Improving Application Performance Using the TAU Performance System

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http://www.paratools.com/sea13

TAU Performance System®

http://tau.uoregon.edu/

- **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**

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?

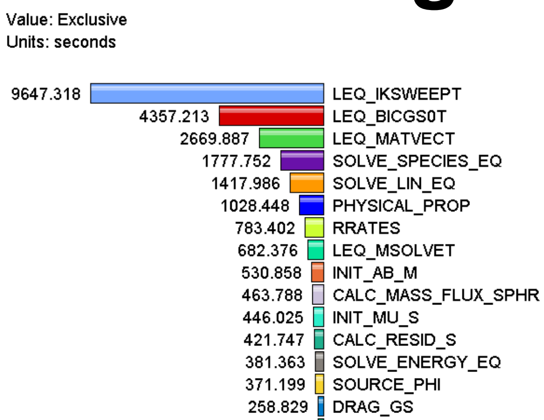
What Can TAU Do?

- **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
- **Multi-language debugging**
  - Identify the source location of a crash by unwinding the system callstack
  - Identify memory errors (off-by-one, etc.)

- 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 **all HPC platforms** and it is free (BSD style license)
- TAU includes instrumentation, measurement and analysis tools

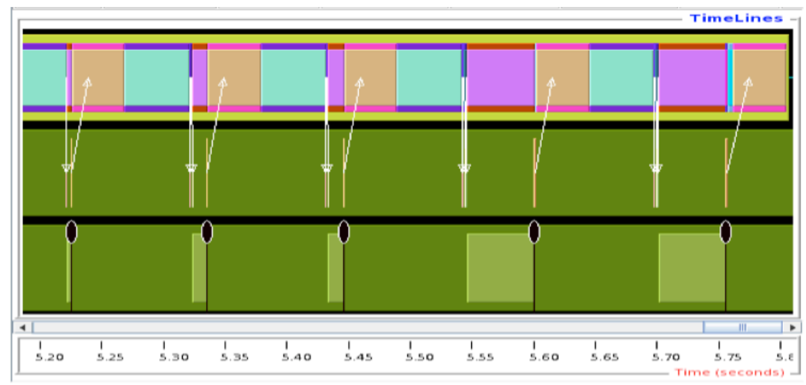
Profiling and Tracing

Profiling



- **Profiling** shows you how much (total) time was spent in each routine

Tracing



- **Tracing** shows you *when* the events take place on a timeline

- Metrics can be time or hardware performance counters (cache misses, instructions)
- TAU can automatically instrument your source code using a package called PDT for routines, loops, I/O, memory, phases, etc.

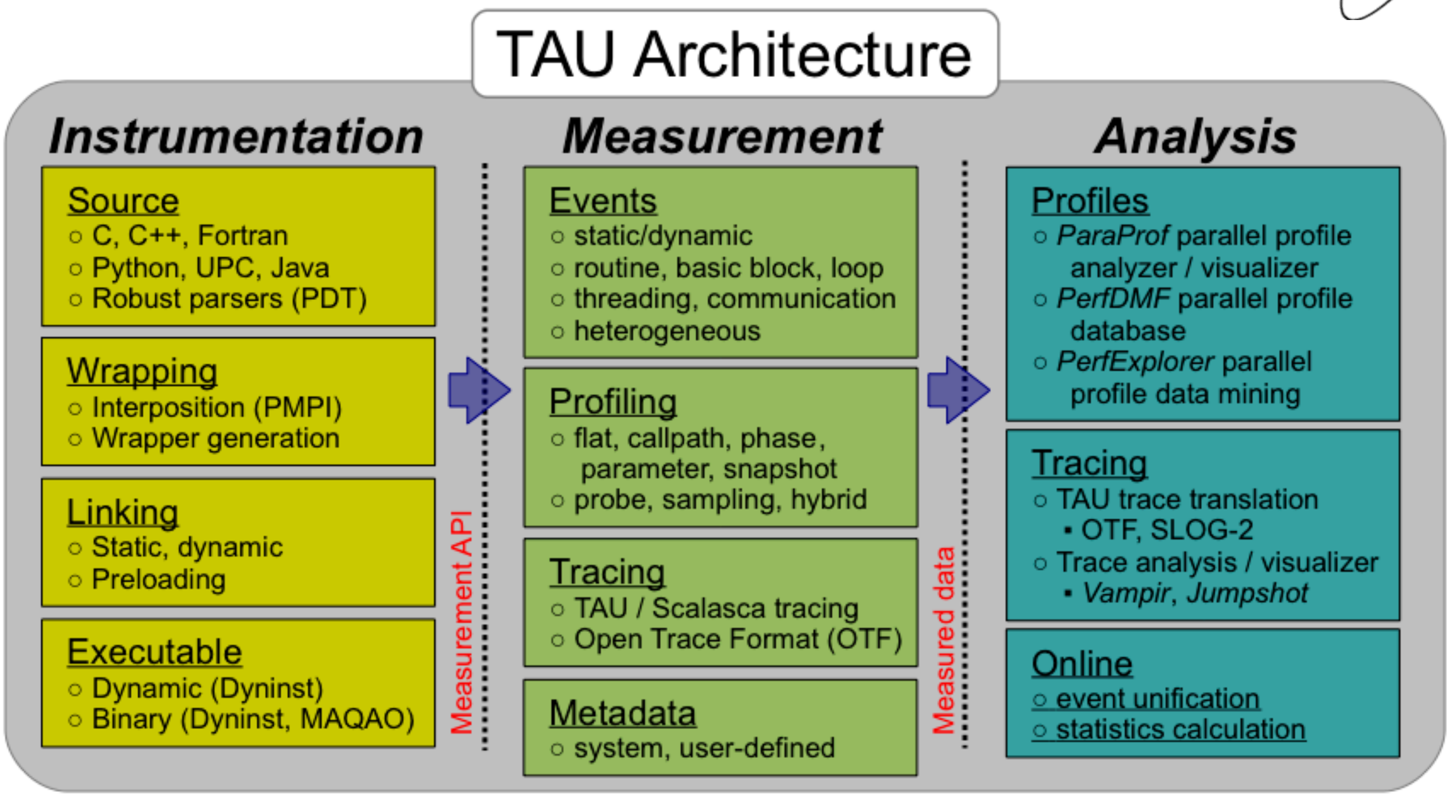
What does TAU support?

C/C++ CUDA UPC OpenCL Python GPI Fortran OpenACC Java MPI pthreads Intel MIC OpenMP Intel GNU LLVM PGI Cray Sun MinGW AIX Linux Windows

Insert yours here

BlueGene Fujitsu ARM NVIDIA Kepler OS X

The TAU Architecture



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)

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

Interval and Atomic Events in TAU

```
xterm
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 show ***duration***

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

% export TAU_CALLPATH_DEPTH=0
% export TAU_TRACK_HEAP=1

Context Events with Callpath

```
NODE 0;CONTEXT 0;THREAD 0:
---------------------------------------------------------------------------------------
%Time    Exclusive    Inclusive       #Call      #Subrs  Inclusive Name
              msec   total msec                          usec/call
---------------------------------------------------------------------------------------
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%
```

% export TAU_CALLPATH_DEPTH=2
% export TAU_TRACK_HEAP=1

Callpath shown on context events

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

Automatic Instrumentation

- **Use TAU's compiler wrappers**
  - Simply replace `CXX` with `tau_cxx.sh, etc.`
  - Automatically instruments source code, links with TAU libraries.
- **Use `tau_cc.sh` for C, `tau_f90.sh` for Fortran, `tau_upc.sh` for UPC, etc.**

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 $<
```

Binary Rewriting Instrumentation

- Support for **Intel, PGI, and GNU** compilers
- Specify a list of routines to instrument
- Specify the TAU measurement library to be injected
- **DyninstAPI**:

```
% tau_run -T [tags] a.out -o a.inst
```

- **MAQAO**:

```
% tau_rewrite -T [tags] a.out -o a.inst
```

- **Pebil**:

```
% tau_pebil_rewrite -T [tags] a.out \
  -o a.inst
```

- Execute the application to get measurement data:

```
% mpiexec ./a.inst
```

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

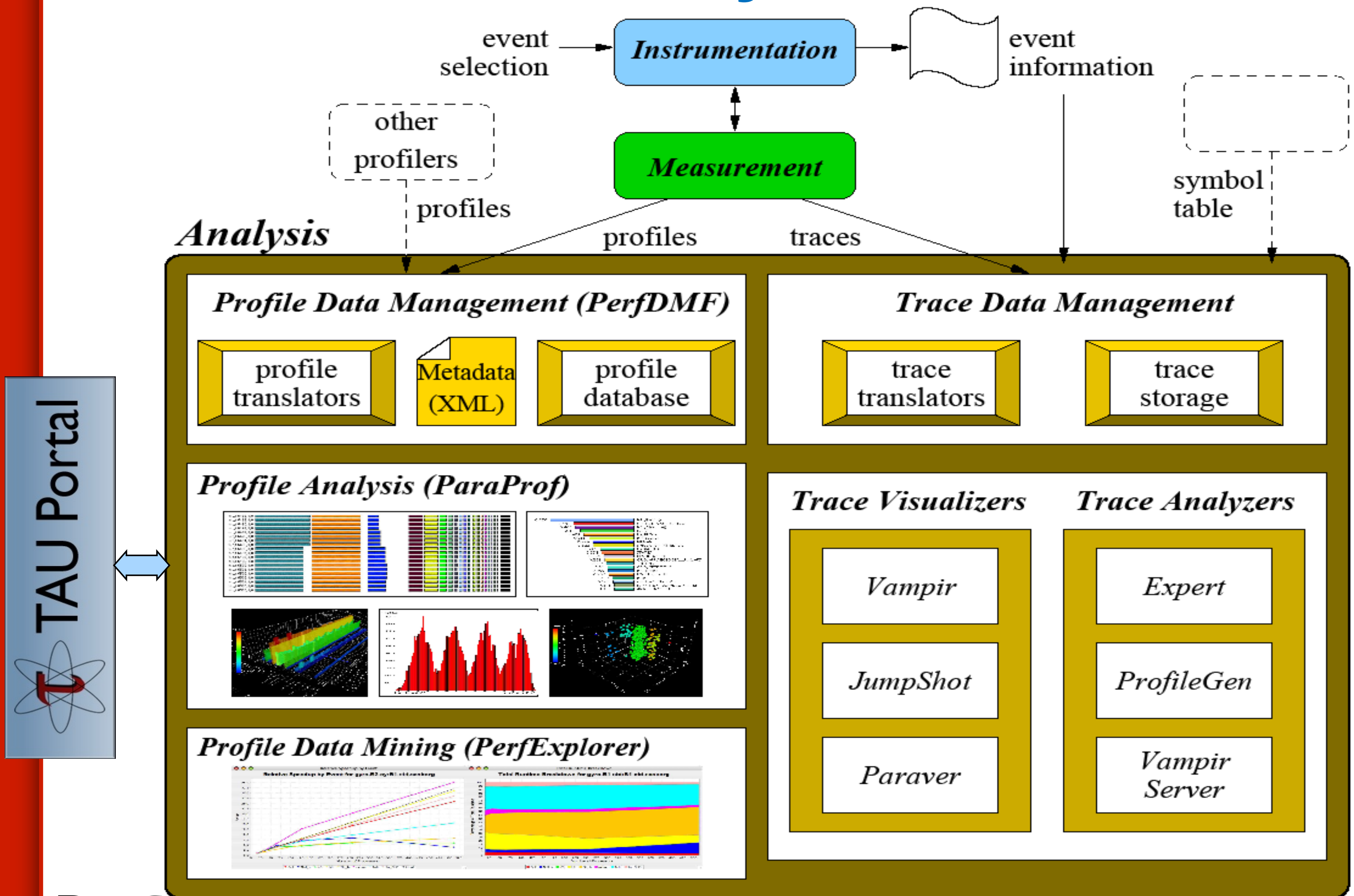
Preloading a library at runtime

- 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

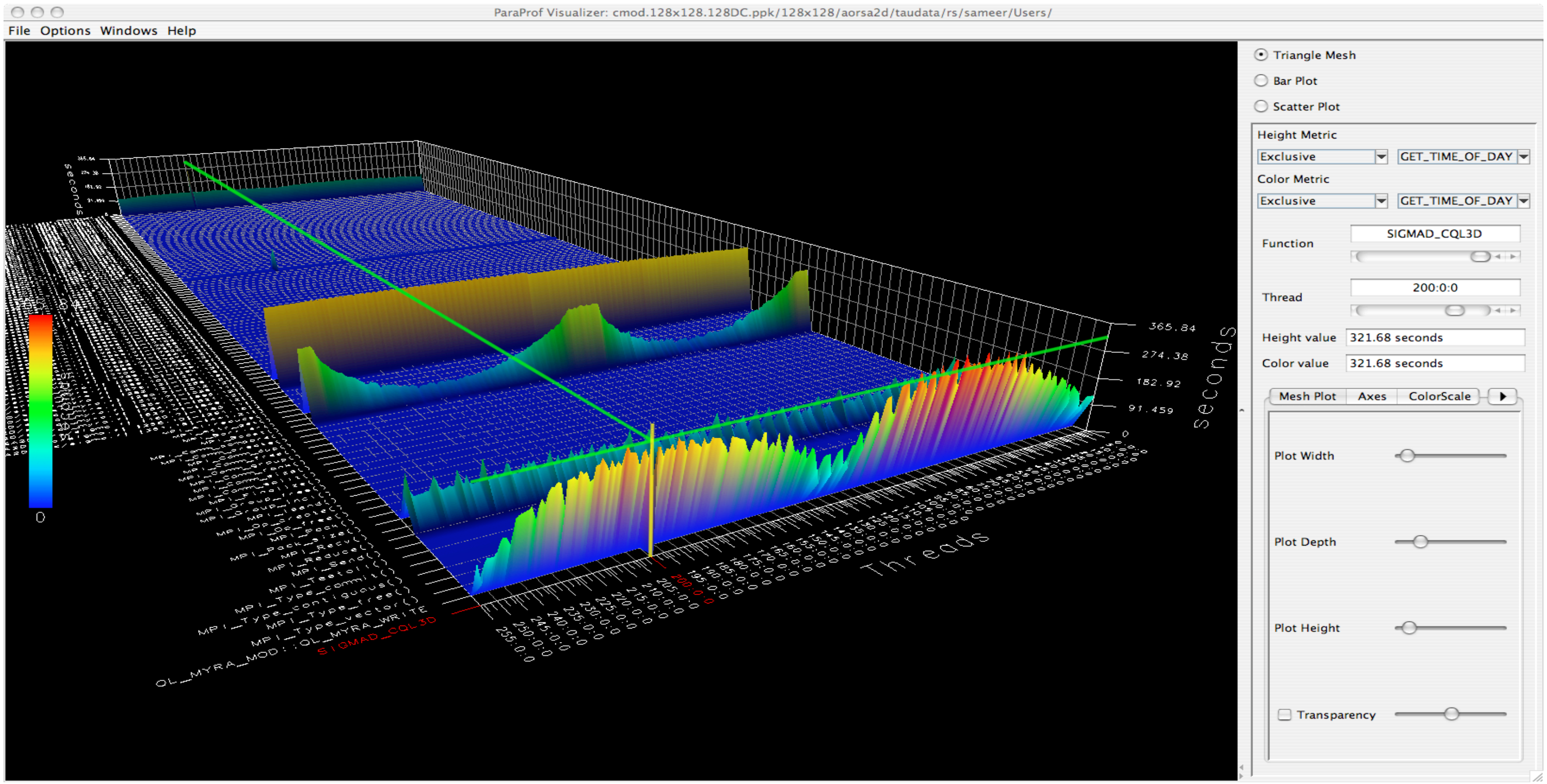
Linker based substitution

- 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

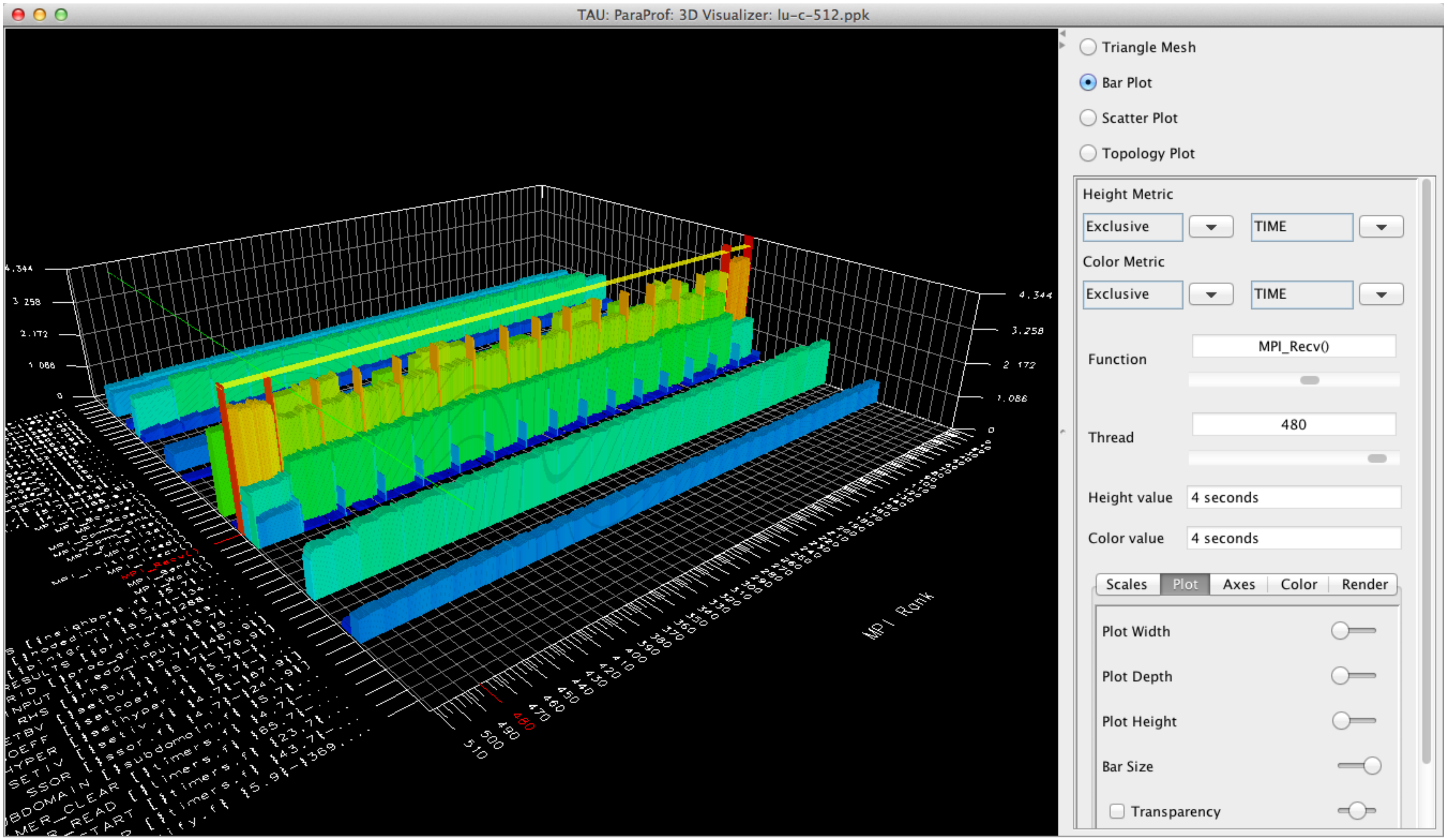
Performance Analysis



ParaProf 3D Profile Browser

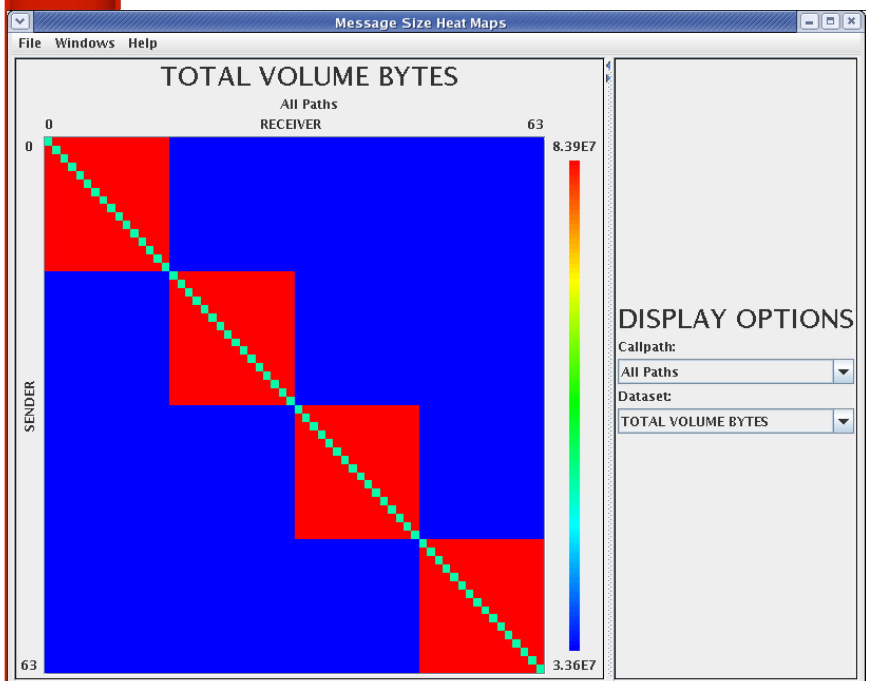


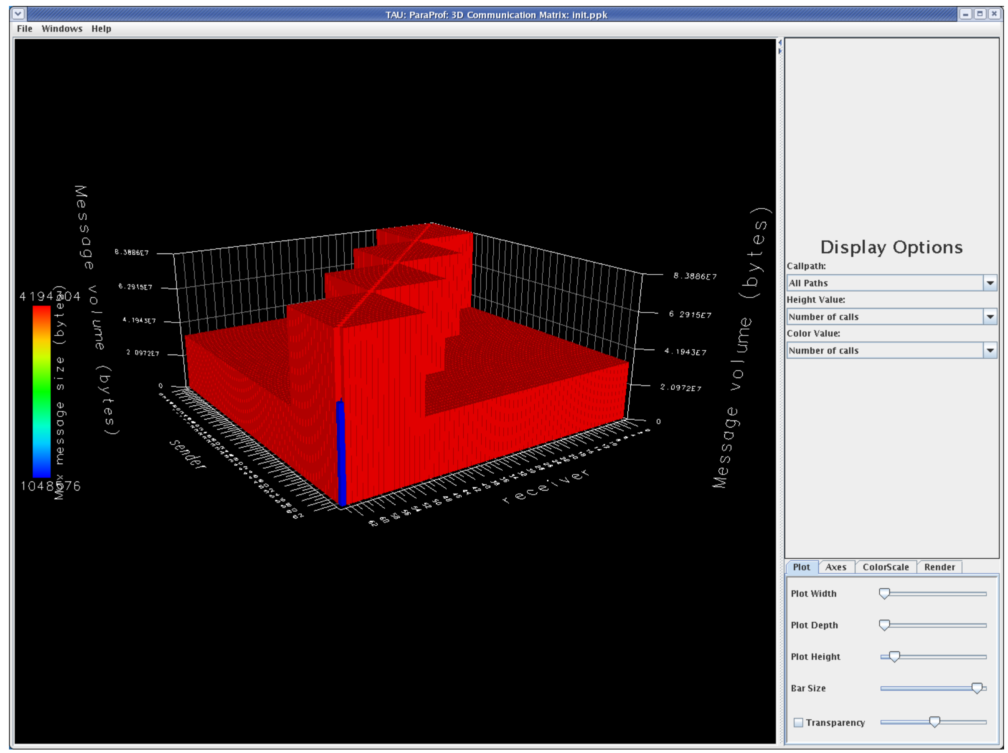
ParaProf 3D Profile Browser



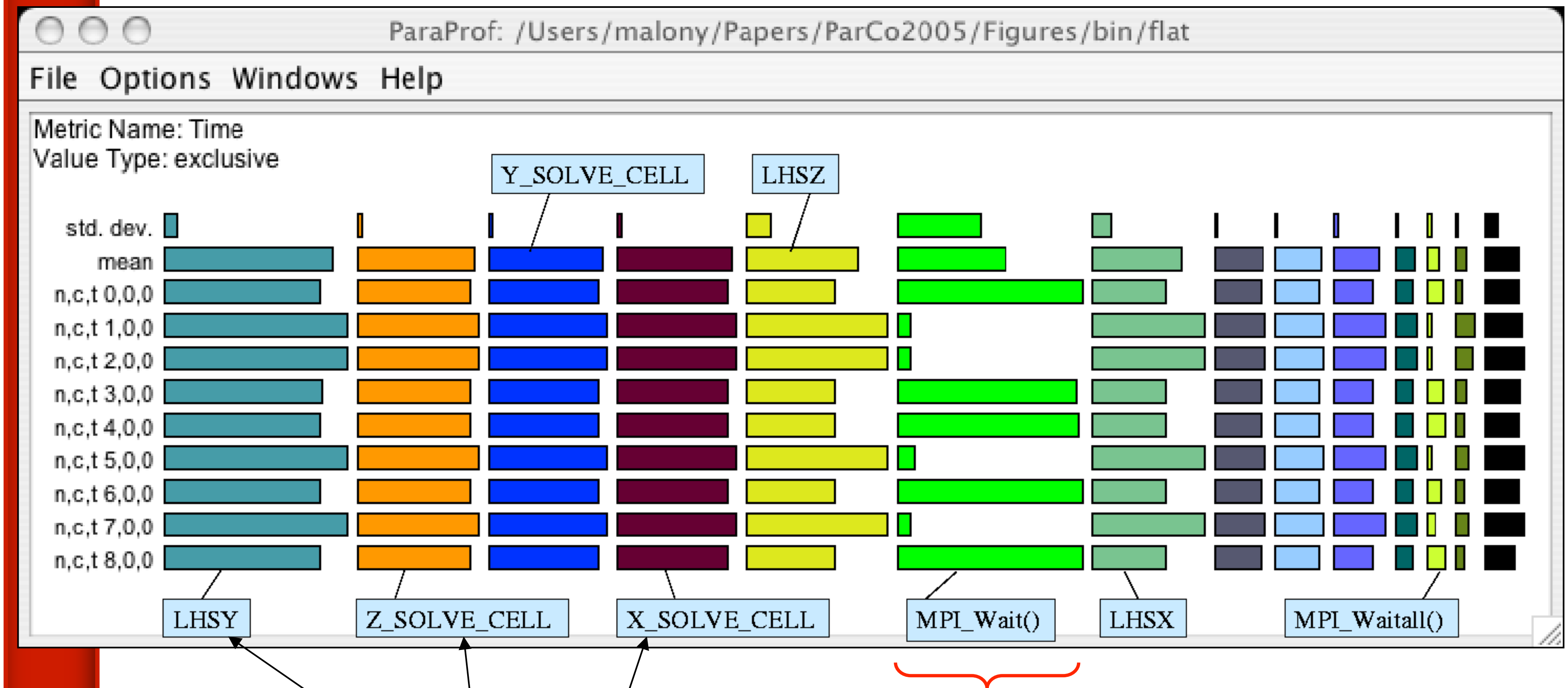
Communication Matrix Display

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





NAS BT – Flat Profile

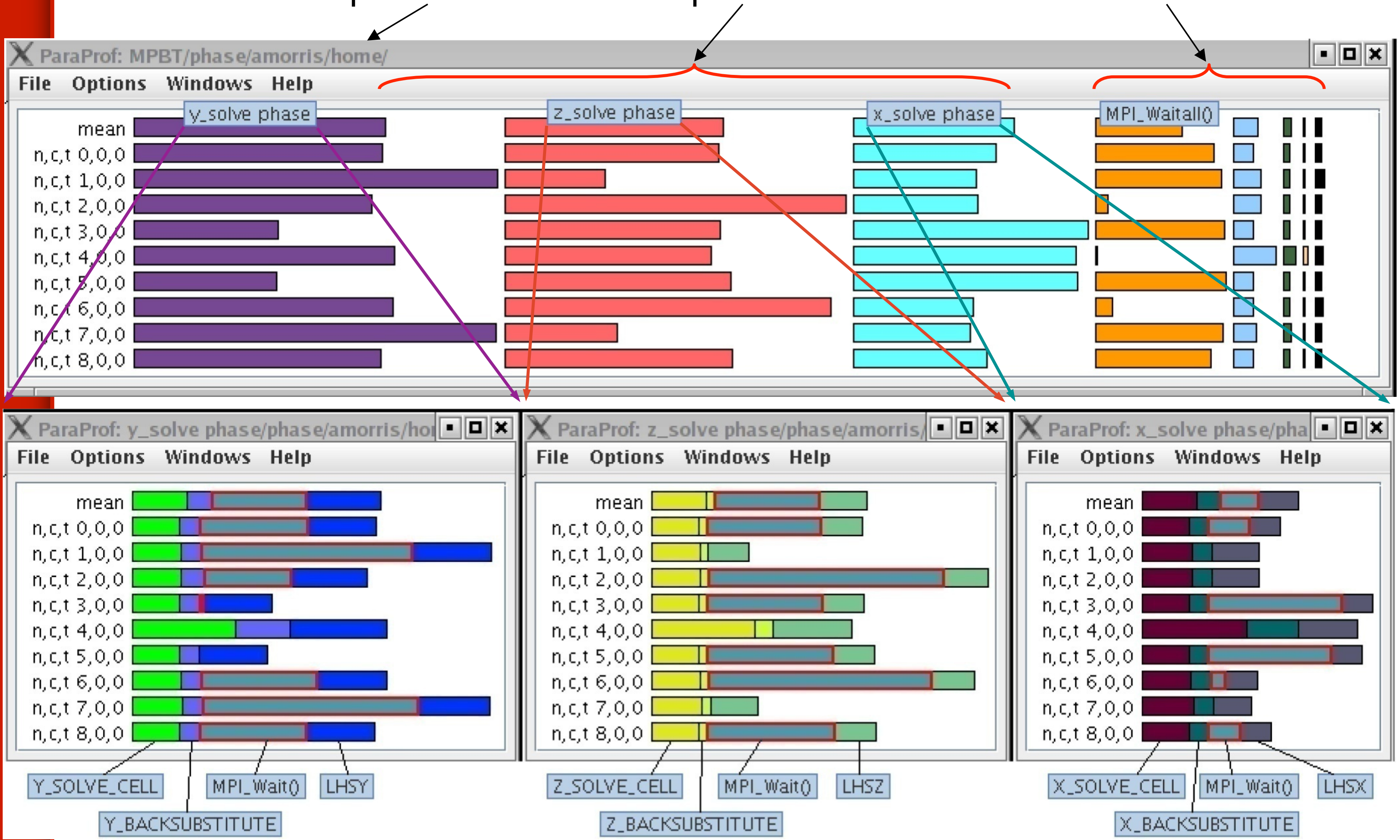


Application routine names reflect phase semantics

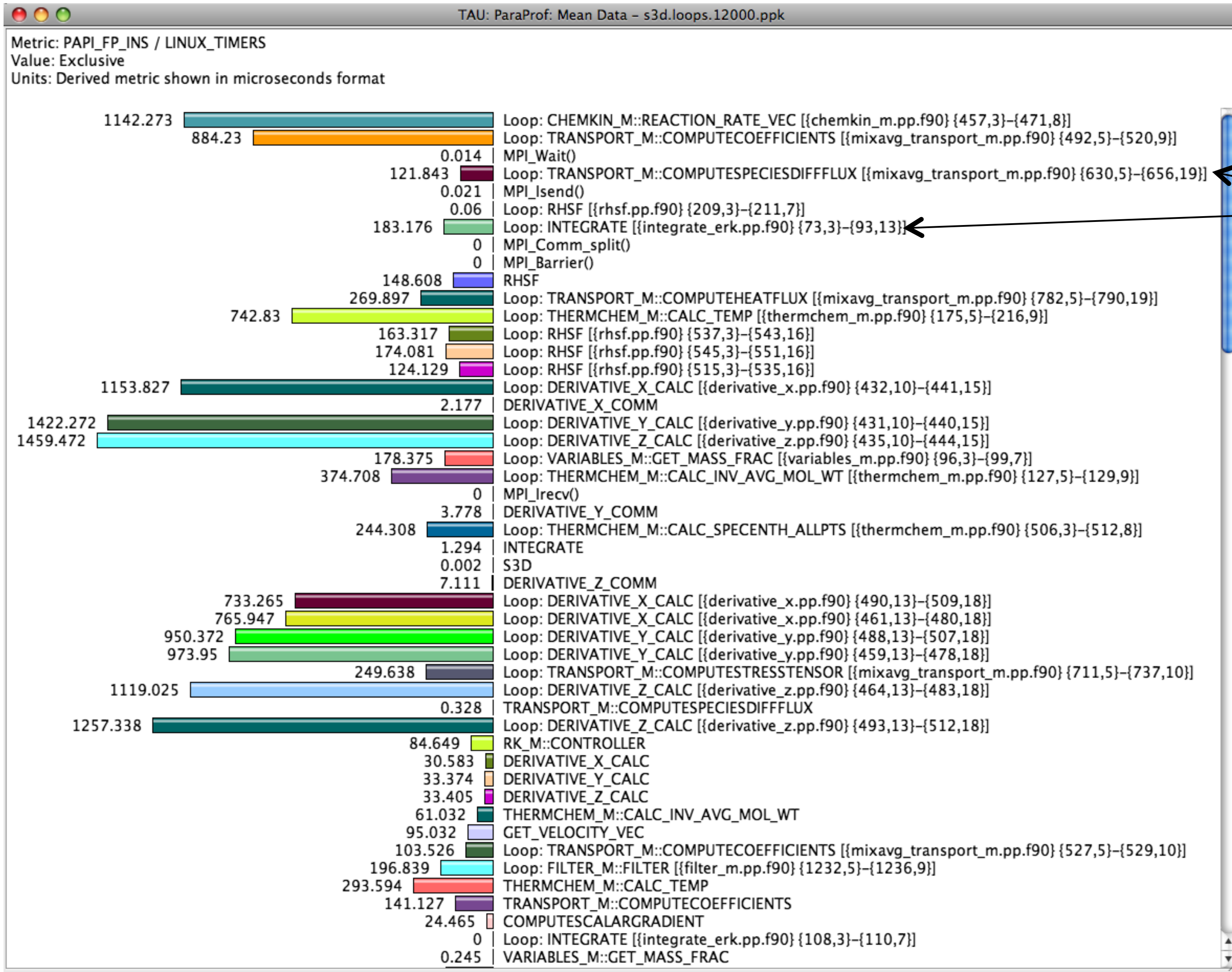
How is MPI_Wait() distributed relative to solver direction?

NAS BT – Phase Profile

Main phase shows nested phases and immediate events



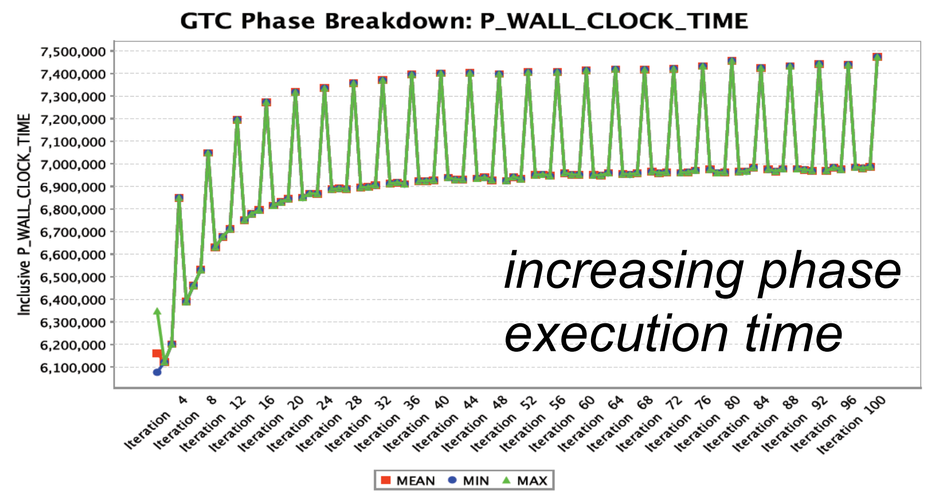
Derived Metrics Help Identify Potential Bottlenecks

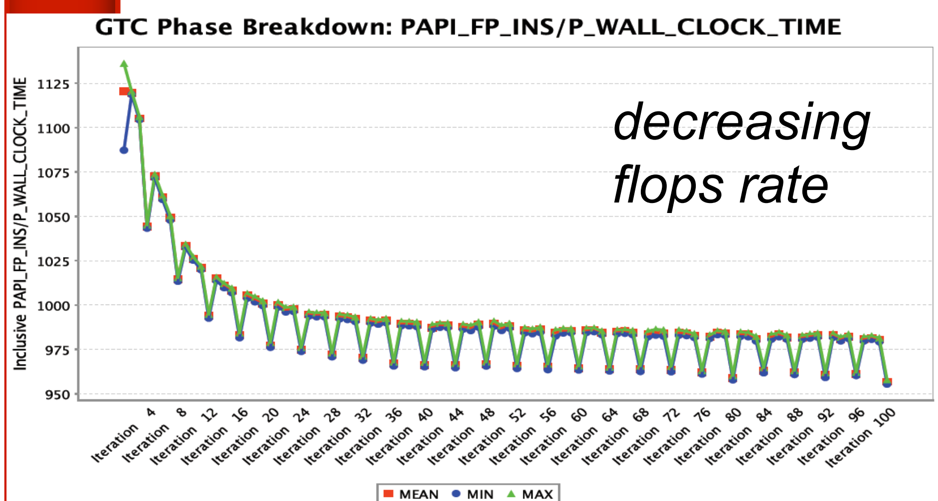


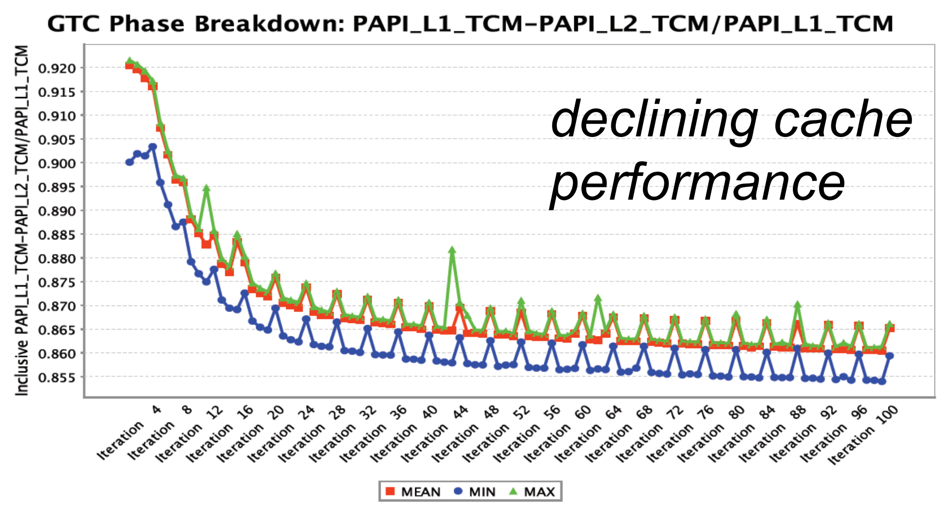
Low MFLOPS in loops?

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







Using TAU: Simplest Case

Uninstrumented code:

- % mpirun.lsf ./a.out

With TAU:

- % module load workshop tau
- % mpirun.lsf tau_exec ./a.out
- % paraprof

Come to the tutorial Thursday and Friday!

Download TAU from U. Oregon

http://tau.uoregon.edu

http://www.hpclinux.com [LiveDVD]

Free download, open source, BSD license

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