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Arm Debugging and Profiling Tools Tutorial

Hosted By NERSC

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Agenda

- Arm Software for Debugging and Profiling
- Debugging with DDT
- Generating Performance Reports
- Profiling with MAP
- Using Arm tools with Python

Arm Software

Arm Forge

An interoperable toolkit for debugging and profiling

Commercially supported by Arm

Fully Scalable

Very user-friendly

The de-facto standard for HPC development

- Available on the vast majority of the Top500 machines in the world
- Fully supported by Arm on x86, IBM Power, Nvidia GPUs, etc.

State-of-the art debugging and profiling capabilities

- Powerful and in-depth error detection mechanisms (including memory debugging)
- Sampling-based profiler to identify and understand bottlenecks
- Available at any scale (from serial to parallel applications running at petascale)

Easy to use by everyone

- Unique capabilities to simplify remote interactive sessions
- Innovative approach to present quintessential information to users

Arm Performance Reports

Characterize and understand the performance of HPC application runs

Commercially supported by Arm

Accurate and astute insight

Relevant advice to avoid pitfalls

Gathers a rich set of data

- Analyzes metrics around CPU, memory, IO, hardware counters, etc.
- Possibility for users to add their own metrics

Build a culture of application performance & efficiency awareness

- Analyzes data and reports the information that matters to users
- Provides simple guidance to help improve workloads' efficiency

Adds value to typical users' workflows

- Define application behaviour and performance expectations
- Integrate outputs to various systems for validation (e.g. continuous integration)
- Can be automated completely (no user intervention)

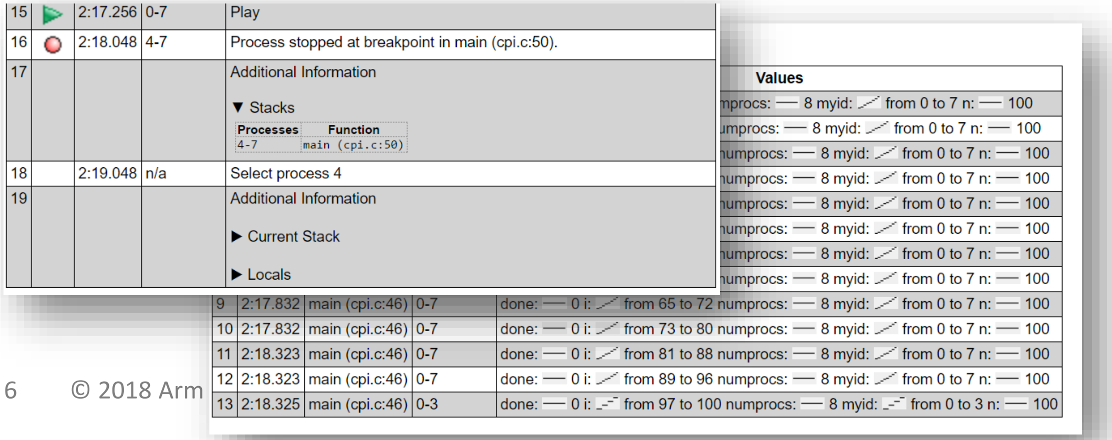
Run and ensure application correctness

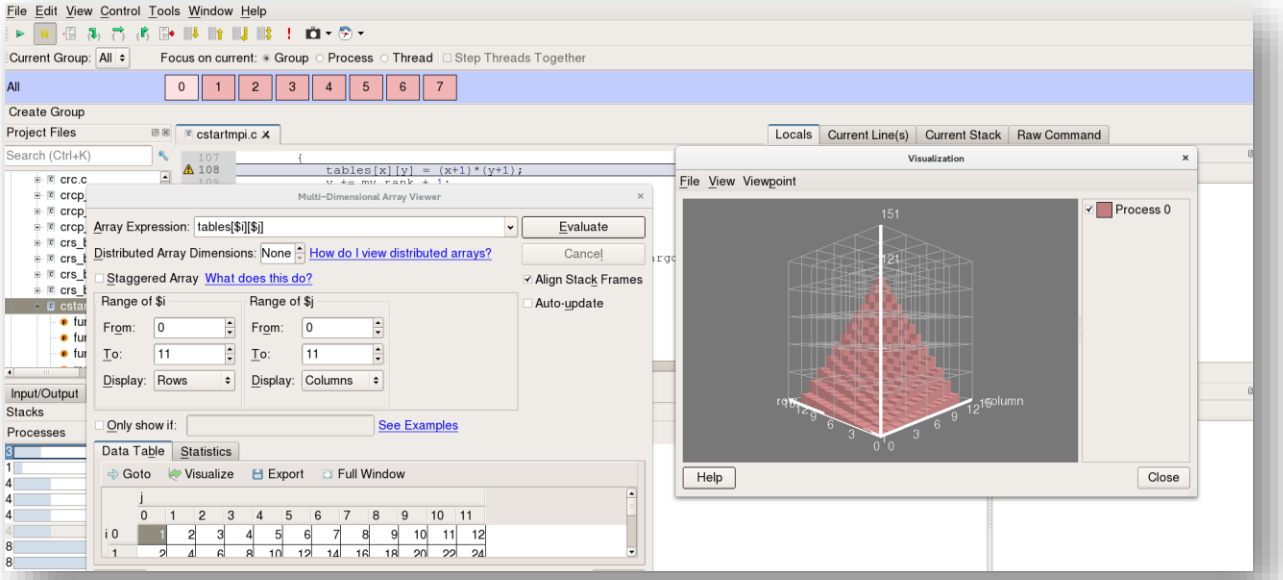
Combination of debugging and re-compilation

- Ensure application correctness with **Arm DDT scalable debugger**
- Integrate with continuous integration system.
- Use version control to track changes and leverage Forge’s built-in VCS support.

Examples:

```
$> ddt --offline aprun -n 48 ./example
$> ddt --connect aprun -n 48 ./example
```



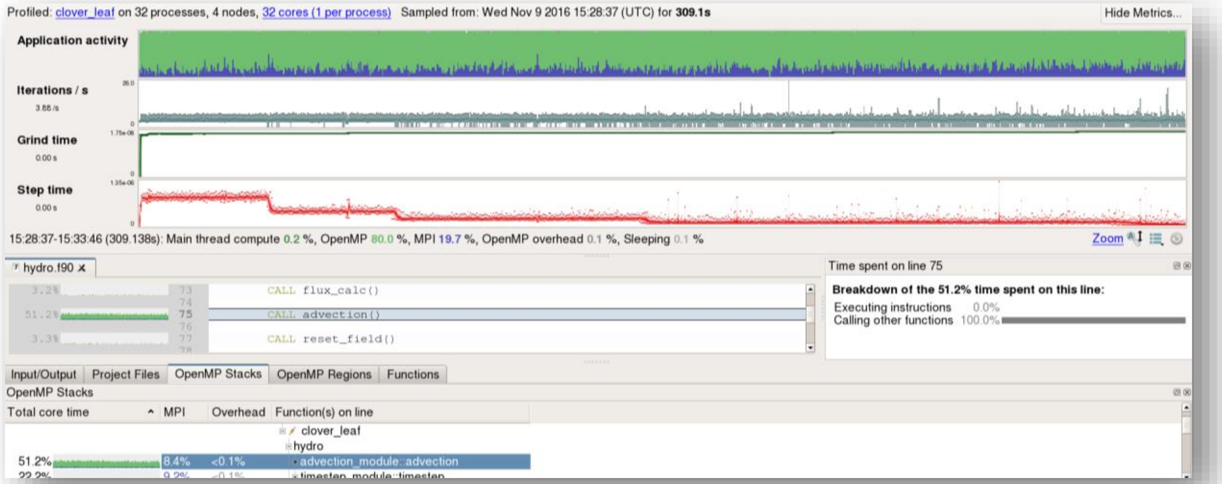


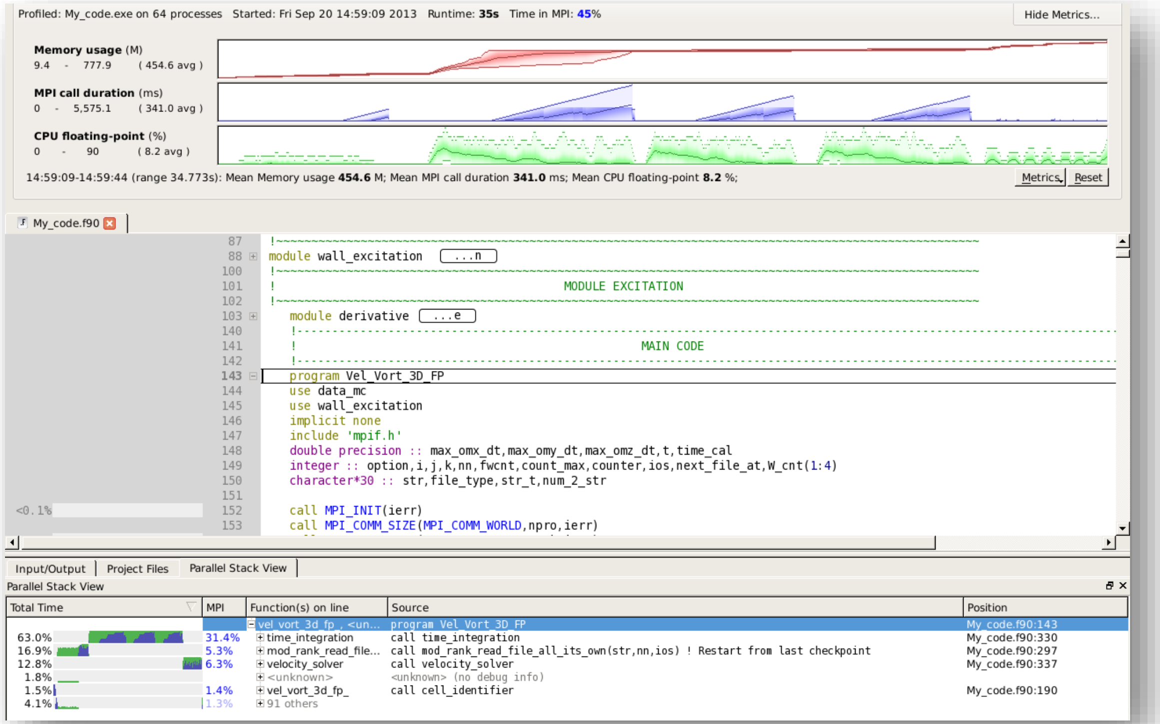
Visualize the performance of your application

- Measure all performance aspects with **Arm MAP parallel profiler**
- Identify bottlenecks and rewrite some code for better performance

Examples:

```
$> map --profile -n 48 ./example
```





Debugging with DDT

Arm DDT – The Debugger

Who had a rogue behaviour ?

- Merges stacks from processes and threads

Where did it happen?

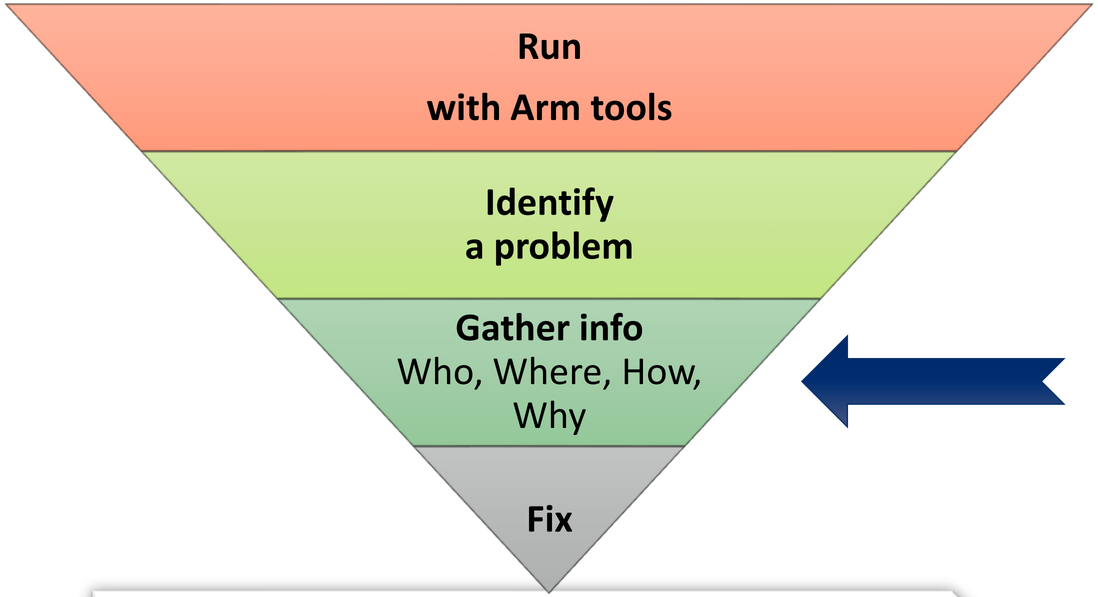
- leaps to source

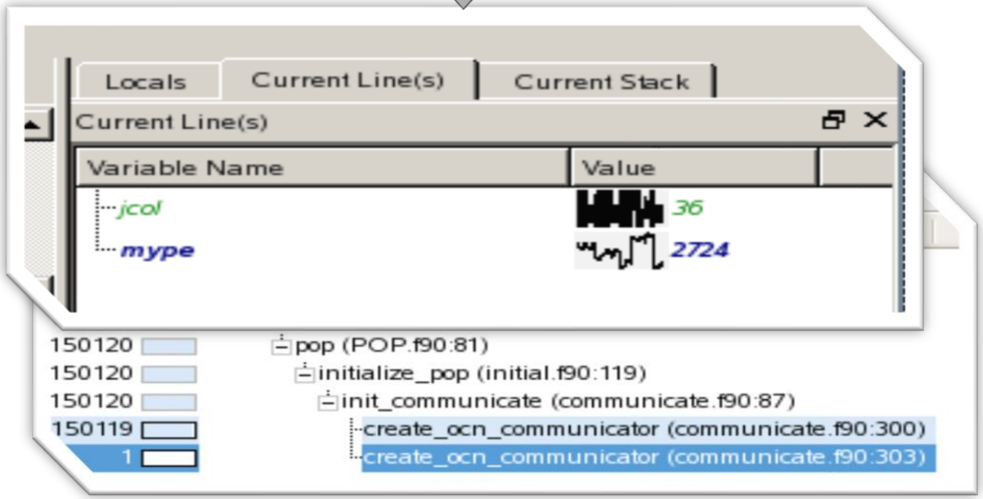
How did it happen?

- Diagnostic messages
- Some faults evident instantly from source

Why did it happen?

- Unique "Smart Highlighting"
- Sparklines comparing data across processes





Preparing Code for Use with DDT

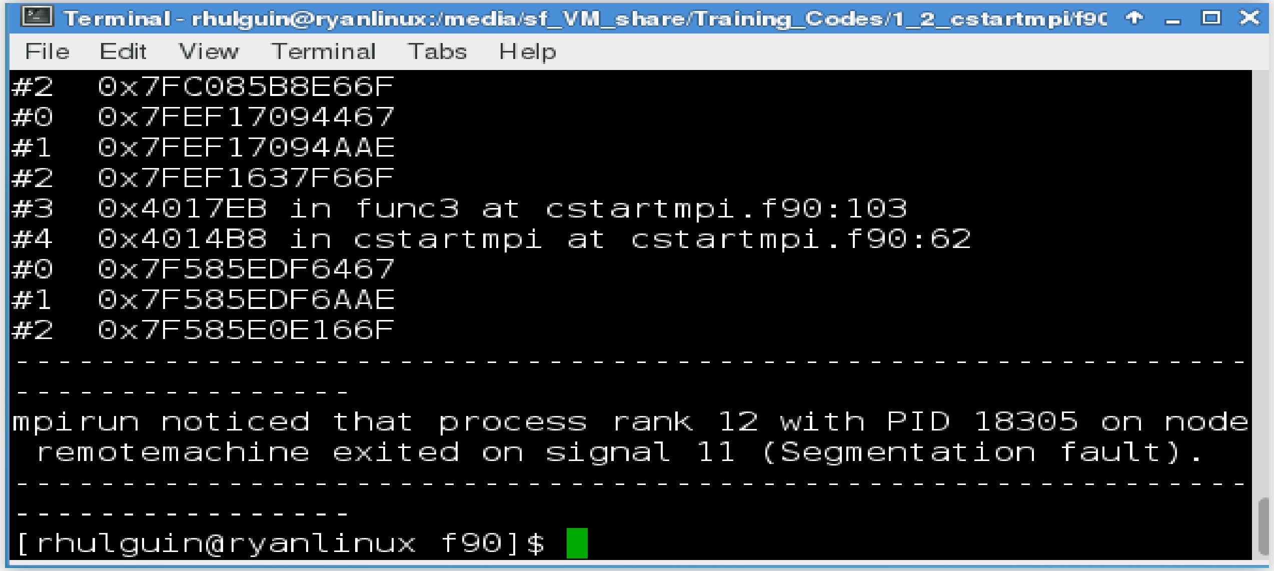
As with any debugger, code must be compiled with the debug flag typically **`-g`**

It is recommended to turn off optimization flags i.e. **`-O0`**

Leaving optimizations turned on can cause the compiler to *optimize out* some variables and even functions making it more difficult to debug

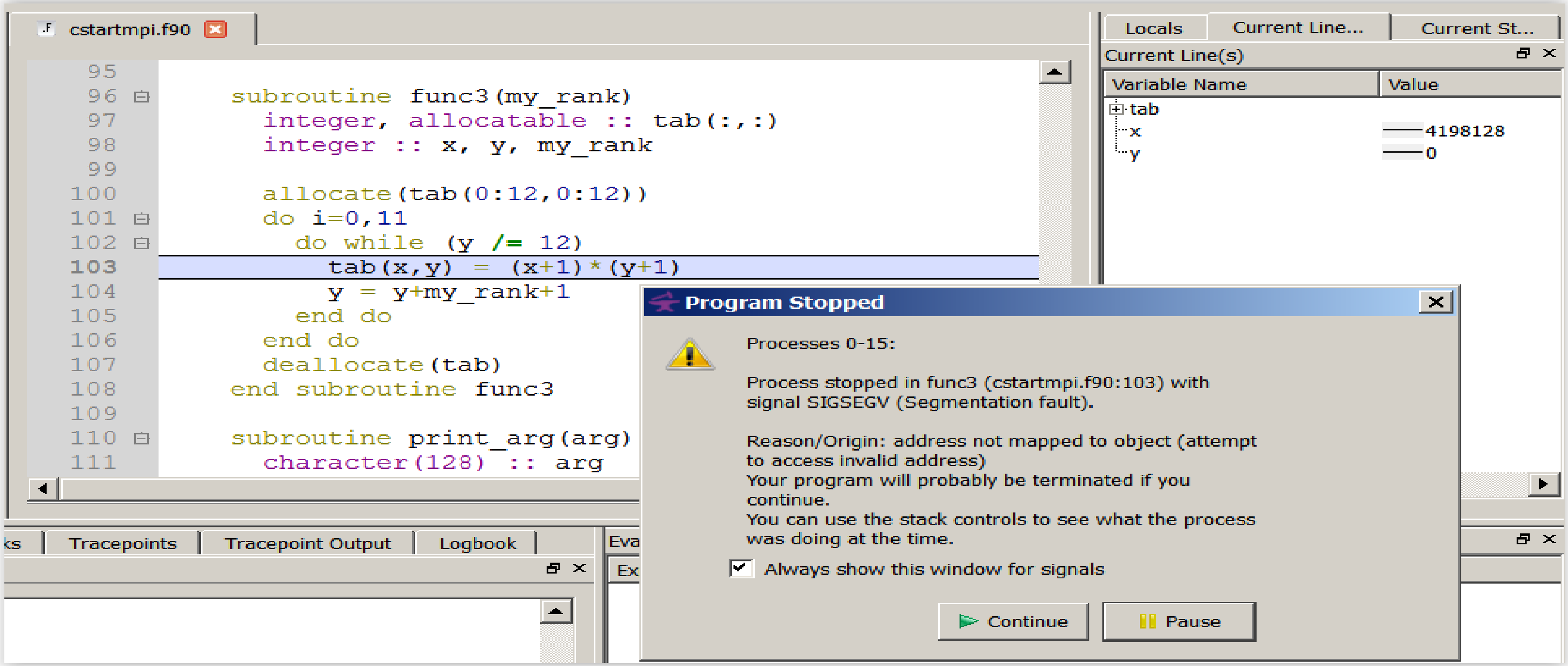
Segmentation Fault

In this example, the application crashes with a segmentation error outside of DDT.



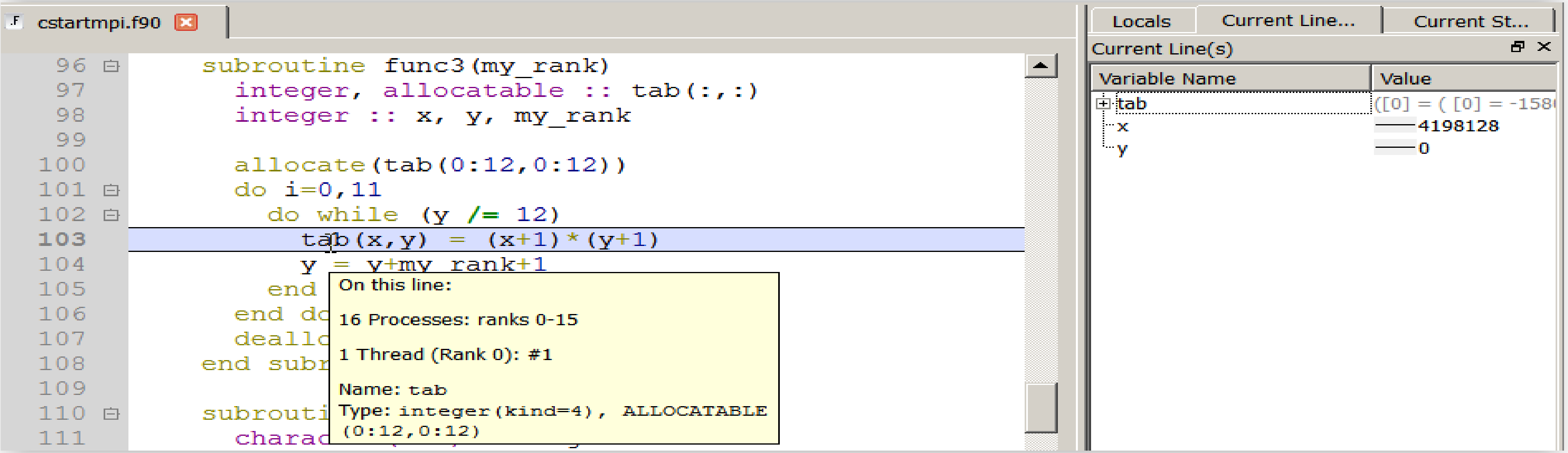
What happens when it runs under DDT?

Segmentation Fault in DDT



DDT takes you to the exact line where Segmentation fault occurred, and you can pause and investigate

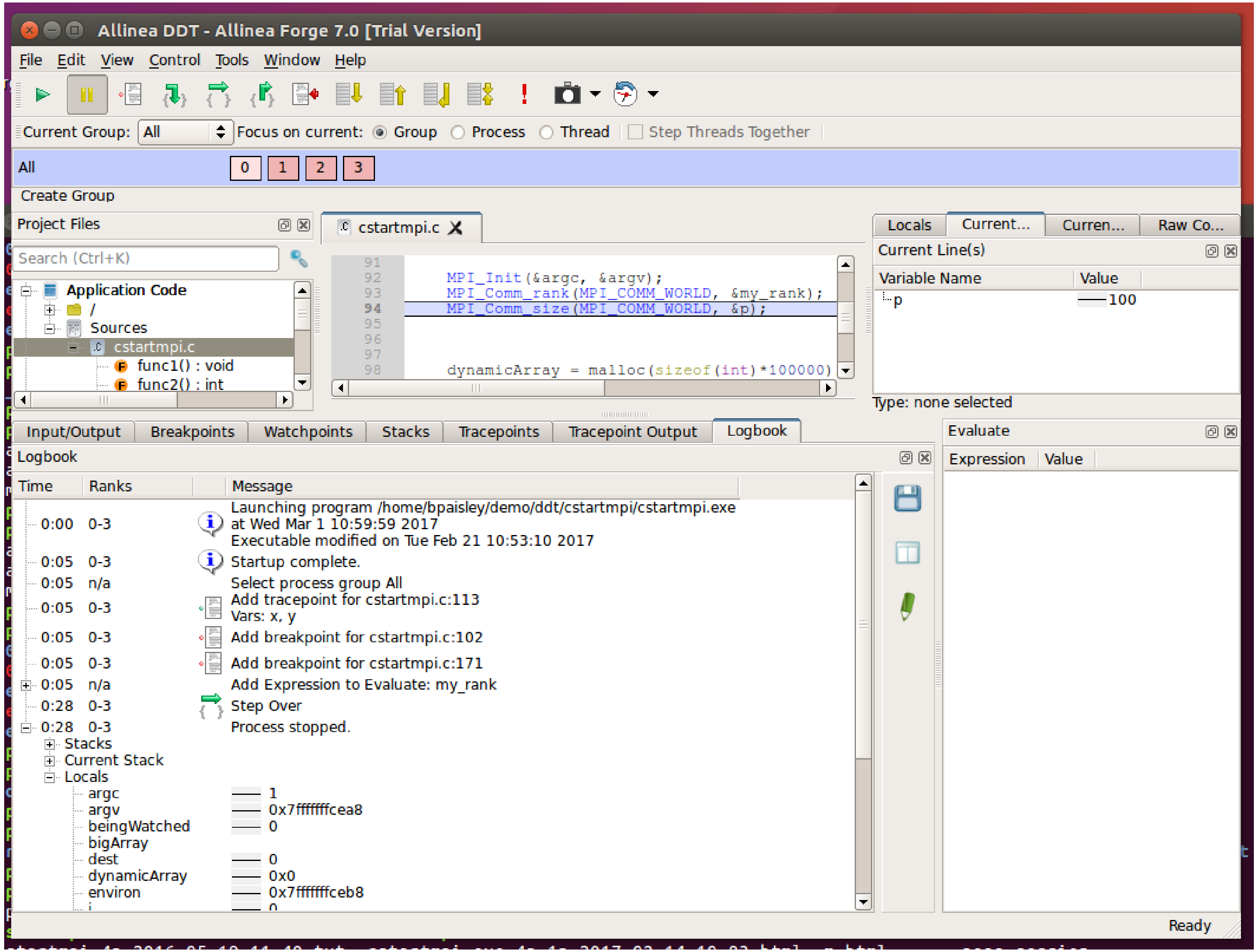
Invalid Memory Access



The array tab is a 13x13 array, but the application is trying to write a value to tab(4198128,0) which causes the segmentation fault.

`i` is not used, and **`x`** and **`y`** are not initialized

Track Your Changes in a Logbook



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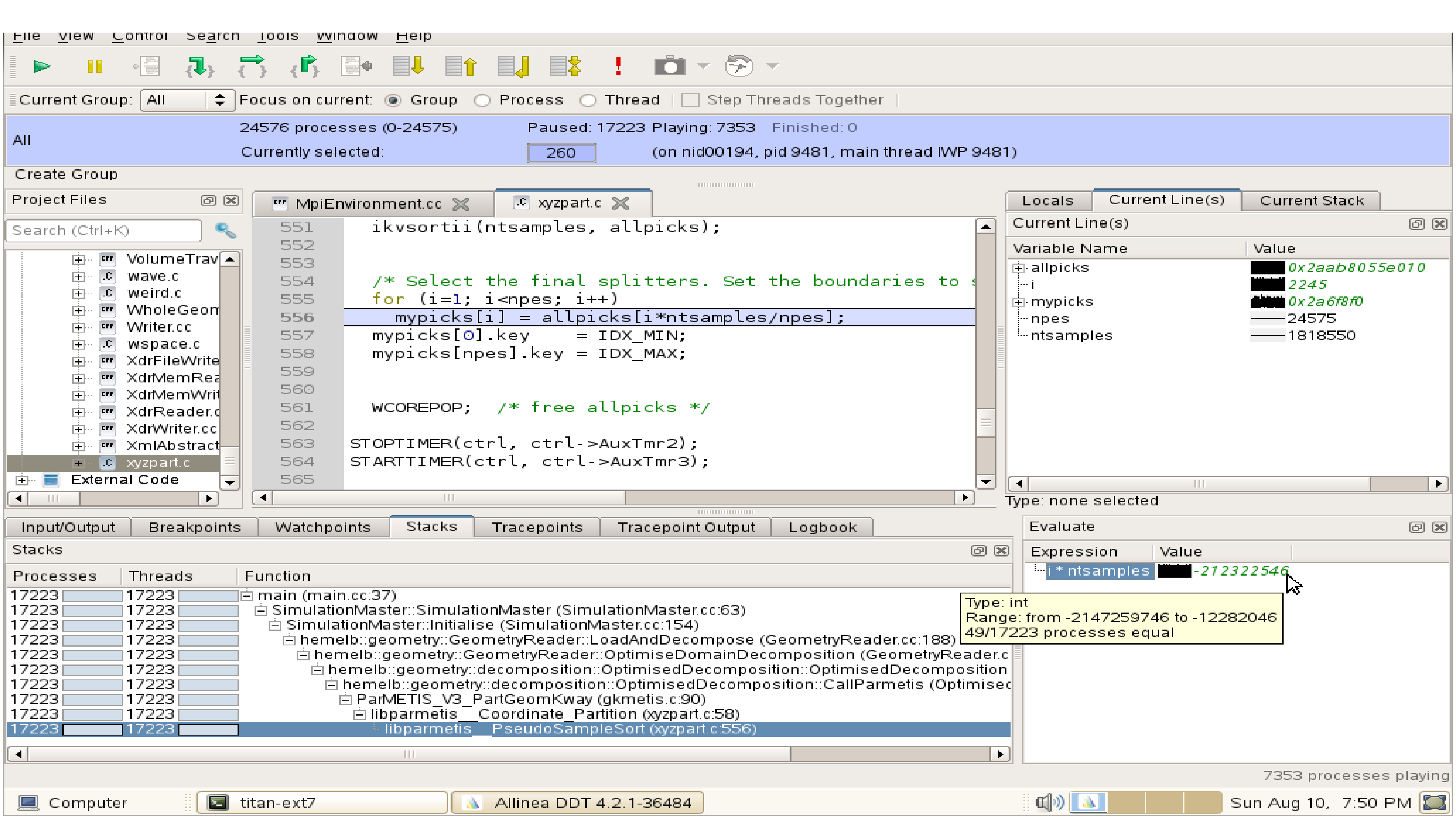
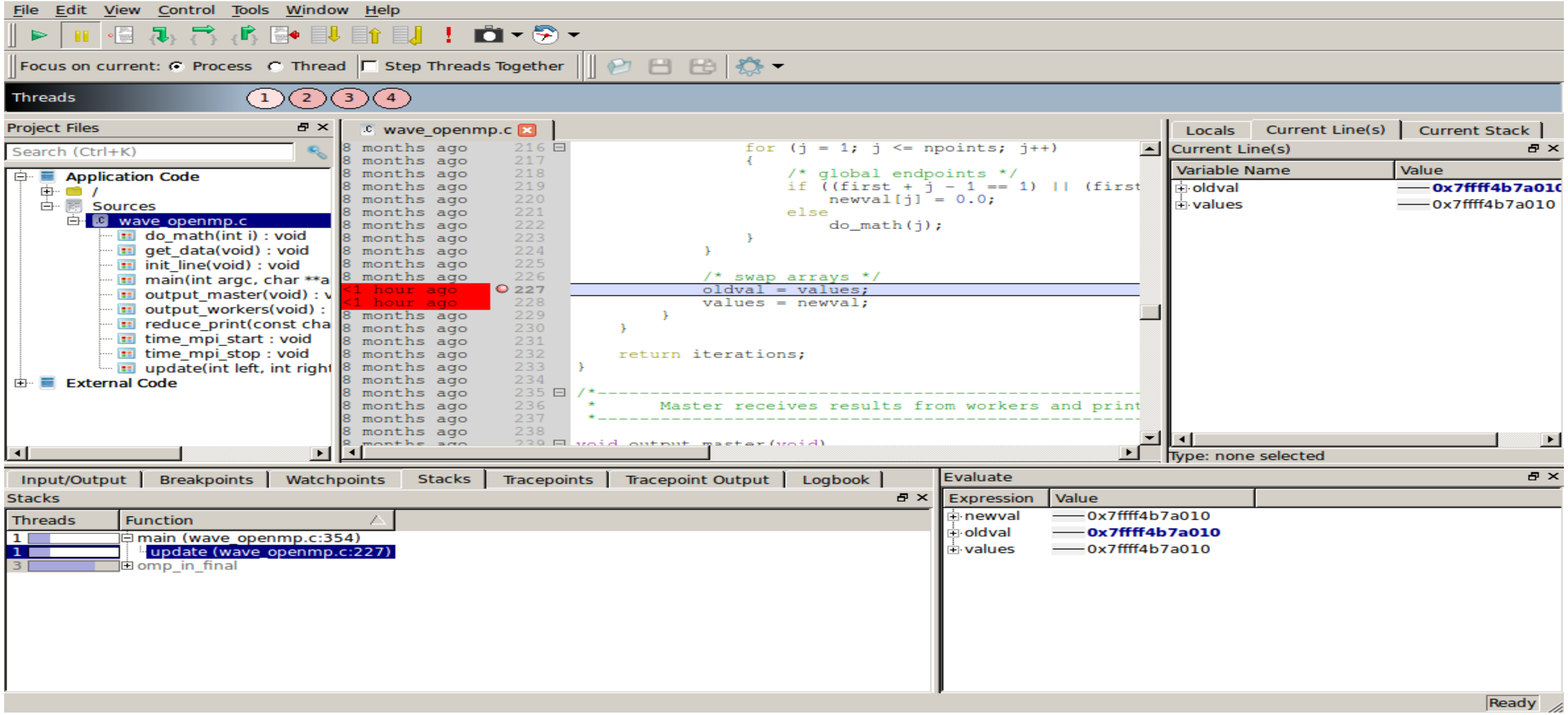

File View Control Search Tools Window Help
Current Group: All
Focus on current: Group Process Thread
Step Threads Together
All
24576 processes (0-24575)
Paused: 17223 Playing: 7353 Finished: 0
Currently selected: 260 (on nid00194, pid 9481, main thread LWP 9481)
Create Group
Project Files
Search (Ctrl+K)
VolumeTrav
wave.c
weird.c
WholeGeom
Writer.cc
wspace.c
XdrFileWrite
XdrMemRea
XdrMemWrit
XdrReader.c
XdrWriter.cc
XmlAbstract
xyzpart.c
External Code
MpiEnvironment.cc
xyzpart.c
551 ikvsortii(ntsamples, allpicks);
552
553
554 /* Select the final splitters. Set the boundaries to s
555 for (i=1; i<npes; i++)
556 mypicks[i] = allpicks[i*ntsamples/npes];
557 mypicks[0].key = IDX_MIN;
558 mypicks[npes].key = IDX_MAX;
559
560
561 WCOREPOP; /* free allpicks */
562
563 STOPTIMER(ctrl, ctrl->AuxTmr2);
564 STARTTIMER(ctrl, ctrl->AuxTmr3);
565
Locals
Current Line(s)
Current Stack
Current Line(s)
Variable Name
Value
allpicks 0x2aab8055e010
i 2245
mypicks 0x2a6f8f0
npes 24575
ntsamples 1818550
Type: none selected
Input/Output
Breakpoints
Watchpoints
Stacks
Tracepoints
Tracepoint Output
Logbook
Stacks
Processes Threads Function
17223 17223 main (main.cc:37)
17223 17223 SimulationMaster::SimulationMaster (SimulationMaster.cc:63)
17223 17223 SimulationMaster::Initialise (SimulationMaster.cc:154)
17223 17223 hemelb::geometry::GeometryReader::LoadAndDecompose (GeometryReader.cc:188)
17223 17223 hemelb::geometry::GeometryReader::OptimiseDomainDecomposition (GeometryReader.c
17223 17223 hemelb::geometry::decomposition::OptimisedDecomposition::OptimisedDecomposition
17223 17223 hemelb::geometry::decomposition::OptimisedDecomposition::CallParmetis (Optimised
17223 17223 ParMETIS_V3_PartGeomKway (gkmetis.c:90)
17223 17223 libparmetis__Coordinate_Partition (xyzpart.c:58)
17223 17223 libparmetis__PseudoSampleSort (xyzpart.c:556)
Evaluate
Expression
Value
i * ntsamples -212322546
Type: int
Range: from -2147259746 to -12282046
49/17223 processes equal
7353 processes playing
Computer
titan-ext7
Allinea DDT 4.2.1-36484
Sun Aug 10, 7:50 PM

New Bugs from Latest Changes



Arm DDT Demo

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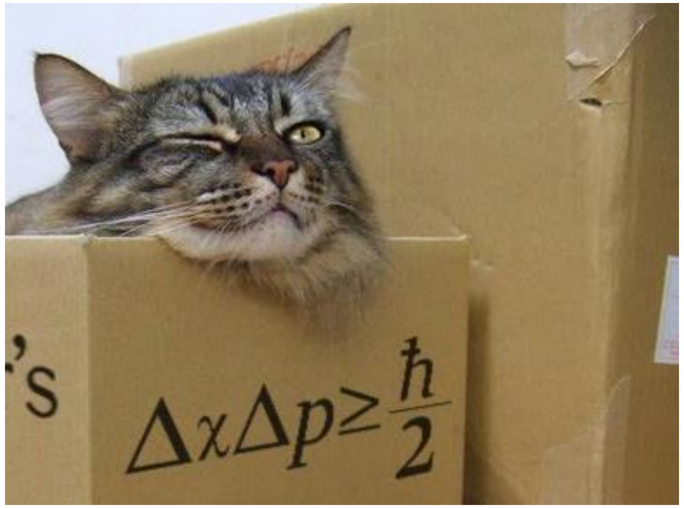
It works… Well, most of the time



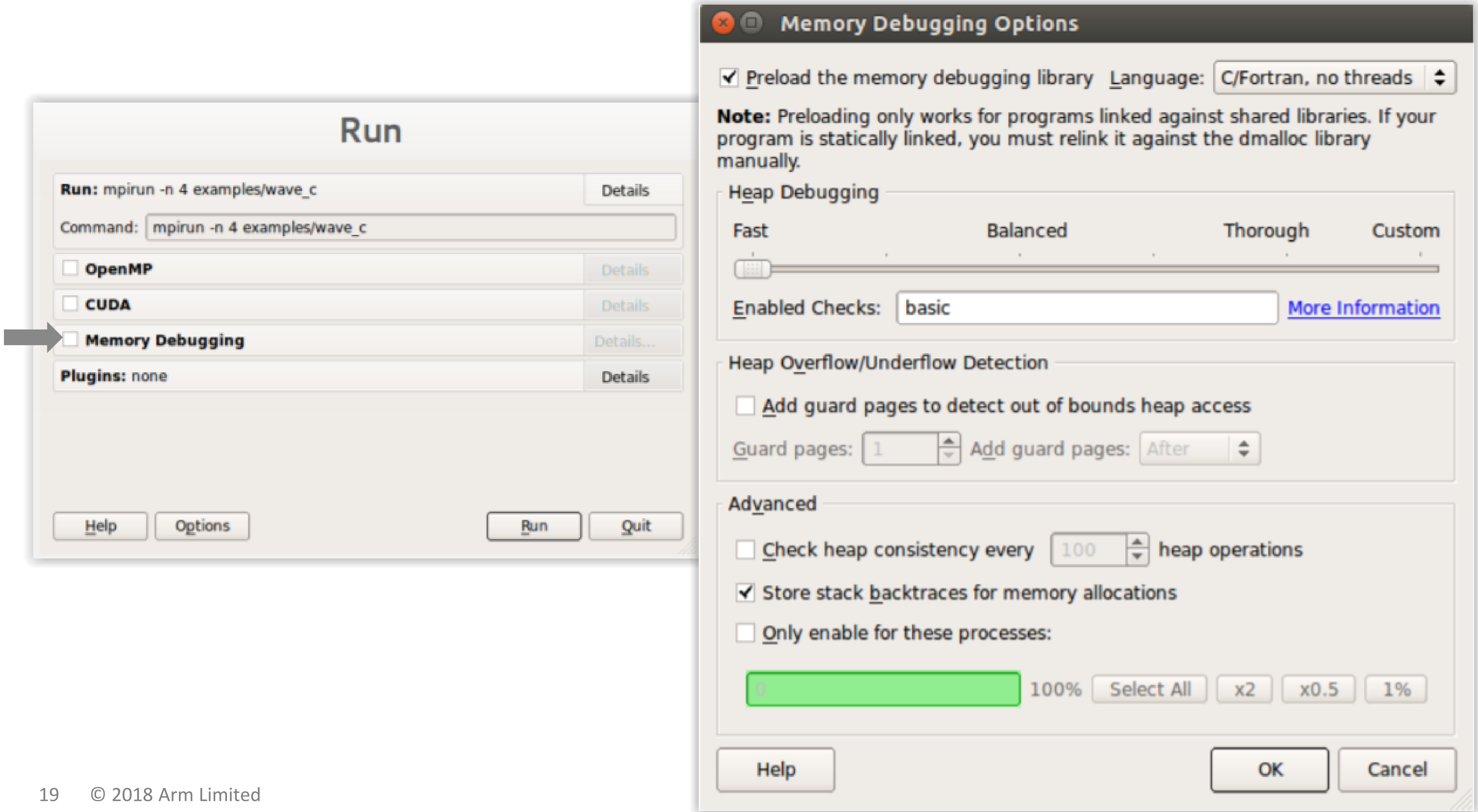
SCHRODIN BUG

!

A strange behaviour where the application “sometimes” crashes is a typical sign of a memory bug

Arm DDT is able to force the crash to happen

Advanced Memory Debugging



Heap debugging options available

Fast

basic
- Detect invalid pointers passed to memory functions (e.g. malloc, free, ALLOCATE, DEALLOCATE,...)

check-fence
- Check the end of an allocation has not been overwritten when it is freed.

free-protect
- Protect freed memory (using hardware memory protection) so subsequent read/writes cause a fatal error.

Added goodiness
- Memory usage, statistics, etc.

Balanced

free-blank
- Overwrite the bytes of freed memory with a known value.

alloc-blank
- Initialise the bytes of new allocations with a known value.

check-heap
- Check for heap corruption (e.g. due to writes to invalid memory addresses).

realloc-copy
- Always copy data to a new pointer when re-allocating a memory allocation (e.g. due to realloc)

Thorough

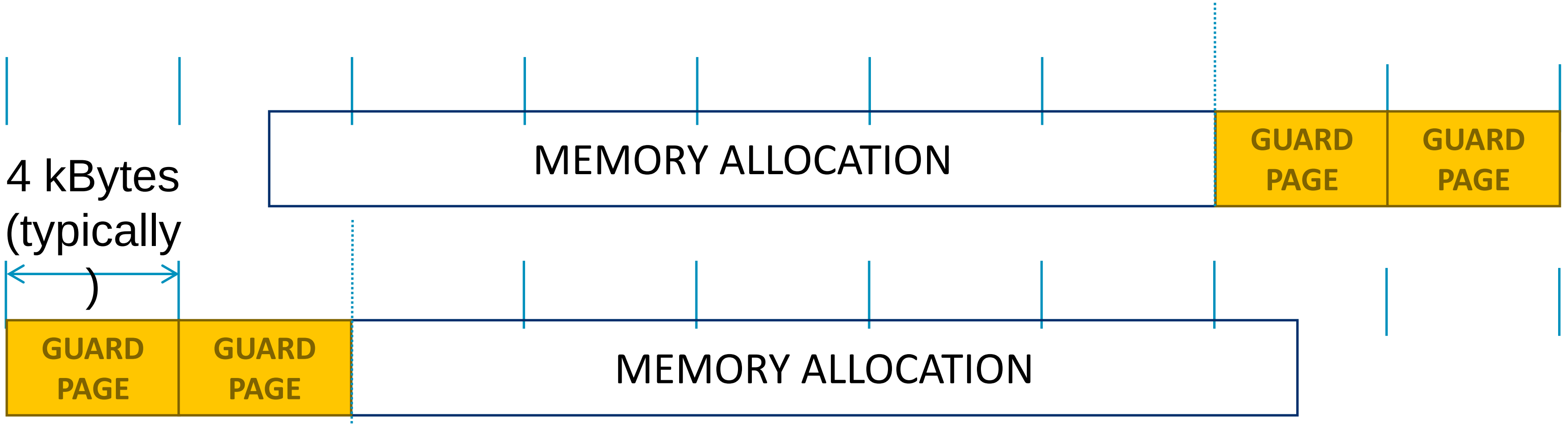
check-blank
- Check to see if space that was blanked when a pointer was allocated/freed has been overwritten.

check-funcs
- Check the arguments of addition functions (mostly string operations) for invalid pointers.

See user-guide:

Chapter 12.3.2

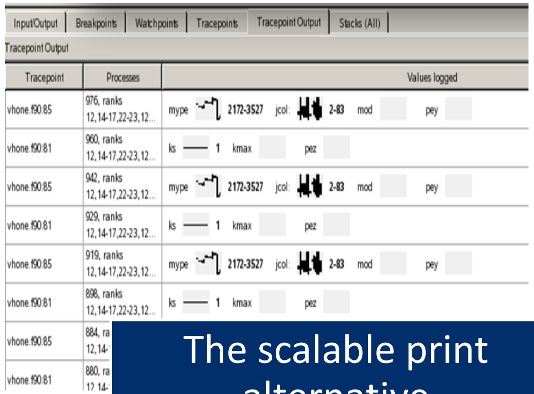
Guard pages (aka "Electric Fences")



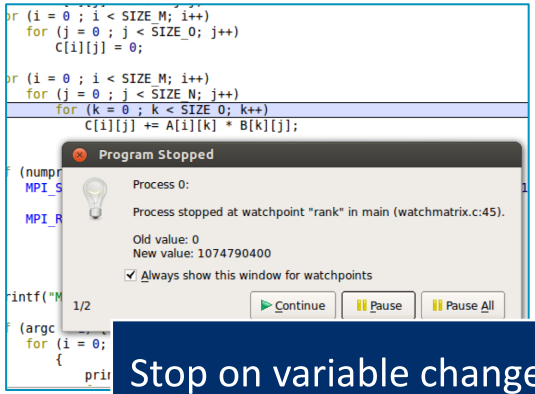
- **A powerful feature…:**
  - Forbids read/write on guard pages throughout the whole execution

    (because it overrides C Standard Memory Management library)
- **… to be used carefully:**
  - Kernel limitation: up to 32k guard pages max ("mprotect fails" error)
  - Beware the additional memory usage cost

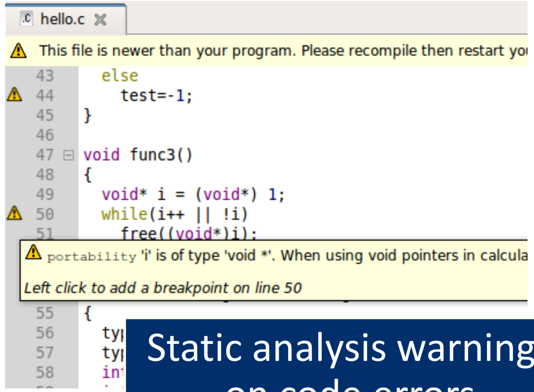
Five great things to try with Allinea DDT



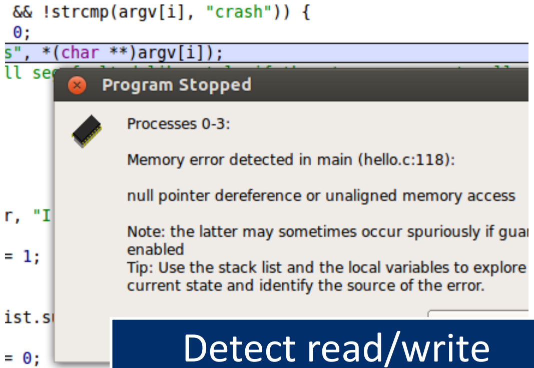
The scalable print alternative



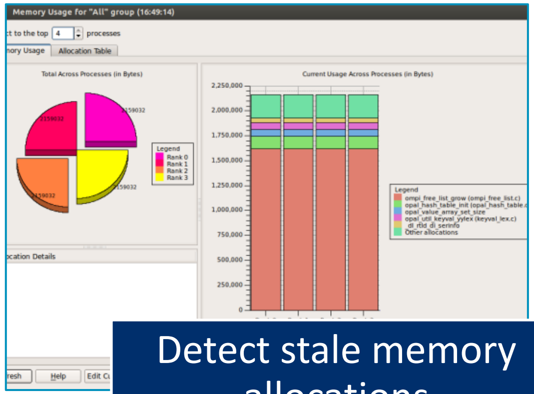
Stop on variable change



Static analysis warnings on code errors



Detect read/write beyond array bounds



Detect stale memory allocations

Arm DDT cheat sheet

Load the environment module

- $ module load **allinea-forge**

Prepare the code

- $ cc **-O0 -g** myapp.c -o myapp.exe

Start Arm DDT in interactive mode

- $ **ddt** srun -n 8 ./myapp.exe arg1 arg2

Or use the reverse connect mechanism

- On the login node:
  - $ ddt &
- (or use the remote client) **<- Preferred method**
- Then, edit the job script to run the following command and submit:
  - **ddt --connect** srun -n 8 ./myapp.exe arg1 arg2

Generating Performance Reports

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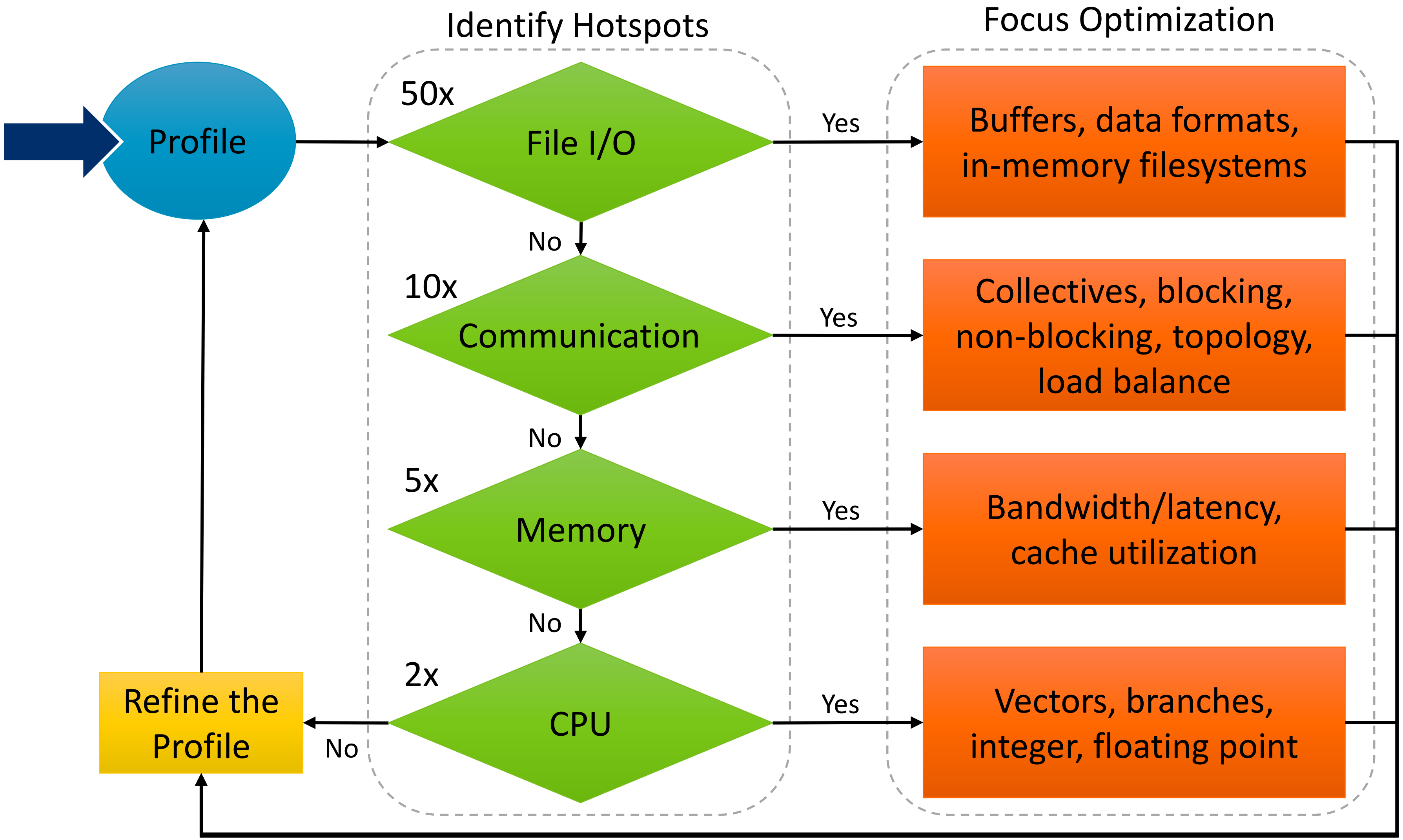
Profiling

Profiling is central to understanding and improving application performance.



Arm Performance Reports

High-level view of application performance shows low write rate.

arm PERFORMANCE REPORTS

Command:	mpiexec.hydra -host node-1,node-2 -map-by socket -n 16 -ppn 8 ./Bin/low_freq/../../Src//hydro -i ./Bin/low_freq/../../../../Input/input_250x125_corner.nml
Resources:	2 nodes (8 physical, 8 logical cores per node)
Memory:	15 GiB per node
Tasks:	16 processes, OMP_NUM_THREADS was 1
Machine:	node-1
Start time:	Thu Jul 9 2015 10:32:13
Total time:	165 seconds (about 3 minutes)
Full path:	Bin/../Src

Summary: hydro is MPI-bound in this configuration

Compute	20.6%	Time spent running application code. High values are usually good. This is **very low**; focus on improving MPI or I/O performance first
MPI	63.2%	Time spent in MPI calls. High values are usually bad. This is **high**; check the MPI breakdown for advice on reducing it
I/O	16.2%	Time spent in filesystem I/O. High values are usually bad. This is **average**; check the I/O breakdown section for optimization advice

I/O

A breakdown of the 16.2% I/O time:

Time in reads	0.0%
Time in writes	100.0%
Effective process read rate	0.00 bytes/s
Effective process write rate	1.38 MB/s

Most of the time is spent in write operations with a very low effective transfer rate. This may be caused by contention for the filesystem or inefficient access patterns. Use an I/O profiler to investigate which write calls are affected.

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After the fix, write rate has improved 41.6x

Eliminating file open/close bottleneck has dramatically improved I/O performance.

arm PERFORMANCE REPORTS

Command:	mpiexec.hydra -host node-1,node-2 -map-by socket -n 16 -ppn 8 ./Bin/../Src//hydro -i ./Bin/../../../Input/input_250x125_corner.nml
Resources:	2 nodes (8 physical, 8 logical cores per node)
Memory:	15 GiB per node
Tasks:	16 processes, OMP_NUM_THREADS was 1
Machine:	node-1
Start time:	Tue Jul 14 2015 13:07:32
Total time:	68 seconds (about 1 minutes)
Full path:	Src

Summary: hydro is MPI-bound in this configuration

Compute	23.5%	Time spent running application code. High values are usually good. This is **very low**; focus on improving MPI or I/O performance first
MPI	75.5%	Time spent in MPI calls. High values are usually bad. This is **very high**; check the MPI breakdown for advice on reducing it
I/O	0.9%	Time spent in filesystem I/O. High values are usually bad. This is **very low**; however single-process I/O may cause MPI wait times

I/O

A breakdown of the 0.9% I/O time:

Time in reads	0.0%
Time in writes	100.0%
Effective process read rate	0.00 bytes/s
Effective process write rate	57.5 MB/s

Most of the time is spent in write operations with a low effective transfer rate. This may be caused by contention for the filesystem or inefficient access patterns. Use an I/O profiler to investigate which write calls are affected.

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Performance Reports Demo

arm

LAMMPS IO Performance Report Suggests Using MPI Profiler

This application run was MPI-bound. A breakdown of this time and advice for investigating further is in the MPI section below.

CPU

A breakdown of the 22.1% CPU time:

Single-core code	96.2%
OpenMP regions	3.8%
Scalar numeric ops	34.4%
Vector numeric ops	0.0%
Memory accesses	65.6%

Per-process performance is dominated by serial sections of computation. Use a profiler to find these or run with fewer threads and more processes.

The per-core performance is memory-bound. Use a profiler to identify time-consuming loops and check their cache performance.

MPI

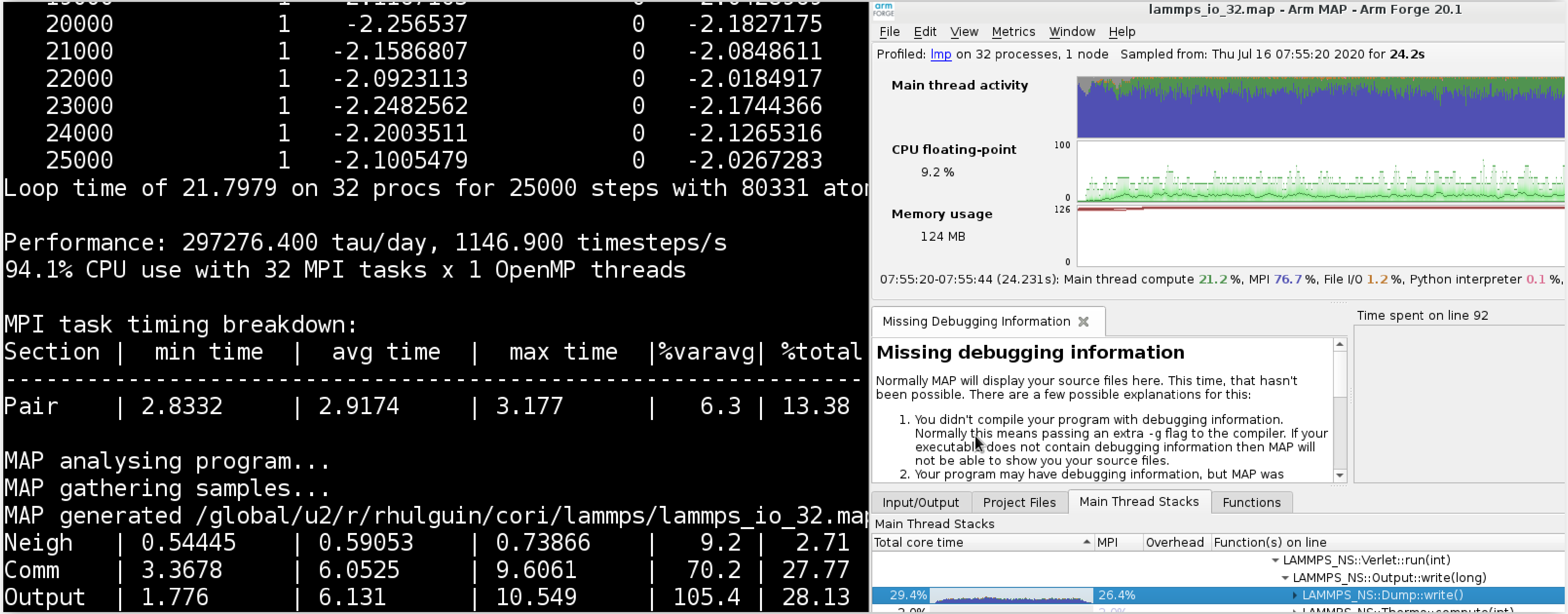
A breakdown of the 76.7% MPI time:

Time in collective calls	38.2%
Time in point-to-point calls	61.8%
Effective process collective rate	293 kB/s
Effective process point-to-point rate	80.8 MB/s

Most of the time is spent in point-to-point calls with a low transfer rate. This can be caused by inefficient message sizes such as many small messages, or by imbalanced workloads causing processes to wait.

The collective transfer rate is very low. This suggests load imbalance is causing synchronization overhead; use an MPI profiler to investigate.

Built-in Timers vs Arm MAP



Break

Profiling with MAP

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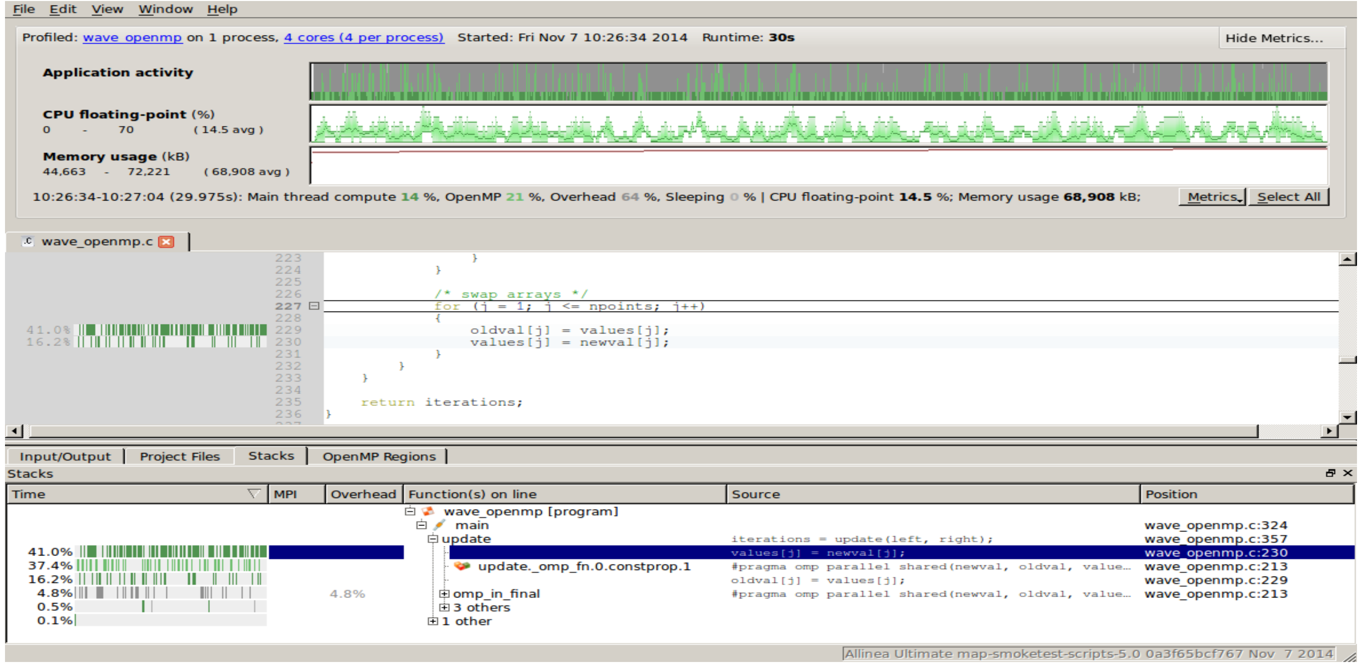
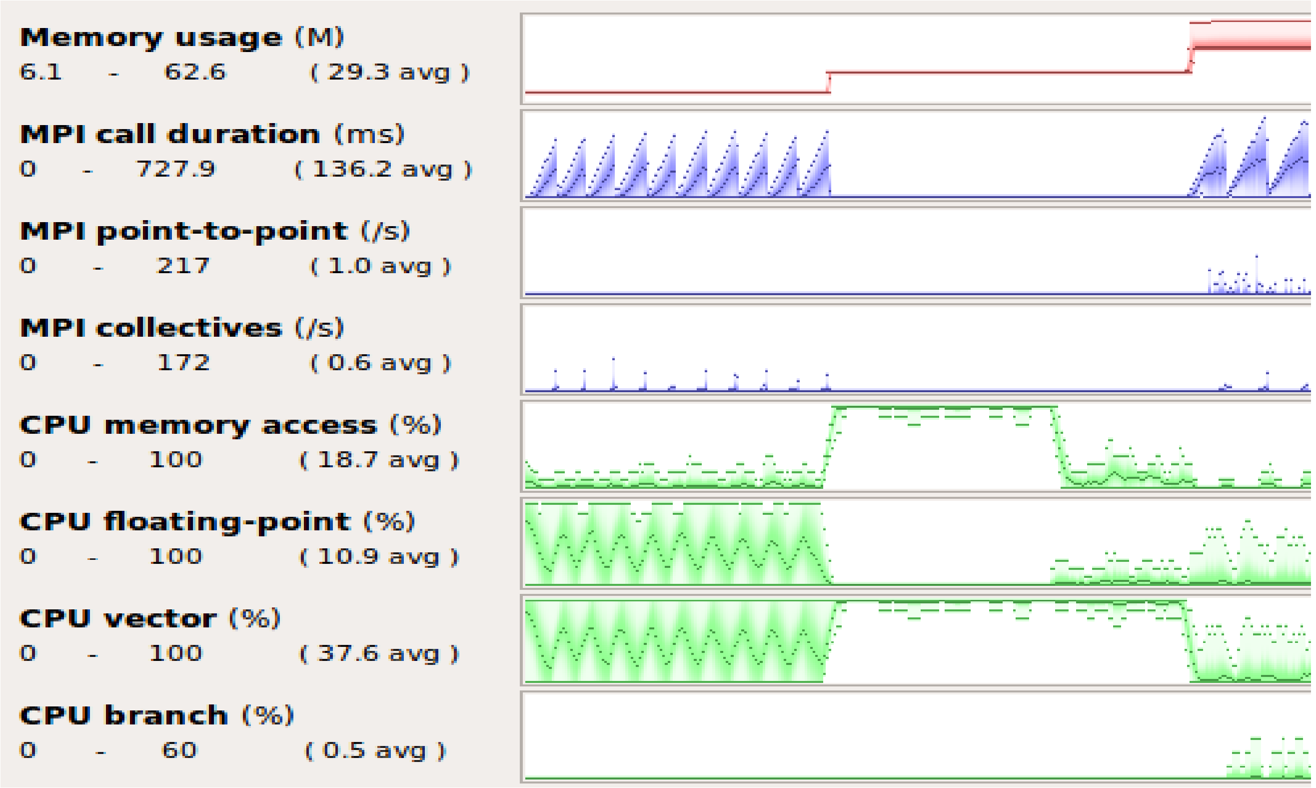
Arm MAP – The Profiler

- Small data files
- <5% slowdown
- No instrumentation
- No recompilation



Glean Deep Insight from our Source-Level Profiler



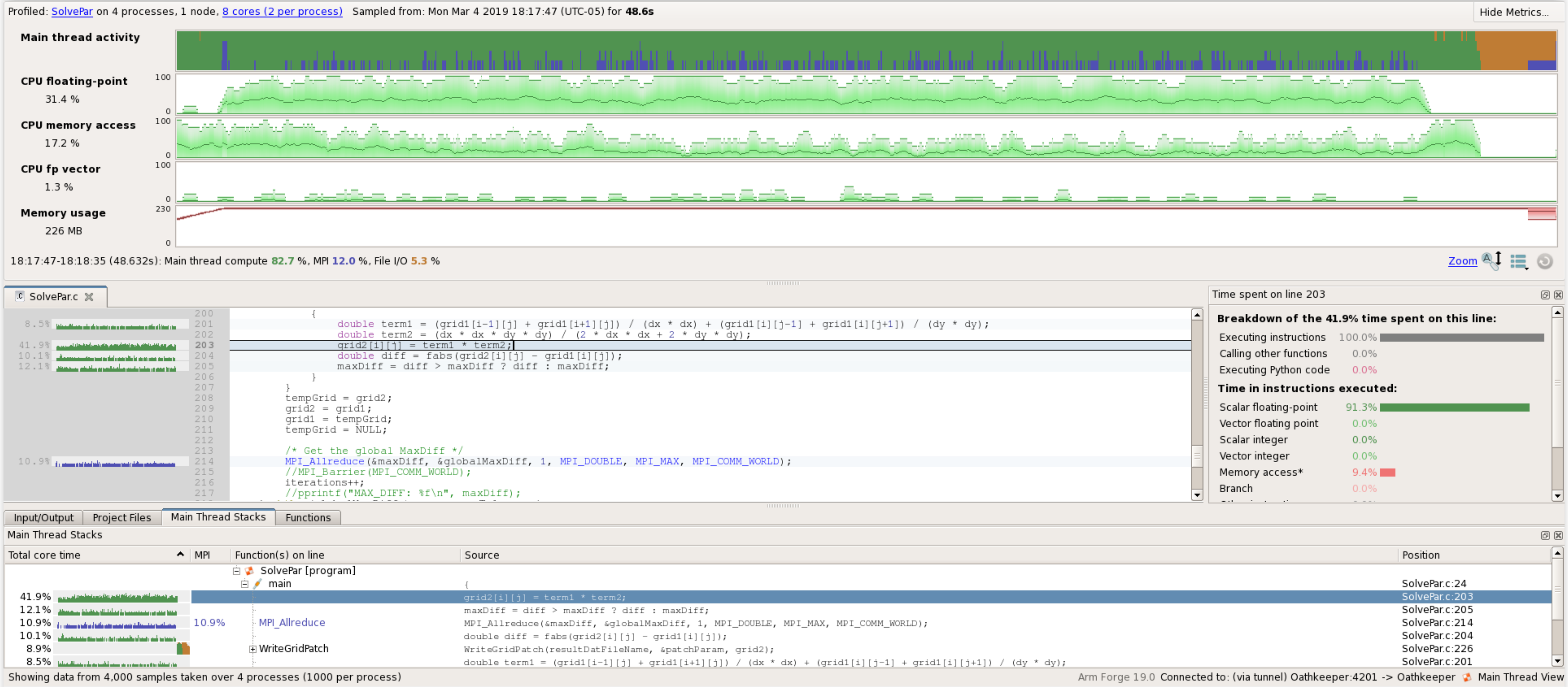
Track memory usage across the entire application over time

Spot MPI and OpenMP imbalance and overhead

Optimize CPU memory and vectorization in loops

Detect and diagnose I/O bottlenecks at real scale

Profile of 2d Laplace Solver with Jacobi Iteration

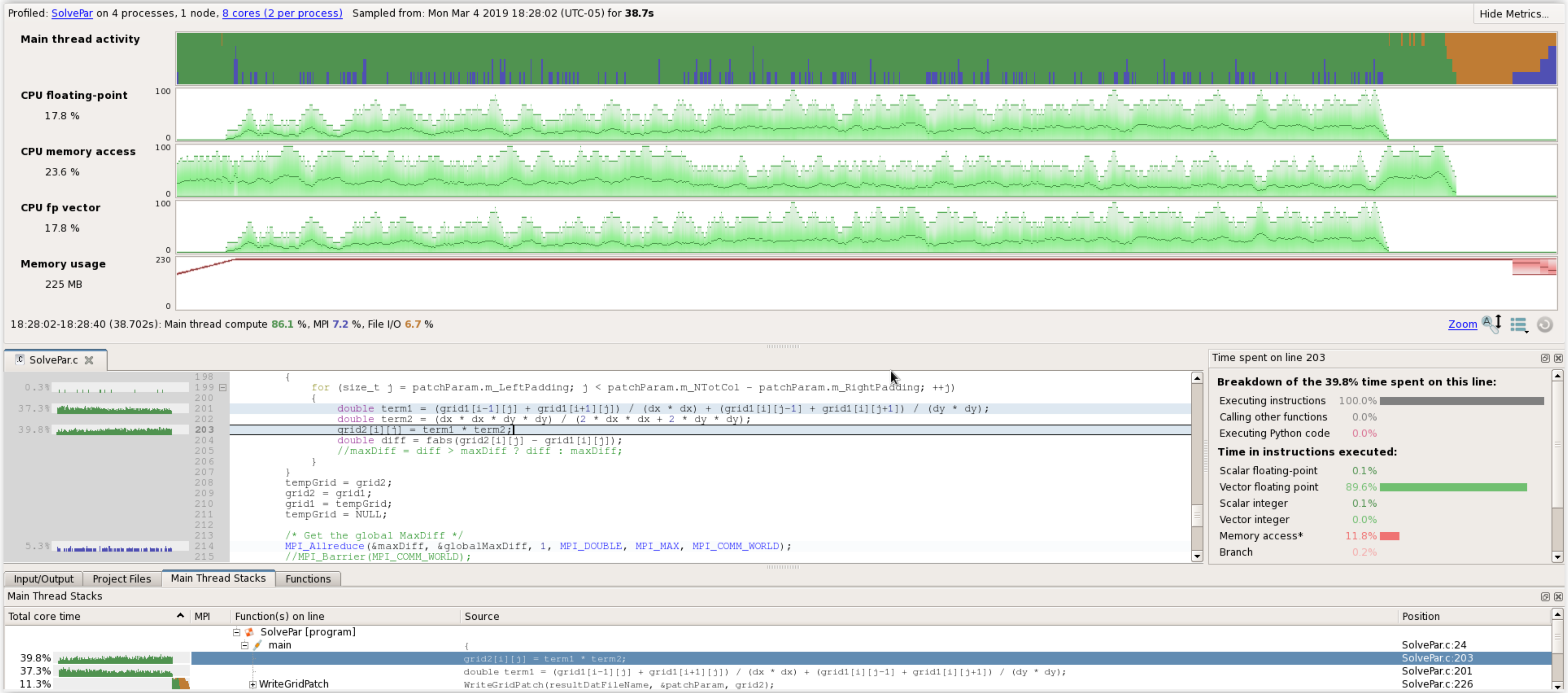


Tracking Largest Change

```
// Compare newly computed value with old value
diff = fabs(grid2[i][j] - grid1[i][j]);
// Track largest change between new and old values
maxDiff = diff > maxDiff ? Diff : maxDiff;


If (diff > maxDiff)
  then maxDiff= diff;
Else
  maxDiff = maxDiff;
```

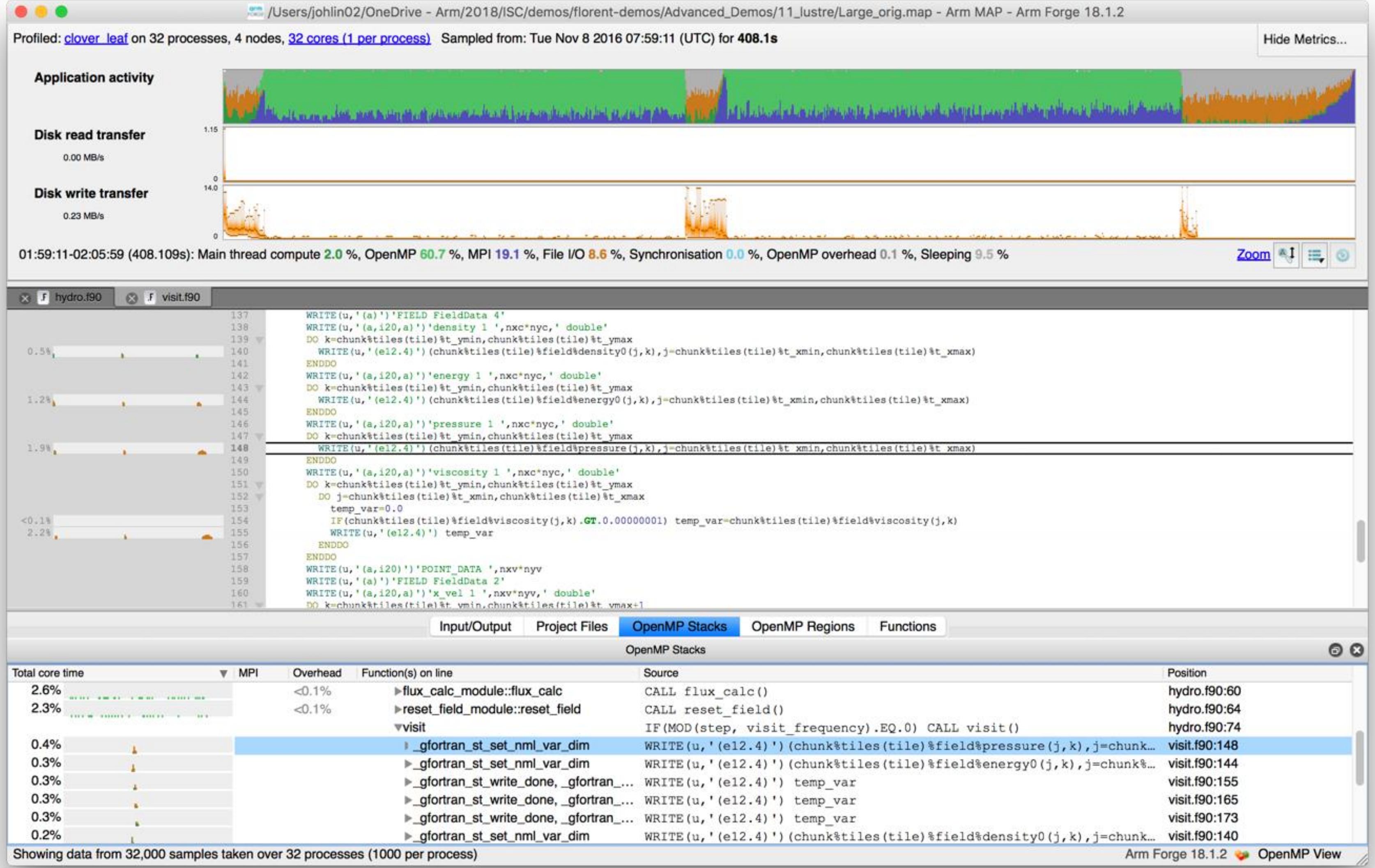

Conditional Removal from Innermost Loop



20 % faster, also operation is now vectorized

Initial profile of CloverLeaf shows surprisingly unequal I/O

Each I/O operation should take about the same time, but it's not the case.



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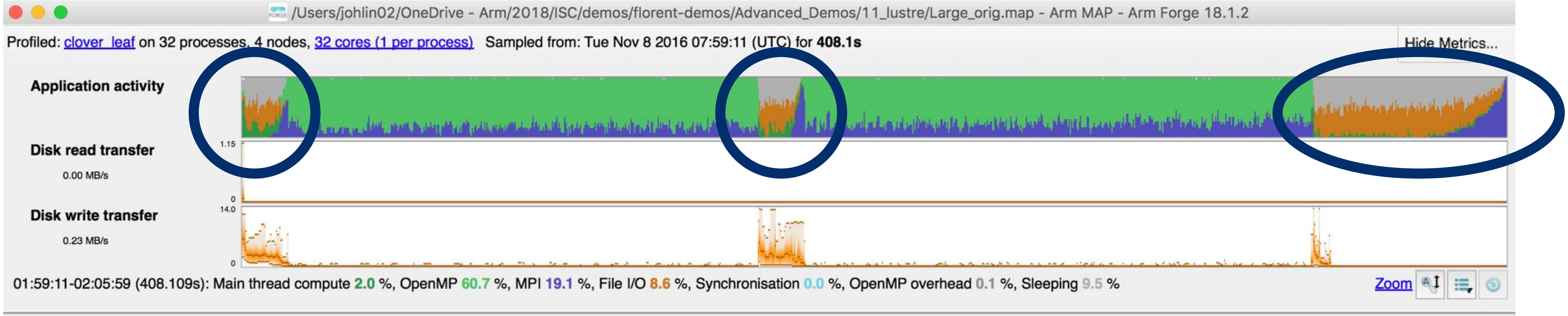
Symptoms and causes of the I/O issues

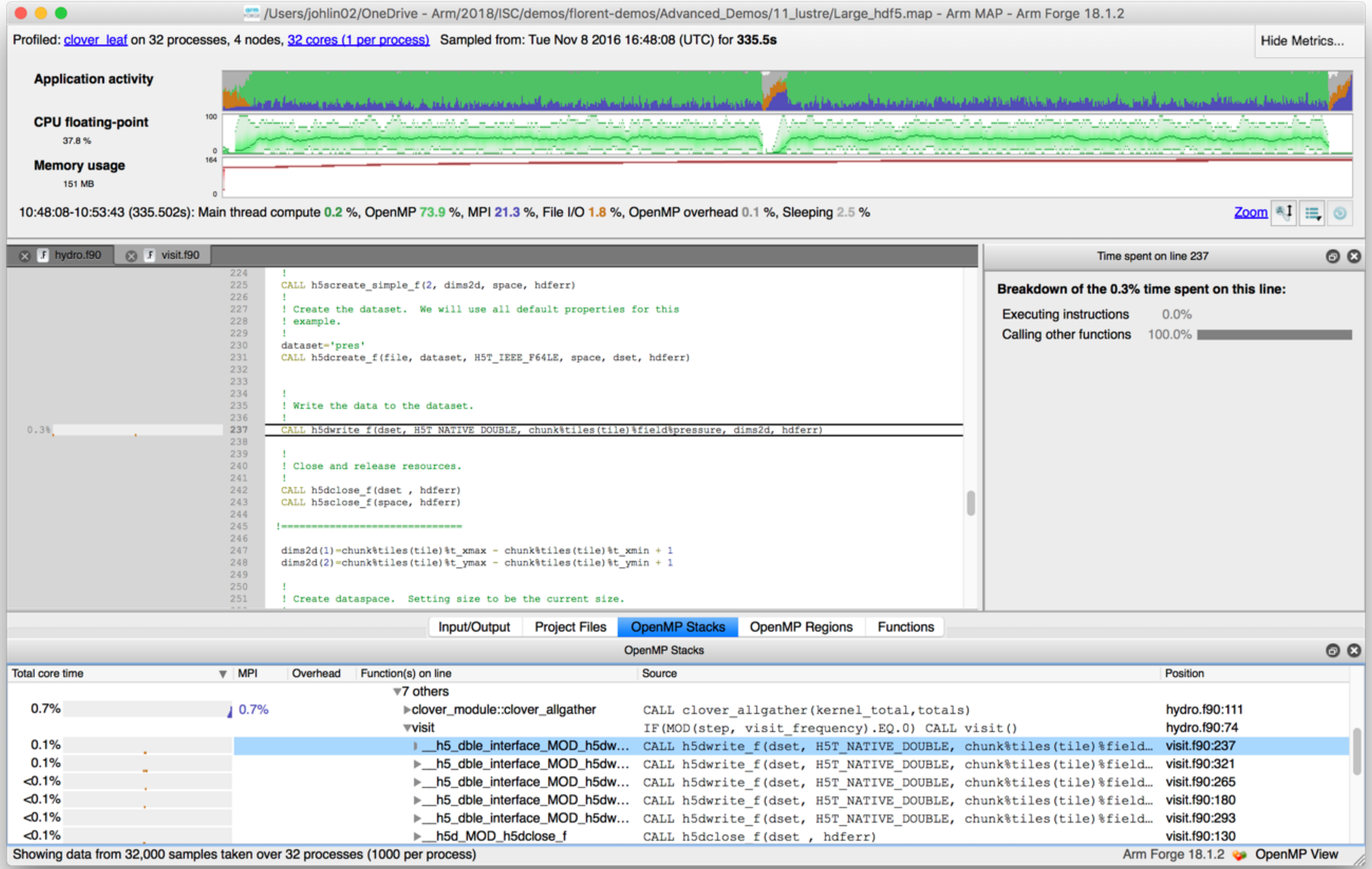
Sub-optimal file format and surprise buffering.



- Write rate is less than 14MB/s.
- Writing an ASCII output file.
- Writes not being flushed until buffer is full.
  - Some ranks have much less buffered data than others.
  - Ranks with small buffers wait in barrier for other ranks to finish flushing their buffers.

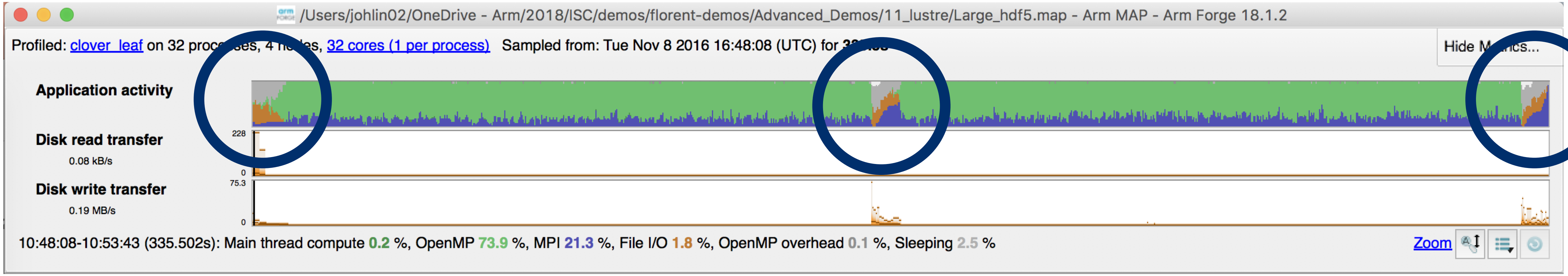
Solution: use HDF5 to write binary files

Using a library optimized for HPC I/O improves performance and portability.



Solution: use HDF5 to write binary files

Using a library optimized for HPC I/O improves performance and portability.



- Replace Fortran write statements with HDF5 library calls.
  - Binary format reduces write volume and can improve data precision.
  - Maximum transfer rate now 75.3 MB/s, over 5x faster.
- Note MPI costs (blue) in the I/O region, so room for improvement.

Arm Map Handson

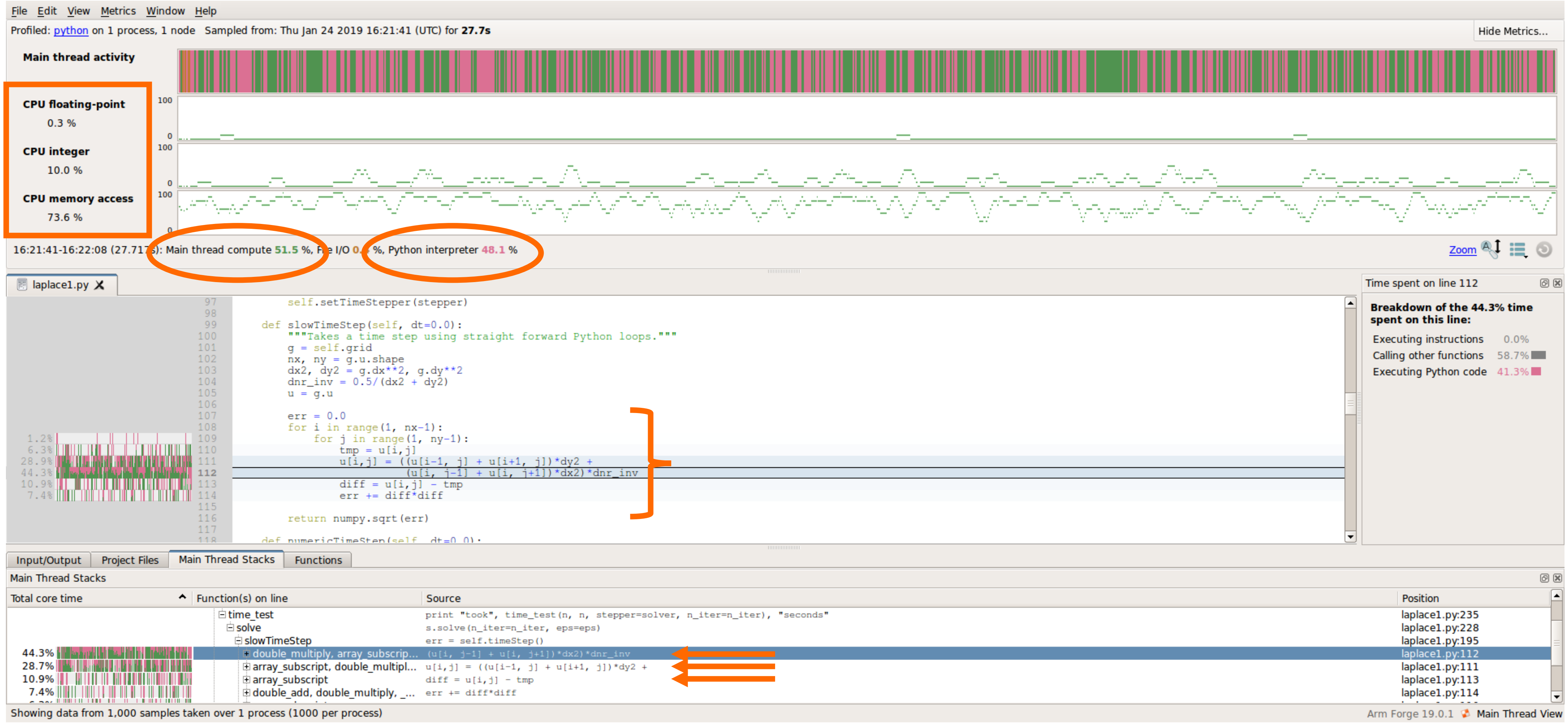
Arm MAP: Python profiling

- Launch command
  - $ **python** ./laplace1.py slow 100 100
- Profiling command
  - $ **map --profile** **python** ./laplace1.py slow 100 100
  - --profile: non-interactive mode
  - --output: name of output file
- Display profiling results
  - $ **map** laplace1.map

Laplace1.py

```
[…]
err = 0.0
for i in range(1, nx-1):
  for j in range(1, ny-1):
    tmp = u[i,j]
    u[i,j] = ((u[i-1, j] + u[i+1, j])*dy2 +
      (u[i, j-1] + u[i, j+1])*dx2)*dnr_inv
    diff = u[i,j] - tmp
    err += diff*diff
return numpy.sqrt(err)
[…]
```

Naïve Python loop (laplace1.py slow 100 1000)



Optimizing computation on NumPy arrays

Naïve Python loop

```
err = 0.0
for i in range(1, nx-1):
  for j in range(1, ny-1):
    tmp = u[i,j]
    u[i,j] = ((u[i-1, j] + u[i+1, j])*dy2 +
    (u[i, j-1] + u[i, j+1])*dx2)*dnr_inv
    diff = u[i,j] - tmp
    err += diff*diff
return numpy.sqrt(err)
```

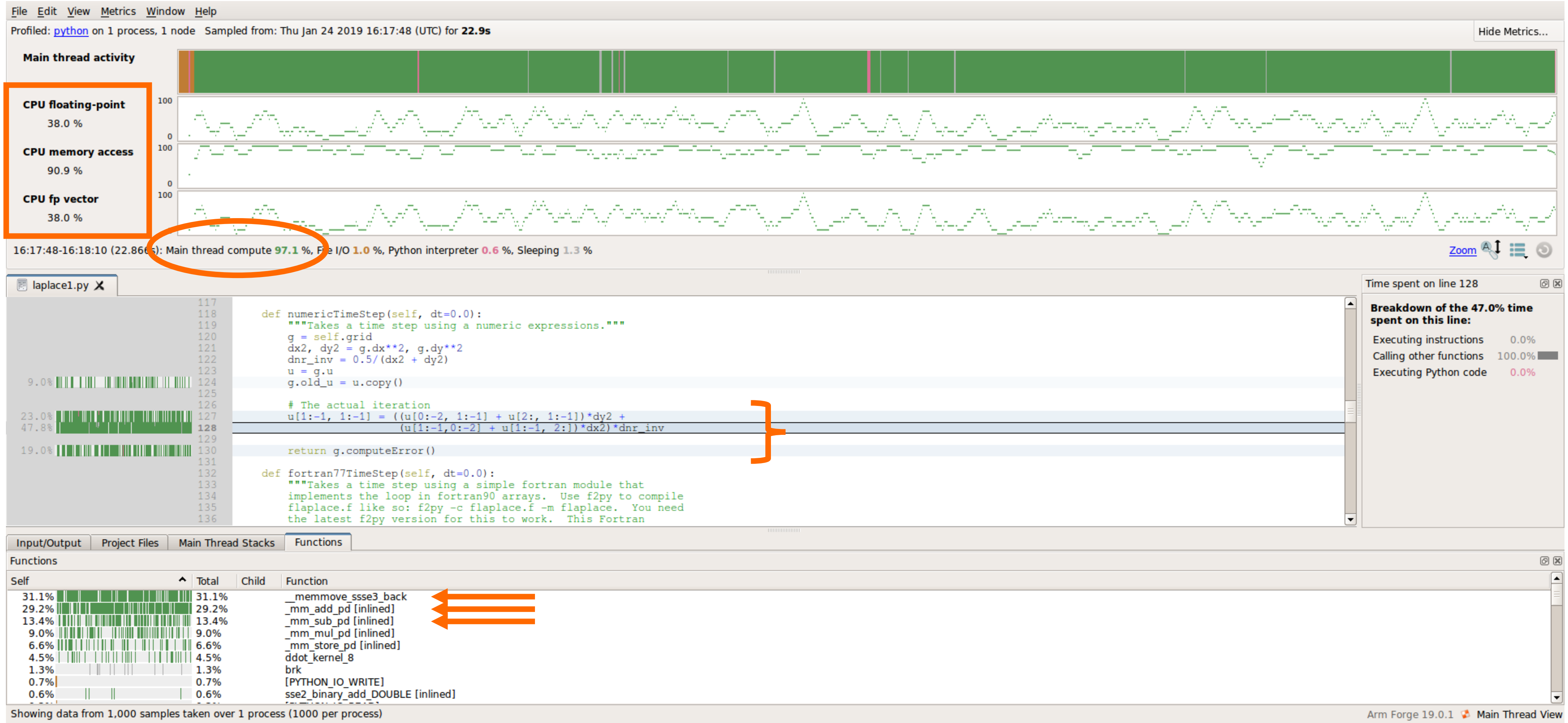
NumPy loop

```
u[1:-1, 1:-1] =
    ((u[0:-2, 1:-1] + u[2:, 1:-1])*dy2 +
     (u[1:-1,0:-2] + u[1:-1, 2:])*dx2)*dnr_inv

return g.computeError()
```

NumPy array notation (laplace1.py numeric 1000 1000)

This is 10 times more iterations than was computed in the previous profile



Arm MAP cheat sheet

Load the environment module (manually specify version)

- $ module load **allinea-forge**

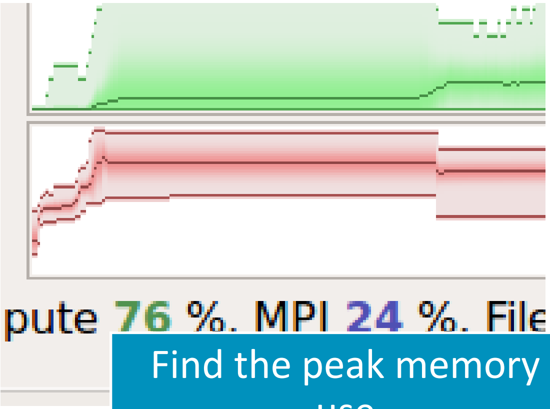
Follow the instructions displayed to prepare the code

- $ cc -O3 **-g** myapp.c -o myapp.exe
- Edit the job script to run Arm MAP in “profile” mode
- $ **map --profile** -n 8 ./myapp.exe arg1 arg2

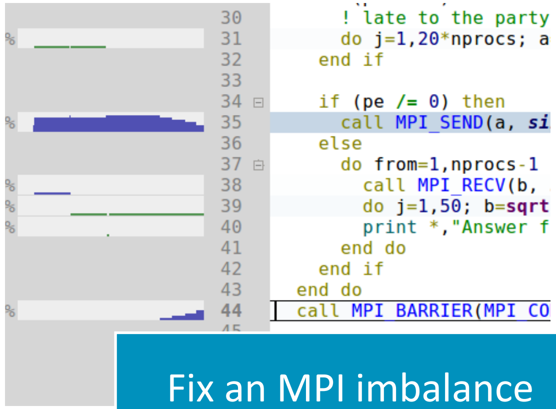
Open the results

- On the login node:
  - $ map myapp_Xp_Yn_YYYY-MM-DD_HH-MM.map
- (or load the corresponding file using the remote client connected to the remote system or locally)
  - $ map **--connect** myapp_Xp_Yn_YYYY-MM-DD_HH-MM.map

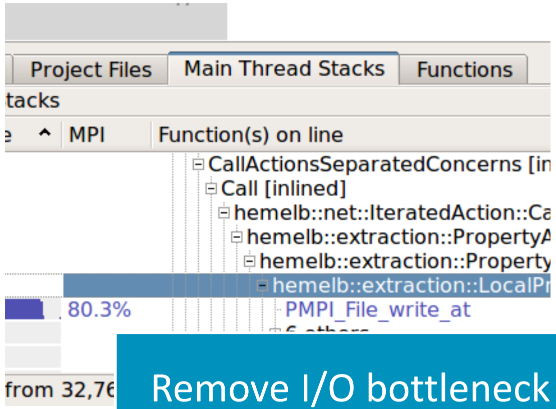
Six Great Things to Try with Allinea MAP



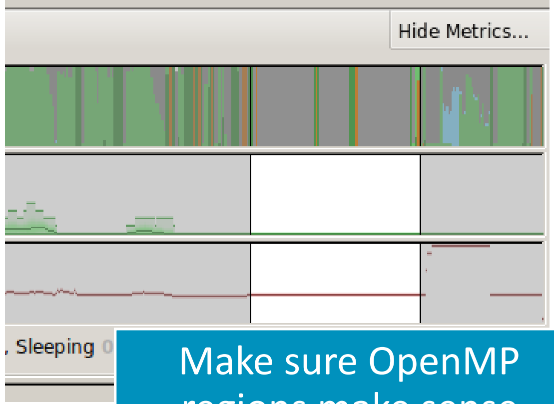
Find the peak memory use



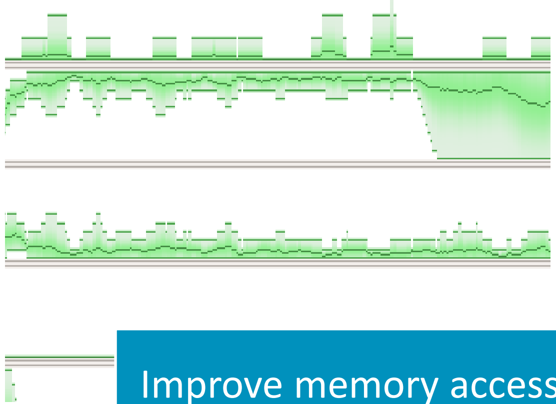
Fix an MPI imbalance



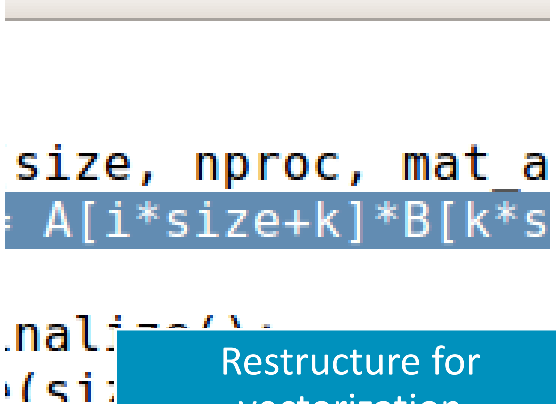
Remove I/O bottleneck



Make sure OpenMP regions make sense



Improve memory access



Restructure for vectorization

arm

Cori Specific Settings

Configure the remote client

Install the Arm Remote Client

https://developer.arm.com/products/software-development-tools/hpc/downloads/download-arm-forge

Connect to the cluster with the remote client

- Open your Remote Client
- Create a new connection: Remote Launch ➔ Configure ➔ Add
  - Hostname: `<username>@cori.nersc.gov`
  - Remote installation directory:

    `/usr/common/software/allinea-forge/20.1-Suse-15.0-x86_64`

Examples for hands-on session

Examples are available at `/global/cfs/cdirs/training/2020/arm-tools/`

```
ddt/ddt_demo

ddt/memory_debugging

perf-report/

map/

python/
```

Questions?

arm

Thank You!

Danke!

Merci!

谢谢!

ありがとう!

Gracias!

Kiitos!

감사합니다

धन्यवाद