Isolating Runtime Faults with Callstack Debugging using TAU

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Outline

- Brief overview of TAU
- Multi-language callstack debugging with TAU
- Design and implementation
- Examples: CREATE-AV Helios and Kestrel
- Summary and conclusions

Brief overview of TAU

Tuning and Analysis Utilities

TAU is a performance evaluation tool

- **TAU supports parallel profiling and tracing**
  - Profiling: *how much time* was spent in each routine
  - Tracing: *when* the events take place in each process
- **TAU can measure hardware performance counters**
- **TAU can automatically instrument your source code**
  - Routines, loops, I/O, memory, phases, etc.
- **TAU runs on all HPC platforms and it is free**
- **TAU has instrumentation, measurement and analysis tools**
  - ParaProf, PerfExplorer, Jumpshot, etc.
- **TAU has performance database technology (TAUdb)**

For more information

Tuning and Analysis Utilities

TAU Website: http://tau.uoregon.edu/

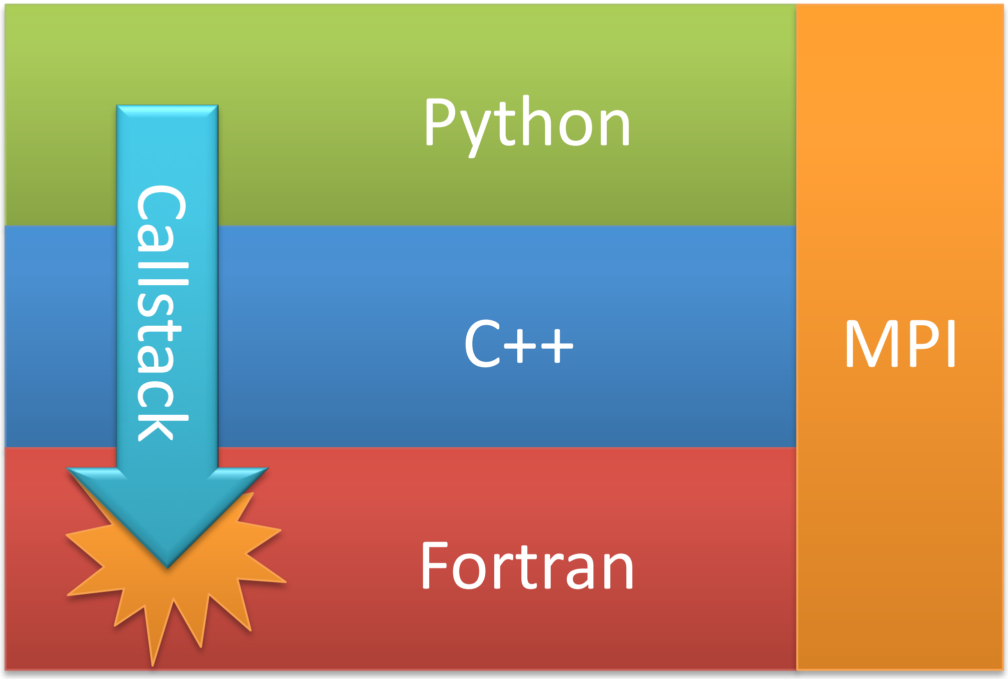
- Software download
- Release notes
- Documentation

TAU LiveDVD: http://www.hpclinux.com/

- Boot up on your laptop or desktop
- Includes TAU and variety of other packages
- Include documentation and tutorial slides

Multi-language callstack debugging with TAU

Segfault! What do you do?



Debugging challenges

- Execution text output rarely sufficient
- Core files aren't much help for 10k processes
- What if the fault occurred in a DSO?
- Most debuggers are monolingual
- Developers need to reproduce the crash to fix it, but program inputs are sensitive or proprietary

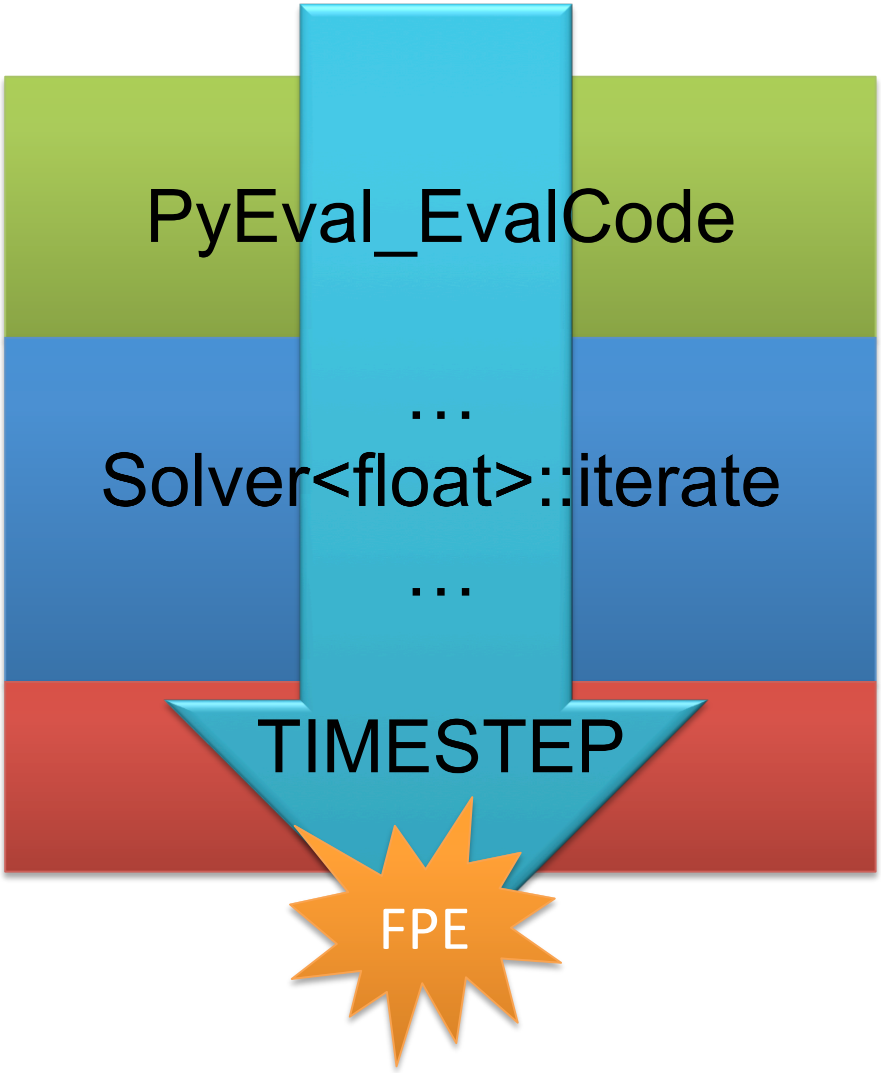
TAU has already solved most of these

- Rich performance information
- Scales to 100k processes and beyond
- Highly efficient packed profile format
- Maintains and updates address maps for DSOs
- C, C++, CUDA, Fortran, UPC, Python, Java, etc.
- With *tau_exec*, recompile not required

TAU callstack debugging has two goals

- **Assist in debugging multi-language applications**
  - Unwind the callstack across C/C++, Fortran, Python, Java, UPC, etc.
  - Explore application performance at all levels
- **Close the loop with developers for more rapid turnaround of bug fixes**
  - Compact, portable, informative reports
  - Independent of sensitive or proprietary inputs

Callstack unwinding is the key to debugging



PyEval_EvalCode

…

Solver<float>::iterate

…

TIMESTEP

aero.py:328

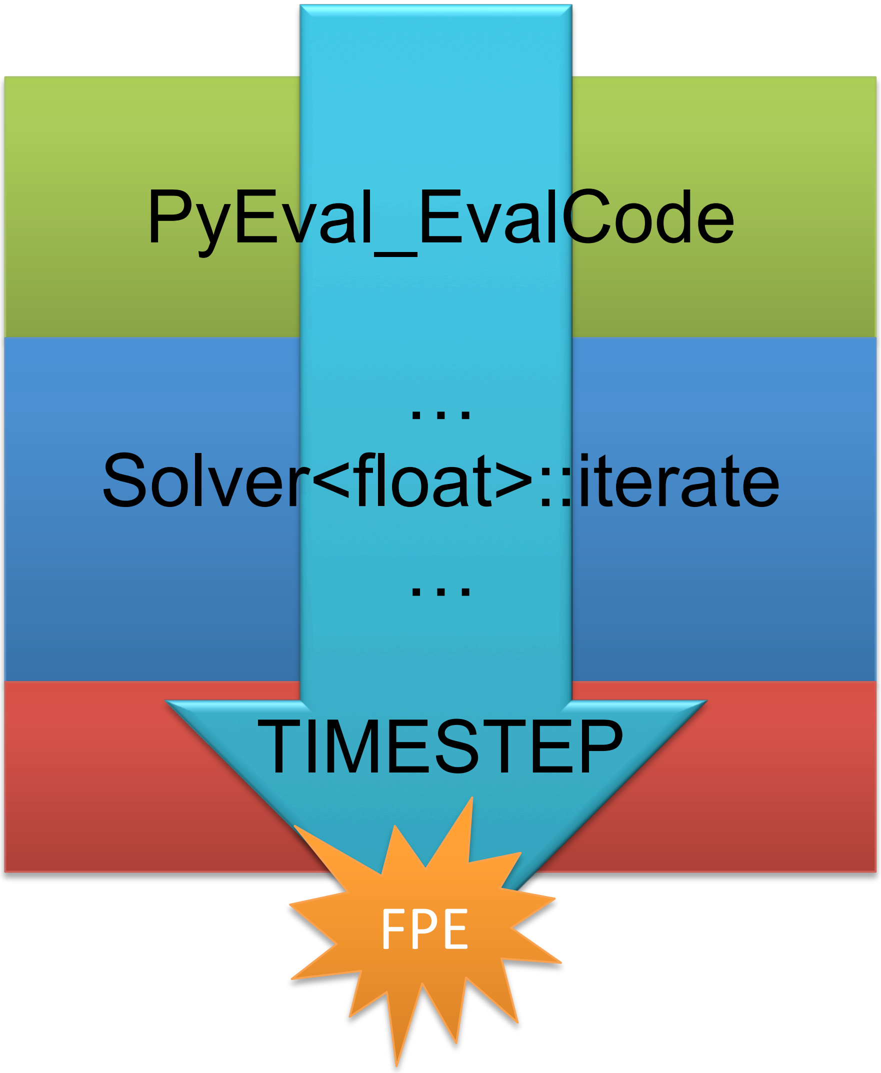
…

Solver.cpp:19

…

JCL1.F:1798

Performance information is retained



PyEval_EvalCode

…

Solver<float>::iterate

…

TIMESTEP

FPE

Started on rank 13

…

MPI_Recv read 451k

…

Allocated 3298k heap

954s runtime

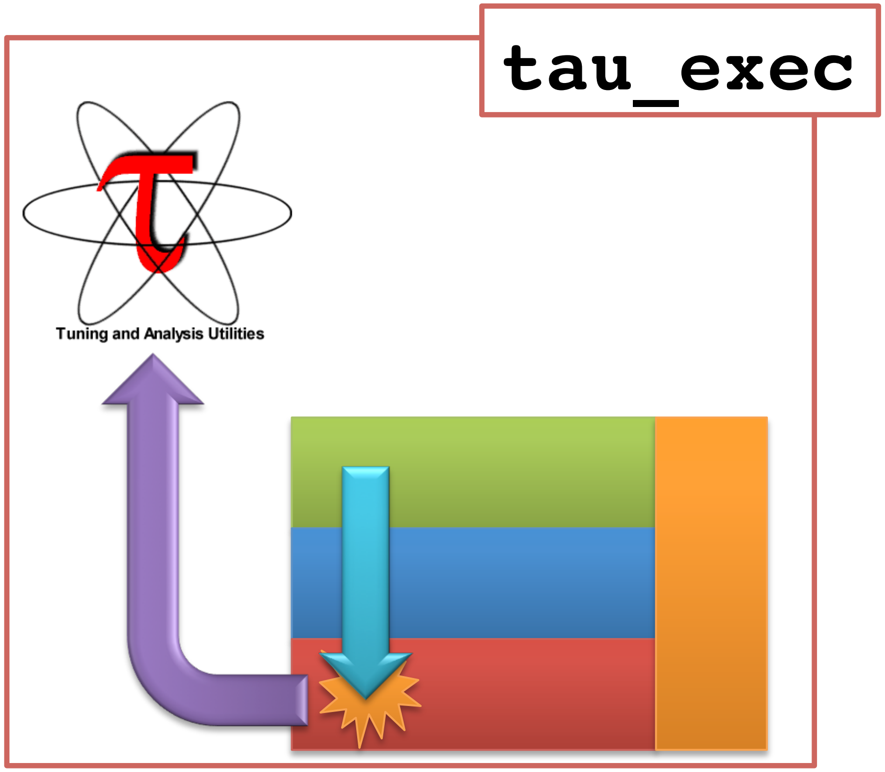
The debugger can answer these questions

1. Where and when did the program fail?
2. What was the nature of the fault?
3. What was the application's heap memory utilization?
4. Where there any memory leaks in the application?
5. What were the application's performance characteristics?
6. How much time did the application spend in I/O and communication operations?

Design and Implementation

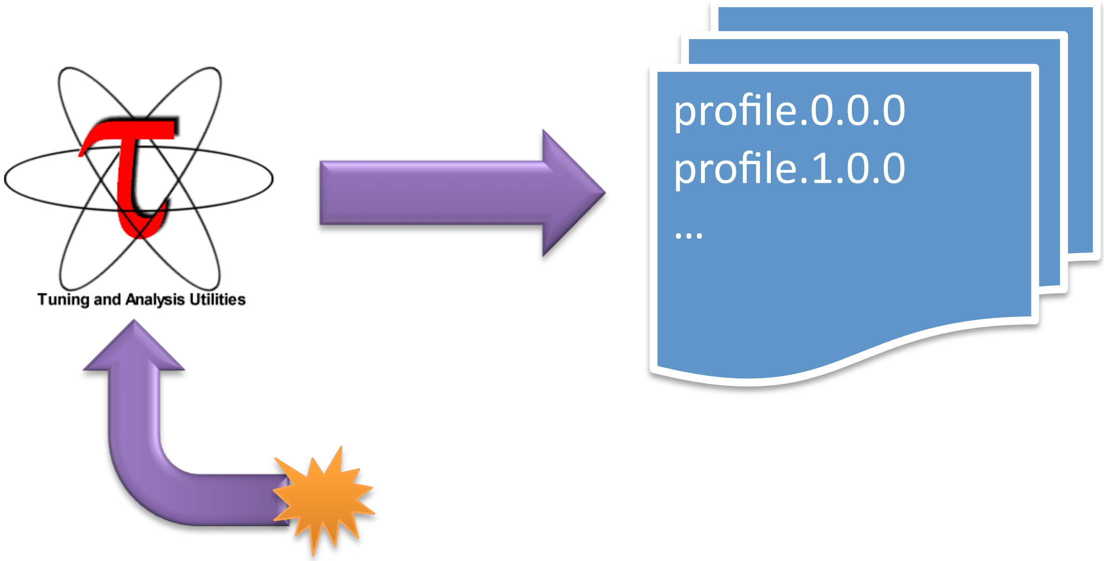
Signal handler intercepts the fault signal

- export TAU_TRACK_SIGNALS=1
- *tau_exec* registers a signal handler
- Error signal triggers callstack unwind



TAU unwinds the callstack of each thread

- **GLIBC backtrace API and GNU binutils determine routine name, file name, source line number**
- **A profile file is created for each thread**



profile.0.0.0
profile.1.0.0
…

TAU orchestrates a graceful shutdown

- Profile files containing diagnostic information are created for all threads, healthy or otherwise
- Healthy threads exit gracefully

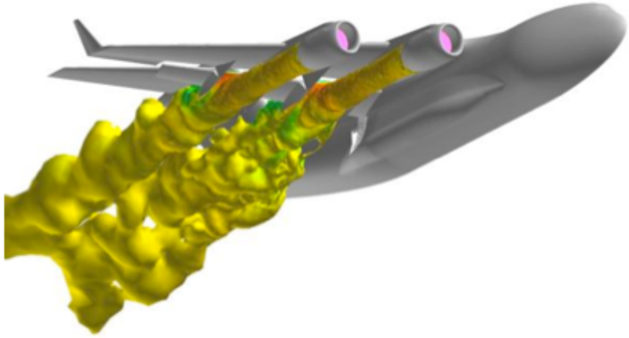
Examples:
CREATE-AV Helios and Kestrel

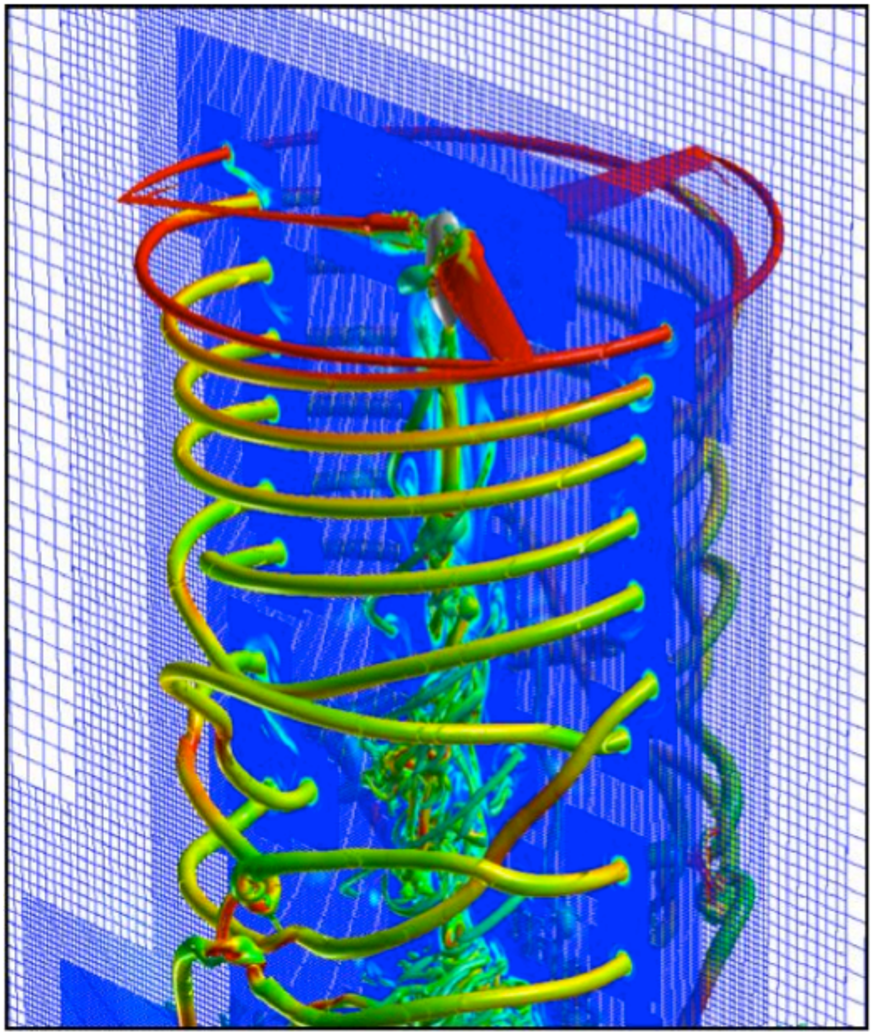
CREATE-AV Helios and Kestrel

CREATE
Computational Research & Engineering Acquisition Tools & Environments

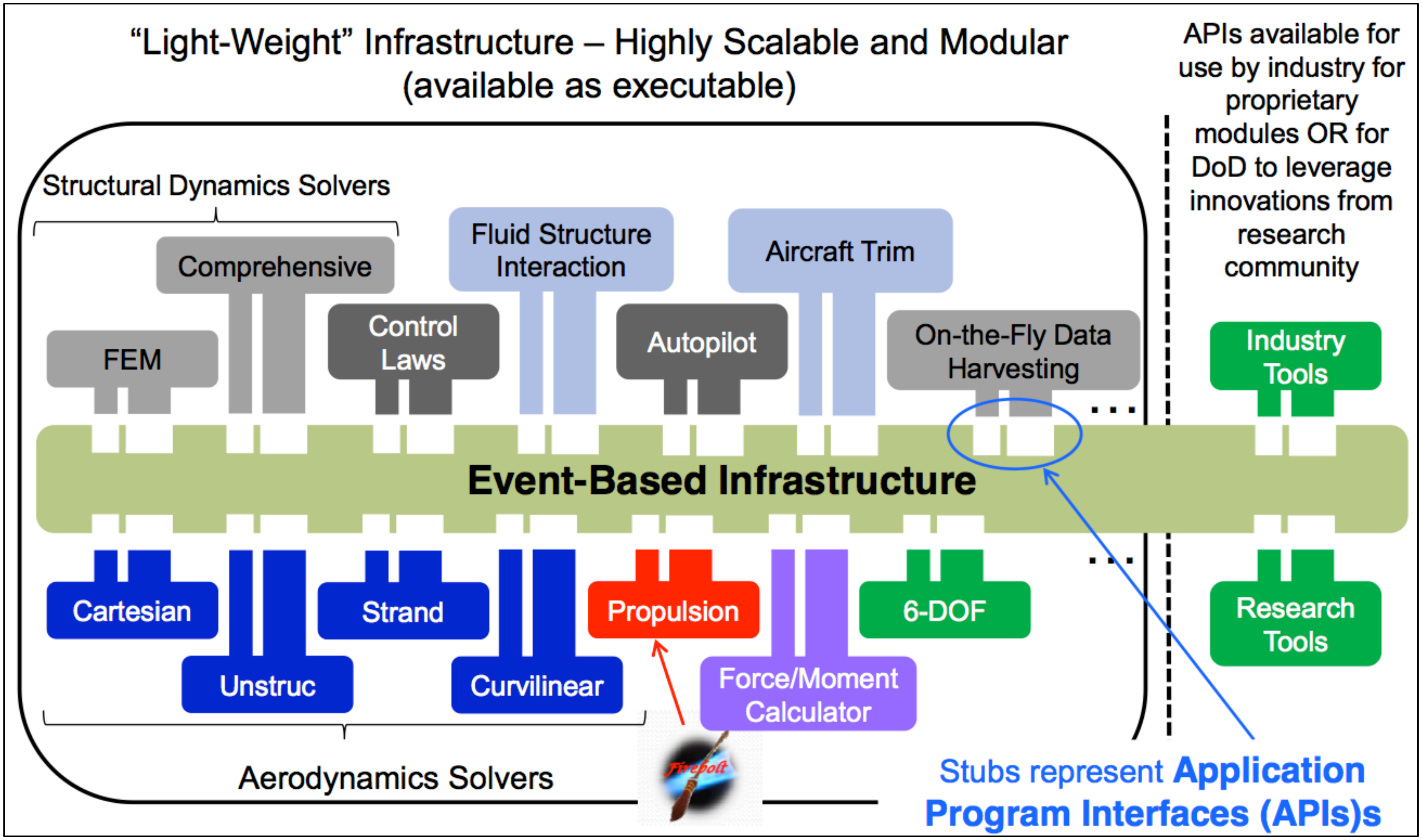
Kestrel

Helios

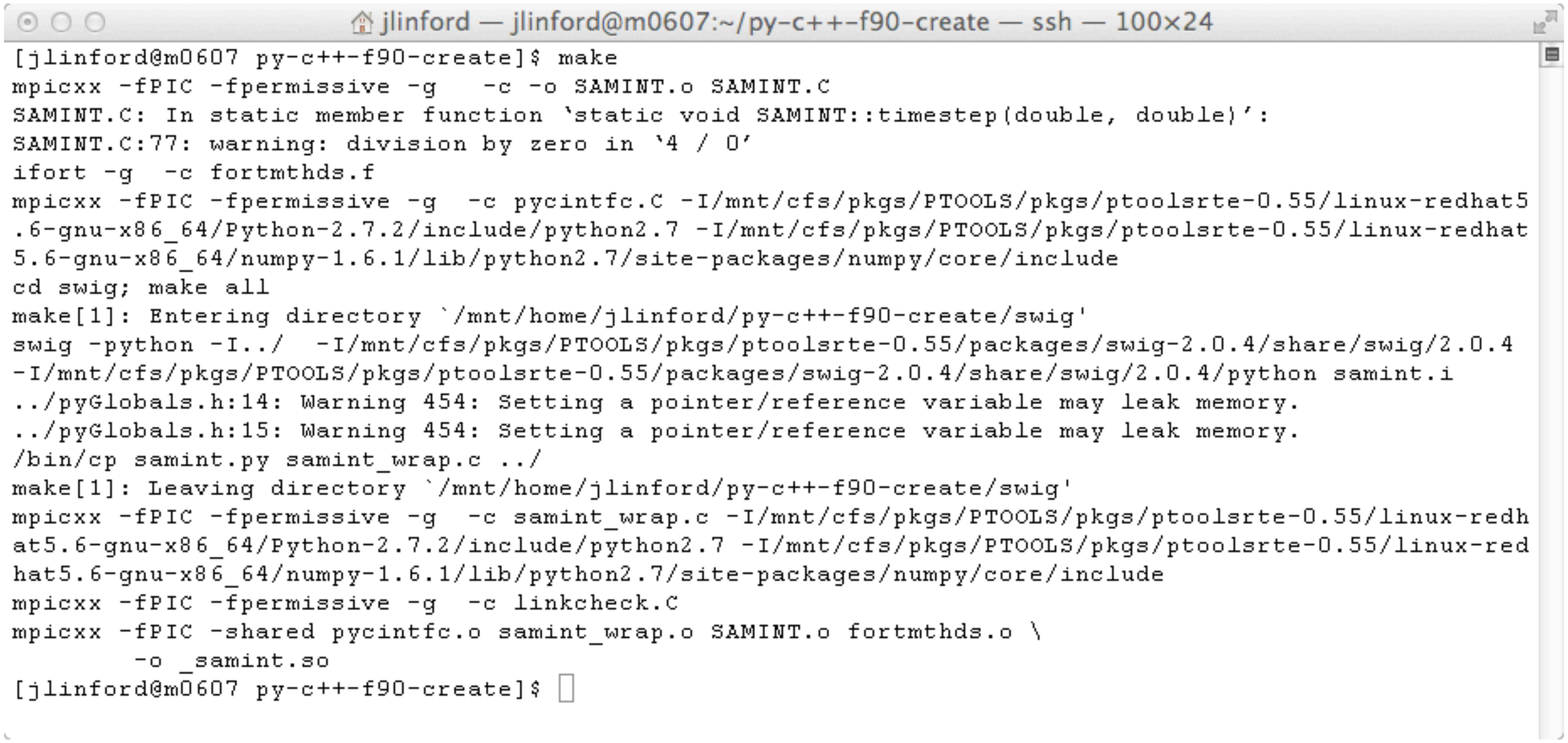




Helios and Kestrel software architecture

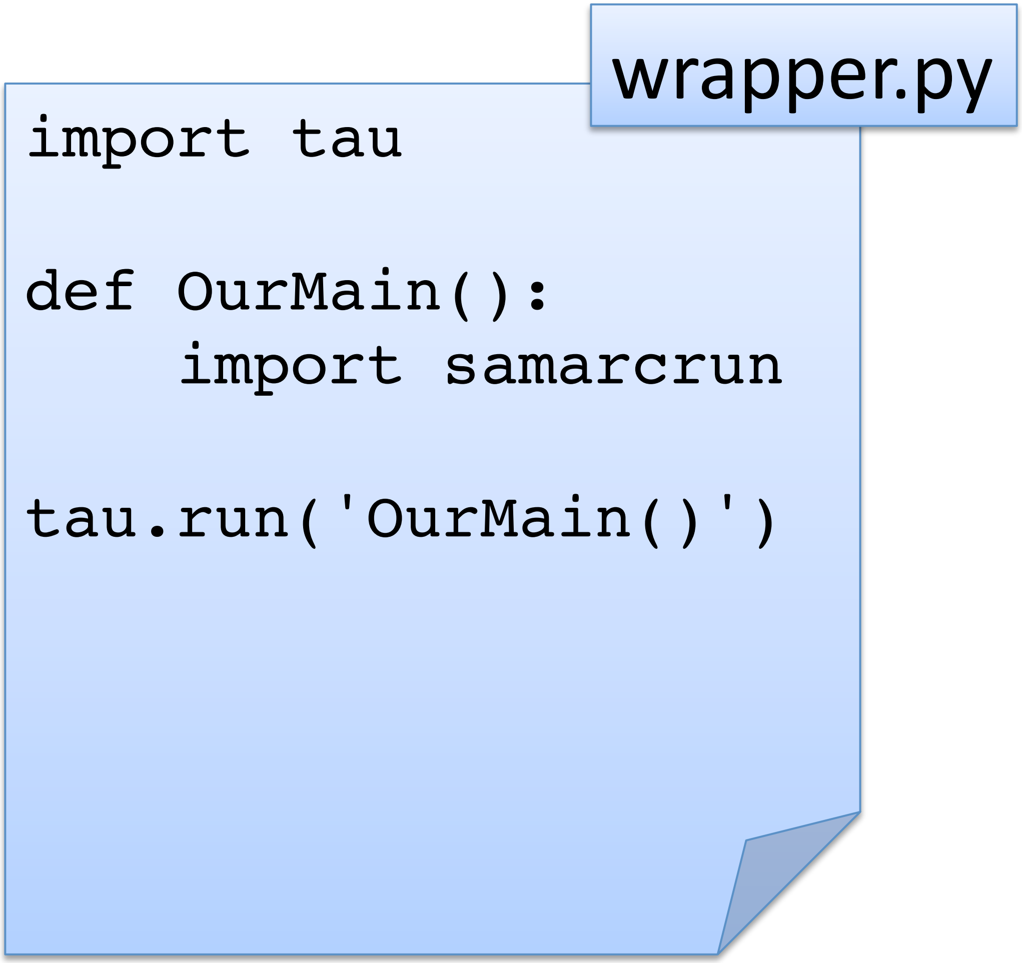

"Light-Weight" Infrastructure – Highly Scalable and Modular (available as executable)
APIs available for use by industry for proprietary modules OR for DoD to leverage innovations from research community
Structural Dynamics Solvers
Comprehensive
FEM
Control Laws
Fluid Structure Interaction
Autopilot
Aircraft Trim
On-the-Fly Data Harvesting
Industry Tools
Event-Based Infrastructure
Cartesian
Unstruc
Strand
Curvilinear
Propulsion
Force/Moment Calculator
6-DOF
Research Tools
Aerodynamics Solvers
Firebolt
Stubs represent Application Program Interfaces (APIs)s

Build with debugging symbols (-g) for a more informative backtrace


jlinford — jlinford@m0607:~/py-c++-f90-create — ssh — 100×24

```
[jlinford@m0607 py-c++-f90-create]$ make
mpicxx -fPIC -fpermissive -g   -c -o SAMINT.o SAMINT.C
SAMINT.C: In static member function ‘static void SAMINT::timestep(double, double)’:
SAMINT.C:77: warning: division by zero in ‘4 / 0’
ifort -g  -c fortmthds.f
mpicxx -fPIC -fpermissive -g  -c pycintfc.C -I/mnt/cfs/pkgs/PTOOLS/pkgs/ptoolsrte-0.55/linux-redhat5
.6-gnu-x86_64/Python-2.7.2/include/python2.7 -I/mnt/cfs/pkgs/PTOOLS/pkgs/ptoolsrte-0.55/linux-redhat
5.6-gnu-x86_64/numpy-1.6.1/lib/python2.7/site-packages/numpy/core/include
cd swig; make all
make[1]: Entering directory `/mnt/home/jlinford/py-c++-f90-create/swig'
swig -python -I../  -I/mnt/cfs/pkgs/PTOOLS/pkgs/ptoolsrte-0.55/packages/swig-2.0.4/share/swig/2.0.4
-I/mnt/cfs/pkgs/PTOOLS/pkgs/ptoolsrte-0.55/packages/swig-2.0.4/share/swig/2.0.4/python samint.i
../pyGlobals.h:14: Warning 454: Setting a pointer/reference variable may leak memory.
../pyGlobals.h:15: Warning 454: Setting a pointer/reference variable may leak memory.
/bin/cp samint.py samint_wrap.c ../
make[1]: Leaving directory `/mnt/home/jlinford/py-c++-f90-create/swig'
mpicxx -fPIC -fpermissive -g  -c samint_wrap.c -I/mnt/cfs/pkgs/PTOOLS/pkgs/ptoolsrte-0.55/linux-redh
at5.6-gnu-x86_64/Python-2.7.2/include/python2.7 -I/mnt/cfs/pkgs/PTOOLS/pkgs/ptoolsrte-0.55/linux-red
hat5.6-gnu-x86_64/numpy-1.6.1/lib/python2.7/site-packages/numpy/core/include
mpicxx -fPIC -fpermissive -g  -c linkcheck.C
mpicxx -fPIC -shared pycintfc.o samint_wrap.o SAMINT.o fortmthds.o \
        -o _samint.so
[jlinford@m0607 py-c++-f90-create]$ 
```

Create a wrapper file to see Python events



wrapper.py

```
import tau

def OurMain():
    import samarcrun

tau.run('OurMain()')
```

Set environment variables and run with *tau_exec*

Normal Execution

```
mpirun -np {n} pyMPI ./samarcrun.py
```

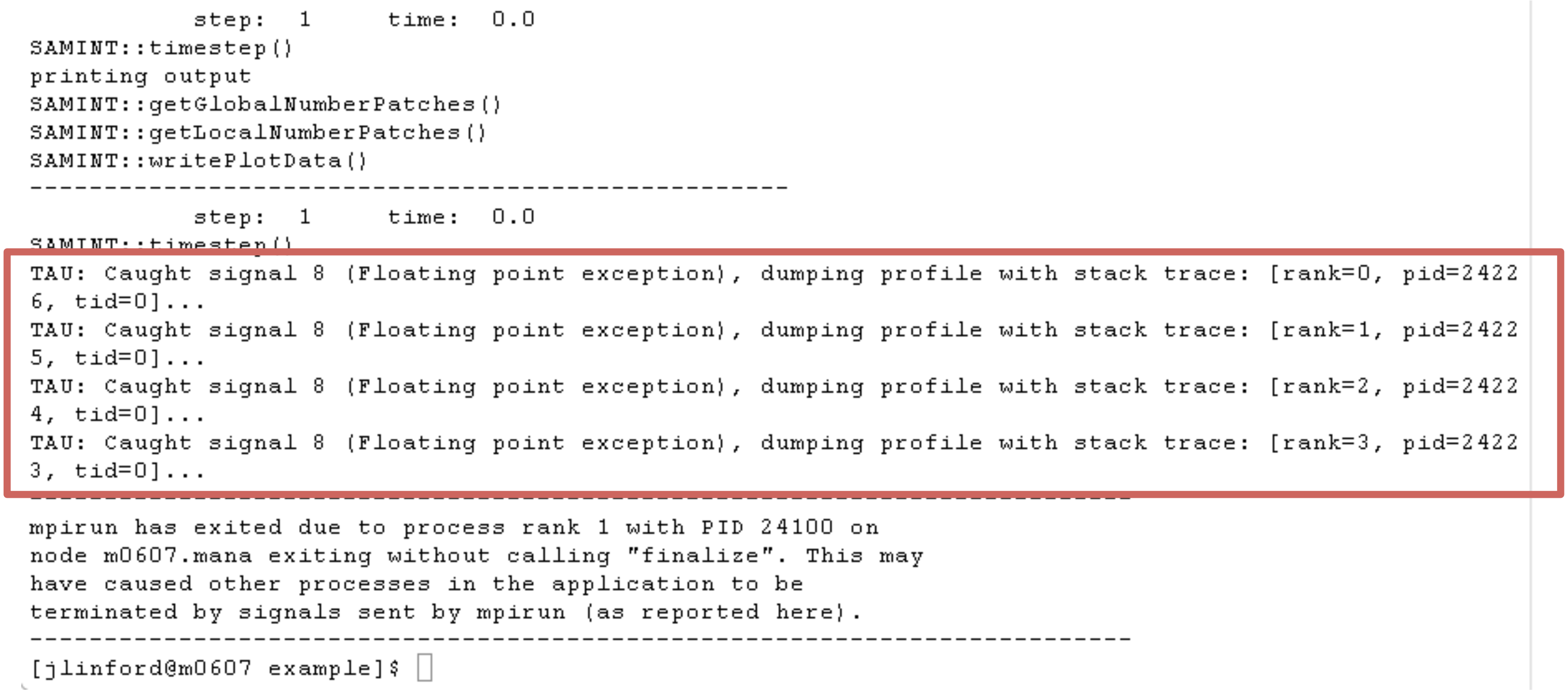
Debugging with TAU

```
export TAU_TRACK_SIGNALS=1
export TAU_CALLPATH_DEPTH=100
mpirun -np {n} tau_exec -T python pyMPI wrapper.py
```

Debugging with TAU + I/O and Memory Tracking

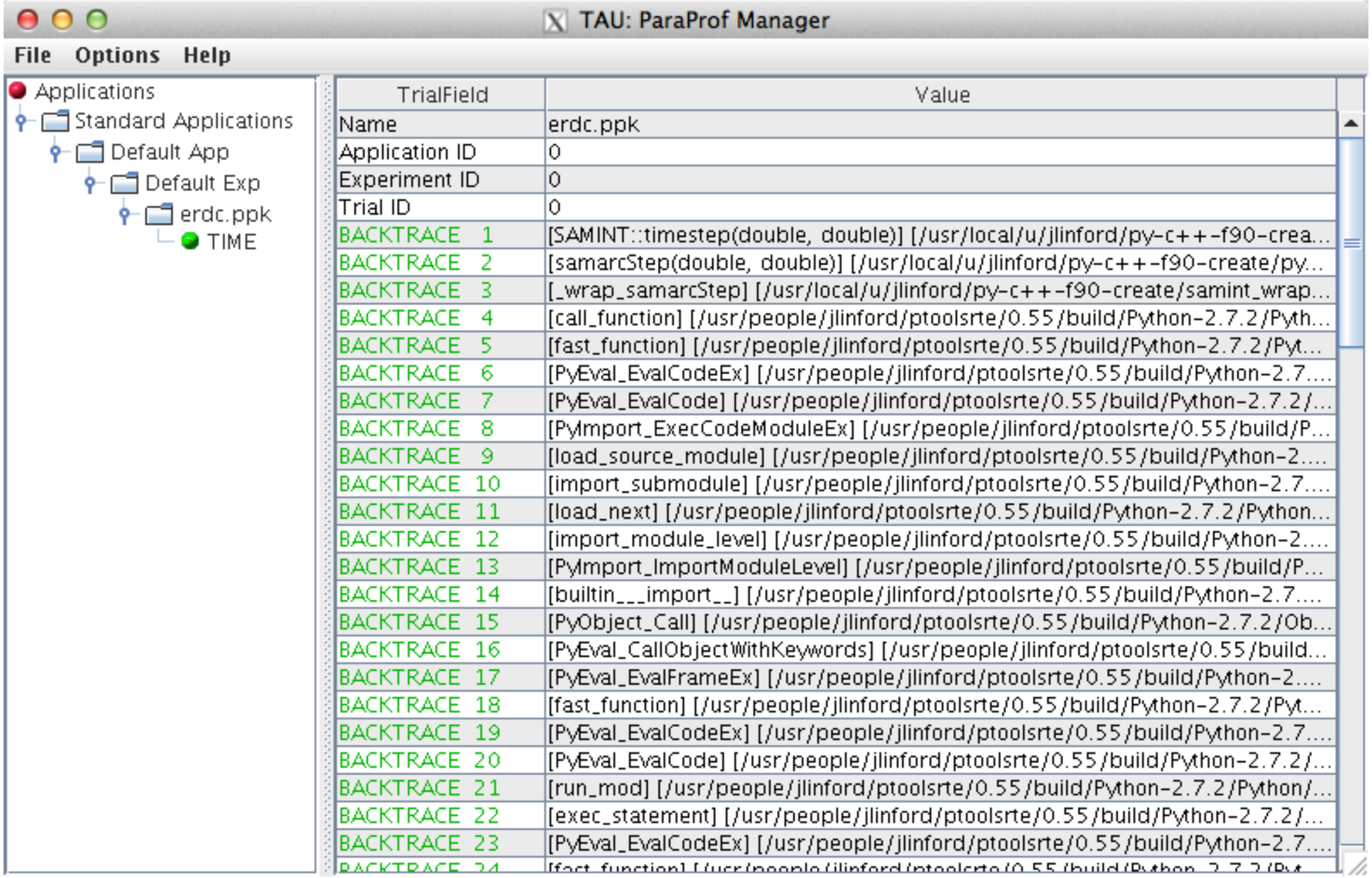
```
mpirun -np {n} tau_exec -T python pyMPI -io -memory \
    wrapper.py
```

TAU generates profile data at time of failure



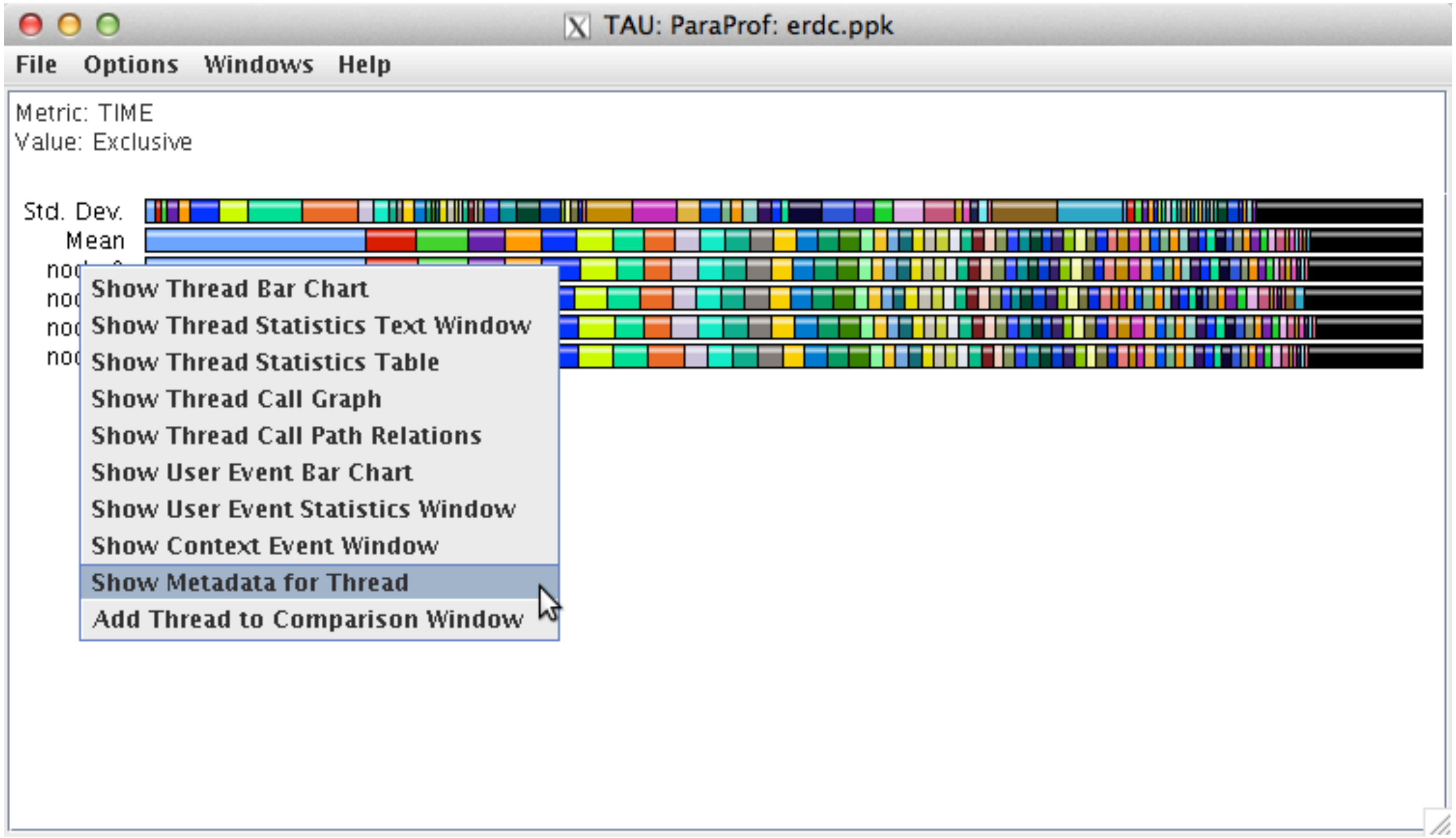
```
           step:  1     time:  0.0
SAMINT::timestep()
printing output
SAMINT::getGlobalNumberPatches()
SAMINT::getLocalNumberPatches()
SAMINT::writePlotData()
---------------------------------------------------
           step:  1     time:  0.0
SAMINT::timestep()
TAU: Caught signal 8 (Floating point exception), dumping profile with stack trace: [rank=0, pid=2422
6, tid=0]...
TAU: Caught signal 8 (Floating point exception), dumping profile with stack trace: [rank=1, pid=2422
5, tid=0]...
TAU: Caught signal 8 (Floating point exception), dumping profile with stack trace: [rank=2, pid=2422
4, tid=0]...
TAU: Caught signal 8 (Floating point exception), dumping profile with stack trace: [rank=3, pid=2422
3, tid=0]...
---------------------------------------------------------------------------
mpirun has exited due to process rank 1 with PID 24100 on
node m0607.mana exiting without calling "finalize". This may
have caused other processes in the application to be
terminated by signals sent by mpirun (as reported here).
---------------------------------------------------------------------------
[jlinford@m0607 example]$ 
```

Use ParaProf to explore the profile data

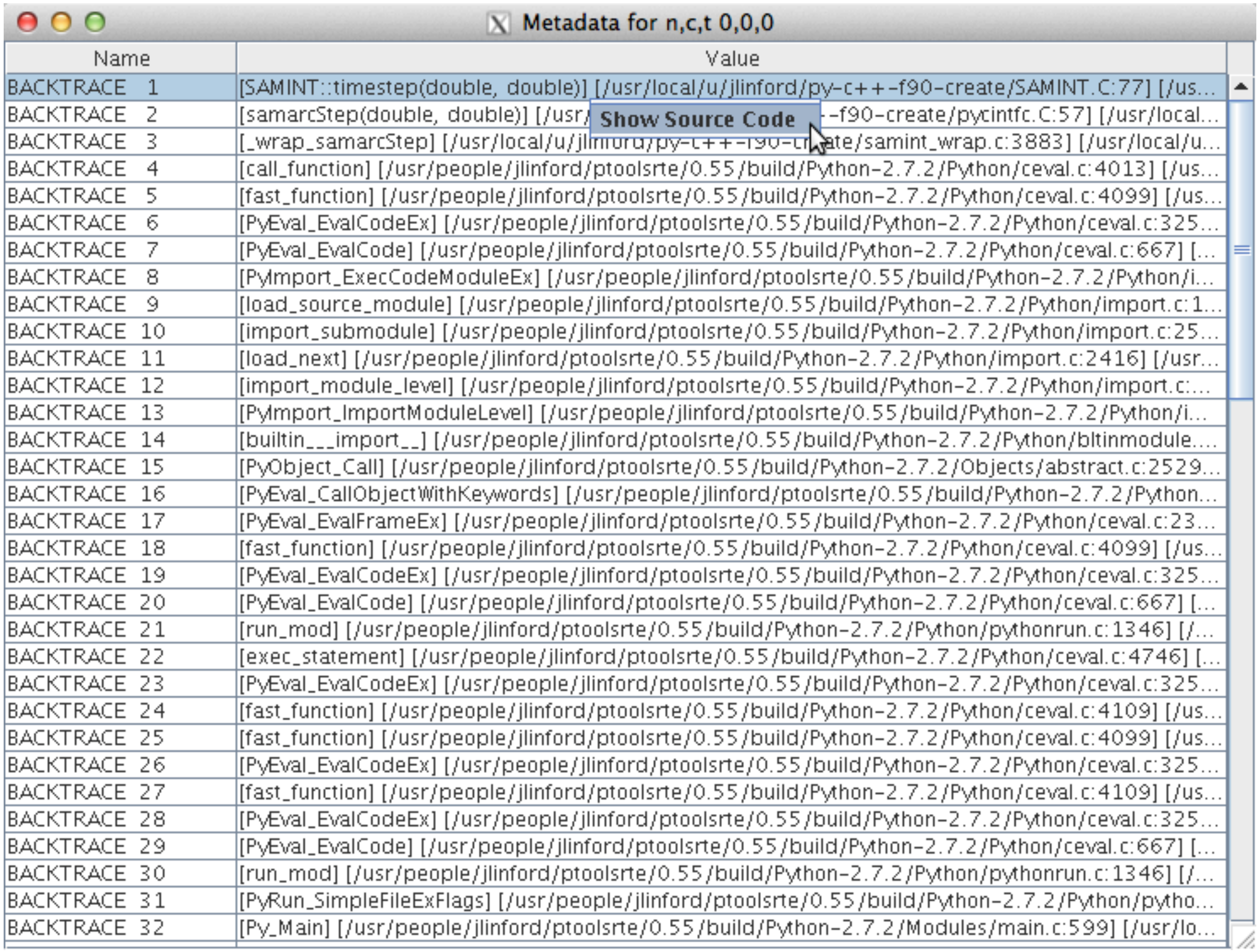


TrialField	Value
Name	erdc.ppk
Application ID	0
Experiment ID	0
Trial ID	0
BACKTRACE 1	[SAMINT::timestep(double, double)] [/usr/local/u/jlinford/py-c++-f90-crea…
BACKTRACE 2	[samarcStep(double, double)] [/usr/local/u/jlinford/py-c++-f90-create/py…
BACKTRACE 3	[_wrap_samarcStep] [/usr/local/u/jlinford/py-c++-f90-create/samint_wrap…
BACKTRACE 4	[call_function] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Pyth…
BACKTRACE 5	[fast_function] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Pyt…
BACKTRACE 6	[PyEval_EvalCodeEx] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.…
BACKTRACE 7	[PyEval_EvalCode] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/…
BACKTRACE 8	[PyImport_ExecCodeModuleEx] [/usr/people/jlinford/ptoolsrte/0.55/build/P…
BACKTRACE 9	[load_source_module] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.…
BACKTRACE 10	[import_submodule] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.…
BACKTRACE 11	[load_next] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python…
BACKTRACE 12	[import_module_level] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.…
BACKTRACE 13	[PyImport_ImportModuleLevel] [/usr/people/jlinford/ptoolsrte/0.55/build/P…
BACKTRACE 14	[builtin___import__] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.…
BACKTRACE 15	[PyObject_Call] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Ob…
BACKTRACE 16	[PyEval_CallObjectWithKeywords] [/usr/people/jlinford/ptoolsrte/0.55/build…
BACKTRACE 17	[PyEval_EvalFrameEx] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.…
BACKTRACE 18	[fast_function] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Pyt…
BACKTRACE 19	[PyEval_EvalCodeEx] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.…
BACKTRACE 20	[PyEval_EvalCode] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/…
BACKTRACE 21	[run_mod] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/…
BACKTRACE 22	[exec_statement] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/…
BACKTRACE 23	[PyEval_EvalCodeEx] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.…
BACKTRACE 24	[fast_function] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Pyt…

Right-click the thread you want to explore

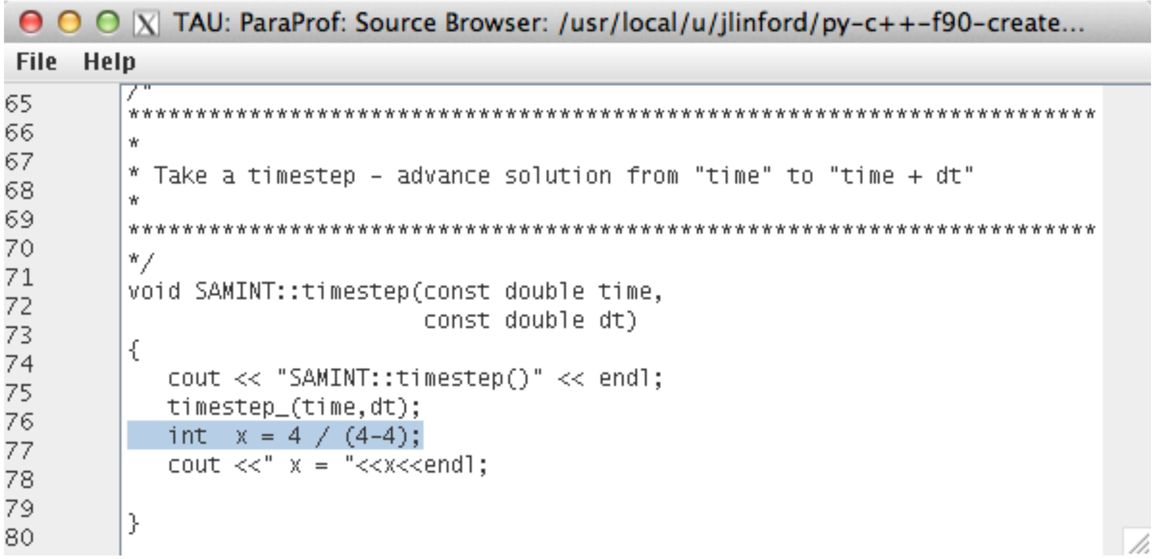

TAU: ParaProf: erdc.ppk
File
Options
Windows
Help
Metric: TIME
Value: Exclusive
Std. Dev.
Mean
noc
noc
noc
noc
Show Thread Bar Chart
Show Thread Statistics Text Window
Show Thread Statistics Table
Show Thread Call Graph
Show Thread Call Path Relations
Show User Event Bar Chart
Show User Event Statistics Window
Show Context Event Window
Show Metadata for Thread
Add Thread to Comparison Window

Use the Metadata window to locate the source line that caused the error



Name	Value
BACKTRACE 1	[SAMINT::timestep(double, double)] [/usr/local/u/jlinford/py-c++-f90-create/SAMINT.C:77] [/us…
BACKTRACE 2	[samarcStep(double, double)] [/usr/ -f90-create/pycintfc.C:57] [/usr/local…
BACKTRACE 3	[_wrap_samarcStep] [/usr/local/u/jlinford/py-c++-f90-create/samint_wrap.c:3883] [/usr/local/u…
BACKTRACE 4	[call_function] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:4013] [/us…
BACKTRACE 5	[fast_function] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:4099] [/us…
BACKTRACE 6	[PyEval_EvalCodeEx] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:325…
BACKTRACE 7	[PyEval_EvalCode] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:667] […
BACKTRACE 8	[PyImport_ExecCodeModuleEx] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/i…
BACKTRACE 9	[load_source_module] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/import.c:1…
BACKTRACE 10	[import_submodule] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/import.c:25…
BACKTRACE 11	[load_next] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/import.c:2416] [/usr…
BACKTRACE 12	[import_module_level] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/import.c:…
BACKTRACE 13	[PyImport_ImportModuleLevel] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/i…
BACKTRACE 14	[builtin___import__] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/bltinmodule.…
BACKTRACE 15	[PyObject_Call] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Objects/abstract.c:2529…
BACKTRACE 16	[PyEval_CallObjectWithKeywords] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python…
BACKTRACE 17	[PyEval_EvalFrameEx] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:23…
BACKTRACE 18	[fast_function] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:4099] [/us…
BACKTRACE 19	[PyEval_EvalCodeEx] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:325…
BACKTRACE 20	[PyEval_EvalCode] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:667] […
BACKTRACE 21	[run_mod] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/pythonrun.c:1346] [/…
BACKTRACE 22	[exec_statement] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:4746] […
BACKTRACE 23	[PyEval_EvalCodeEx] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:325…
BACKTRACE 24	[fast_function] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:4109] [/us…
BACKTRACE 25	[fast_function] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:4099] [/us…
BACKTRACE 26	[PyEval_EvalCodeEx] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:325…
BACKTRACE 27	[fast_function] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:4109] [/us…
BACKTRACE 28	[PyEval_EvalCodeEx] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:325…
BACKTRACE 29	[PyEval_EvalCode] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/ceval.c:667] […
BACKTRACE 30	[run_mod] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/pythonrun.c:1346] [/…
BACKTRACE 31	[PyRun_SimpleFileExFlags] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Python/pytho…
BACKTRACE 32	[Py_Main] [/usr/people/jlinford/ptoolsrte/0.55/build/Python-2.7.2/Modules/main.c:599] [/usr/lo…

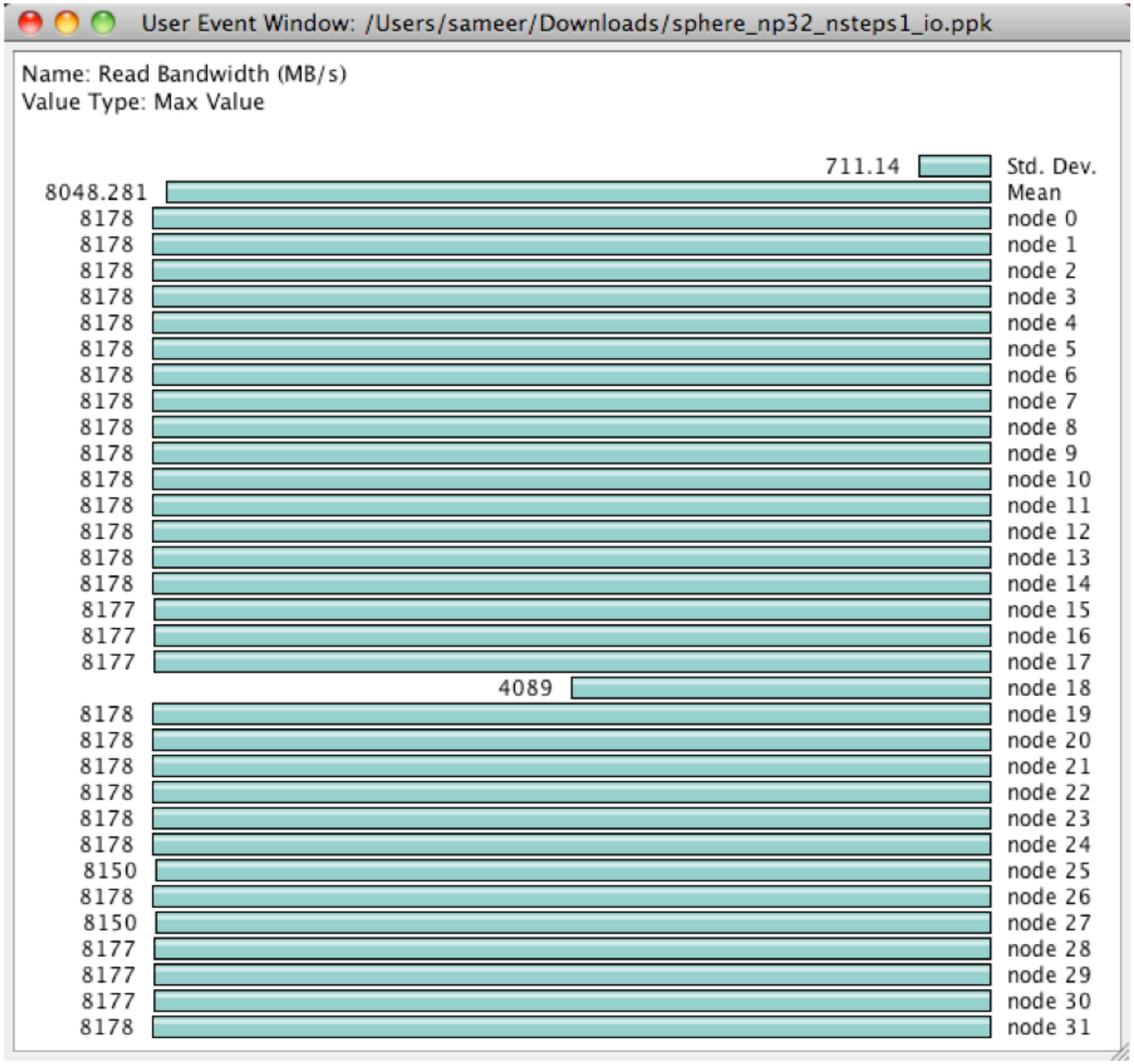
ParaProf highlights the erroneous line


TAU: ParaProf: Source Browser: /usr/local/u/jlinford/py-c++-f90-create...
File
Help

```
/*
************************************************************************
*
* Take a timestep - advance solution from "time" to "time + dt"
*
************************************************************************
*/
void SAMINT::timestep(const double time,
                      const double dt)
{
   cout << "SAMINT::timestep()" << endl;
   timestep_(time,dt);
   int  x = 4 / (4-4);
   cout <<" x = "<<x<<endl;

}
```

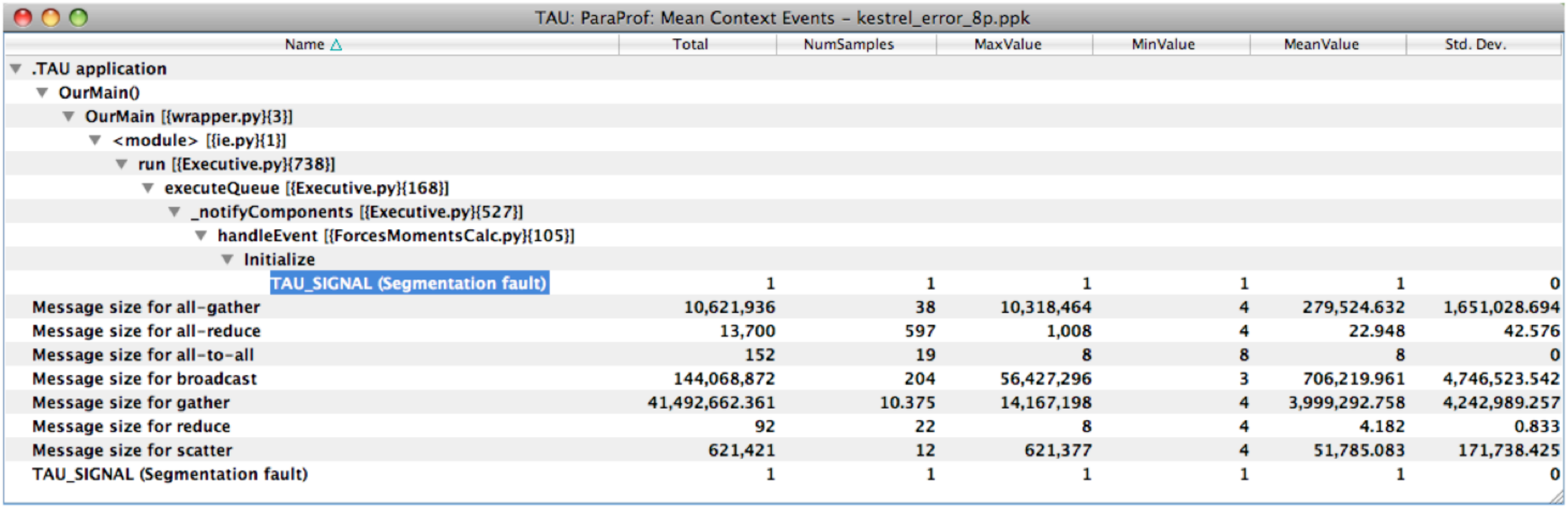
Peak read bandwidth in Helios



User Event Window: /Users/sameer/Downloads/sphere_np32_nsteps1_io.ppk

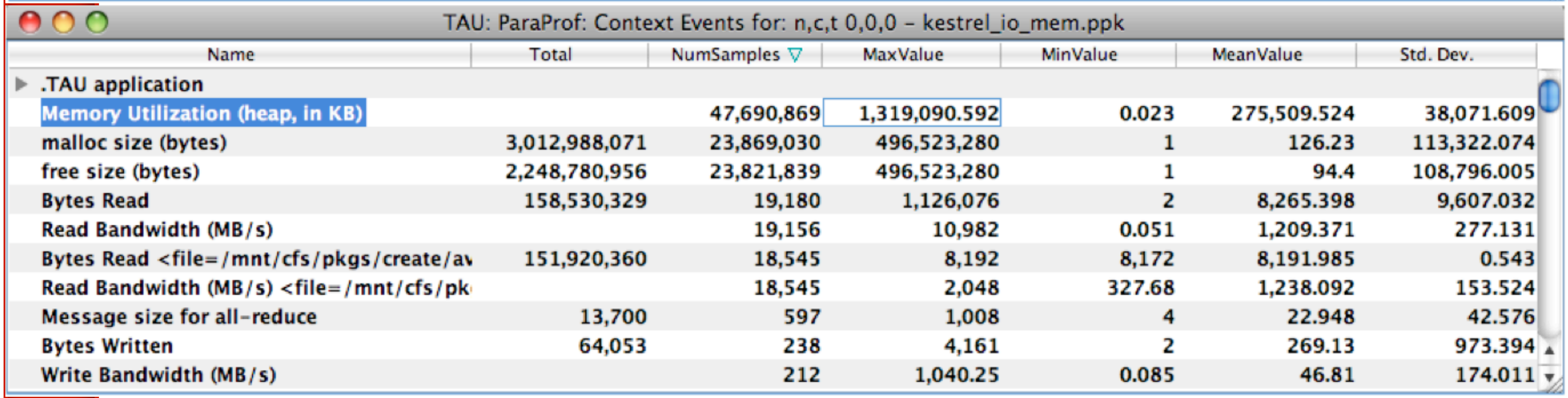
Name: Read Bandwidth (MB/s)
Value Type: Max Value

A segmentation fault in Kestrel with memory and I/O diagnostics



TAU: ParaProf: Mean Context Events – kestrel_error_8p.ppk

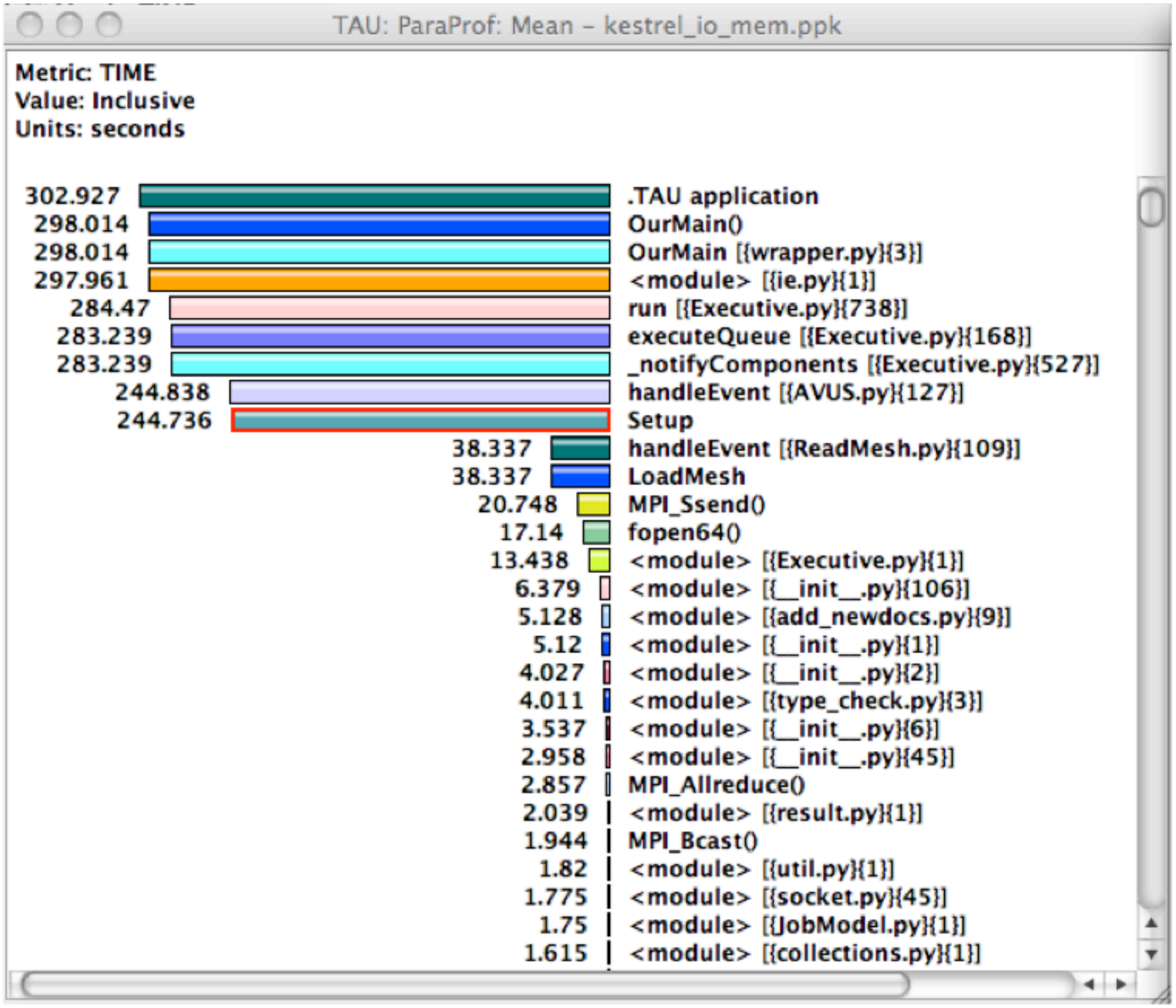
Name △	Total	NumSamples	MaxValue	MinValue	MeanValue	Std. Dev.
▼ .TAU application						
▼ OurMain()						
▼ OurMain [{wrapper.py}{3}]						
▼ <module> [{ie.py}{1}]						
▼ run [{Executive.py}{738}]						
▼ executeQueue [{Executive.py}{168}]						
▼ _notifyComponents [{Executive.py}{527}]						
▼ handleEvent [{ForcesMomentsCalc.py}{105}]						
▼ Initialize						
TAU_SIGNAL (Segmentation fault)	1	1	1	1	1	0
Message size for all-gather	10,621,936	38	10,318,464	4	279,524.632	1,651,028.694
Message size for all-reduce	13,700	597	1,008	4	22.948	42.576
Message size for all-to-all	152	19	8	8	8	0
Message size for broadcast	144,068,872	204	56,427,296	3	706,219.961	4,746,523.542
Message size for gather	41,492,662.361	10.375	14,167,198	4	3,999,292.758	4,242,989.257
Message size for reduce	92	22	8	4	4.182	0.833
Message size for scatter	621,421	12	621,377	4	51,785.083	171,738.425
TAU_SIGNAL (Segmentation fault)	1	1	1	1	1	0



TAU: ParaProf: Context Events for: n,c,t 0,0,0 – kestrel_io_mem.ppk

Name	Total	NumSamples ▽	MaxValue	MinValue	MeanValue	Std. Dev.
▶ .TAU application						
Memory Utilization (heap, in KB)		47,690,869	1,319,090.592	0.023	275,509.524	38,071.609
malloc size (bytes)	3,012,988,071	23,869,030	496,523,280	1	126.23	113,322.074
free size (bytes)	2,248,780,956	23,821,839	496,523,280	1	94.4	108,796.005
Bytes Read	158,530,329	19,180	1,126,076	2	8,265.398	9,607.032
Read Bandwidth (MB/s)		19,156	10,982	0.051	1,209.371	277.131
Bytes Read <file=/mnt/cfs/pkgs/create/av	151,920,360	18,545	8,192	8,172	8,191.985	0.543
Read Bandwidth (MB/s) <file=/mnt/cfs/pk		18,545	2,048	327.68	1,238.092	153.524
Message size for all-reduce	13,700	597	1,008	4	22.948	42.576
Bytes Written	64,053	238	4,161	2	269.13	973.394
Write Bandwidth (MB/s)		212	1,040.25	0.085	46.81	174.011

Inclusive time spent in Kestrel code regions

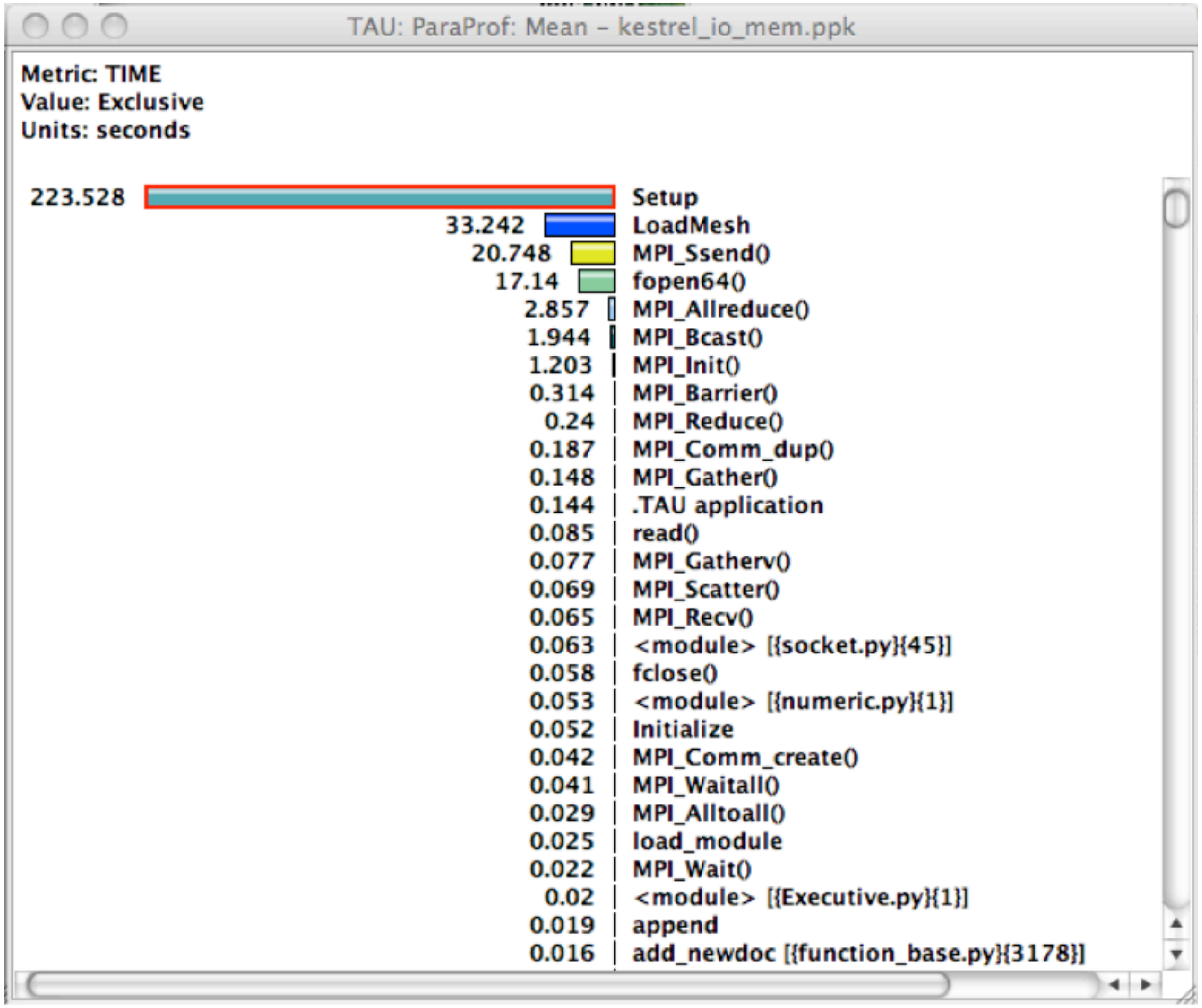


TAU: ParaProf: Mean – kestrel_io_mem.ppk

```
Metric: TIME
Value: Inclusive
Units: seconds

302.927  .TAU application
298.014  OurMain()
298.014  OurMain [{wrapper.py}{3}]
297.961  <module> [{ie.py}{1}]
284.47   run [{Executive.py}{738}]
283.239  executeQueue [{Executive.py}{168}]
283.239  _notifyComponents [{Executive.py}{527}]
244.838  handleEvent [{AVUS.py}{127}]
244.736  Setup
38.337   handleEvent [{ReadMesh.py}{109}]
38.337   LoadMesh
20.748   MPI_Ssend()
17.14    fopen64()
13.438   <module> [{Executive.py}{1}]
6.379    <module> [{__init__.py}{106}]
5.128    <module> [{add_newdocs.py}{9}]
5.12     <module> [{__init__.py}{1}]
4.027    <module> [{__init__.py}{2}]
4.011    <module> [{type_check.py}{3}]
3.537    <module> [{__init__.py}{6}]
2.958    <module> [{__init__.py}{45}]
2.857    MPI_Allreduce()
2.039    <module> [{result.py}{1}]
1.944    MPI_Bcast()
1.82     <module> [{util.py}{1}]
1.775    <module> [{socket.py}{45}]
1.75     <module> [{JobModel.py}{1}]
1.615    <module> [{collections.py}{1}]
```

Exclusive time spent in Kestrel code regions



Metric: TIME
Value: Exclusive
Units: seconds

```
223.528  Setup
 33.242  LoadMesh
 20.748  MPI_Ssend()
  17.14  fopen64()
  2.857  MPI_Allreduce()
  1.944  MPI_Bcast()
  1.203  MPI_Init()
  0.314  MPI_Barrier()
   0.24  MPI_Reduce()
  0.187  MPI_Comm_dup()
  0.148  MPI_Gather()
  0.144  .TAU application
  0.085  read()
  0.077  MPI_Gatherv()
  0.069  MPI_Scatter()
  0.065  MPI_Recv()
  0.063  <module> [{socket.py}{45}]
  0.058  fclose()
  0.053  <module> [{numeric.py}{1}]
  0.052  Initialize
  0.042  MPI_Comm_create()
  0.041  MPI_Waitall()
  0.029  MPI_Alltoall()
  0.025  load_module
  0.022  MPI_Wait()
   0.02  <module> [{Executive.py}{1}]
  0.019  append
  0.016  add_newdoc [{function_base.py}{3178}]
```

Summary and conclusions

1. TAU callstack debugging isolates errors in multi-language HPC software by intercepting signals at runtime
2. Run codes with *tau_exec* to register the TAU signal handler, create profile files, and shutdown gracefully
3. The profile can be sent to developers when sensitive or proprietary inputs cannot be provided
4. Developers use ParaProf to analyze the fault location and runtime performance data in the profiles
5. Memory use, IO, and runtime performance are recorded
6. No recompilation necessary

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