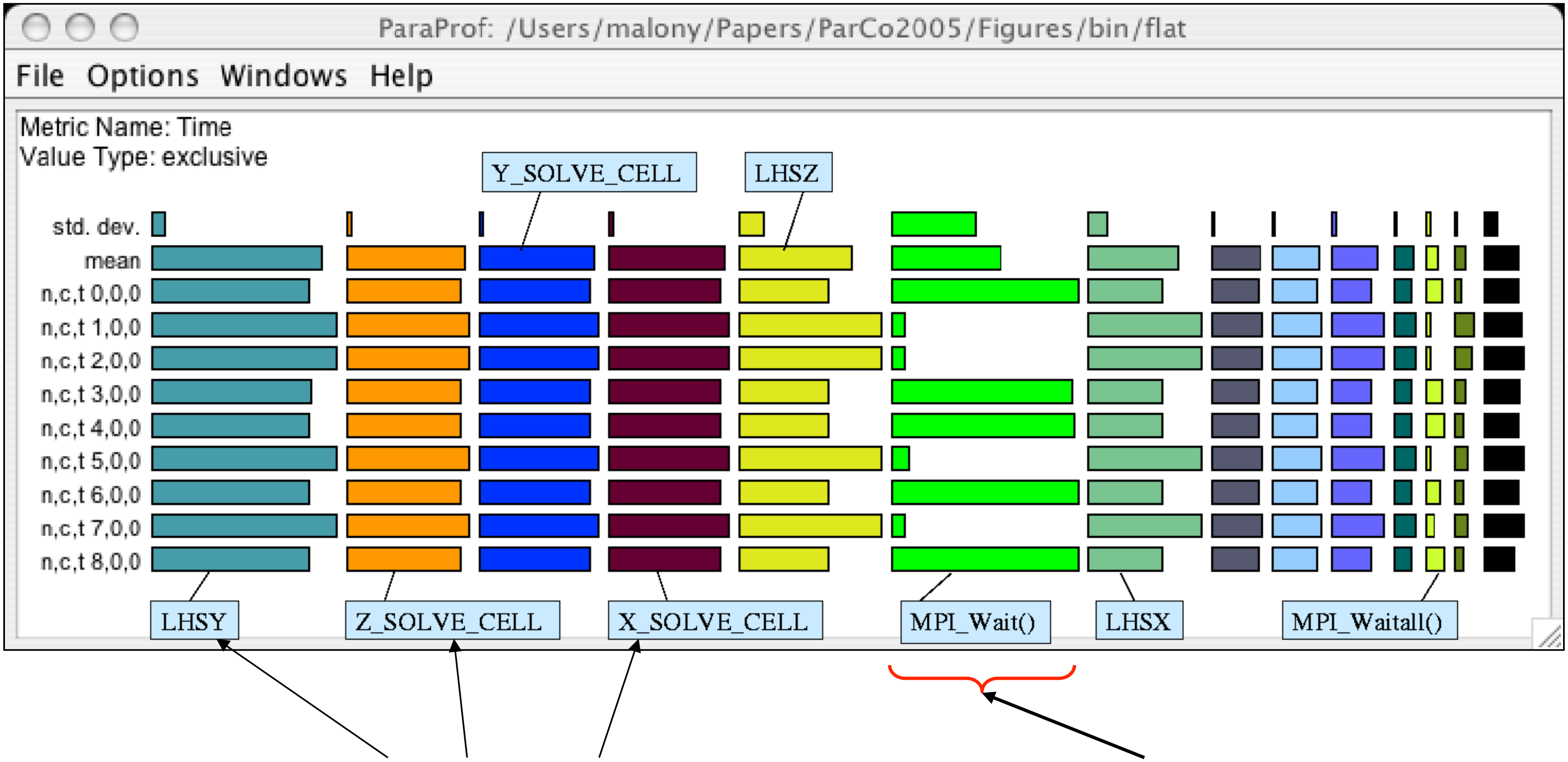
Performance Analysis

- Analysis of parallel profile and trace measurement
- Parallel profile analysis (ParaProf)
  - Java-based analysis and visualization tool
  - Support for large-scale parallel profiles
- Performance data management framework (PerfDMF)
- Parallel trace analysis
  - Translation to VTF (V3.0), EPILOG, OTF formats
  - Integration with Vampir / Vampir Server (TU Dresden)
  - Profile generation from trace data
- Online parallel analysis and visualization
- Integration with CUBE browser (Scalasca, UTK / FZJ)

ParaProf Profile Analysis Framework



NAS BT – Flat Profile



Application routine names reflect phase semantics

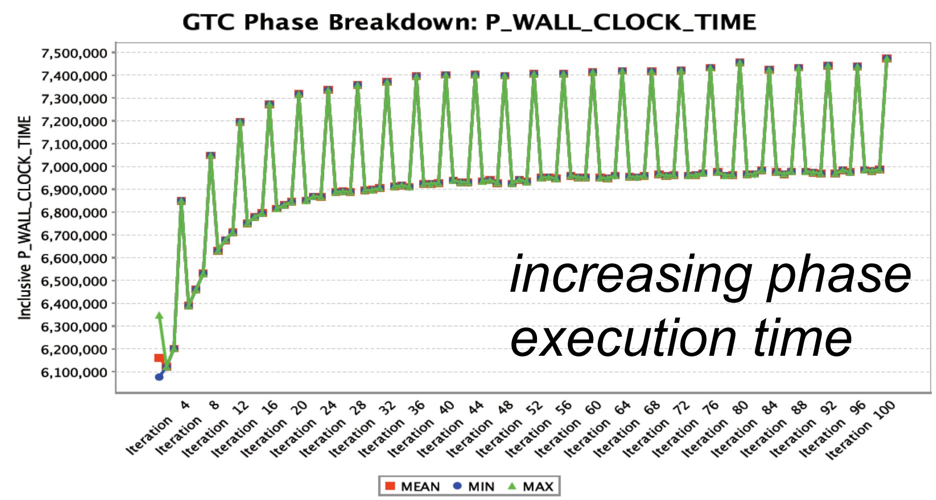
How is MPI_Wait() distributed relative to solver direction?

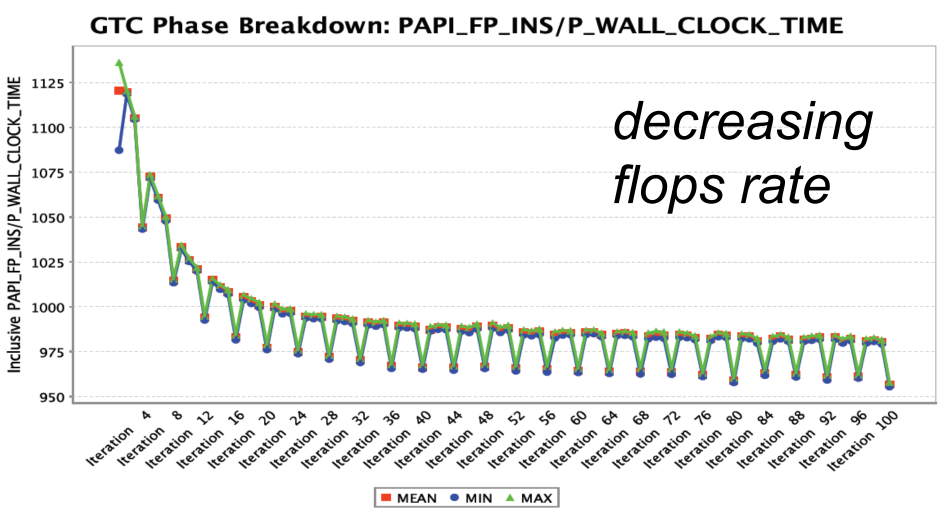
NAS BT – Phase Profile

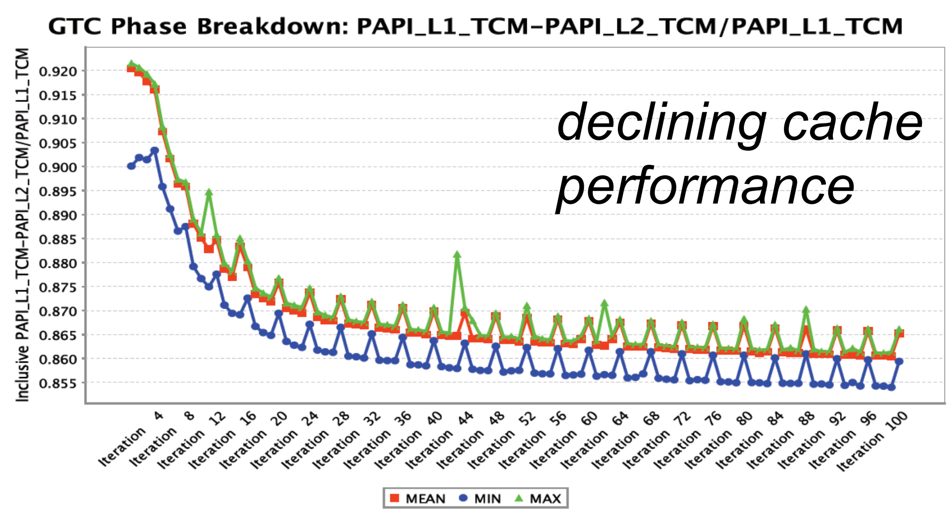
Main phase shows nested phases and immediate events

Phase Profiling of HW Counters

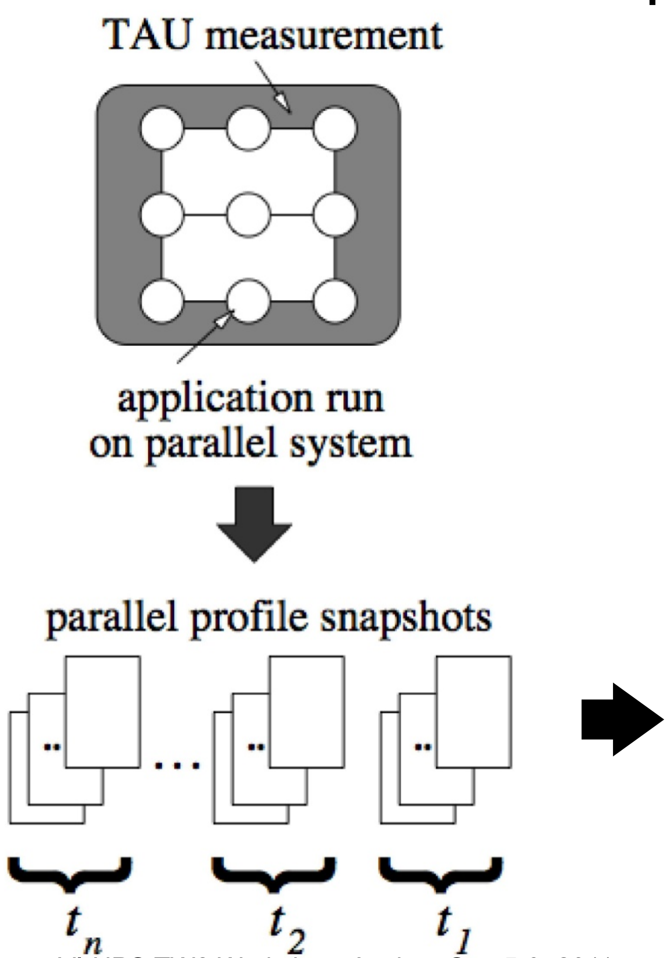
- GTC particle-in-cell simulation of fusion turbulence
- Phases assigned to iterations
- Poor temporal locality for one important data
- Automatically generated by PE2 python script

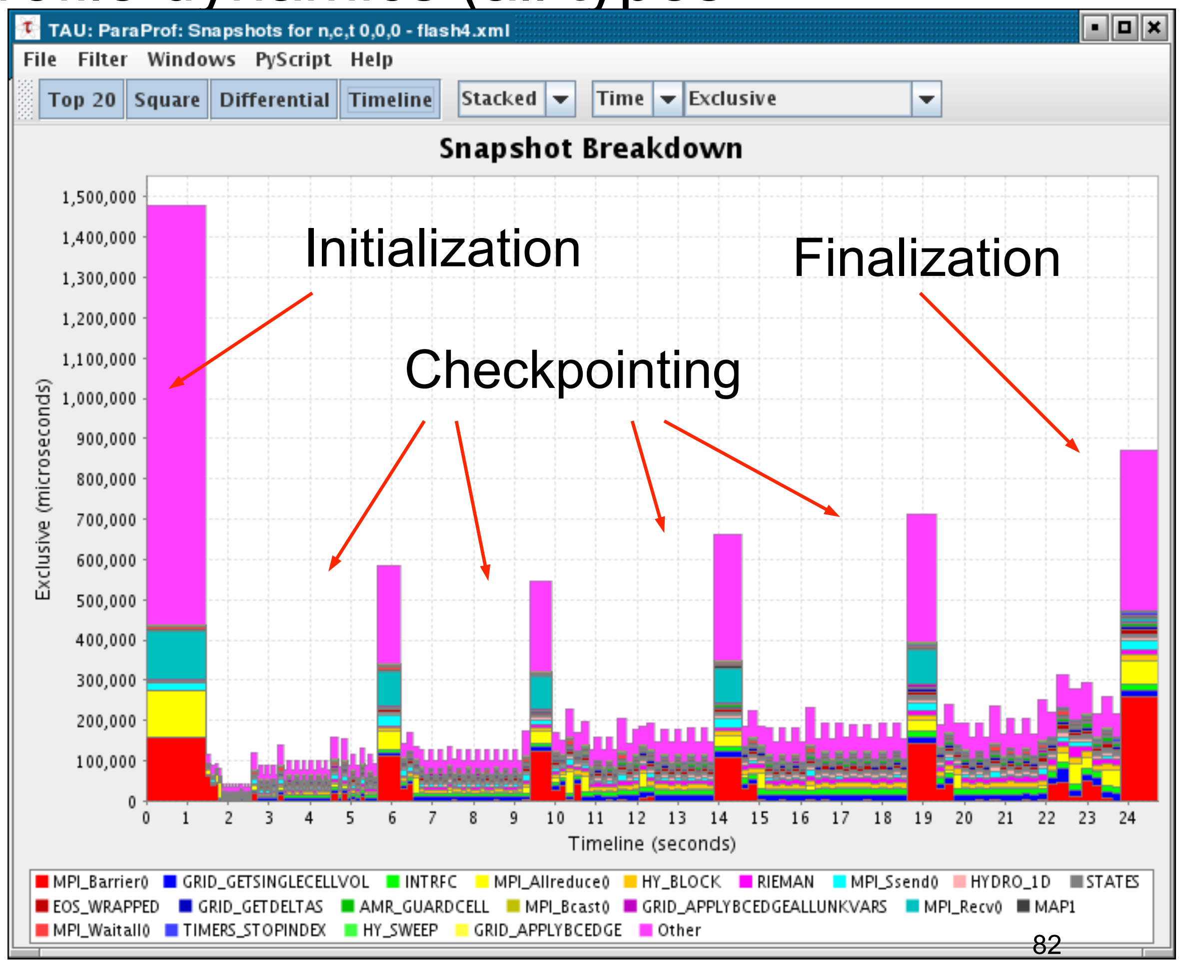






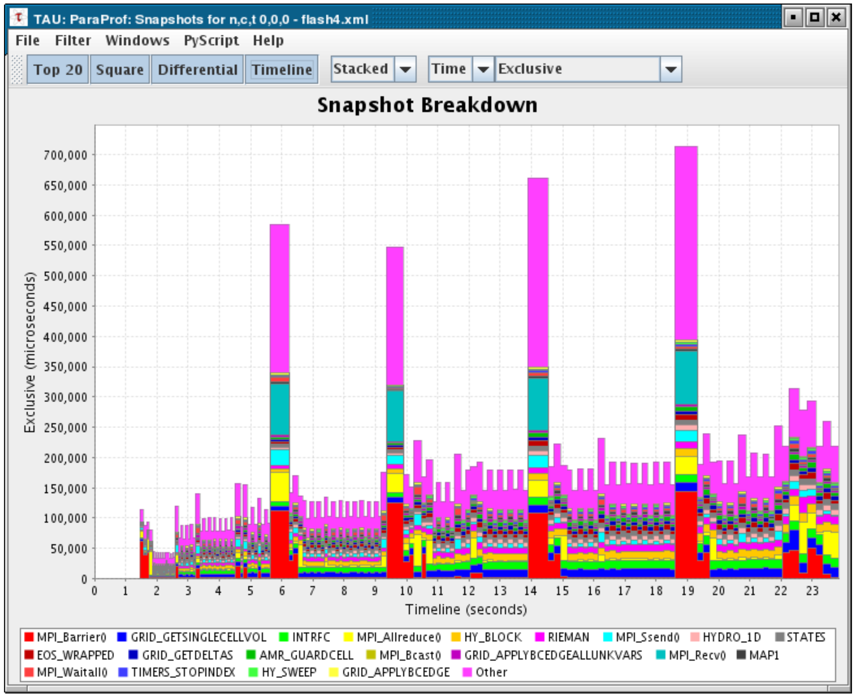
- Profile snapshots are parallel profiles recorded at runtime
- Shows performance profile dynamics (all types

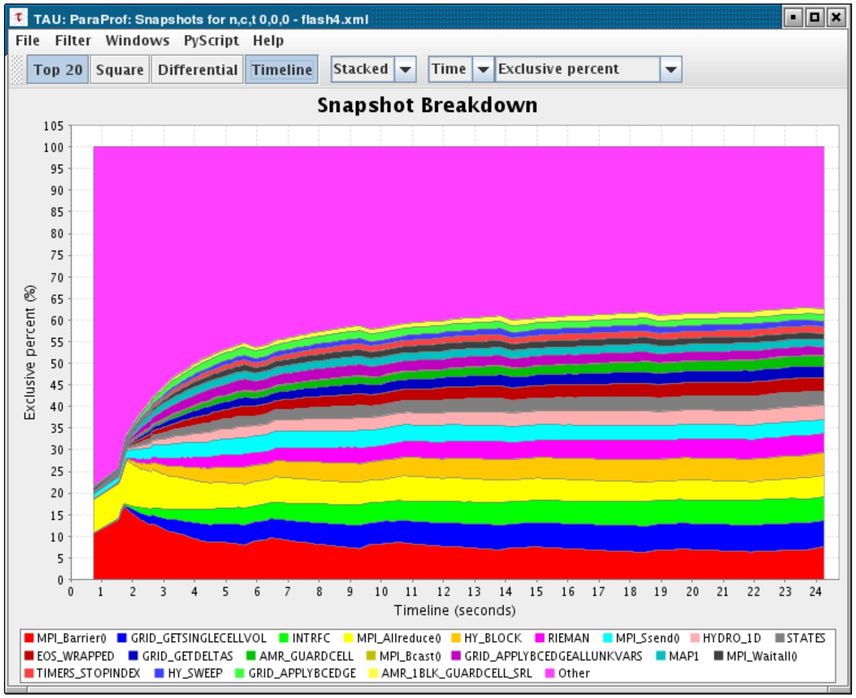




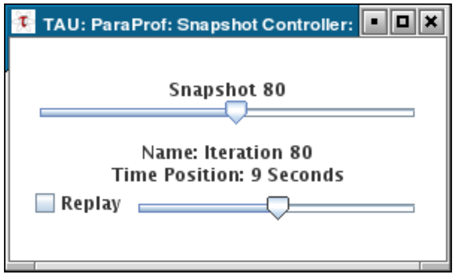
Profile Snapshot Views

- Percentage breakdown
- Only show main loop

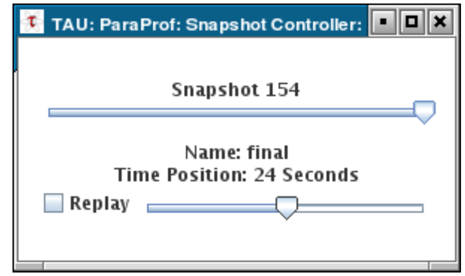


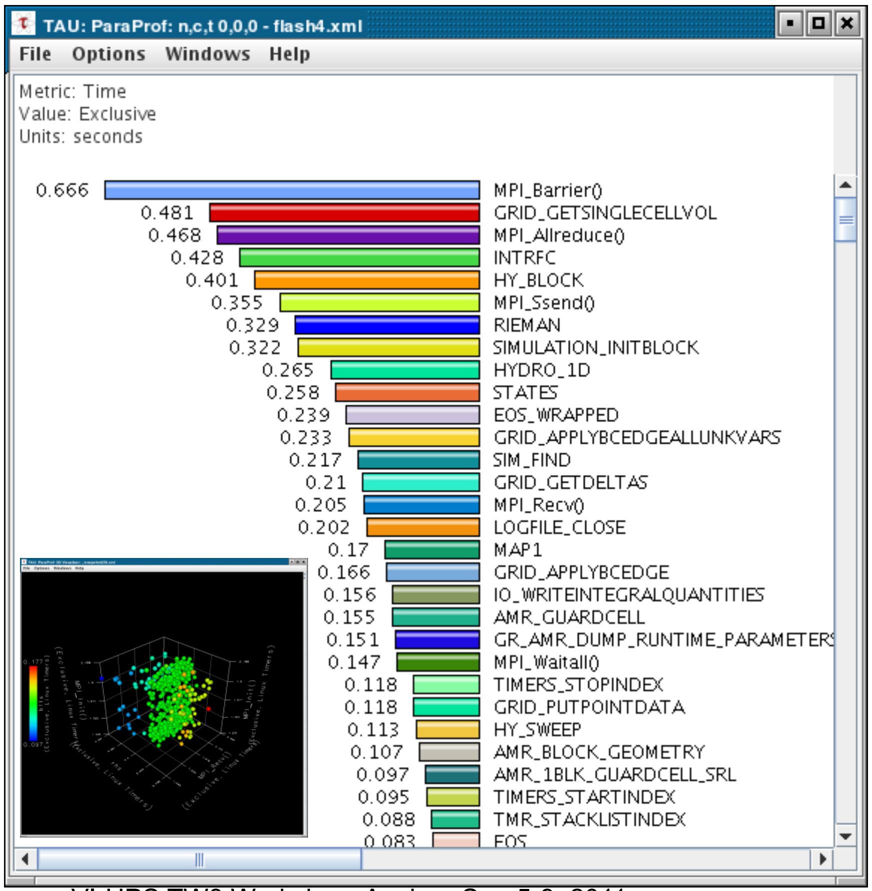


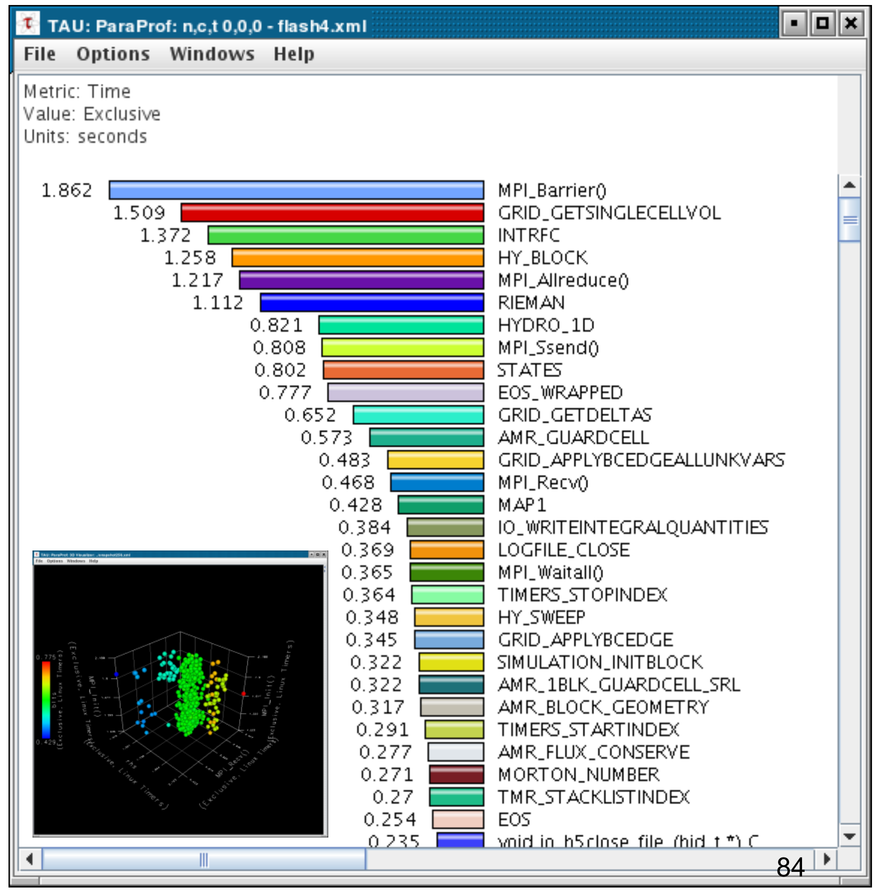
Snapshot Replay in ParaProf



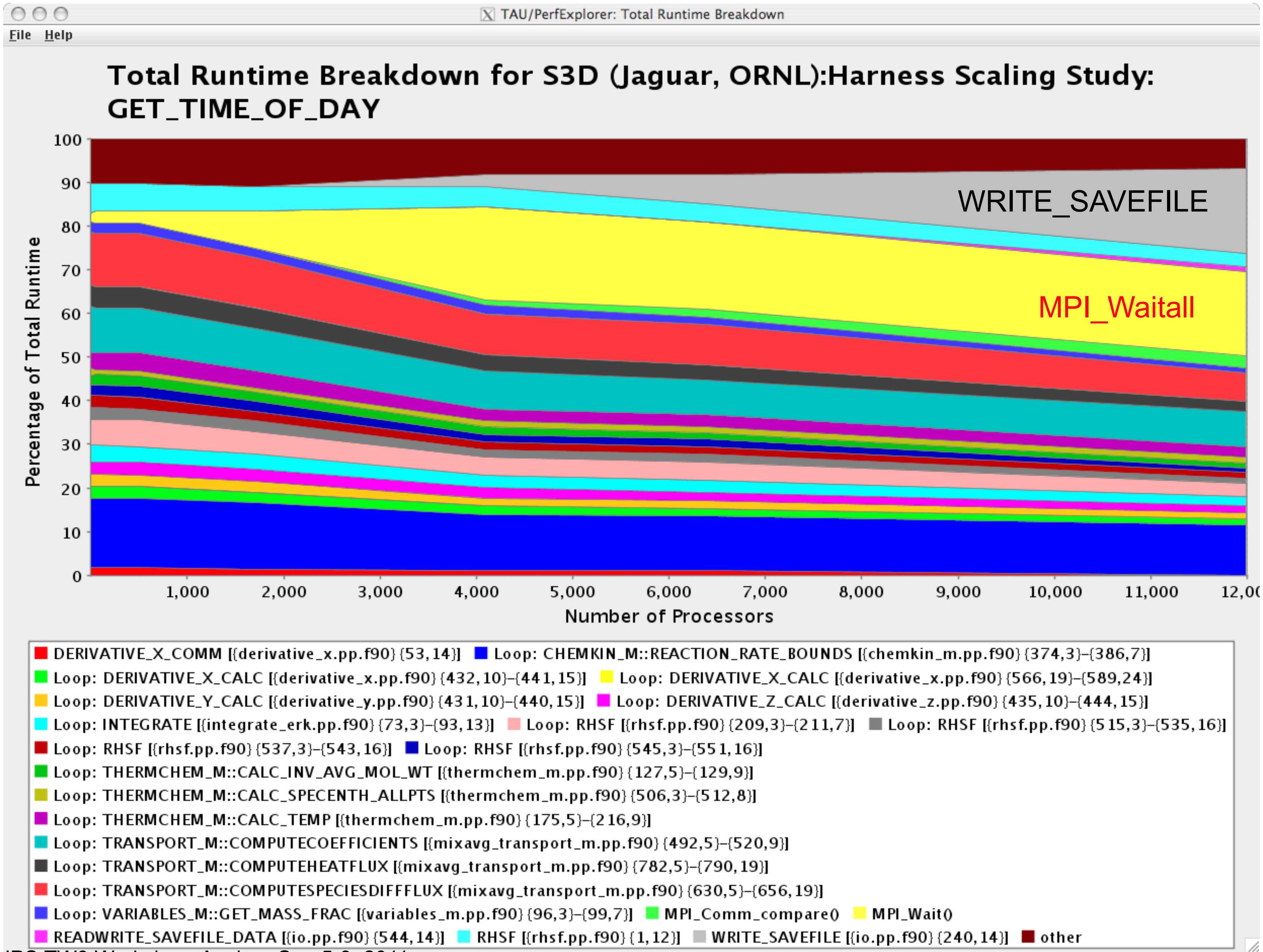
All windows dynamically update





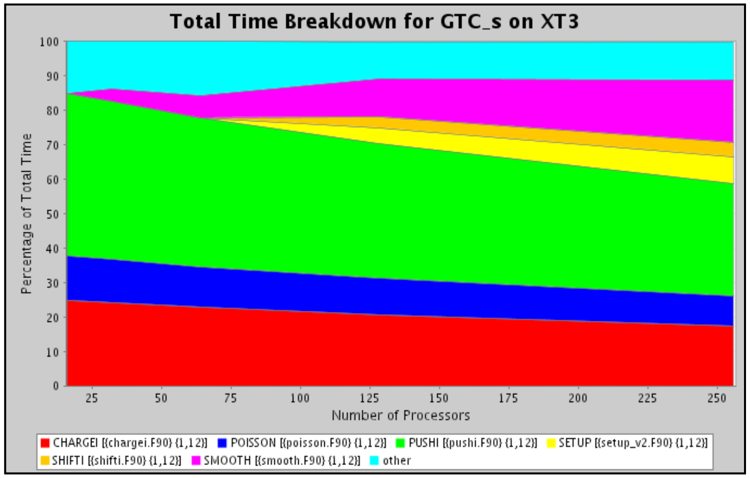


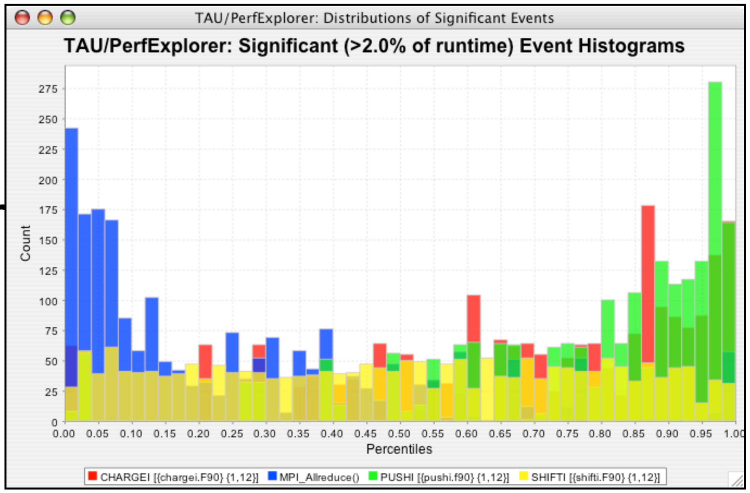
PerfExplorer – Runtime Breakdown



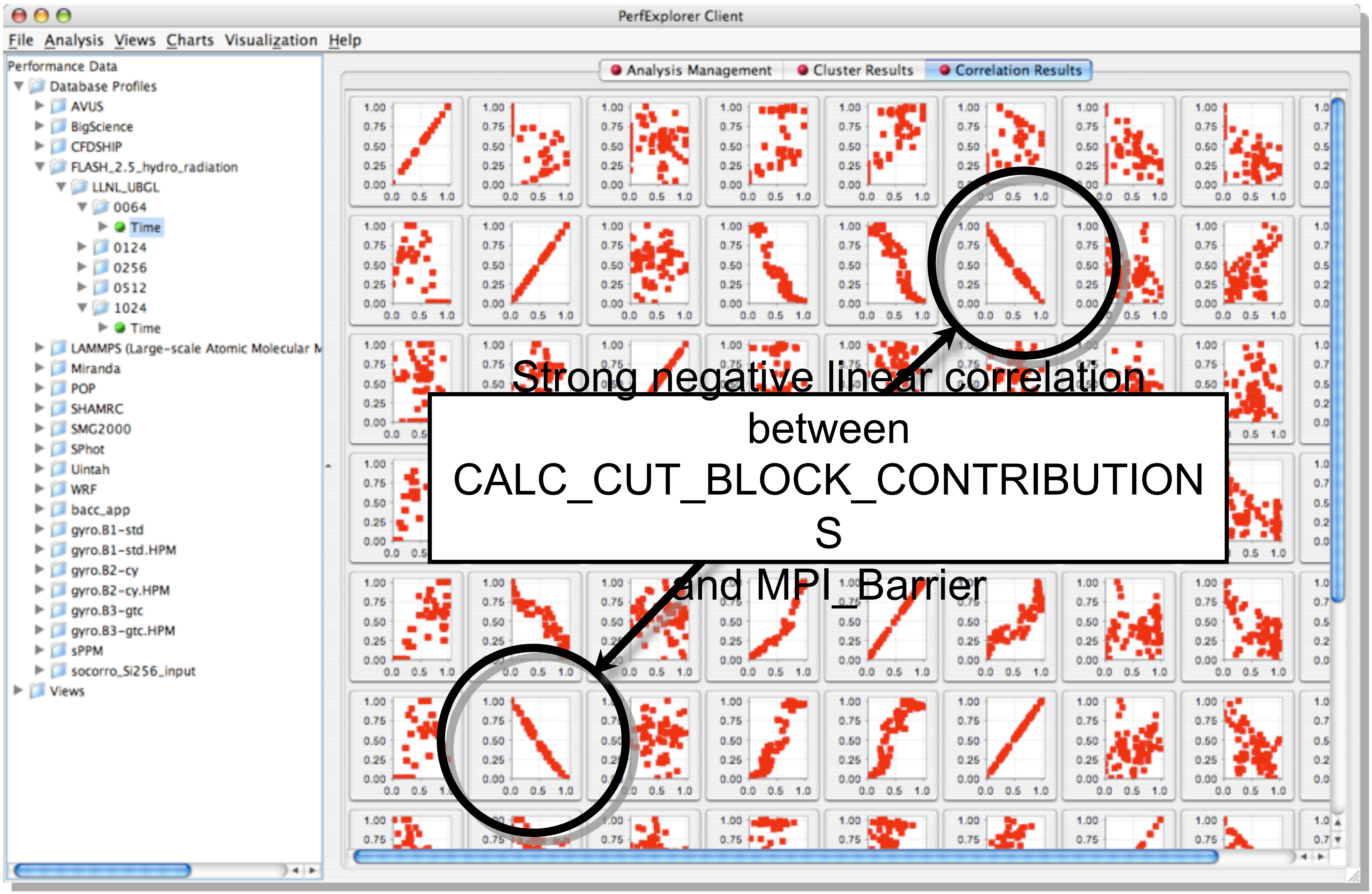
PerfExplorer – Relative Comparisons

- Total execution time
- Timesteps per second
- Relative efficiency
- Relative efficiency per event
- Relative speedup
- Relative speedup per event
- Group fraction of total
- Runtime breakdown
- Correlate events with total runtim
- Relative efficiency per phase
- Relative speedup per phase
- Distribution visualizations



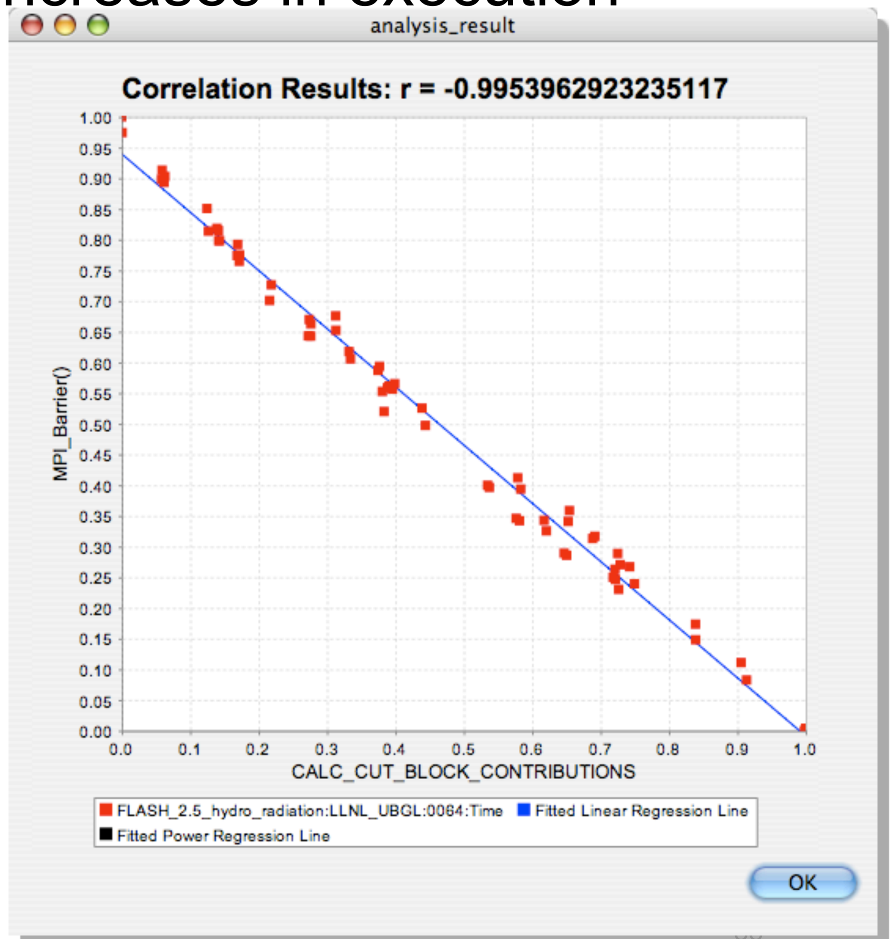


PerfExplorer – Correlation Analysis

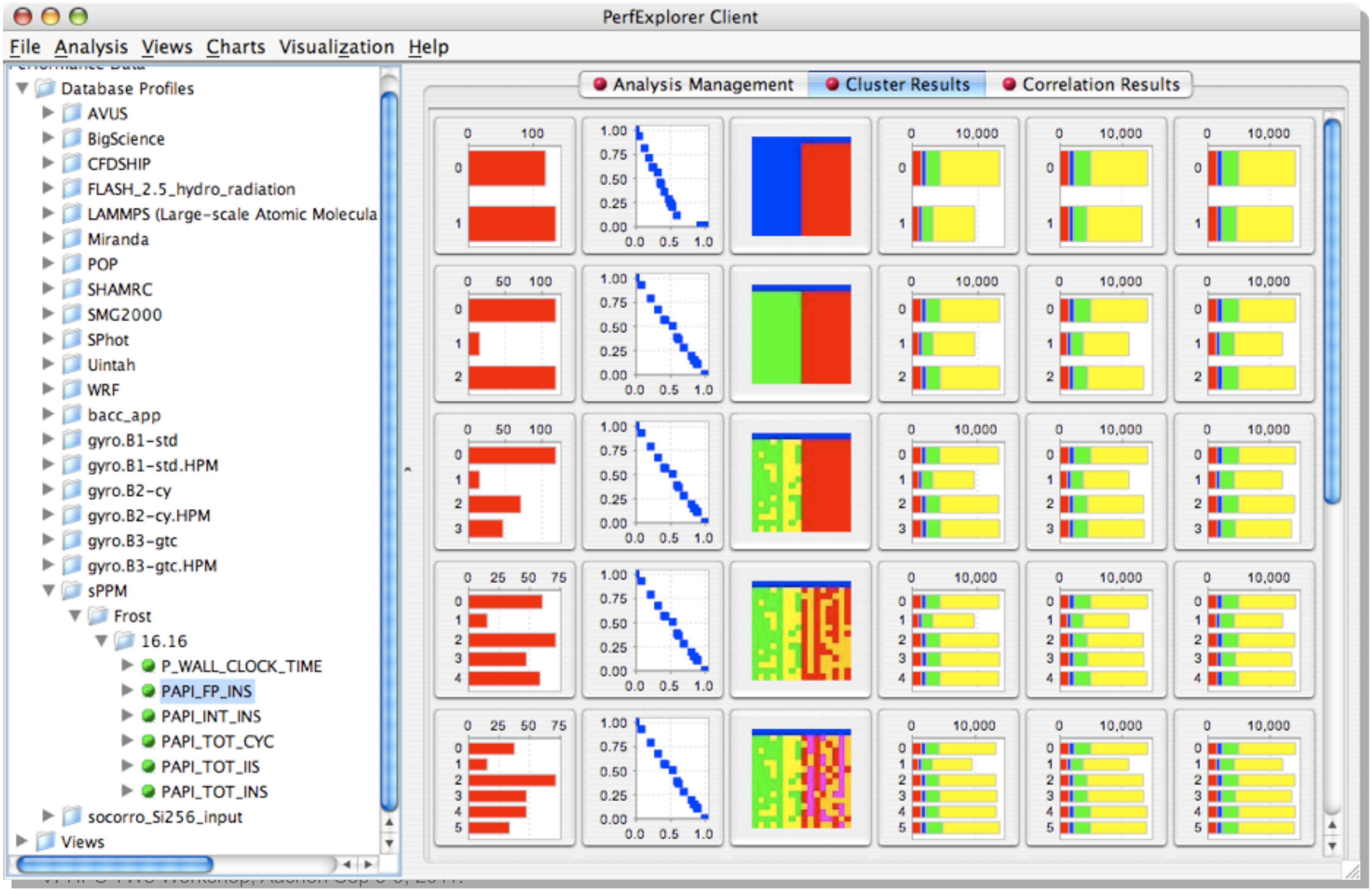


PerfExplorer – Correlation Analysis

- -0.995 indicates strong, negative relationship
- As CALC_CUT_ BLOCK_CONTRIBUTIONS() increases in execution time, MPI_Barrier() decreases

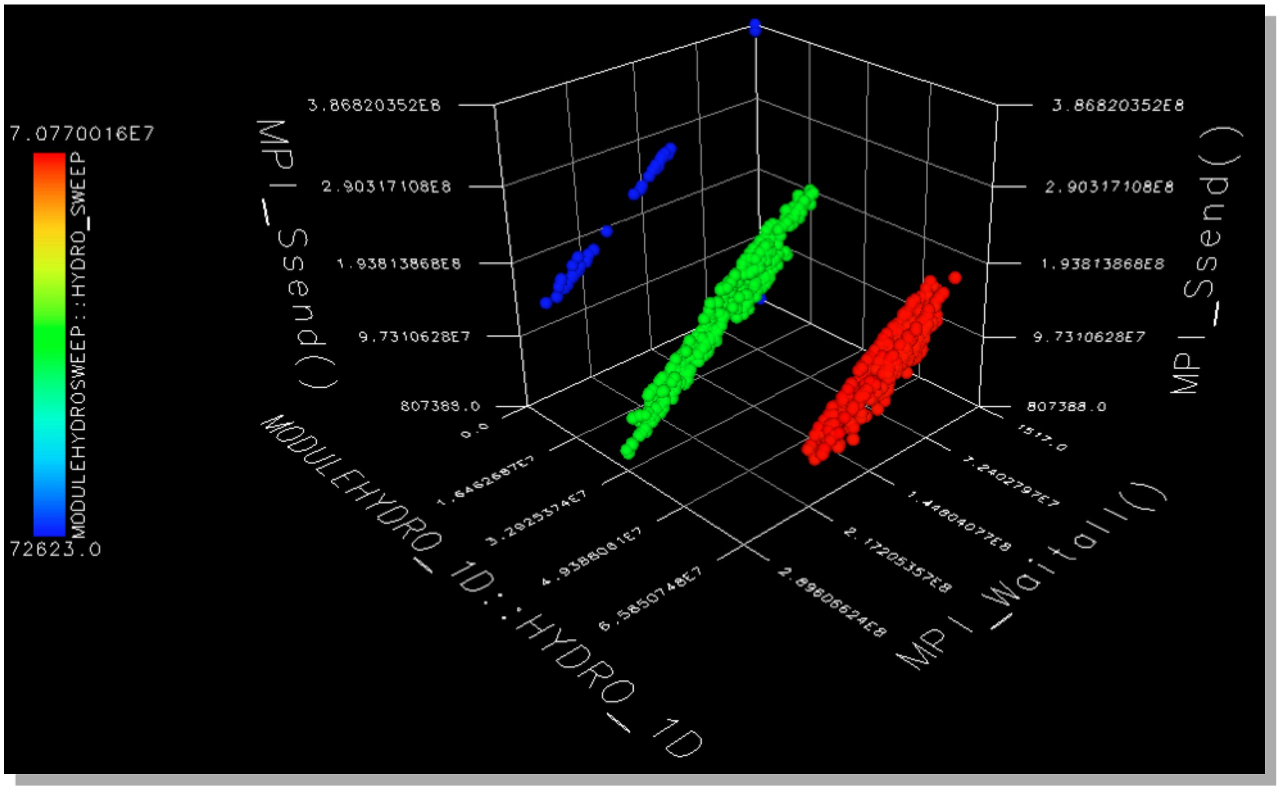


PerfExplorer – Cluster Analysis

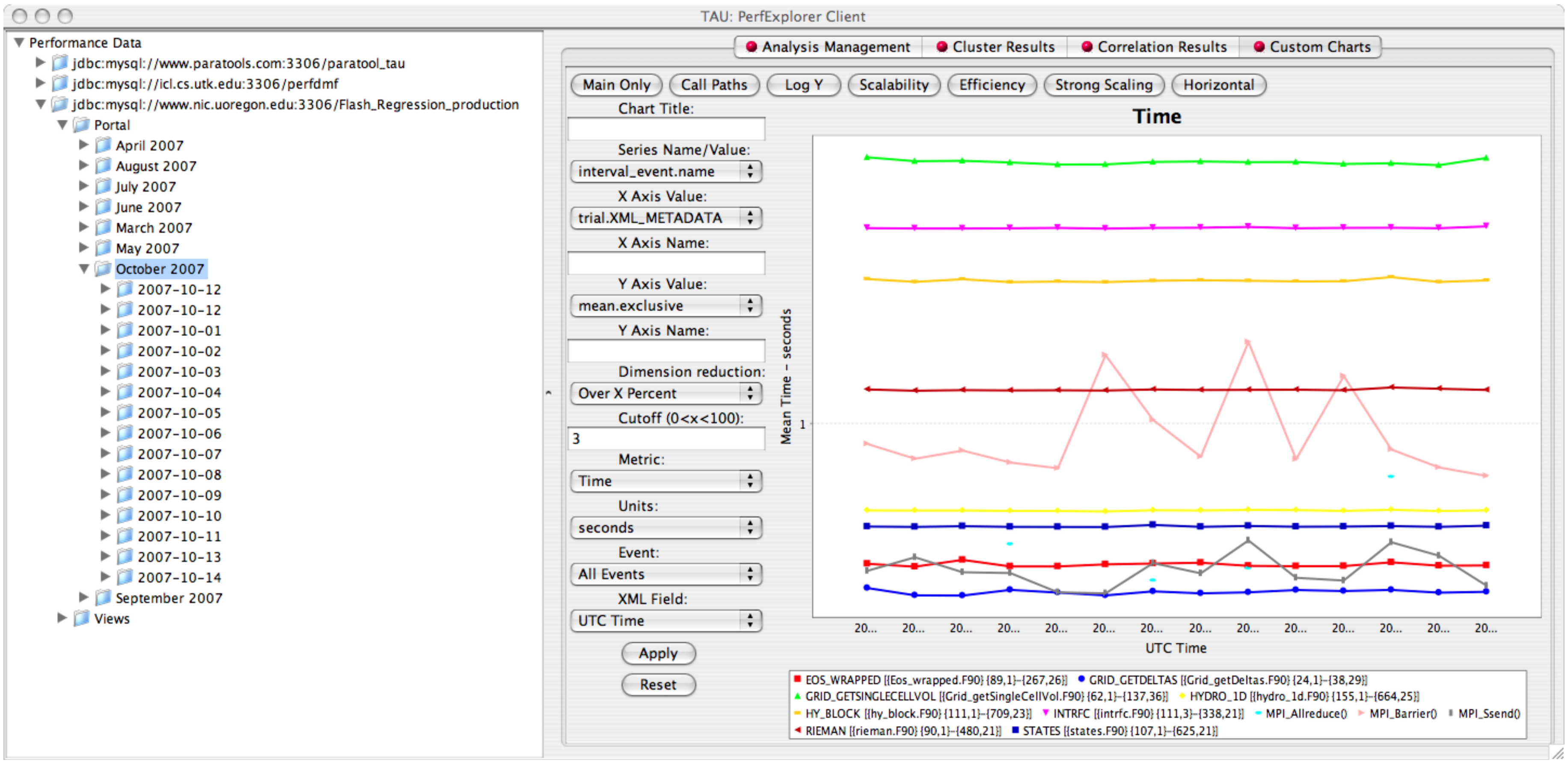


PerfExplorer – Cluster Analysis

- Four significant events automatically selected
- Clusters and correlations are visible

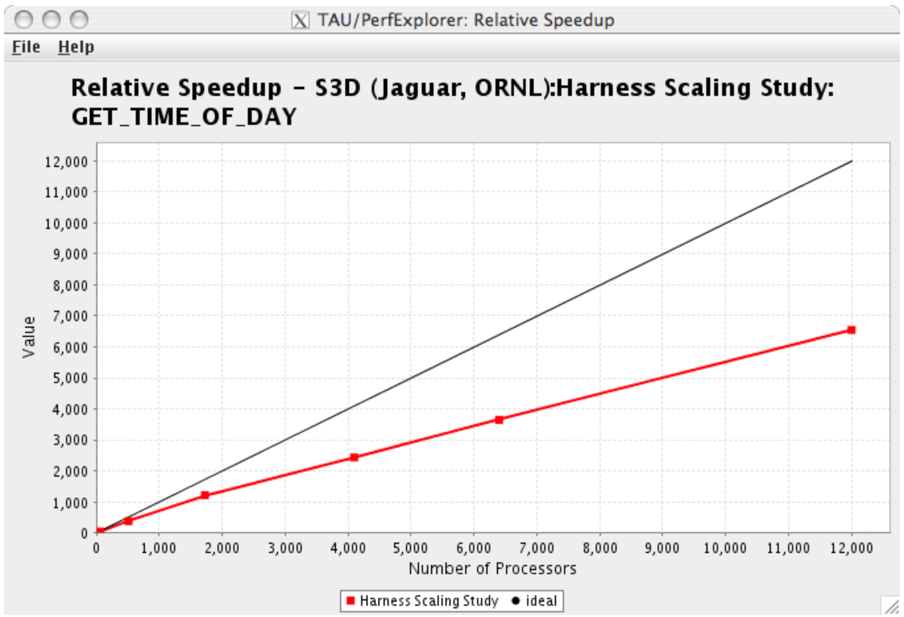


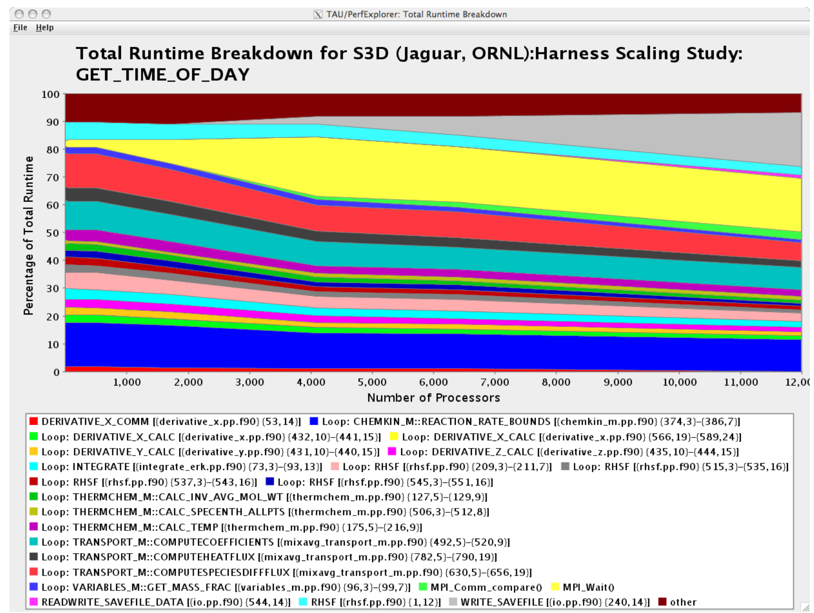
PerfExplorer – Performance Regression



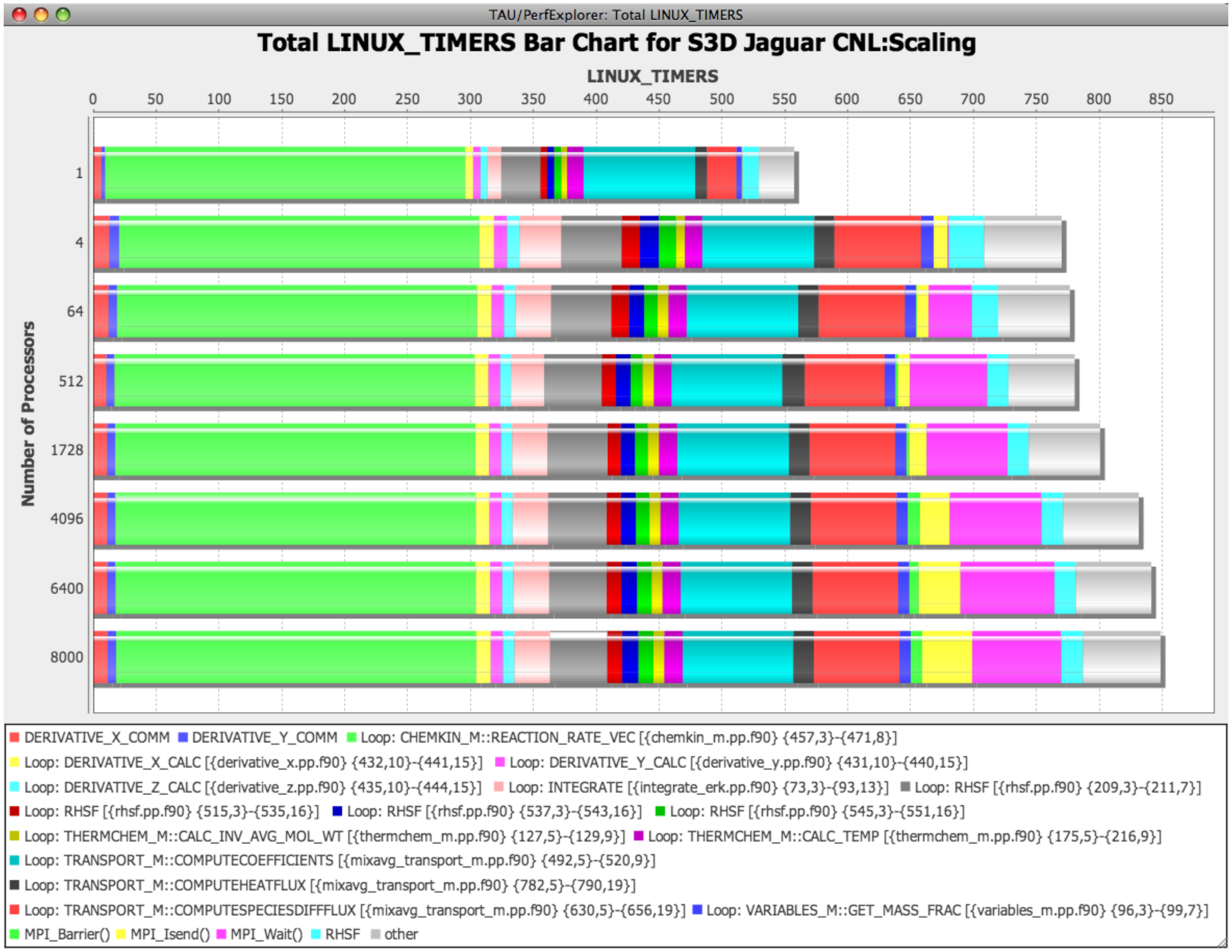
Usage Scenarios: Evaluate Scalability

- Goal: How does my application scale? What bottlenecks at what CPU counts?
- Load profiles in PerfDMF database and examine with PerfExplorer

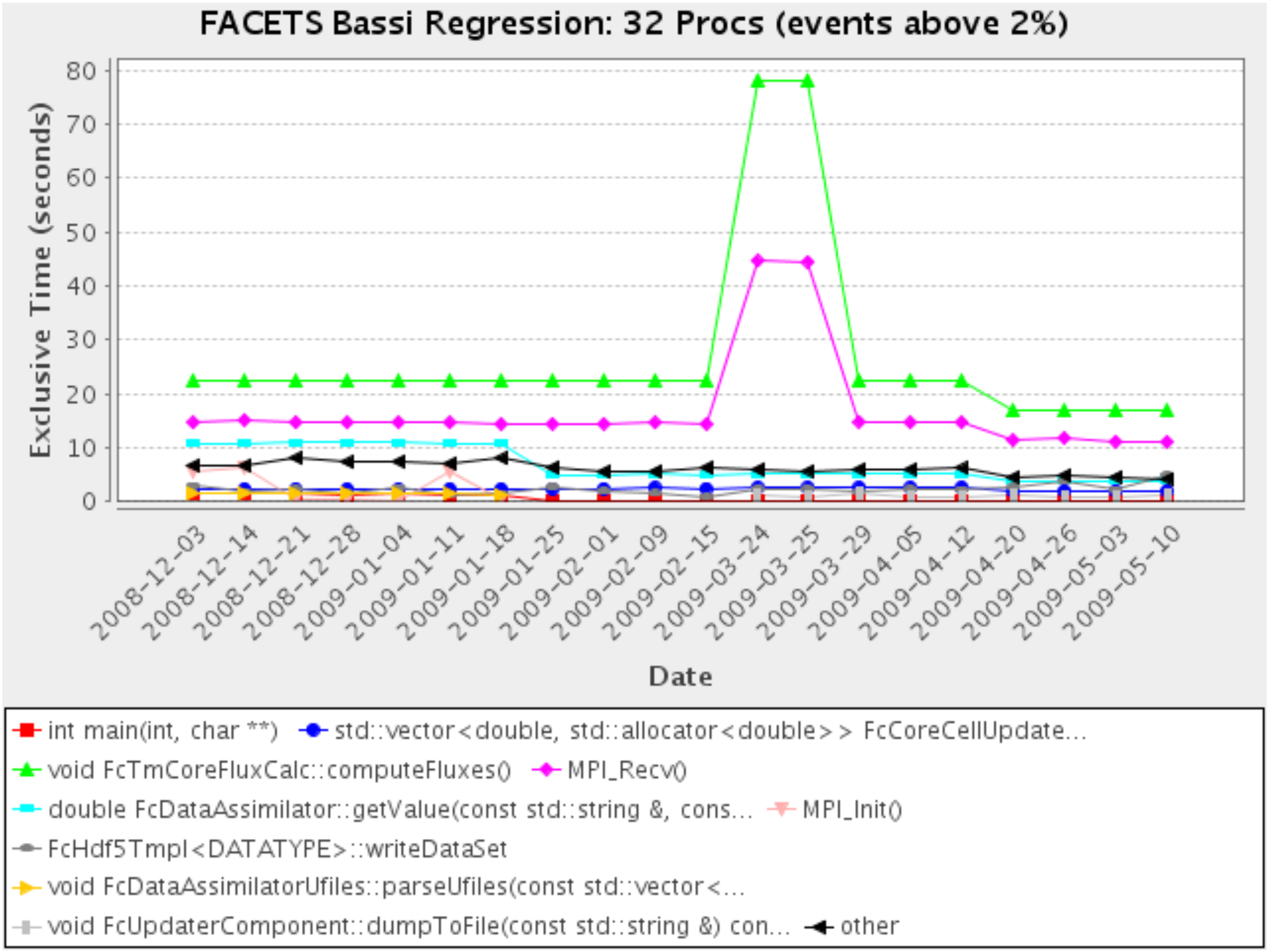




Usage Scenarios: Evaluate Scalability



Performance Regression Testing



Evaluate Scalability using PerfExplorer Charts

```
% export TAU_MAKEFILE=<taudir>/<arch>
                /lib/Makefile.tau-mpi-pdt
% export PATH=<taudir>/<arch>/bin:$PATH
% make F90=tau_f90.sh
(Or edit Makefile and change F90=tau_f90.sh)
% qsub  run1p.job
% paraprof --pack 1p.ppk
% qsub  run2p.job …
% paraprof --pack 2p.ppk … and so on.
On your client:
% perfdmf_configure
(Choose derby, blank user/passwd, yes to save passwd, defaults)
% perfexplorer_configure
(Yes to load schema, defaults)
% paraprof
(load each trial: DB -> Add Trial -> Type (Paraprof Packed
Profile) -> OK, OR use perfdmf_loadtrial on the commandline)
% perfexplorer
(Charts -> Speedup)
```

Other Projects in TAU

- TAU Portal
  - Support collaborative performance study
- Kernel-level system measurements (KTAU)
  - Application to OS noise analysis and I/O system analysis
- TAU performance monitoring
  - TAUoverSupermon and TAUoverMRNet
- PerfExplorer integration and expert-based analysis
  - OpenUH compiler optimizations
  - Computational quality of service in CCA
- Eclipse CDT and PTP integration
- Performance tools integration (NSF POINT project)

Support Acknowledgements

- US Department of Energy (DOE)
  - Office of Science contracts
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  - LLNL-LANL-SNL ASC/NNSA contract
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- T.U. Dresden, GWT
  - Dr. Wolfgang Nagel and Dr. Andreas Knupfer
- Research Centre Juelich
  - Dr. Bernd Mohr, Dr. Felix Wolf
    Dr. Markus Geimer, Dr. Brian Wylie

For more information

- TAU Website:
  http://tau.uoregon.edu
  - Software
  - Release notes
  - Documentation