



# MAQAO

## Performance Analysis and Optimization Tool

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<http://www.maqao.org>

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# MAQAO Framework and Toolsuite

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R&D Team: develop performance evaluation and optimization tools



Open Source software (LGPL 3)

- Currently only binary release (source => ongoing)
- Profilers (generic and MPI) work on any LSB/Most Unix
- Code quality analysis and hardware counters support only available for Intel x86-64 and Xeon Phi



Funded by UVSQ, Intel and CEA (French department of energy)

Establish partnerships:

- Optimize industrial applications
- Provide building blocks (framework services) to other tools:
  - TAU tool *tau\_rewrite*: binary rewriting feature (MIL)
  - ATOS/BULL tool *bullxprof* : binary rewriting feature (MIL)

# Introduction

## *Performance analysis (1/2)*

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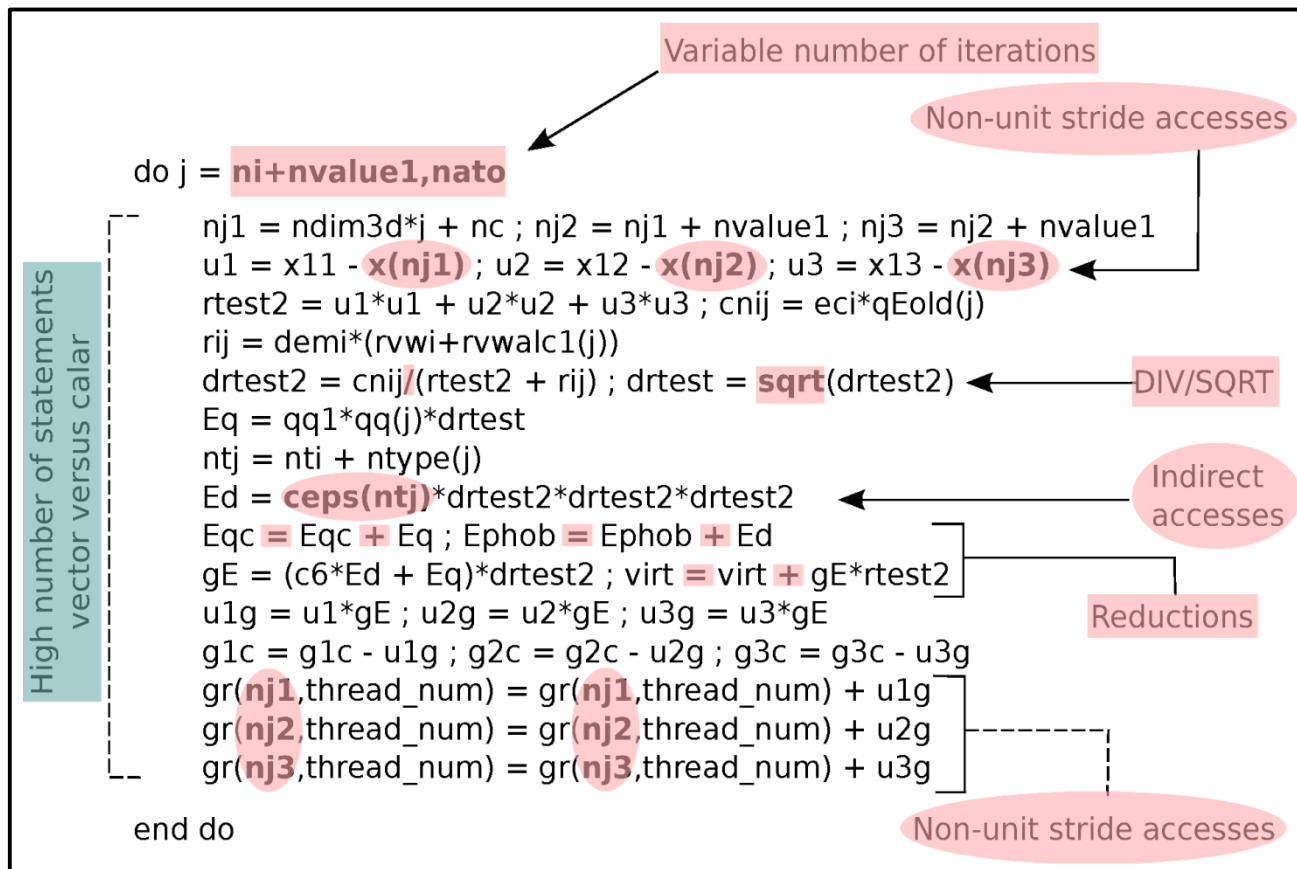
- Characterize the performance of an application
  - Complex multicore CPUs and memory systems
  - How well does it behaves on a given machine
- Generally a multifaceted problem
  - What are the issues (numerous but finite) ?
  - Which one(s) dominates ?
  - Maximizing the number of views
  - => Need for specialized tools
- Three main classes of issues
  - Find/Select relevant algorithms
  - Work sharing/decomposition
  - Exploiting performance available at CPU level



# Introduction

## Performance analysis (2/2)

Motivating example: loop ~10% walltime



Source code and associated issues:

- 1) High number of statements
- 2) Non-unit stride accesses
- 3) Indirect accesses
- 4) DIV/SQRT
- 5) Reductions
- 6) Vector vs Scalar



## Introduction

### ***MAQAO: working at binary level (1/2)***

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Why ???

Most of the time the compiler changes source code

Some source code instrumentation may prevent the compiler from applying transformation

- i.e.: loop interchange

We want to evaluate the “real” executed code

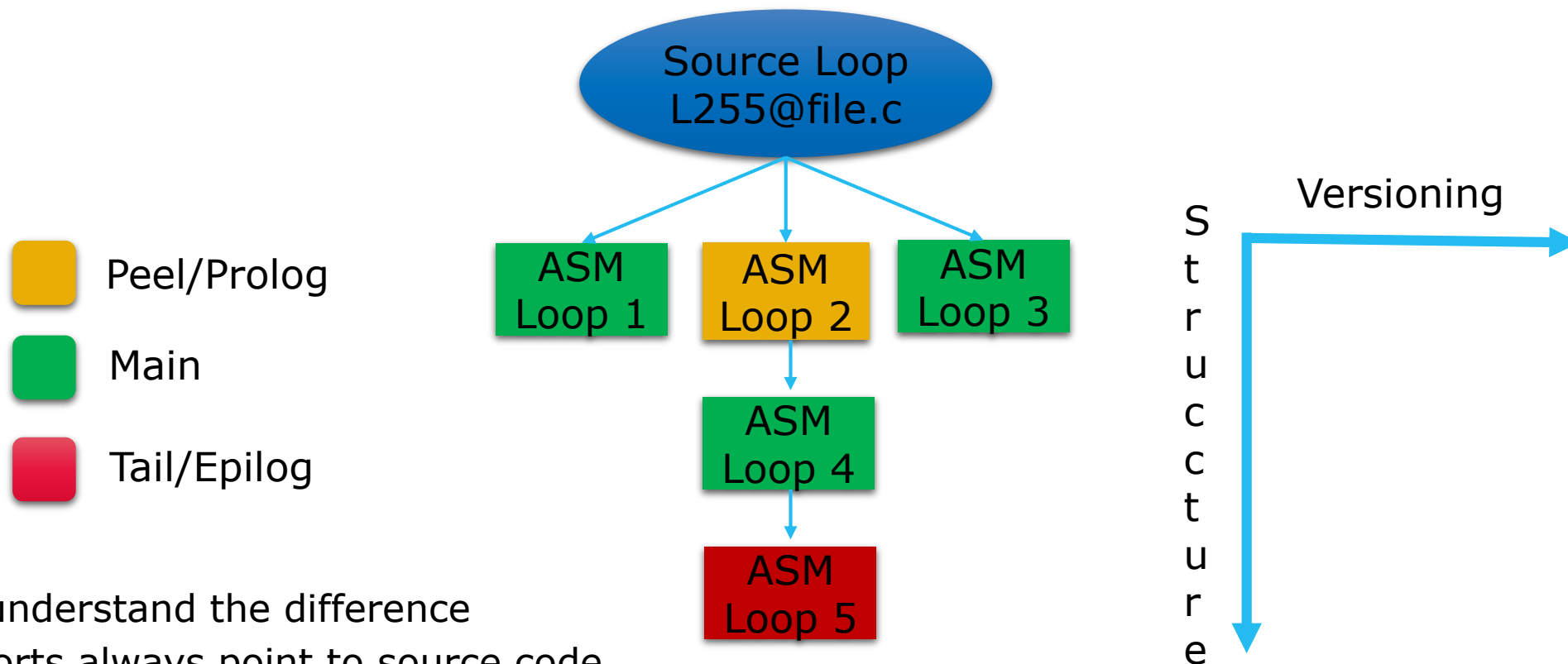
We are able to reconstruct an abstract view with functions and loops in order to be able to correlate with your source code.

One little difference is understanding loops at assembly level

## Introduction

### *MAQAO: working at binary level (2/2)*

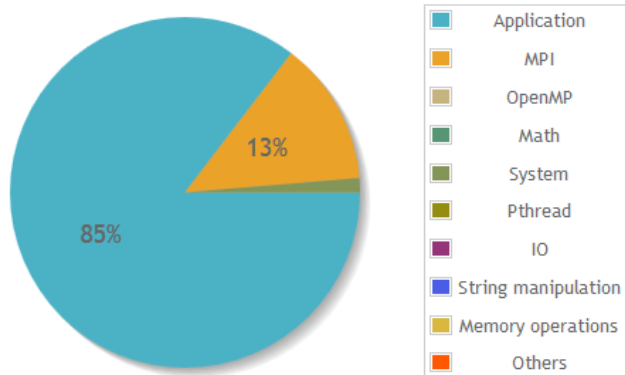
Source level V.S. Assembly level



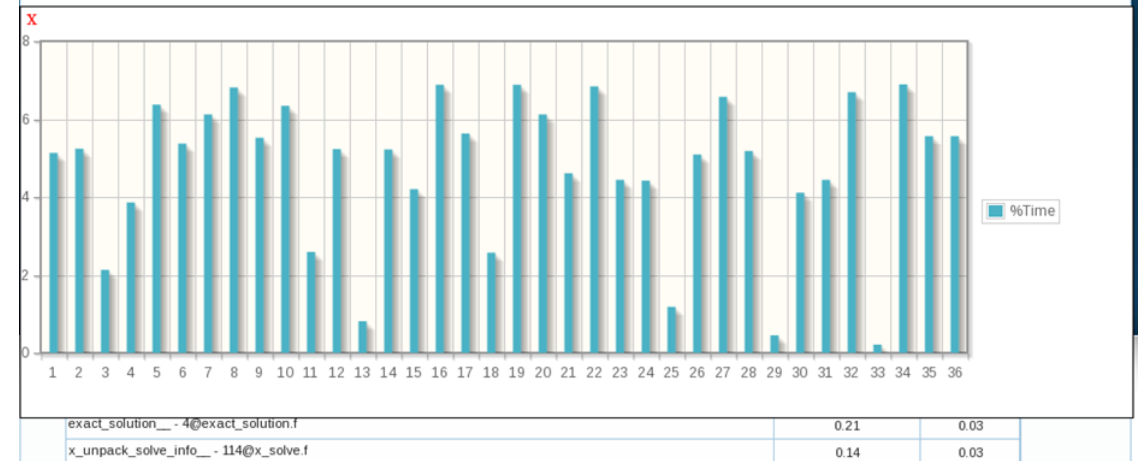
You just need to understand the difference  
But our tools' reports always point to source code

## MAQAO LProf: locating hotspots

Time categorization - mz-mpich-3.1.sp-mz.C.8



Hotspots - Functions



# MAQAO LProf: locating hotspots

## *Introduction*

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Locating most time consuming hotspots is the first step you want to accomplish.

Multiple measurement methods available:

- Why is it important to know this ?
- Instrumentation
  - Through binary rewriting
  - High overhead / More precision
- Sampling
  - Hardware counters (through `perf_event_open` system call)
  - Linux kernel timers
  - No instrumentation / Very low overhead / less details (i.e. function calls count)
- Default method: Sampling using hardware counters (if available) or timers

Runtime-agnostic: Only system processes and threads are considered

Where is time spent ? Which one(s) should I investigate first ?



## MAQAO LProf: locating hotspots

### *Time categorization*

Sadly, executing an application is not just doing the science you are supposed to !

Work sharing/splitting

- Shared: Pthreads, OpenMP, etc ...
- Distributed: MPI, etc...

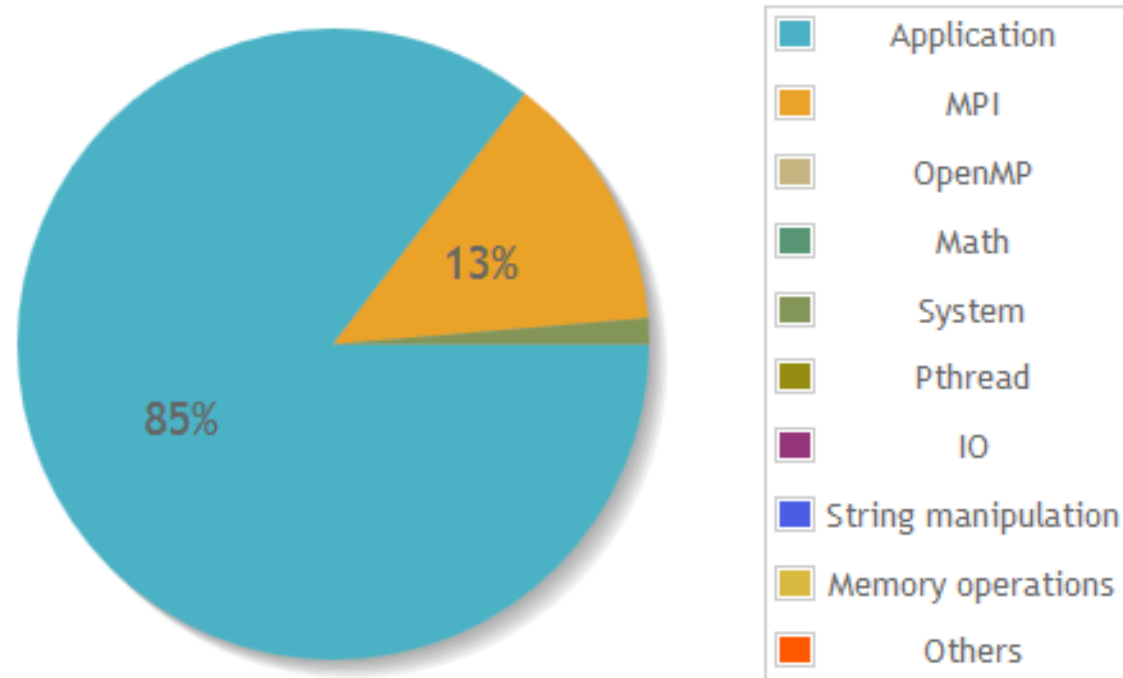
Programming

- IO
- String manipulation
- Memory management
- Math (external libraries)

Doing actual science (Application)

- Functions
- Loops

**Time categorization - mz-mpich-3.1.sp-mz.C.8**



## MAQAO LProf: locating hotspots

### *Function and loop hotspots (1/3)*

Lets focus on science !

First we want to check function hotspots load balancing vue at (multi)node level

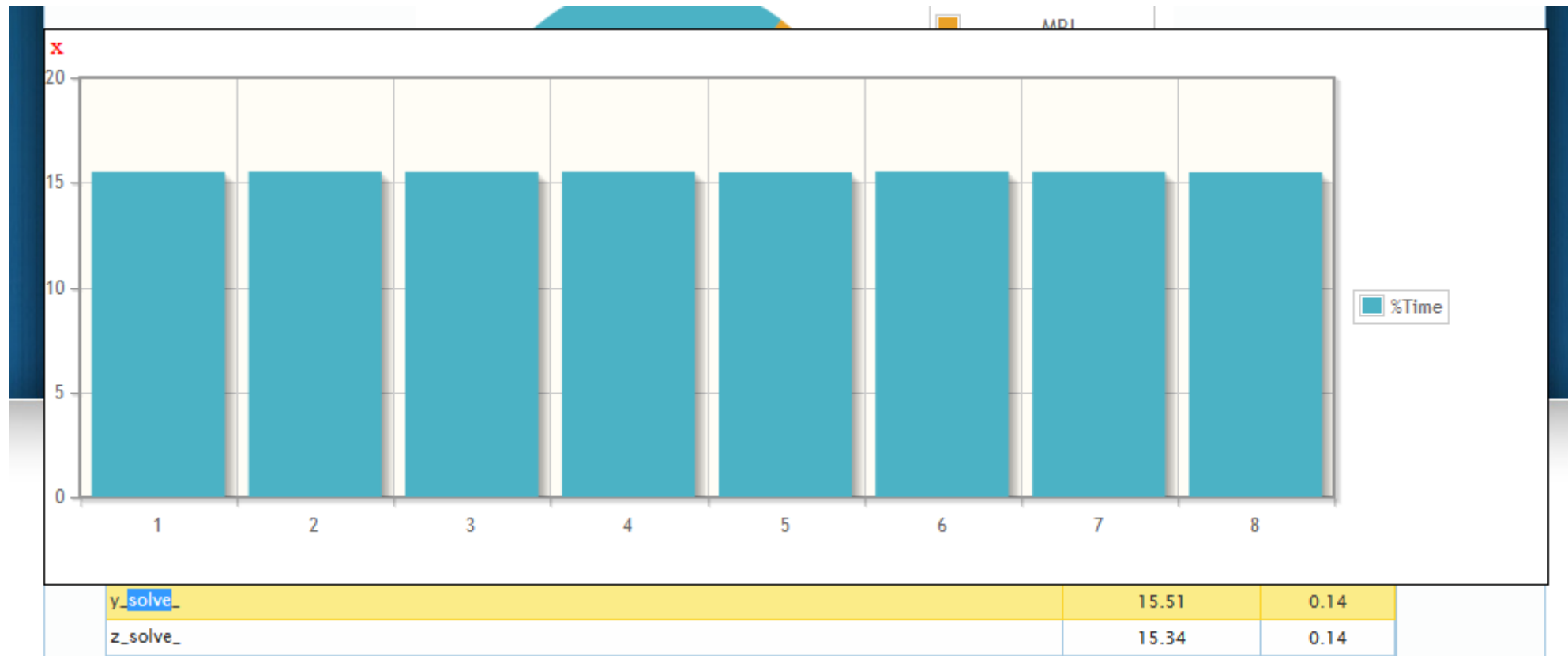
- For the same function
- Does it behave the same way on all the nodes ?

#### Hotspots - Functions

Name	Median Excl %Time	Deviation
compute_rhs_	30.88	0.14
y_solve_	15.51	0.14
z_solve_	15.34	0.14
x_solve_	15.07	0.14
MPIDI_CH3I_Progress	5.61	0.14

## MAQAO LProf: locating hotspots

### *Function and loop hotspots (2/3)*



## MAQAO LProf: locating hotspots

### *Function and loop hotspots (3/3)*

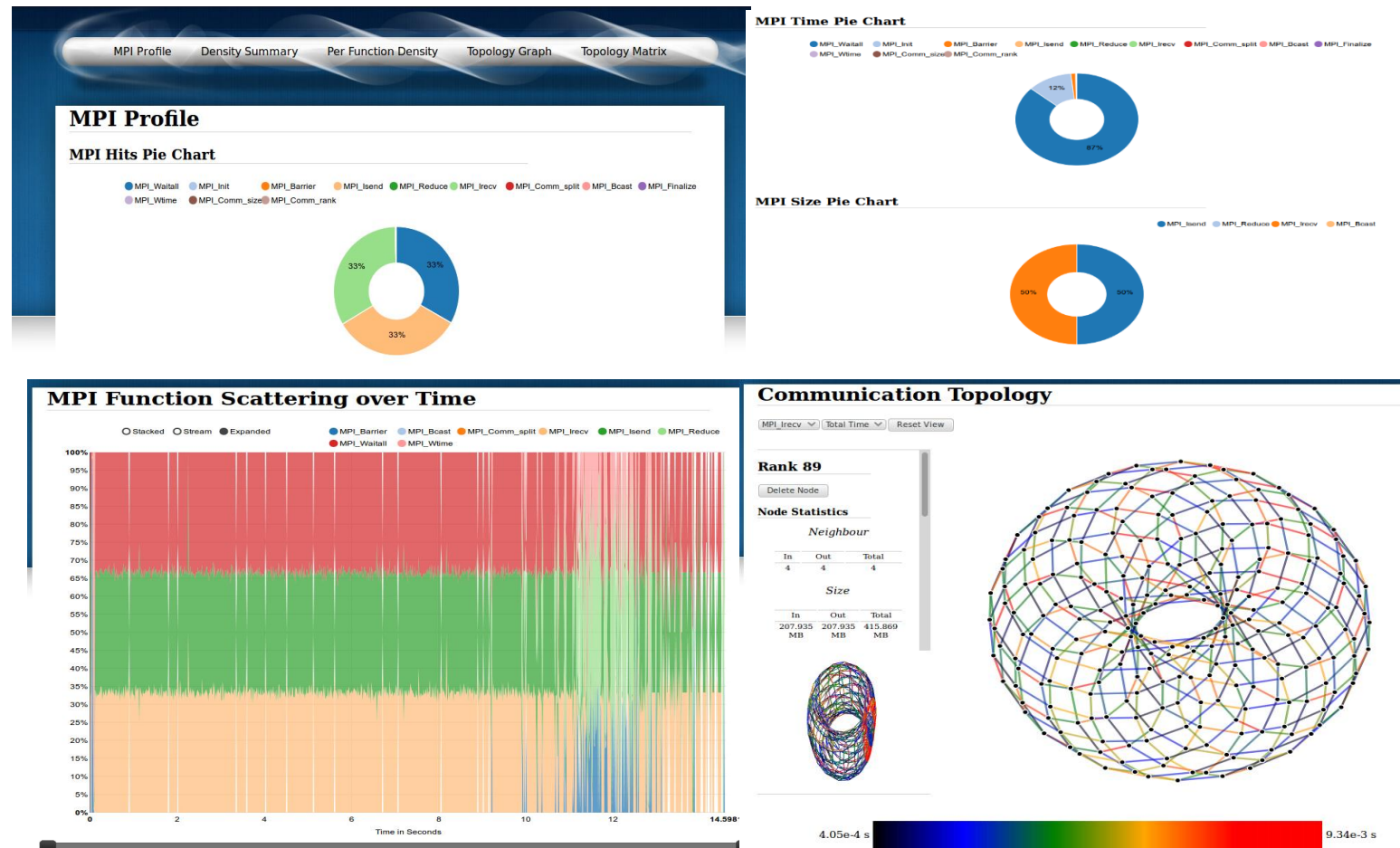
Then analyse time spent in loops:

- Time spent in loop w.r.t. function

- Use MAQAO CQA tool to analyse loops of interest

dauvergne - Process #14213 - Thread #14201			
Name	Excl %Time	Excl Time (s)	
binvcrhs - 206@solve_subs.f	17.27	2.23	
MPIDI_CH3I_Progress	15.24	1.96	
poll_active_fboxes	13.71	1.77	
▼ y_solve_omp_fn.0 - 45@y_solve.f	8.47	1.09	
▼ loops	8.47		
▼ Loop 121 - y_solve.f@45	0		
▼ Loop 122 - y_solve.f@45	0.16		
○ Loop 124 - y_solve.f@45	0.14		
○ Loop 125 - y_solve.f@145	5.12		
○ Loop 126 - y_solve.f@55	2.03		
○ Loop 123 - y_solve.f@45	1.02		
▼ x_solve_omp_fn.0 - 48@x_solve.f	8.23	1.06	
▶ loops	8.23		

# MAQAO LProf/MPI: MPI characterization





## MAQAO LProf/MPI: MPI characterization

### *Introduction (1/2)*

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The previous profiler module only provided a global figure about time spent in the MPI runtime (X%)

We want the same kind of insight but dealing with MPI primitives

Our methodology:

- Coarse grain: overview, global trends/patterns => cheapest possible cost/overhead
- Fine grain: filtering precise issues => accept to pay higher cost/overhead if worth

Online profiling:

- No traces to void IO wall: no IOs (only one result file with pre-processed data)
- Avoid memory : reduced memory footprint thanks to aggregated metrics
- Scalable on 1000+ MPI processes

## MAQAO LProf/MPI: MPI characterization

### *Introduction (2/2)*

Summary: LProf/MPI is a simple MPI profiling tool targeting lightweight metrics which can be reduced online (no trace required).

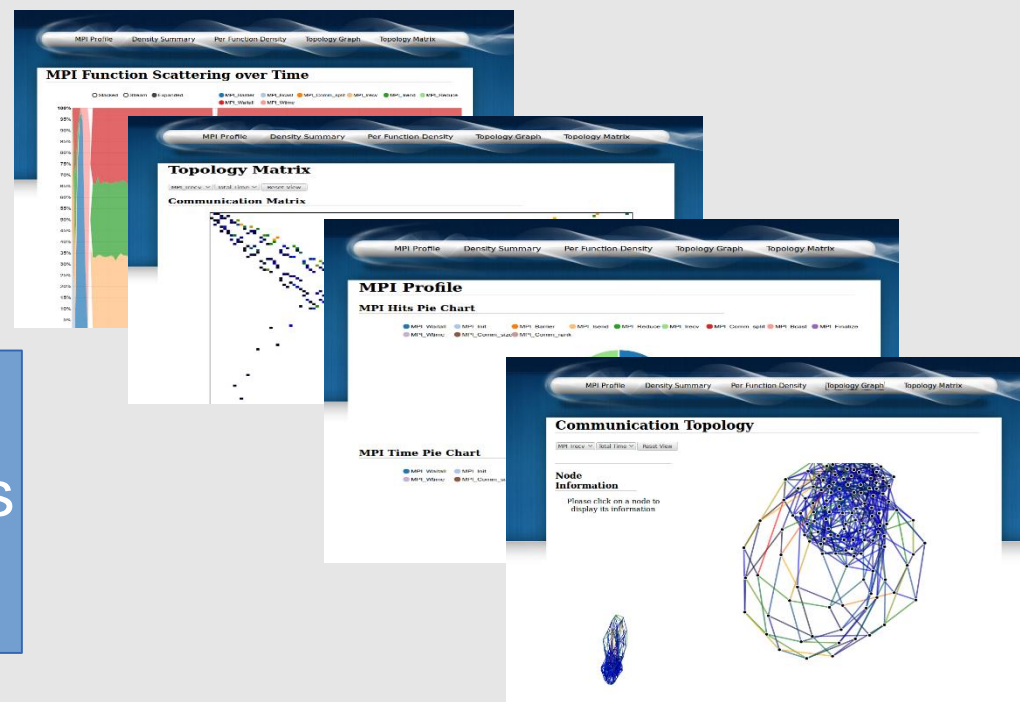
APPLICATION

MAQAO

profile.js

Does not require recompiling

### In-browser Visualizer



## MAQAO LProf/MPI: MPI characterization

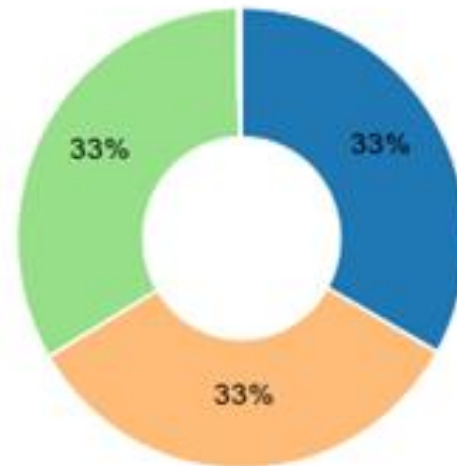
### *Global profile (1/3)*

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Summary vue: MPI primitives classified by hits (calls), time and size (if applicable)

### MPI Hits Pie Chart

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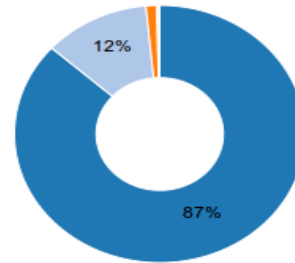


# MAQAO LProf/MPI: MPI characterization

## *Global profile (2/3)*

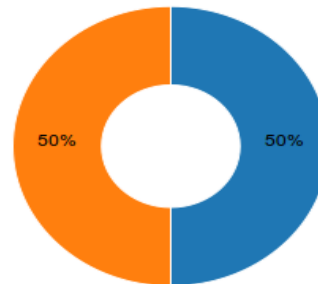
### MPI Time Pie Chart

● MPI\_Waitall ● MPI\_Init ● MPI\_Barrier ● MPI\_Isend ● MPI\_Reduce ● MPI\_Irecv ● MPI\_Comm\_split ● MPI\_Bcast ● MPI\_Finalize  
● MPI\_Wtime ● MPI\_Comm\_size ● MPI\_Comm\_rank



### MPI Size Pie Chart

● MPI\_Isend ● MPI\_Reduce ● MPI\_Irecv ● MPI\_Bcast



## MAQAO LProf/MPI: MPI characterization

### *Global profile: flat vue (3/3)*

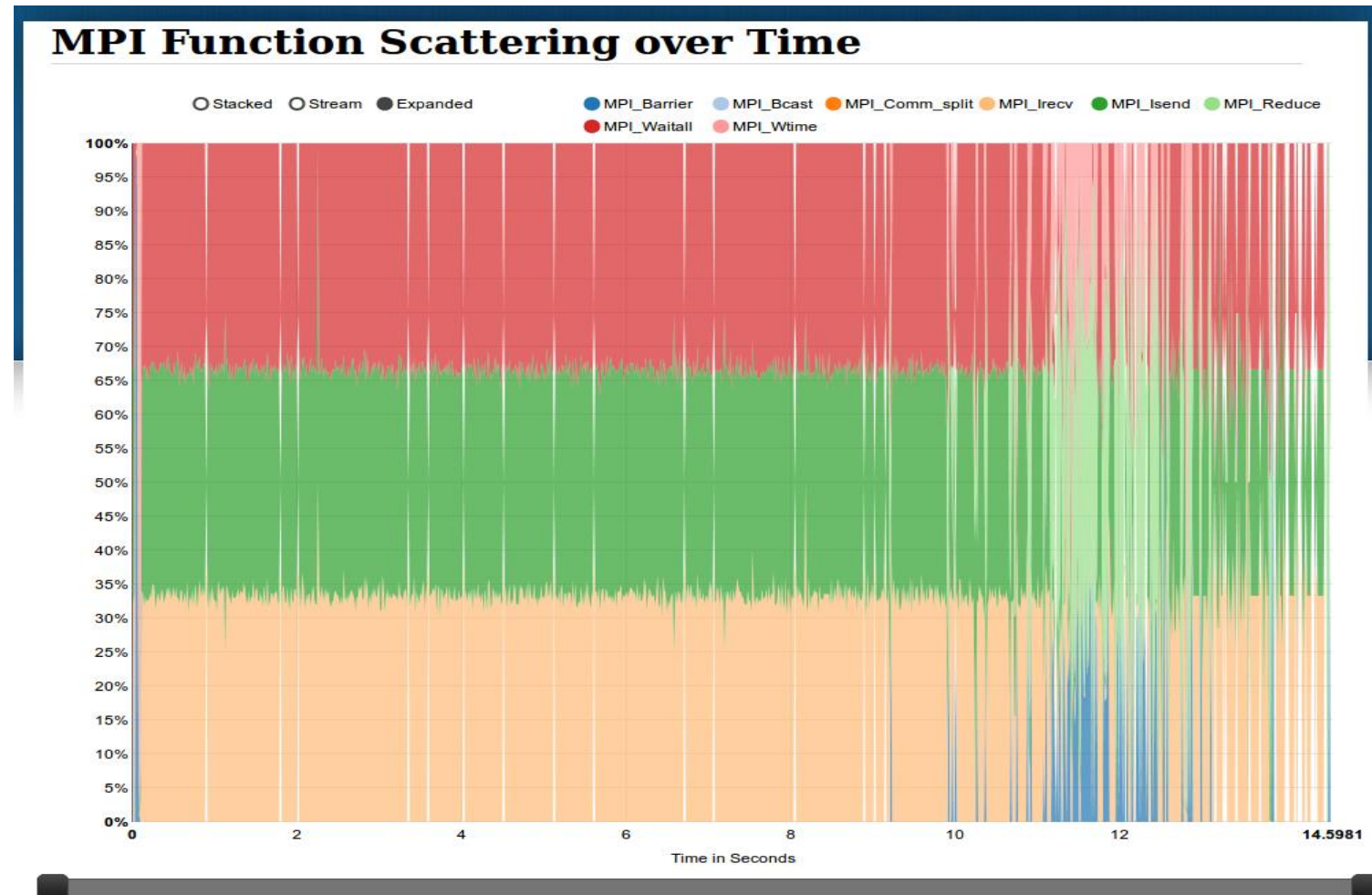
#### MPI Profile

Function	Hits	Time	Size	Walltime %
MPI_Waitall	192960	13 m 1.51 s	0 B	52.333%
MPI_Init	128	1 m 46.60 s	0 B	7.138%
MPI_Barrier	256	10.88 s	0 B	0.729%
MPI_Isend	192960	1.47 s	4.568 GB	0.098%
MPI_Reduce	384	5.36e-1 s	11.000 KB	0.036%
MPI_Irecv	192960	4.62e-1 s	4.568 GB	0.031%
MPI_Comm_split	128	4.05e-1 s	0 B	0.027%
MPI_Bcast	1152	3.12e-2 s	132.000 KB	0.002%
MPI_Finalize	128	2.07e-3 s	0 B	0.000%
MPI_Wtime	256	3.53e-4 s	0 B	0.000%
MPI_Comm_size	128	1.30e-4 s	0 B	0.000%
MPI_Comm_rank	256	4.28e-5 s	0 B	0.000%



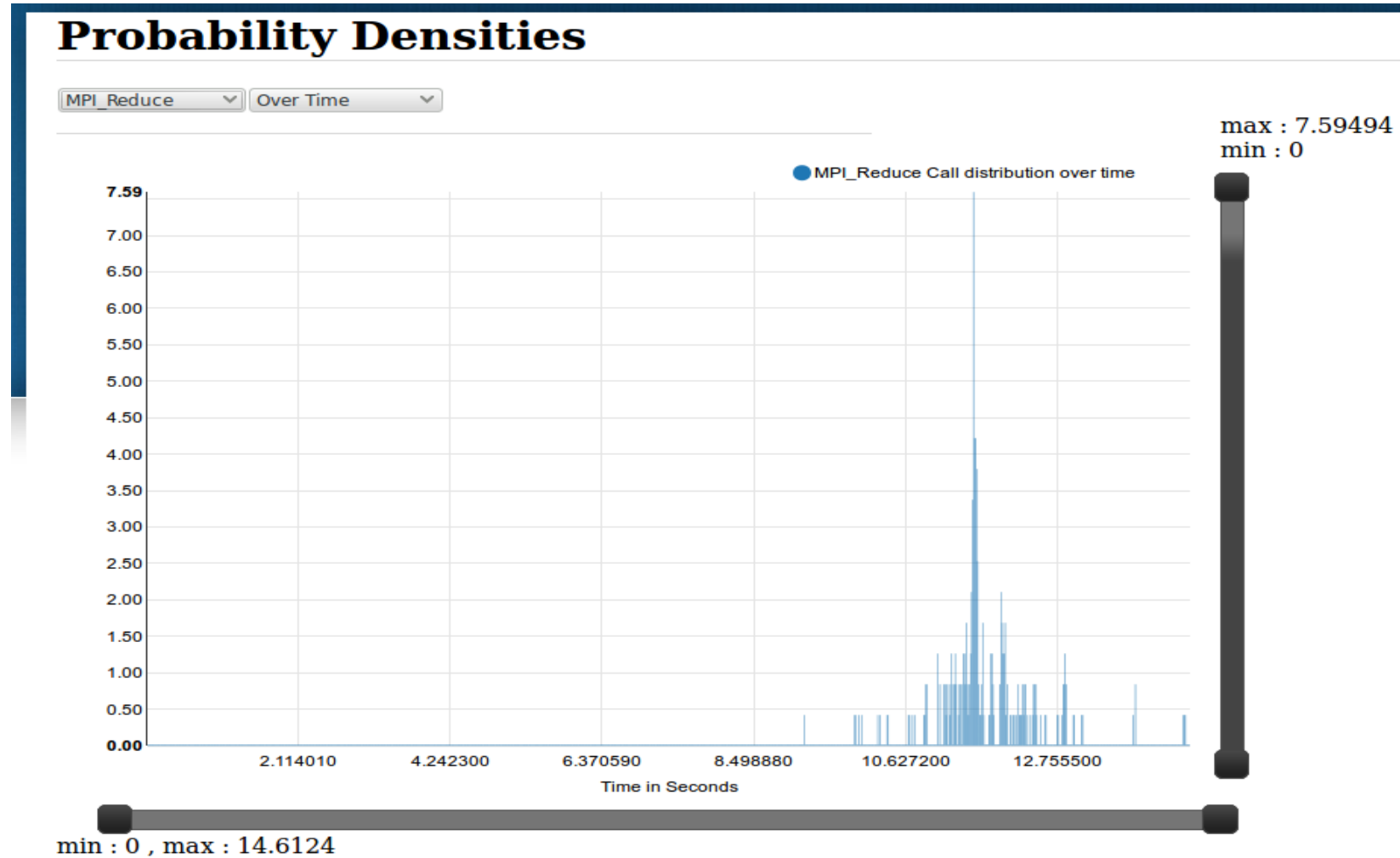
# MAQAO LProf/MPI: MPI characterization

## *Function scattering over time*



# MAQAO LProf/MPI: MPI characterization

## *Probability densities: when and how long ?*



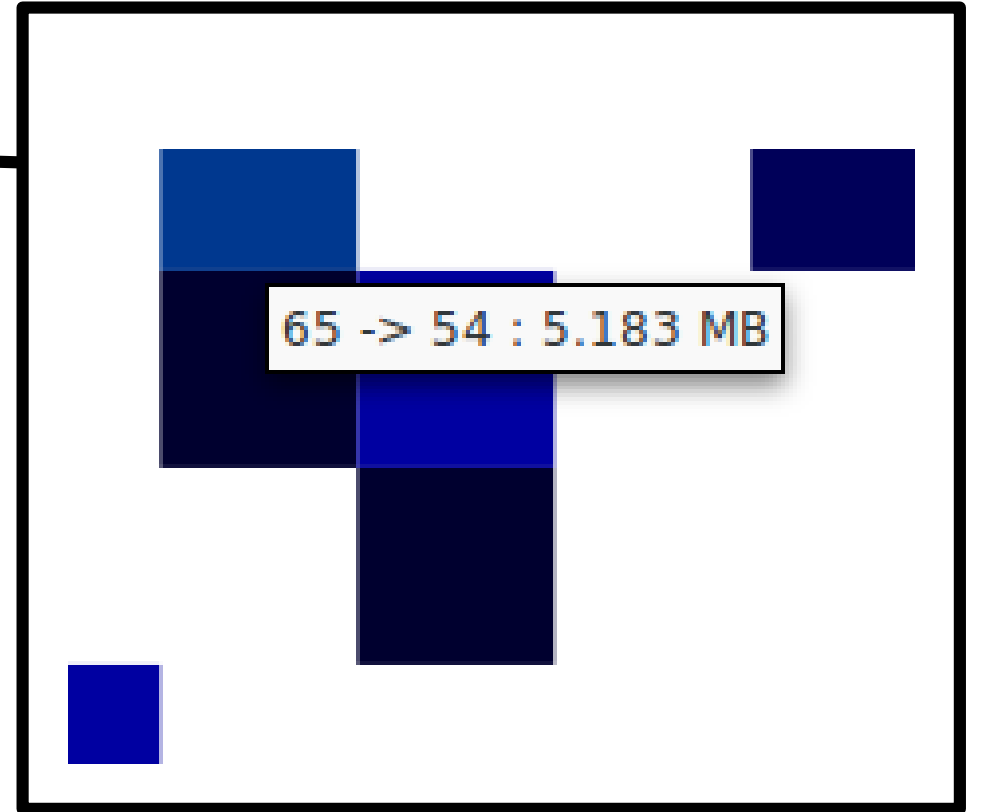
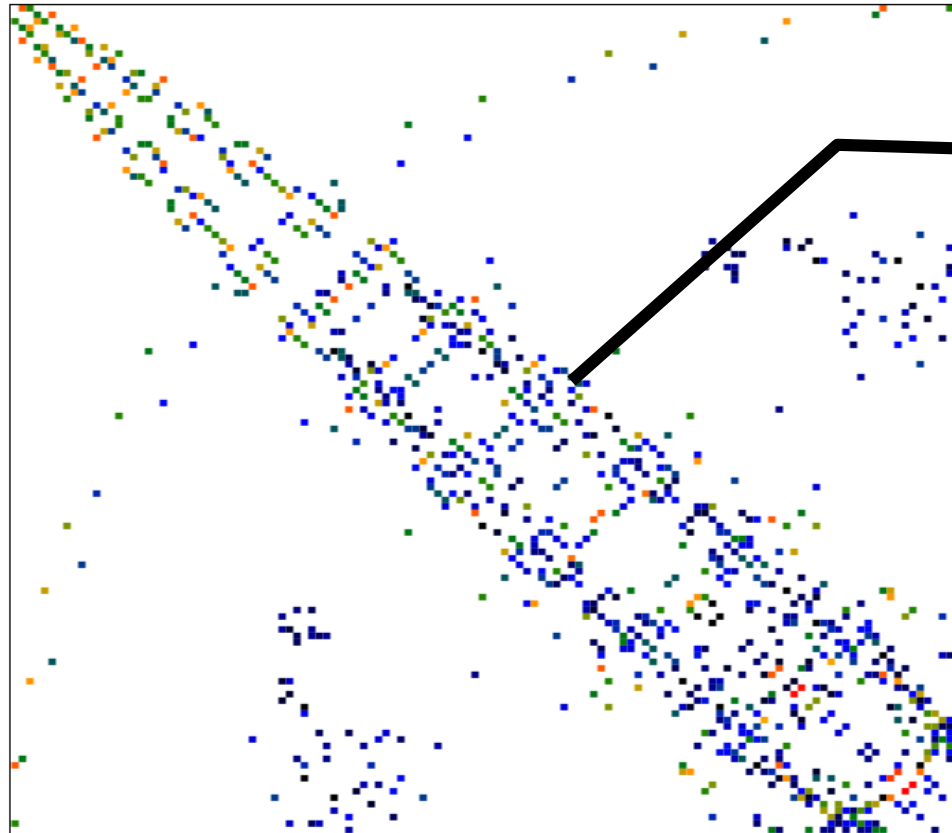
# MAQAO LProf/MPI: MPI characterization

## 2D communication matrix

Hit, time, size

MPI Irecv Total Size Reset View

Communication Matrix



1.196 MB



15.350 MB

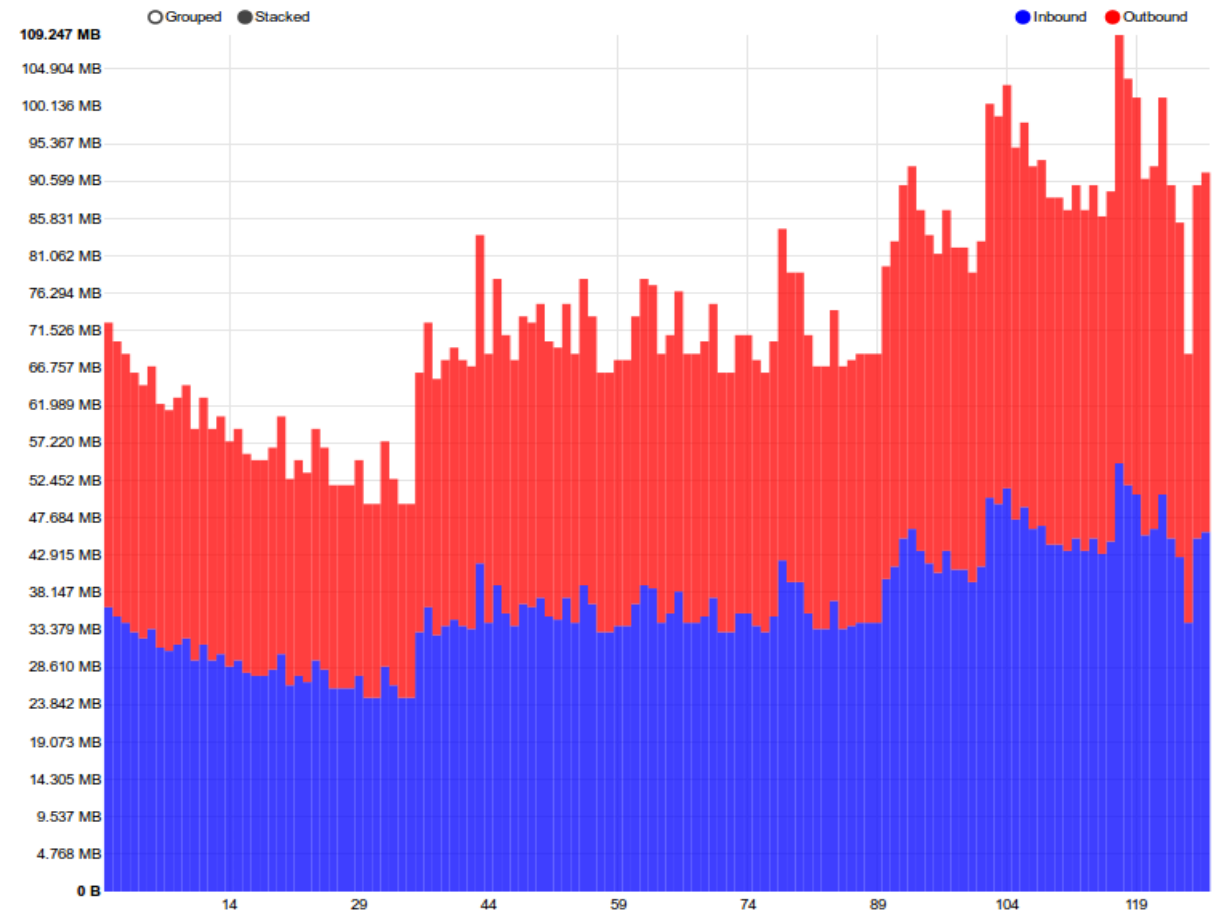
# MAQAO LProf/MPI: MPI characterization

## *Per rank distribution*

Hit, time, size

Check load balancing

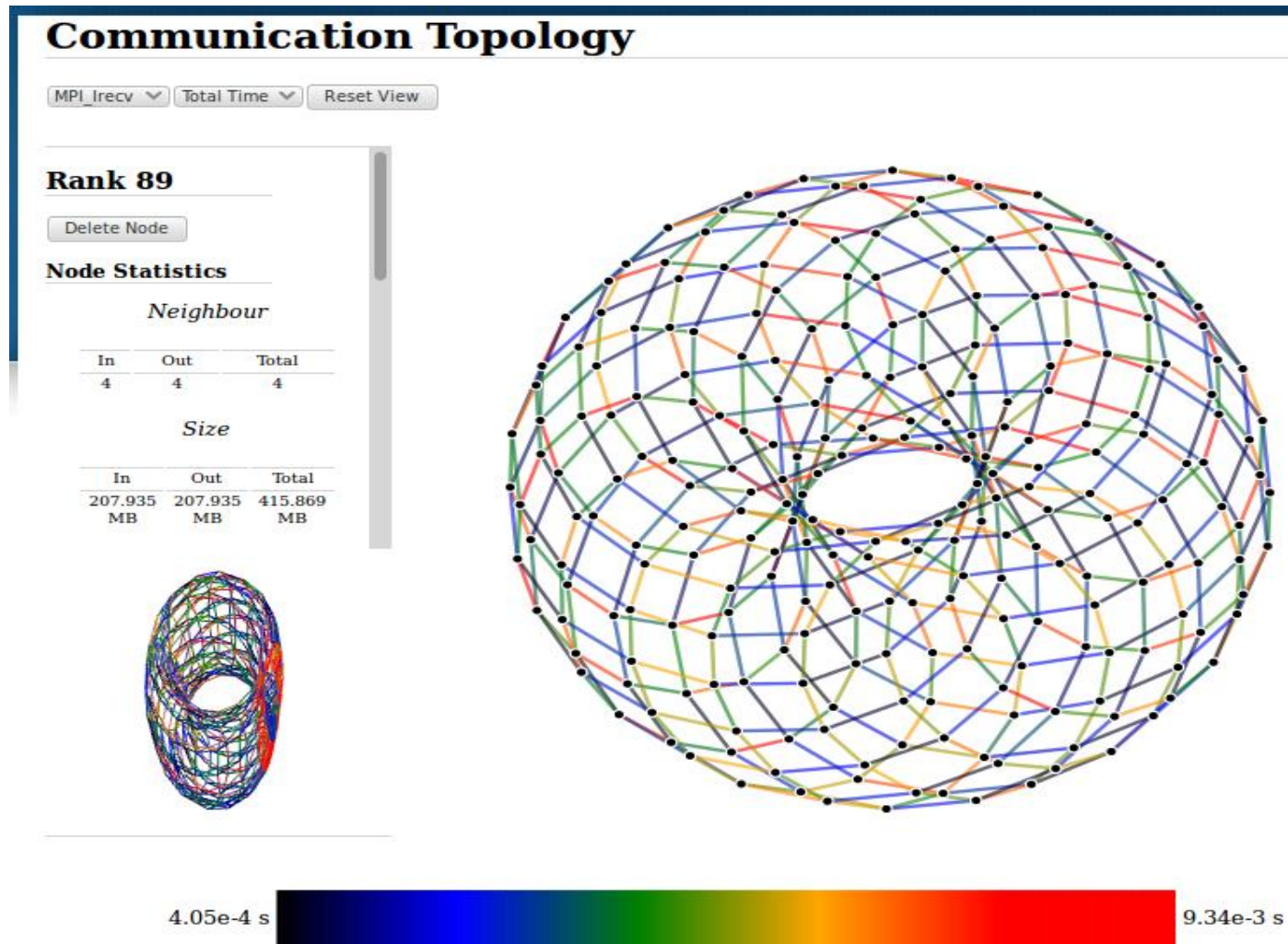
Per Rank distribution





# MAQAO LProf/MPI: MPI characterization

## 3D Topology





# MAQAO CQA: Analysing the code quality of your loops

The image shows a screenshot of the MAQAO Code Quality Analysis (CQA) interface. The interface has a dark blue header with the MAQAO logo and the title "Code quality analysis". Below the header, there is a section titled "Source loop ending at line 682". Under this, a sub-section "MAQAO binary loop id: 238" is expanded, showing details about the loop's definition and performance. The loop is defined in MPI/BT/x\_solve.f:519-682 and uses 15% of peak computational performance (1.23 out of 8.00 FLOP per cycle at 1GHz). There are four tabs: "Gain", "Potential gain", "Hints", and "Experts only". The "Gain" tab is selected, showing a "Vectorization" section. This section explains that the loop is not fully vectorized and could benefit from full vectorization, which would reduce the cost of an iteration from 190.00 to 60.75 cycles (3.13x speedup). It also provides a "Proposed solution(s)" with two propositions: trying another compiler or updating/tuning the current one, and removing inter-iteration dependencies. Below this, a "Bottlenecks" section states that removing all bottlenecks could lower the cost of an iteration from 190.00 to 143.00 cycles (1.33x speedup). The interface also shows a "Source loop ending at line 734" section at the bottom.

**MAQAO**

## Code quality analysis

▼ Source loop ending at line 682

▼ MAQAO binary loop id: 238

The loop is defined in MPI/BT/x\_solve.f:519-682  
15% of peak computational performance is used (1.23 out of 8.00 FLOP per cycle (GFLOPS @ 1GHz))

**Gain** Potential gain Hints Experts only

### Vectorization

Your loop is processing FP elements but is NOT OR PARTIALLY VECTORIZED and could benefit from full vectorization. By fully vectorizing your loop, you can lower the cost of an iteration from 190.00 to 60.75 cycles (3.13x speedup).  
*Since your execution units are vector units, only a fully vectorized loop can use their full power.*

**Proposed solution(s):**

Two propositions:

- Try another compiler or update/tune your current one:
- Remove inter-iterations dependences from your loop and make it unit-stride.

### Bottlenecks

By removing all these bottlenecks, you can lower the cost of an iteration from 190.00 to 143.00 cycles (1.33x speedup).

► Source loop ending at line 734

# MAQAO CQA: Analysing the code quality of your loops

## *Introduction*

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Main performance issues:

- Work sharing / communications / multicore interactions
- Core level

Most of the time core level is forgotten ! But that's where science is computed

CQA works at (assembly) loop level:

- In HPC most of the time is spent in loops (V.S. functions)
- Assess the quality of code generated by the compiler
- Take into account processor's (micro)architecture via simulation
- Hints and workarounds to improve static performance

Compute bound :

- this tool is not meant for optimizing memory issues
- It assumes that you have fixed them

## MAQAO CQA: Analysing the code quality of your loops

**Goal: how will it help you ?**

Produce reports:

- We deal with low level details (assembly, microarchitecture details)

- You get high level reports

Provide high level reports:

- Provide source loop context when available (-g or equivalent)
- Describing a pathology/bottleneck
- Suggesting workarounds to improve static performance
- Reports categorized by confidence level:
  - gain, potential gain, hint and expert

No runtime cost/overhead:

- You don't need to execute your app
- Static analysis

Source loop ending at line 10

MAQAO binary loop id: 2

The loop is defined in /zhome/academic/HLRS/xhp/xhpeo/TEST/matmul/kernel.c:9-10  
2% of peak computational performance is used (0.67 out of 32.00 FLOP per cycle (1.67 GFLOPS @ 2.50GHz))

Gain Potential gain Hints Experts only

**Vectorization**

Your loop is processing FP elements but is NOT OR PARTIALLY VECTORIZED and could benefit from full vectorization. By fully vectorizing your loop, you can lower the cost of an iteration from 3.00 to 0.38 cycles (8.00x speedup). Since your execution units are vector units, only a fully vectorized loop can use their full power.

**Proposed solution(s):**

Two propositions:

- Try another compiler or update/tune your current one:
- Remove inter-iterations dependences from your loop and make it unit-stride.

\* If your arrays have 2 or more dimensions, check whether elements are accessed contiguously and, otherwise, try to permute loops accordingly. C storage order is row-major: for(i) for(j) a[j][i] = b[j][i]; (slow, non stride 1) => for(i) for(j) a[i][j] = b[i][j]; (fast, stride 1)

\* If your loop streams arrays of structures (AoS), try to use structures of arrays instead (SoA):  
for(i) a[i].x = b[i].x; (slow, non stride 1) => for(i) a.x[i] = b.x[i]; (fast, stride 1)

## MAQAO CQA: Analysing the code quality of your loops

### *Processor Architecture: Core level*

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Maybe you want an efficient code that gets the best out of available computing resources ?

Concepts:

- Peak performance, TOP500/LINPACK
- Execution pipeline
- Ressources/Functional units

Most of the time applications only exploit at best 5% to 10% of the peak performance

Key performance levers:

- Vectorization
- Get rid of high latency instructions if possible
- Make the compiler generated an efficient code

**Same instruction – Same cost**



# MAQAO CQA: Analysing the code quality of your loops

## *The compiler*

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Compiler remains our best friend

Be sure to select proper flags

- Know default flags (e.g., -xHost on AVX capable machines)
- Bypass conservative behavior when possible (e.g., 1/X precision)

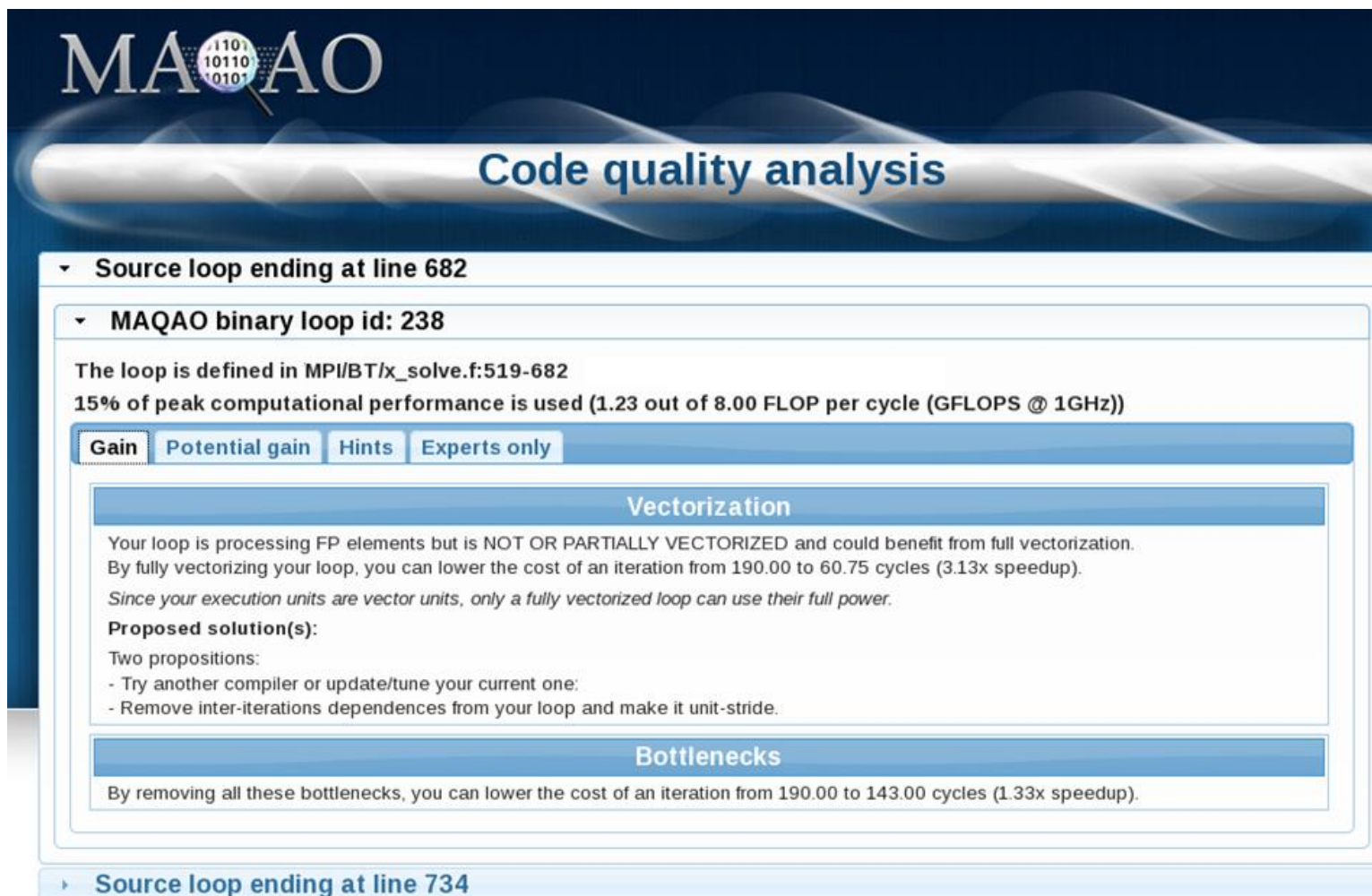
Pragmas:

- Vectorization, Alignement, Unrolling, etc...
- Portable transformations



# MAQAO CQA: Analysing the code quality of your loops

## GUI sample (1/2)



The screenshot displays the MAQAO Code quality analysis interface. At the top, the MAQAO logo is shown next to the title "Code quality analysis". Below this, a dropdown menu indicates the "Source loop ending at line 682". Underneath, another dropdown shows the "MAQAO binary loop id: 238". The main text area provides details about the loop: "The loop is defined in MPI/BT/x\_solve.f:519-682" and "15% of peak computational performance is used (1.23 out of 8.00 FLOP per cycle (GFLOPS @ 1GHz))". A navigation bar with four tabs is present: "Gain" (selected), "Potential gain", "Hints", and "Experts only". The "Gain" tab is active, showing a section titled "Vectorization". This section contains the text: "Your loop is processing FP elements but is NOT OR PARTIALLY VECTORIZED and could benefit from full vectorization. By fully vectorizing your loop, you can lower the cost of an iteration from 190.00 to 60.75 cycles (3.13x speedup). Since your execution units are vector units, only a fully vectorized loop can use their full power." Below this, it lists "Proposed solution(s):" with two propositions: "Try another compiler or update/tune your current one:" and "Remove inter-iterations dependences from your loop and make it unit-stride." A second section titled "Bottlenecks" follows, stating: "By removing all these bottlenecks, you can lower the cost of an iteration from 190.00 to 143.00 cycles (1.33x speedup)." At the bottom, a dropdown menu shows the next "Source loop ending at line 734".

MAQAO

### Code quality analysis

▼ Source loop ending at line 682

▼ MAQAO binary loop id: 238

The loop is defined in MPI/BT/x\_solve.f:519-682  
15% of peak computational performance is used (1.23 out of 8.00 FLOP per cycle (GFLOPS @ 1GHz))

**Gain** Potential gain Hints Experts only

#### Vectorization

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**Proposed solution(s):**

Two propositions:

- Try another compiler or update/tune your current one:
- Remove inter-iterations dependences from your loop and make it unit-stride.

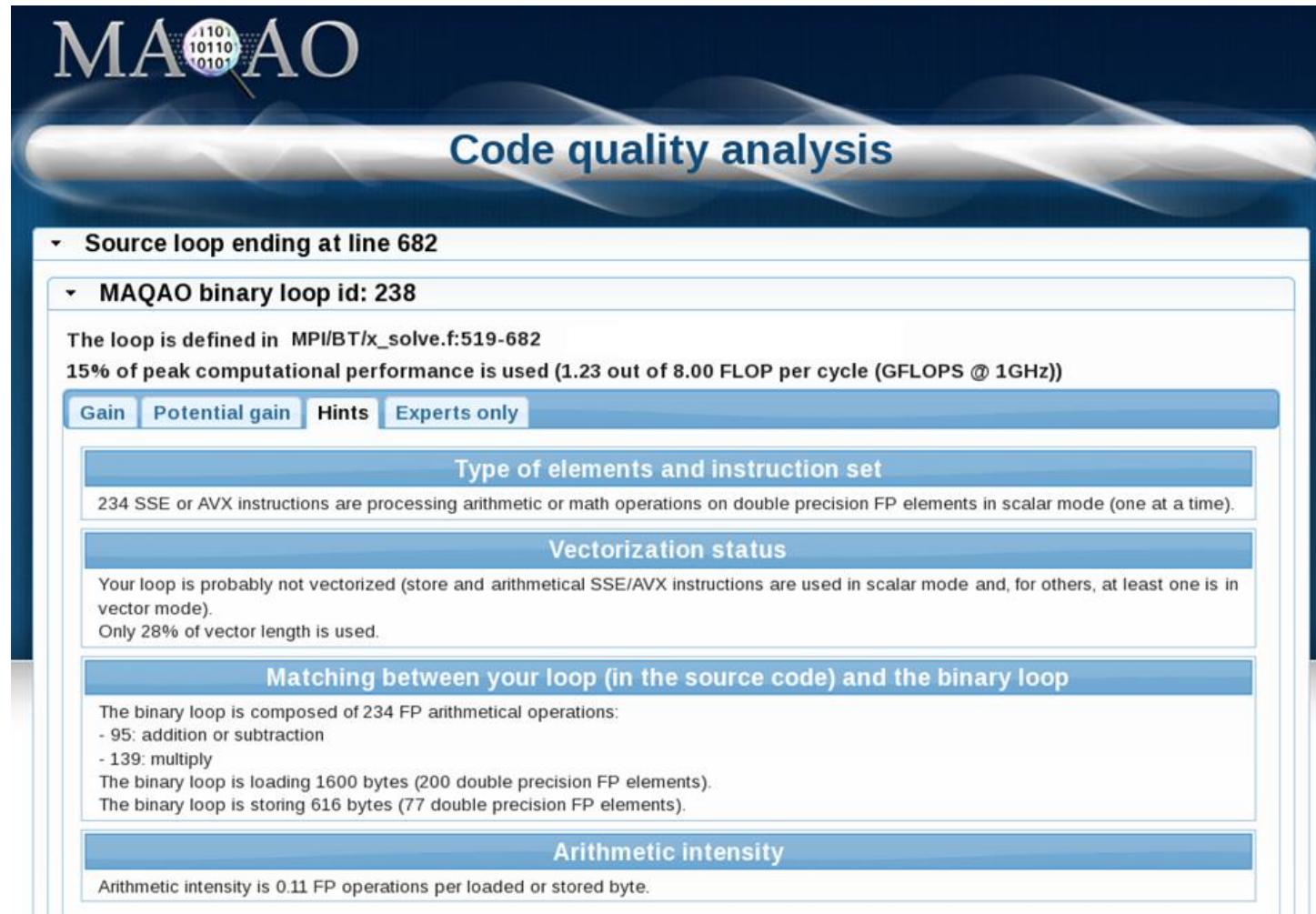
#### Bottlenecks

By removing all these bottlenecks, you can lower the cost of an iteration from 190.00 to 143.00 cycles (1.33x speedup).

► Source loop ending at line 734

# MAQAO CQA: Analysing the code quality of your loops

## GUI sample (2/2)



The screenshot displays the MAQAO Code quality analysis interface. At the top, the MAQAO logo is shown with a magnifying glass icon over the 'A'. Below the logo, the title "Code quality analysis" is centered. The main content area is divided into sections. The first section, "Source loop ending at line 682", is expanded. Below it, the "MAQAO binary loop id: 238" section is also expanded. This section contains the text: "The loop is defined in MPI/BT/x\_solve.f:519-682" and "15% of peak computational performance is used (1.23 out of 8.00 FLOP per cycle (GFLOPS @ 1GHz))". Below this text are four tabs: "Gain", "Potential gain", "Hints", and "Experts only". The "Hints" tab is currently selected. Under the "Hints" tab, there are four sub-sections: "Type of elements and instruction set", "Vectorization status", "Matching between your loop (in the source code) and the binary loop", and "Arithmetic intensity". Each sub-section contains specific analysis results.

**MAQAO**

### Code quality analysis

▼ Source loop ending at line 682

▼ MAQAO binary loop id: 238

The loop is defined in MPI/BT/x\_solve.f:519-682  
15% of peak computational performance is used (1.23 out of 8.00 FLOP per cycle (GFLOPS @ 1GHz))

**Gain** **Potential gain** **Hints** **Experts only**

#### Type of elements and instruction set

234 SSE or AVX instructions are processing arithmetic or math operations on double precision FP elements in scalar mode (one at a time).

#### Vectorization status

Your loop is probably not vectorized (store and arithmetical SSE/AVX instructions are used in scalar mode and, for others, at least one is in vector mode).  
Only 28% of vector length is used.

#### Matching between your loop (in the source code) and the binary loop

The binary loop is composed of 234 FP arithmetical operations:  
- 95: addition or subtraction  
- 139: multiply  
The binary loop is loading 1600 bytes (200 double precision FP elements).  
The binary loop is storing 616 bytes (77 double precision FP elements).

#### Arithmetic intensity

Arithmetic intensity is 0.11 FP operations per loaded or stored byte.

**Thank you for your attention**

**Questions**