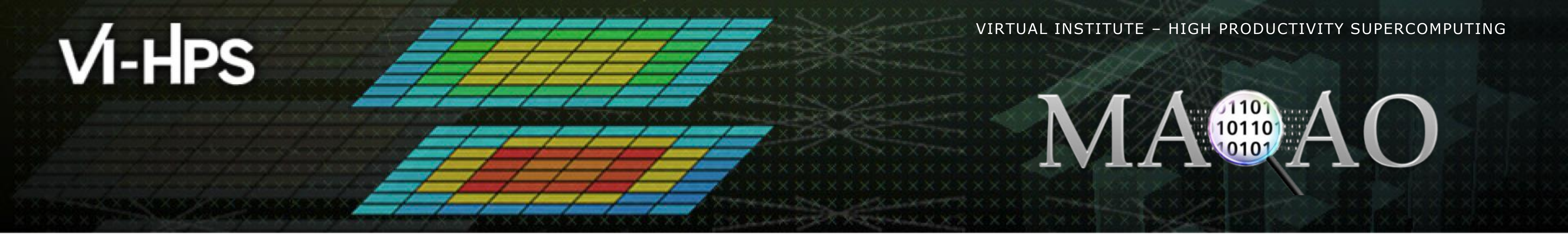

MAQAO
Performance Analysis and Optimization Tool

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UNIVERSITÉ DE VERSAILLES SAINT-QUENTIN-EN-YVELINES

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PeXL

Introduction
Performance analysis (1/2)

Characterizing application performance:

- Profiling application
- Pinpointing the performance bottlenecks
  - Complex multicore and manycore CPUs
  - Complex memory hierarchy
- Making best use of the machine features

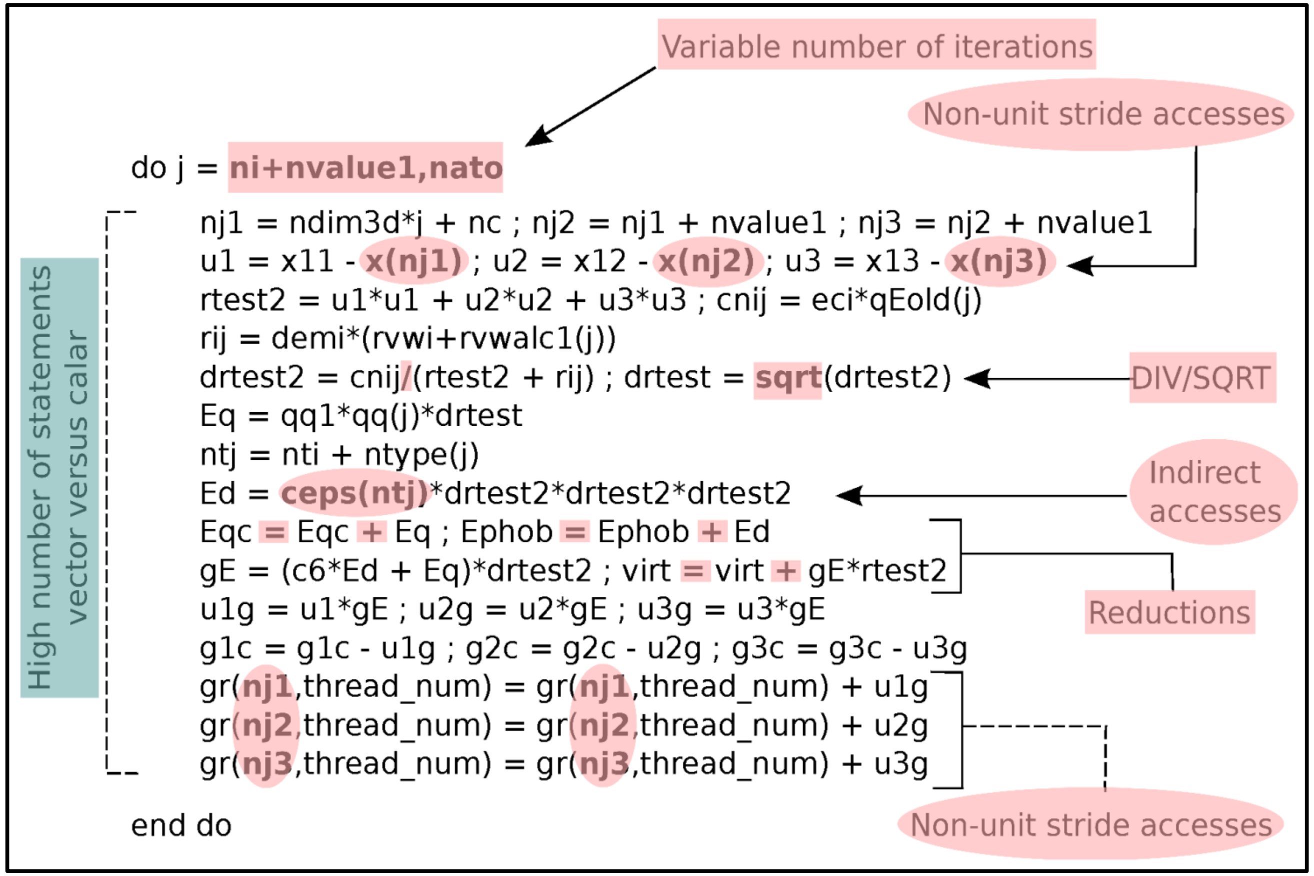
Facing a multifaceted problem:

- How to determine the dominant issues?
  - Algorithms choice
  - Implementation
  - Parallelization
  - …
- Maximizing the number of views

=> Need for dedicated and complementary tools

Introduction
Performance analysis (2/2)

Motivating example: loop ~10% walltime



```
do j = ni+nvalue1,nato
    nj1 = ndim3d*j + nc ; nj2 = nj1 + nvalue1 ; nj3 = nj2 + nvalue1
    u1 = x11 - x(nj1) ; u2 = x12 - x(nj2) ; u3 = x13 - x(nj3)
    rtest2 = u1*u1 + u2*u2 + u3*u3 ; cnij = eci*qEold(j)
    rij = demi*(rvwi+rvwalc1(j))
    drtest2 = cnij/(rtest2 + rij) ; drtest = sqrt(drtest2)
    Eq = qq1*qq(j)*drtest
    ntj = nti + ntype(j)
    Ed = ceps(ntj)*drtest2*drtest2*drtest2
    Eqc = Eqc + Eq ; Ephob = Ephob + Ed
    gE = (c6*Ed + Eq)*drtest2 ; virt = virt + gE*rtest2
    u1g = u1*gE ; u2g = u2*gE ; u3g = u3*gE
    g1c = g1c - u1g ; g2c = g2c - u2g ; g3c = g3c - u3g
    gr(nj1,thread_num) = gr(nj1,thread_num) + u1g
    gr(nj2,thread_num) = gr(nj2,thread_num) + u2g
    gr(nj3,thread_num) = gr(nj3,thread_num) + u3g
end do
```

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
7) Variable number of iterations

Introduction
MAQAO: Modular Assembly Quality Analyzer and Optimizer

Objectives:

- Performance characterization of HPC applications
- Focus optimization efforts
- Estimation of R.O.I.

Main functionalities:

- Profiling and hardware counters collection
- Code quality analysis

Characteristics:

- Modular tool
- Support for Intel x86-64 and Xeon Phi
- LGPL3 Open Source software
- Developed at UVSQ since 2004

Introduction
Partnerships

MAQAO was funded by UVSQ, Intel and CEA (French department of energy) through Exascale Computing Research (ECR) and the French Ministry of Industry through various FUI/ITEA projects (H4H, COLOC, PerfCloud, ELCI, etc...)

Provides core technology to be integrated with other tools:

- TAU performance tools with MADRAS patcher through MIL (MAQAO Instrumentation Language)
- ATOS bullxprof with MADRAS through MIL
- Intel AmplifierXE
- INRIA Bordeaux HWLOC

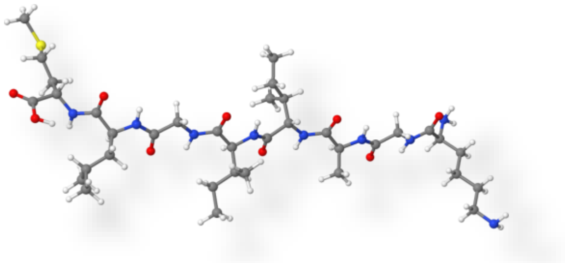
PeXL ISV also contributes to MAQAO:

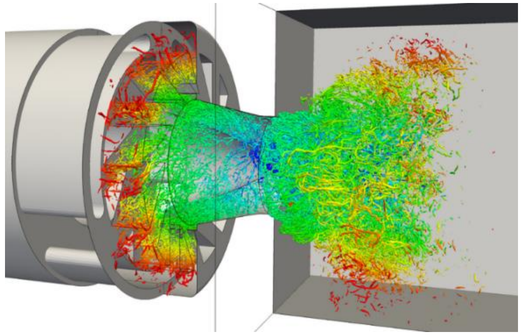
- Commercial performance optimization expertise
- Training and software development

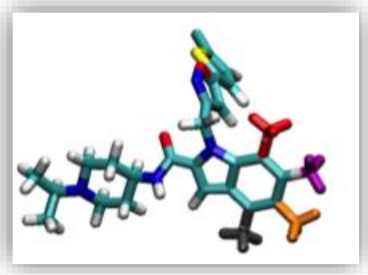
Introduction
Success stories

MAQAO was used for optimizing industrial and academic HPC applications:

- QMC=CHEM (IRSAMC)
  - Quantum chemistry
  - Speedup: > 3x
- Yales2 (CORIA)
  - Computational fluid dynamics
  - Speedup: up to 2,8x
- Polaris (CEA)
  - Molecular dynamics
  - Speedup: 1,5x – 1,7x
- AVBP (CERFACS)
  - Computational fluid dynamics
  - Speedup: 1,08x – 1,17x







Introduction
Some MAQAO Collaborators

- Prof. William Jalby
- Prof. Denis Barthou
- Prof. David J. Kuck
- Andrés S. Charif-Rubial, Ph D
- Jean-Thomas Acquaviva, Ph D
- Stéphane Zuckerman, Ph D
- Julien Jaeger, Ph D
- Souad Koliaï, Ph D
- Cédric Valensi, Ph D
- Eric Petit, Ph D
- Zakaria Bendifallah, Ph D
- Emmanuel Oseret, Ph D
- Pablo de Oliveira, Ph D
- Tipp Moseley, Ph D
- David C. Wong, Ph D
- Jean-Christophe Beyler, Ph D
- Mathieu Tribalat
- Hugo Bolloré
- Jean-Baptiste Le Reste
- Sylvain Henry, Ph D
- Salah Ibn Amar
- Youenn Lebras
- Othman Bouizi, Ph D
- José Noudohouennou, Ph D
- …

Introduction
MAQAO: Analysis at binary level

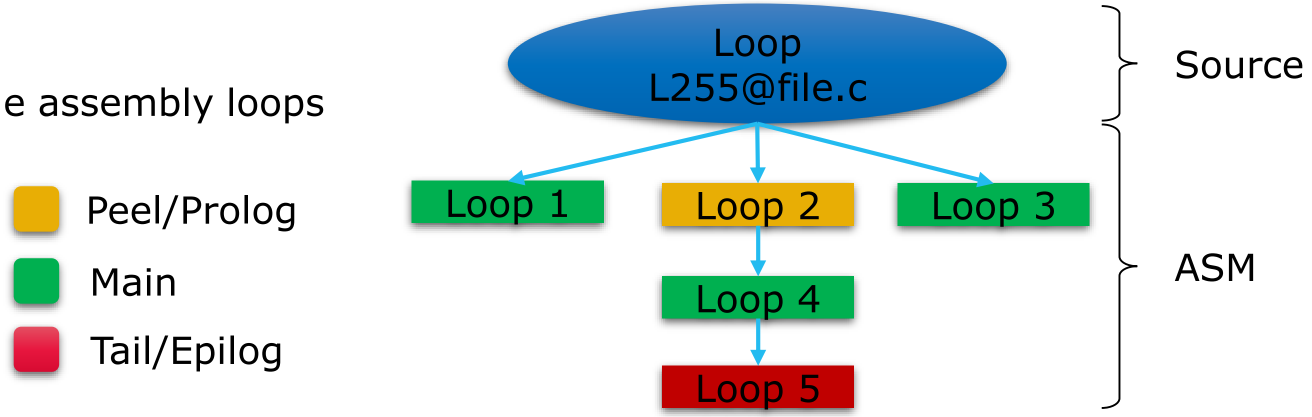
Advantages of binary analysis:

- Compiler optimizations increase the distance between the executed code and the source
- Source code instrumentation may prevent the compiler from applying some transformations

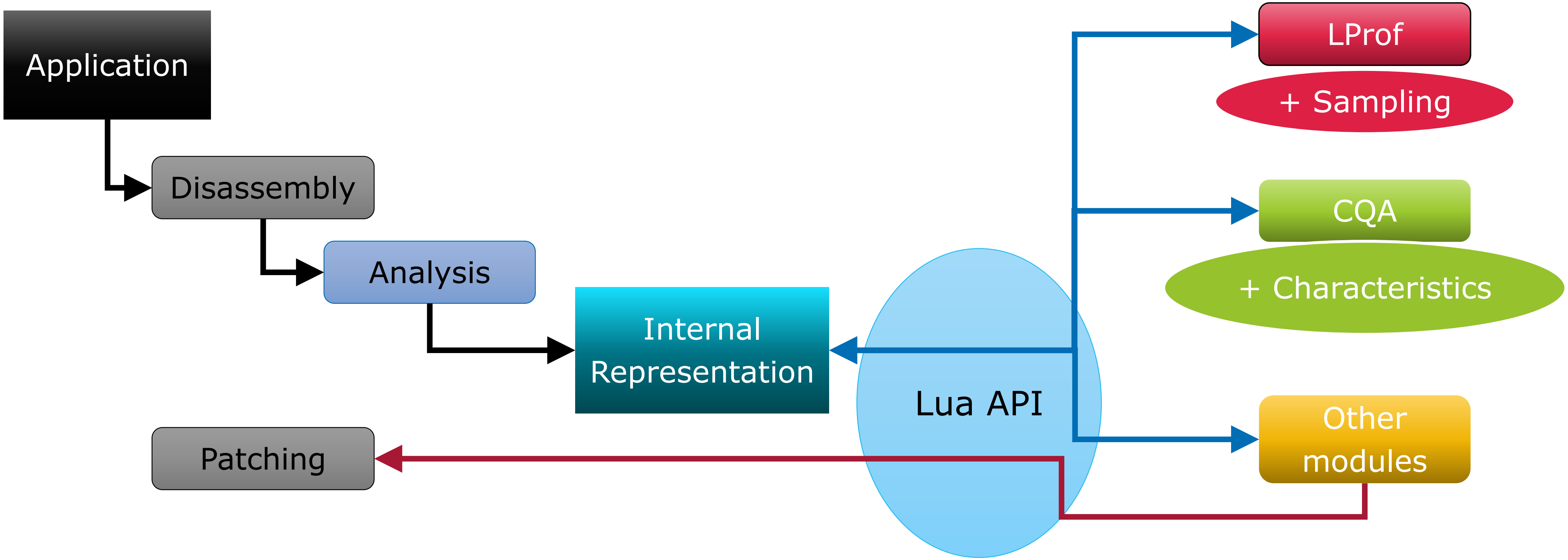
We want to evaluate the "real" executed code: What You Analyze Is What You Run

Main steps:

- Reconstruct the program structure
- Relate the analyses to source code
  - A single source loop can be compiled as multiple assembly loops

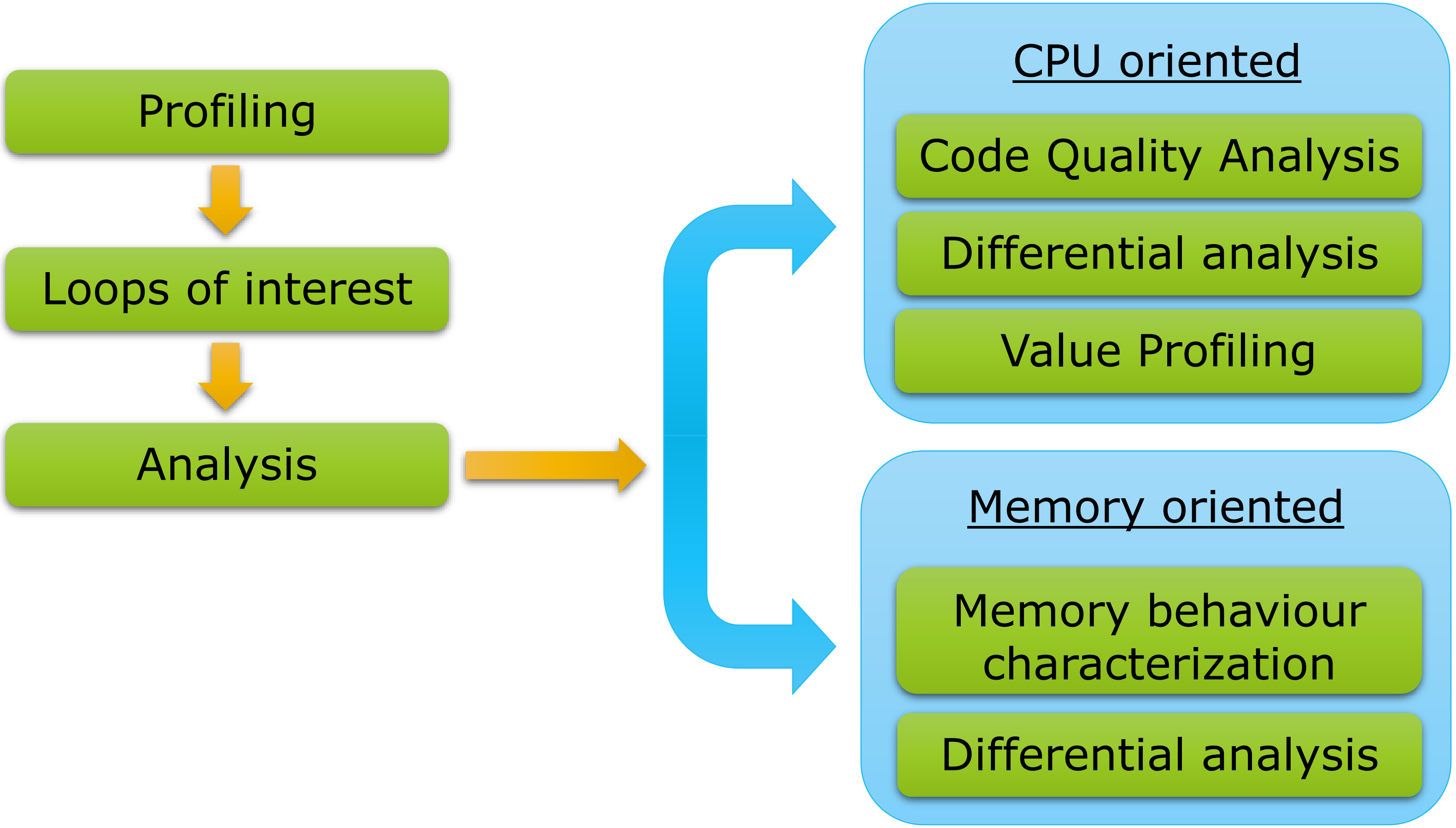


Introduction
MAQAO Main Structure

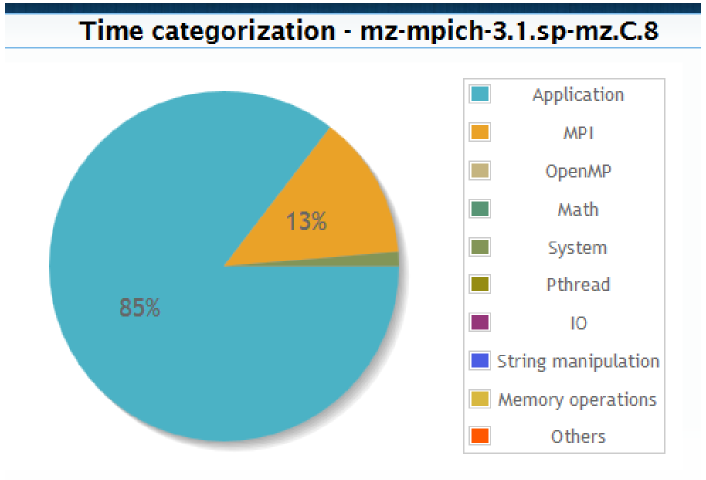


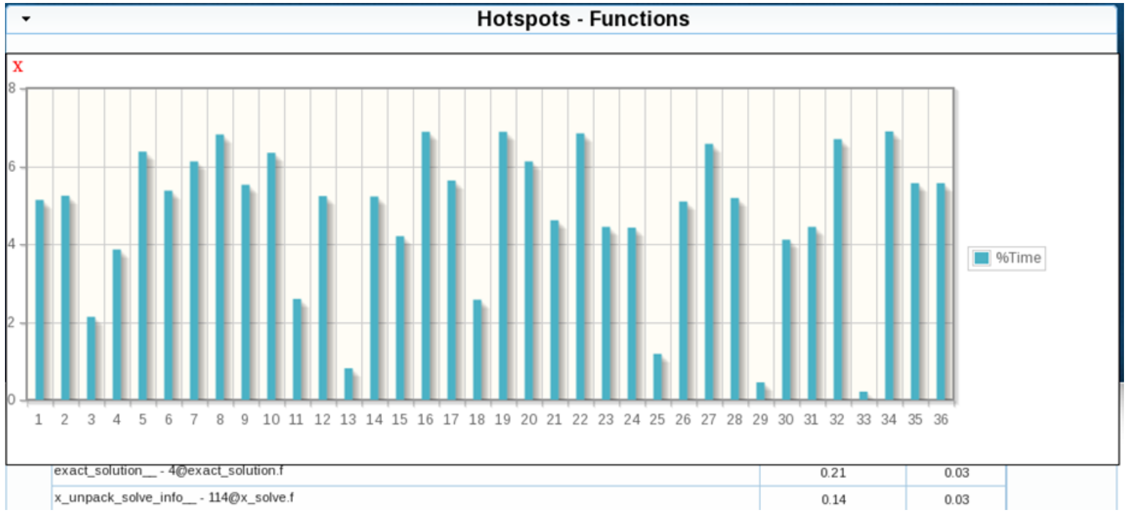
Introduction
MAQAO methodology

Decision tree



MAQAO LProf: Lightweight Profiler





exact_solution__ - 4@exact_solution.f	0.21	0.03
x_unpack_solve_info__ - 114@x_solve.f	0.14	0.03

MAQAO LProf: Lightweight Profiler
Introduction

Lightweight localization of application hotspots

Multiple measurement methods available:

- Sampling (default)
  - Hardware counters (through perf_event_open system call)
  - Non intrusive, low overhead
- Instrumentation: for targeting specific issues
  - Binary rewriting
  - Extra overhead

Runtime-agnostic

MAQAO LProf: Lightweight Profiler
Time categorization

Parallelization overhead:

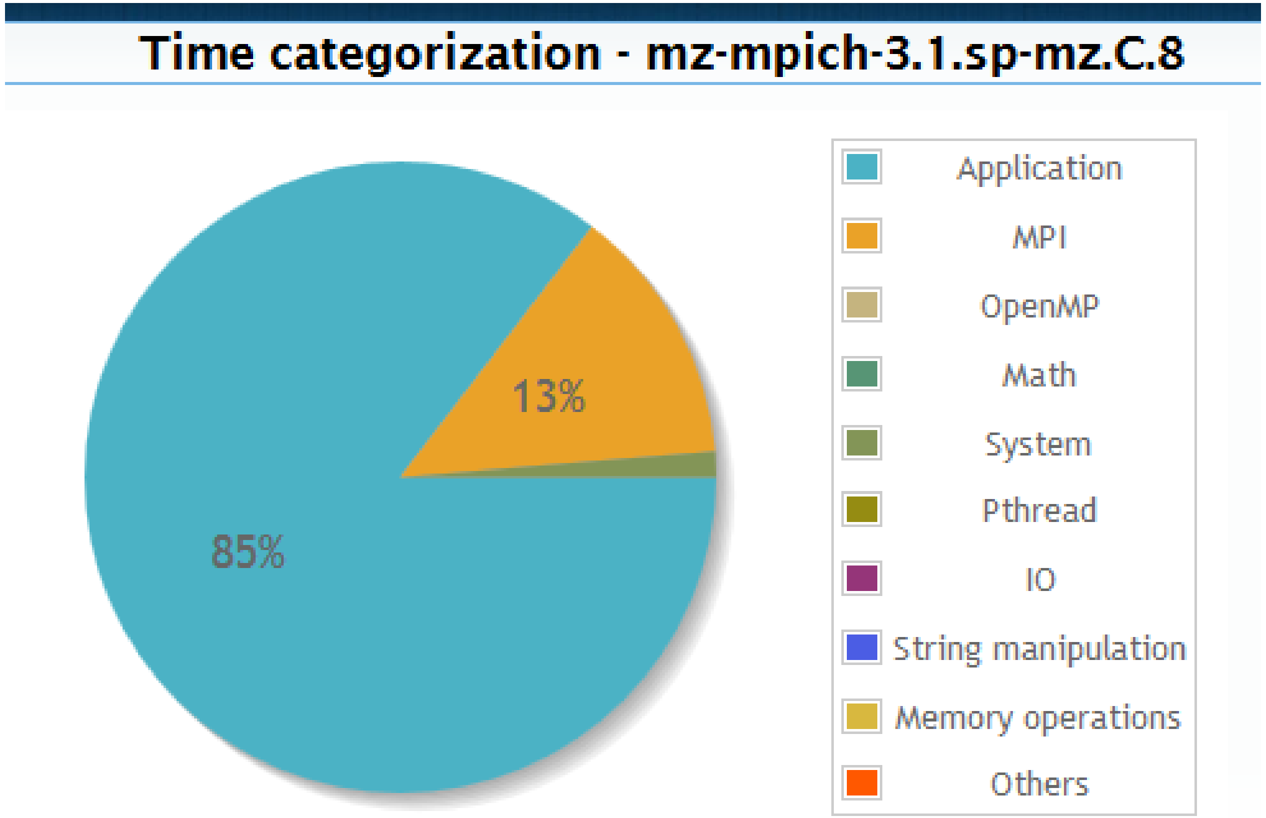
- Shared: Pthreads, OpenMP, etc …
- Distributed: MPI, etc…

Programming:

- IO operations
- String operations
- Memory management
- External libraries such as libm / libmkl

User time breakdown:

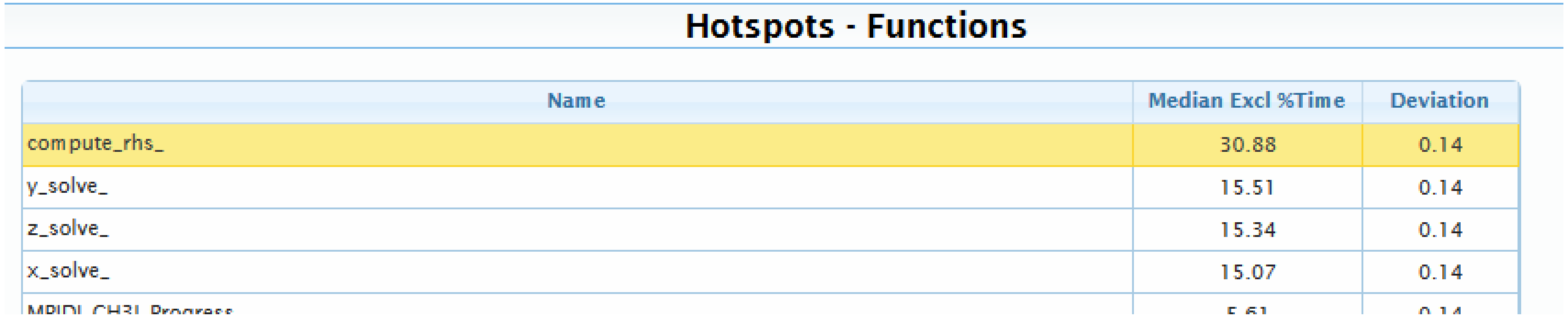
- Functions
- Loops



MAQAO LProf: Lightweight Profiler
Function and loop hotspots (1/3)

Focusing on user time:

- Function hotspots
- Load balancing across the nodes



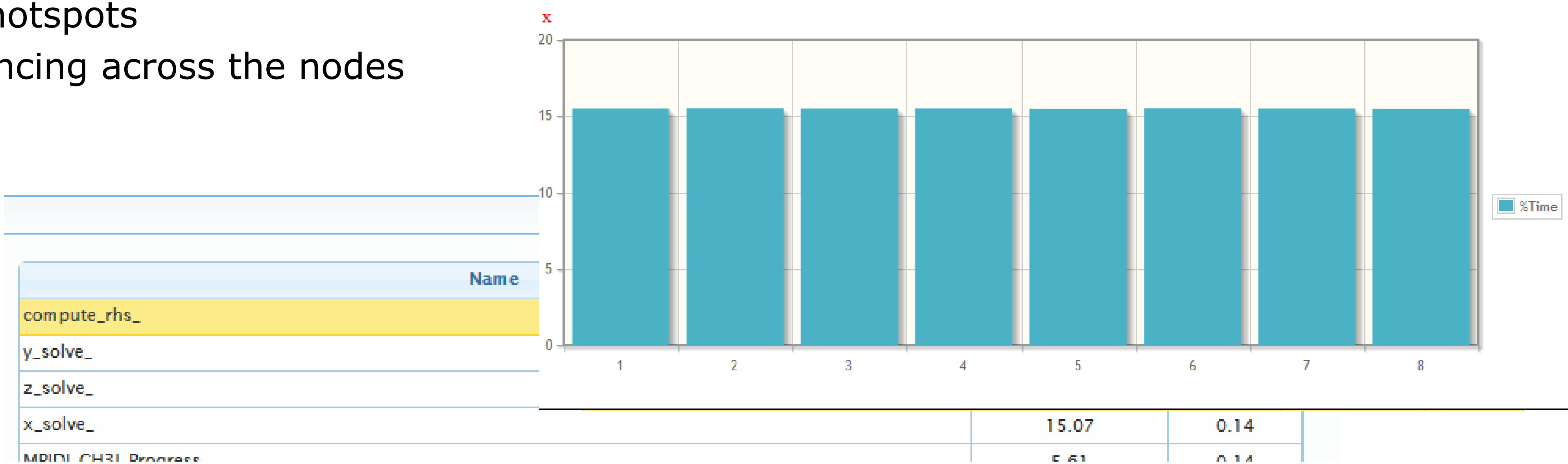
Hotspots - Functions

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: Lightweight Profiler
Function and loop hotspots (2/3)

Focusing on user time:

- Function hotspots
- Load balancing across the nodes

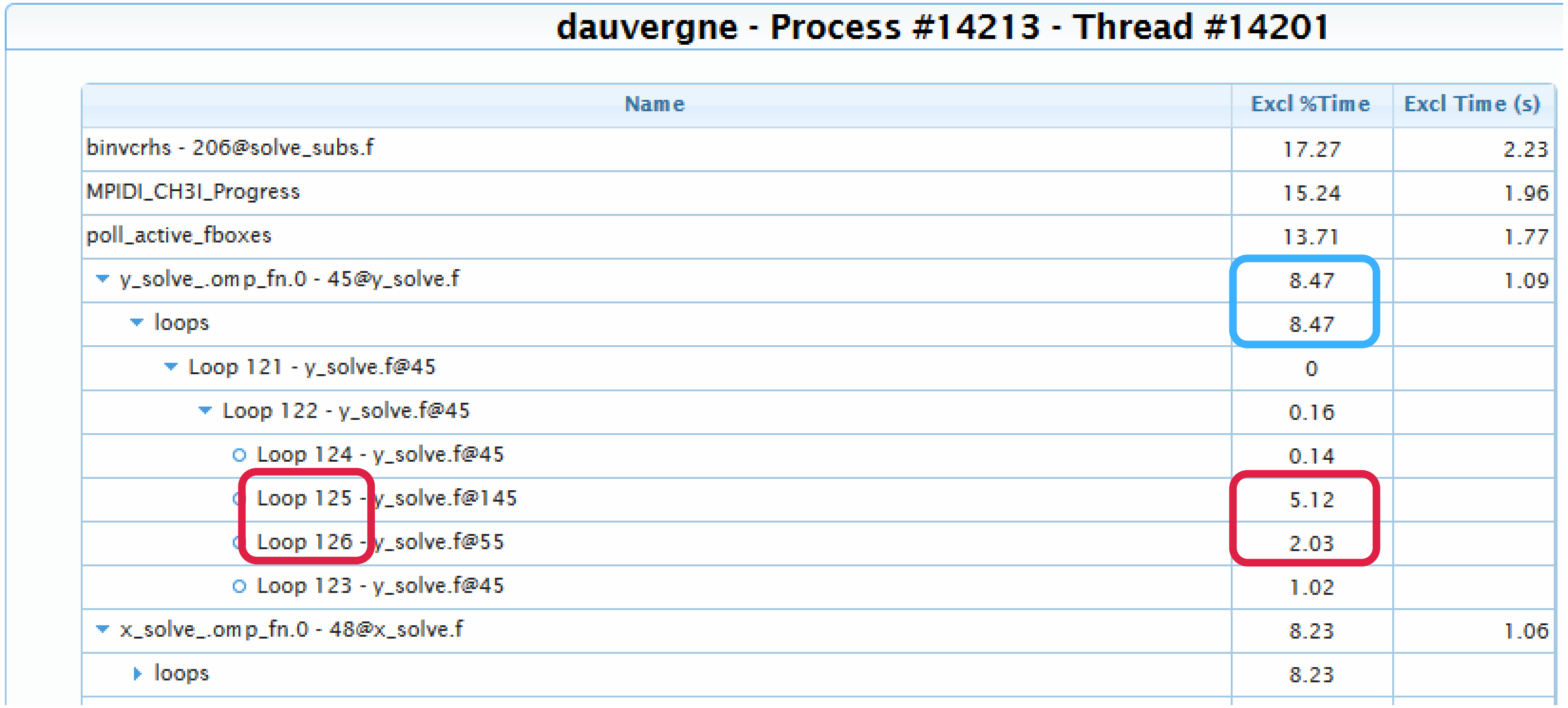


Name		
compute_rhs_		
y_solve_		
z_solve_		
x_solve_	15.07	0.14
MPIDI_CH3I_Progress	5.61	0.14

MAQAO LProf: Lightweight Profiler
Function and loop hotspots (3/3)

Analyzing the time spent at loop level:

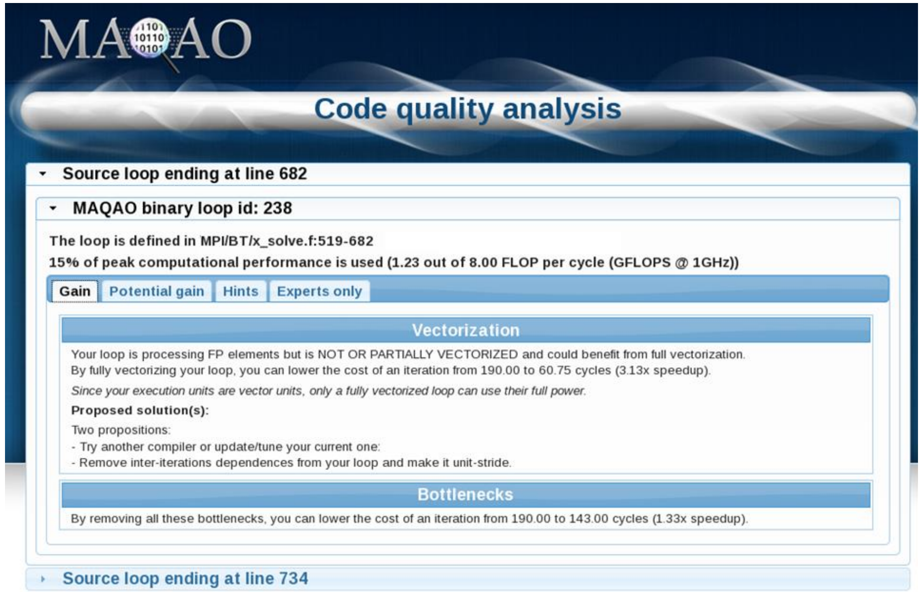
- Finding the most time consuming
- Providing direct link to MAQAO CQA analyses



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 CQA: Code Quality Analyzer



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))

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: Code Quality Analyzer
Introduction

Improving performance of the user code

Performing static analysis of assembly code (no execution needed)

- Relies on a microarchitecture model
- Evaluates the quality of the compiler generated code
- Returns hints and workarounds to the developer

Focusing on loops:

- In HPC most of the time is spent in loops

Targets compute bound codes

MAQAO CQA: Code Quality Analyzer
Processor Architecture: Core level

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

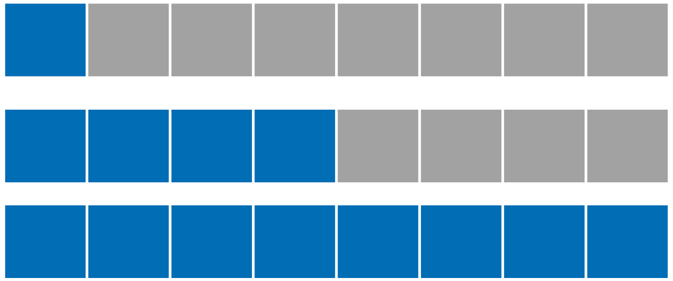
Concepts:

- Peak performance
- Execution pipeline
- Resources/Functional units

Key performance levers for core level efficiency:

- Vectorizing
- Avoiding high latency instructions if possible
- Having the compiler generate an efficient code

Same instruction – Same cost



Process up to 8X (SP) data

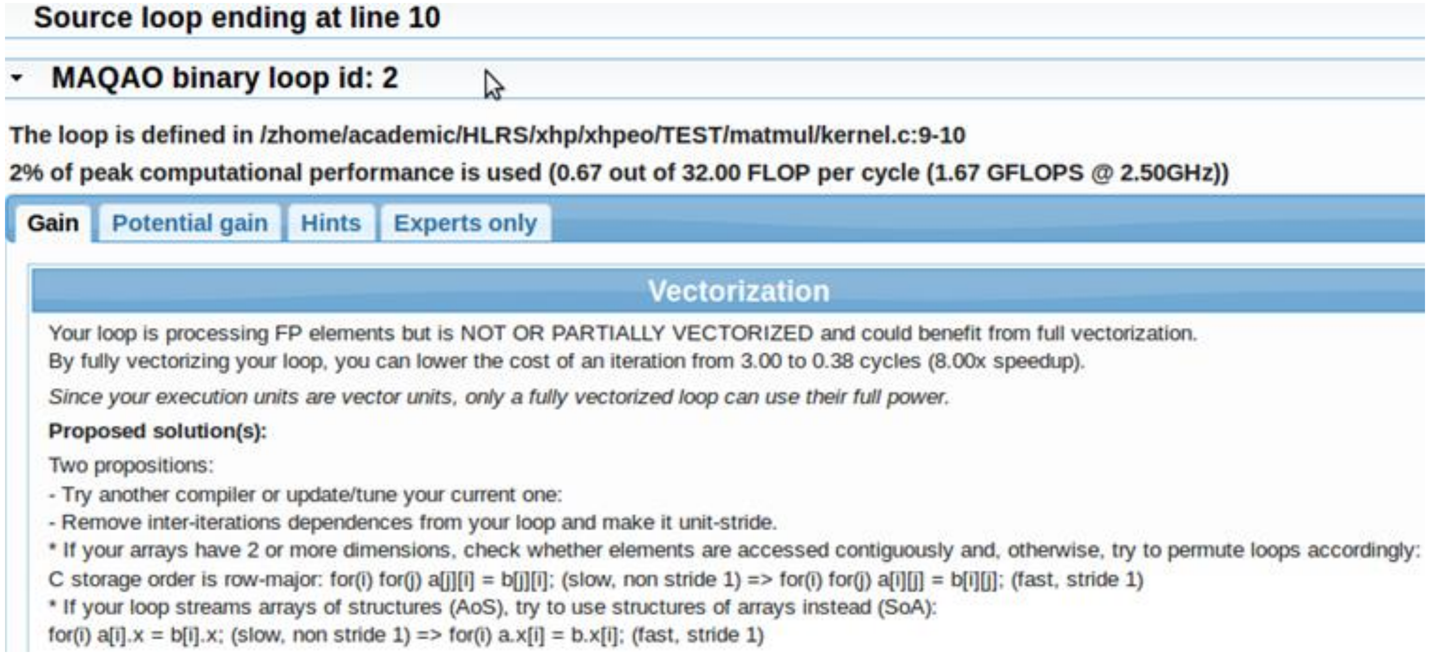
MAQAO CQA: Code Quality Analyzer
Output

High level reports:

- Reference to the source code
- Bottleneck description
- Hints to improve performance
- Reports categorized by confidence level
  - gain, potential gain

Low level report for performance experts

No runtime cost/overhead



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))

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: Code Quality Analyzer *Compiler and programmer hints*

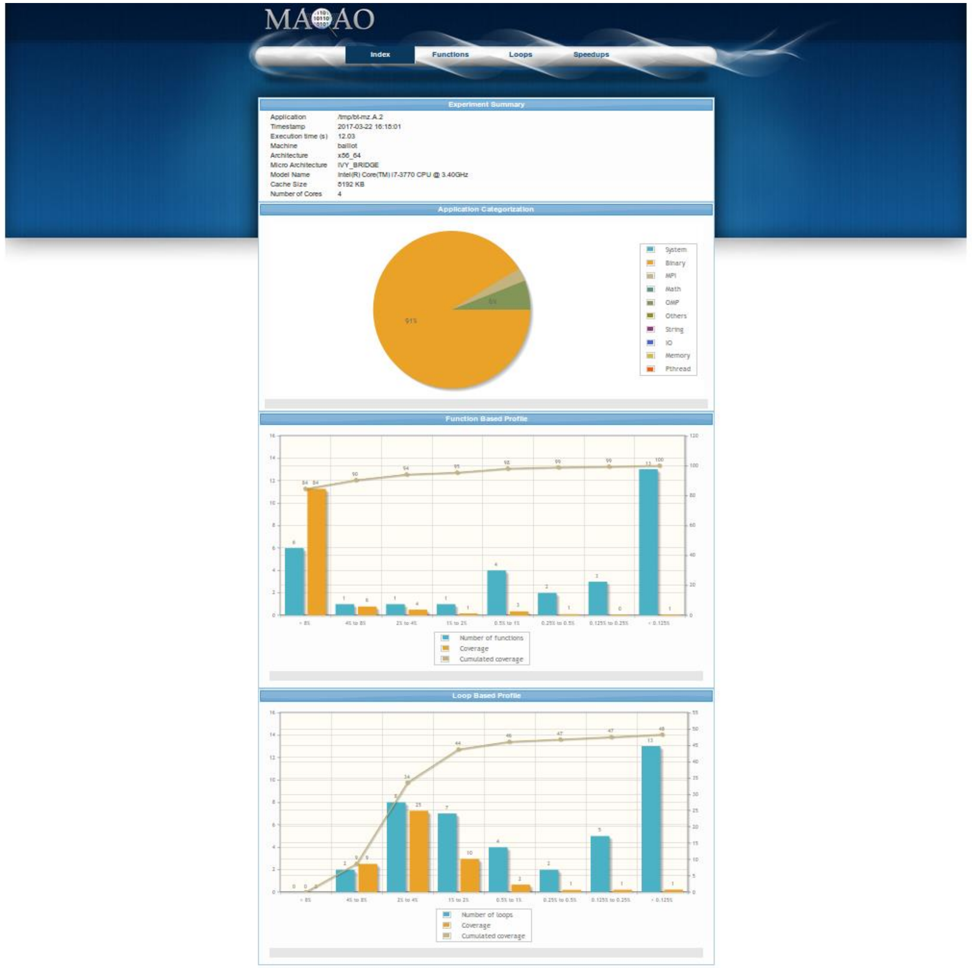
Compiler can be driven using flags and pragmas:

- Ensuring full use of architecture capabilities (e.g. using flag -xHost on AVX capable machines)
- Forcing optimization (unrolling, vectorization, alignment, …)
- Bypassing conservative behavior when possible (e.g. 1/X precision)

Implementation changes

- Improve data access
  - Loop interchange
  - Changing loop strides
- Avoid instructions with high latency

MAQAO ONE View: Performance View Aggregator



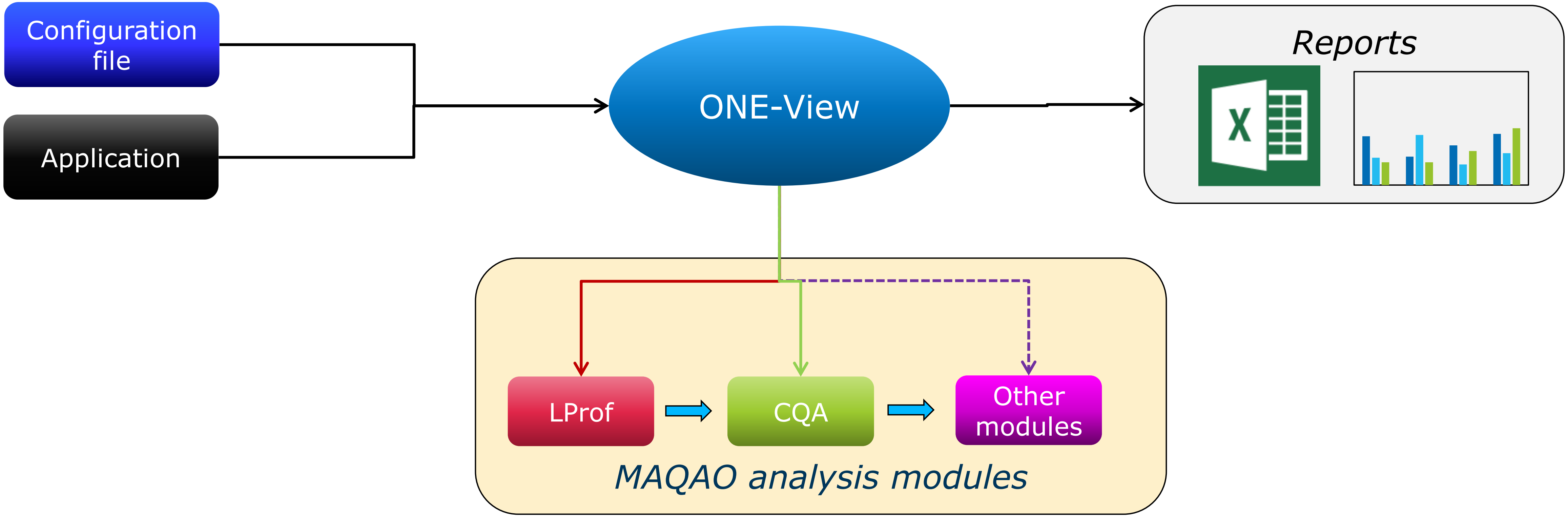
Experiment Summary

Application	/tmp/bt-mz.A.2
Timestamp	2017-03-22 16:18:01
Execution time (s)	12.03
Machine	bailliot
Architecture	x86_64
Micro Architecture	IVY_BRIDGE
Model Name	Intel(R) Core(TM) i7-3770 CPU @ 3.40GHz
Cache Size	8192 KB
Number of Cores	4

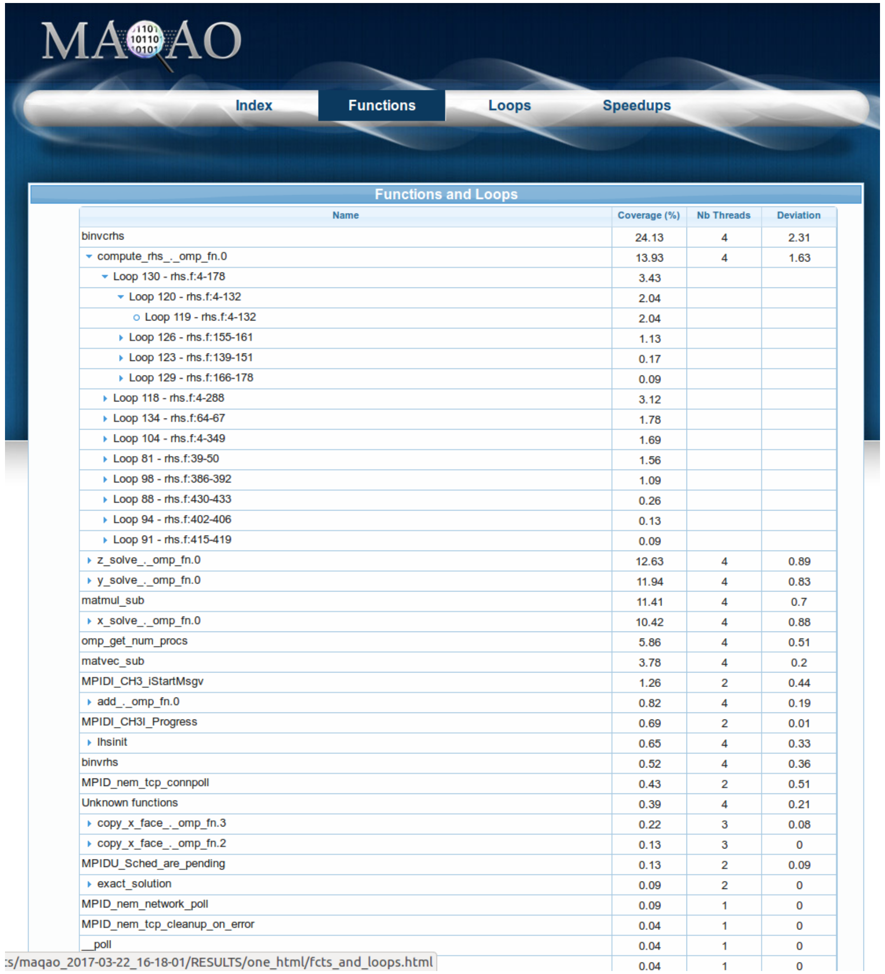
MAQAO ONE View: Performance View Aggregator
Introduction

Automatizing the full analysis process

- Invocation of the MAQAO modules
- Generation of aggregated performance views as HTML or XLS graphs



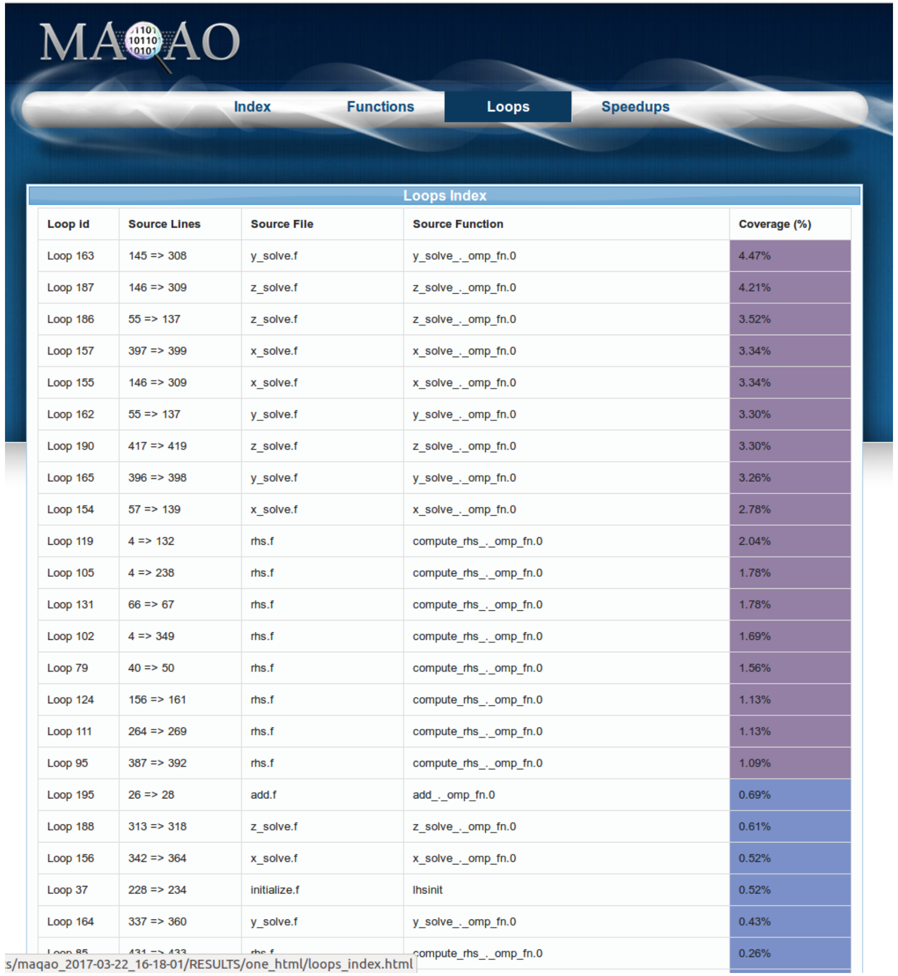
MAQAO ONE View: Performance View Aggregator
GUI sample (1/3)



Functions and Loops

Name	Coverage (%)	Nb Threads	Deviation
binvcrhs	24.13	4	2.31
▾ compute_rhs_._omp_fn.0	13.93	4	1.63
▾ Loop 130 - rhs.f:4-178	3.43		
▾ Loop 120 - rhs.f:4-132	2.04		
○ Loop 119 - rhs.f:4-132	2.04		
▸ Loop 126 - rhs.f:155-161	1.13		
▸ Loop 123 - rhs.f:139-151	0.17		
▸ Loop 129 - rhs.f:166-178	0.09		
▸ Loop 118 - rhs.f:4-288	3.12		
▸ Loop 134 - rhs.f:64-67	1.78		
▸ Loop 104 - rhs.f:4-349	1.69		
▸ Loop 81 - rhs.f:39-50	1.56		
▸ Loop 98 - rhs.f:386-392	1.09		
▸ Loop 88 - rhs.f:430-433	0.26		
▸ Loop 94 - rhs.f:402-406	0.13		
▸ Loop 91 - rhs.f:415-419	0.09		
▸ z_solve_._omp_fn.0	12.63	4	0.89
▸ y_solve_._omp_fn.0	11.94	4	0.83
matmul_sub	11.41	4	0.7
▸ x_solve_._omp_fn.0	10.42	4	0.88
omp_get_num_procs	5.86	4	0.51
matvec_sub	3.78	4	0.2
MPIDI_CH3_iStartMsgv	1.26	2	0.44
▸ add_._omp_fn.0	0.82	4	0.19
MPIDI_CH3I_Progress	0.69	2	0.01
▸ lhsinit	0.65	4	0.33
binvrhs	0.52	4	0.36
MPID_nem_tcp_connpoll	0.43	2	0.51
Unknown functions	0.39	4	0.21
▸ copy_x_face_._omp_fn.3	0.22	3	0.08
▸ copy_x_face_._omp_fn.2	0.13	3	0
MPIDU_Sched_are_pending	0.13	2	0.09
▸ exact_solution	0.09	2	0
MPID_nem_network_poll	0.09	1	0
MPID_nem_tcp_cleanup_on_error	0.04	1	0
__poll	0.04	1	0
[illegible]	0.04	1	0

:s/maqao_2017-03-22_16-18-01/RESULTS/one_html/fcts_and_loops.html

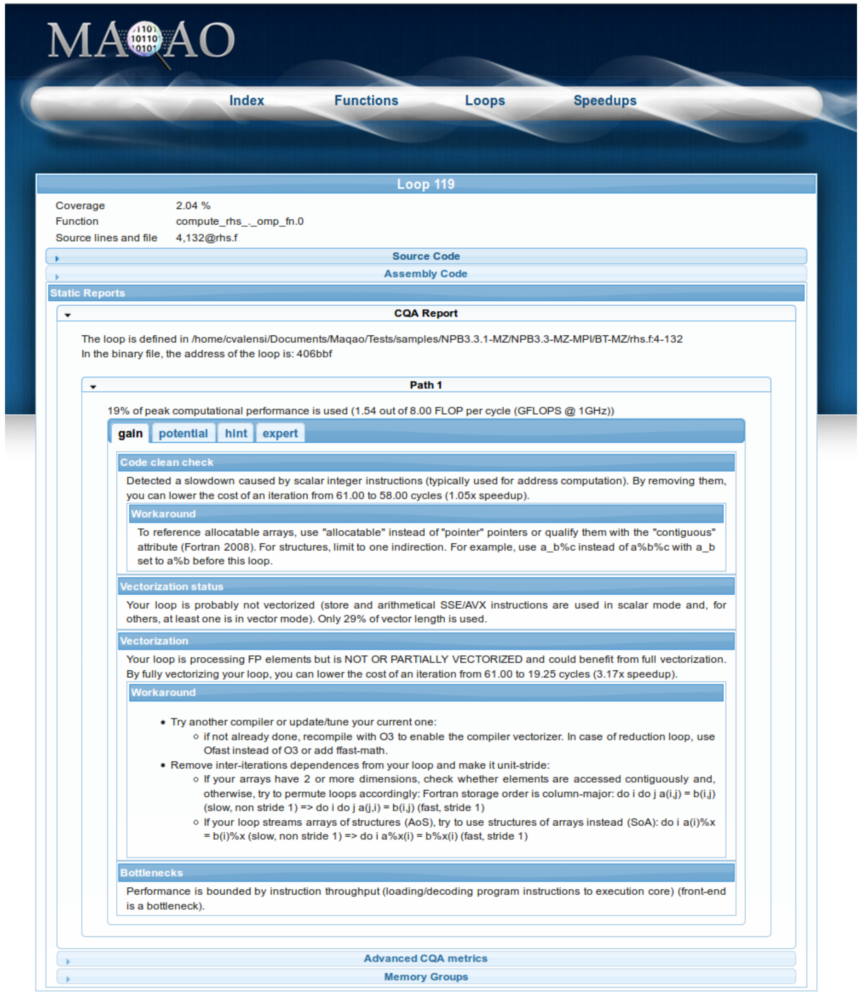


Loops Index

Loop id	Source Lines	Source File	Source Function	Coverage (%)
Loop 163	145 => 308	y_solve.f	y_solve_._omp_fn.0	4.47%
Loop 187	146 => 309	z_solve.f	z_solve_._omp_fn.0	4.21%
Loop 186	55 => 137	z_solve.f	z_solve_._omp_fn.0	3.52%
Loop 157	397 => 399	x_solve.f	x_solve_._omp_fn.0	3.34%
Loop 155	146 => 309	x_solve.f	x_solve_._omp_fn.0	3.34%
Loop 162	55 => 137	y_solve.f	y_solve_._omp_fn.0	3.30%
Loop 190	417 => 419	z_solve.f	z_solve_._omp_fn.0	3.30%
Loop 165	396 => 398	y_solve.f	y_solve_._omp_fn.0	3.26%
Loop 154	57 => 139	x_solve.f	x_solve_._omp_fn.0	2.78%
Loop 119	4 => 132	rhs.f	compute_rhs_._omp_fn.0	2.04%
Loop 105	4 => 238	rhs.f	compute_rhs_._omp_fn.0	1.78%
Loop 131	66 => 67	rhs.f	compute_rhs_._omp_fn.0	1.78%
Loop 102	4 => 349	rhs.f	compute_rhs_._omp_fn.0	1.69%
Loop 79	40 => 50	rhs.f	compute_rhs_._omp_fn.0	1.56%
Loop 124	156 => 161	rhs.f	compute_rhs_._omp_fn.0	1.13%
Loop 111	264 => 269	rhs.f	compute_rhs_._omp_fn.0	1.13%
Loop 95	387 => 392	rhs.f	compute_rhs_._omp_fn.0	1.09%
Loop 195	26 => 28	add.f	add_._omp_fn.0	0.69%
Loop 188	313 => 318	z_solve.f	z_solve_._omp_fn.0	0.61%
Loop 156	342 => 364	x_solve.f	x_solve_._omp_fn.0	0.52%
Loop 37	228 => 234	initialize.f	lhsinit	0.52%
Loop 164	337 => 360	y_solve.f	y_solve_._omp_fn.0	0.43%
Loop 85	431 => 433	rhs.f	compute_rhs_._omp_fn.0	0.26%

:s/maqao_2017-03-22_16-18-01/RESULTS/one_html/loops_index.html

MAQAO ONE View: Performance View Aggregator
GUI sample (2/3)



Loop 119

Coverage	2.04 %
Function	compute_rhs_._omp_fn.0
Source lines and file	4,132@rhs.f

CQA Report

The loop is defined in /home/cvalensi/Documents/Maqao/Tests/samples/NPB3.3.1-MZ/NPB3.3-MZ-MPI/BT-MZ/rhs.f:4-132
In the binary file, the address of the loop is: 406bbf

Path 1

19% of peak computational performance is used (1.54 out of 8.00 FLOP per cycle (GFLOPS @ 1GHz))

Code clean check

Detected a slowdown caused by scalar integer instructions (typically used for address computation). By removing them, you can lower the cost of an iteration from 61.00 to 58.00 cycles (1.05x speedup).

Workaround

To reference allocatable arrays, use "allocatable" instead of "pointer" pointers or qualify them with the "contiguous" attribute (Fortran 2008). For structures, limit to one indirection. For example, use a_b%c instead of a%b%c with a_b set to a%b before this loop.

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 29% of vector length is used.

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 61.00 to 19.25 cycles (3.17x speedup).

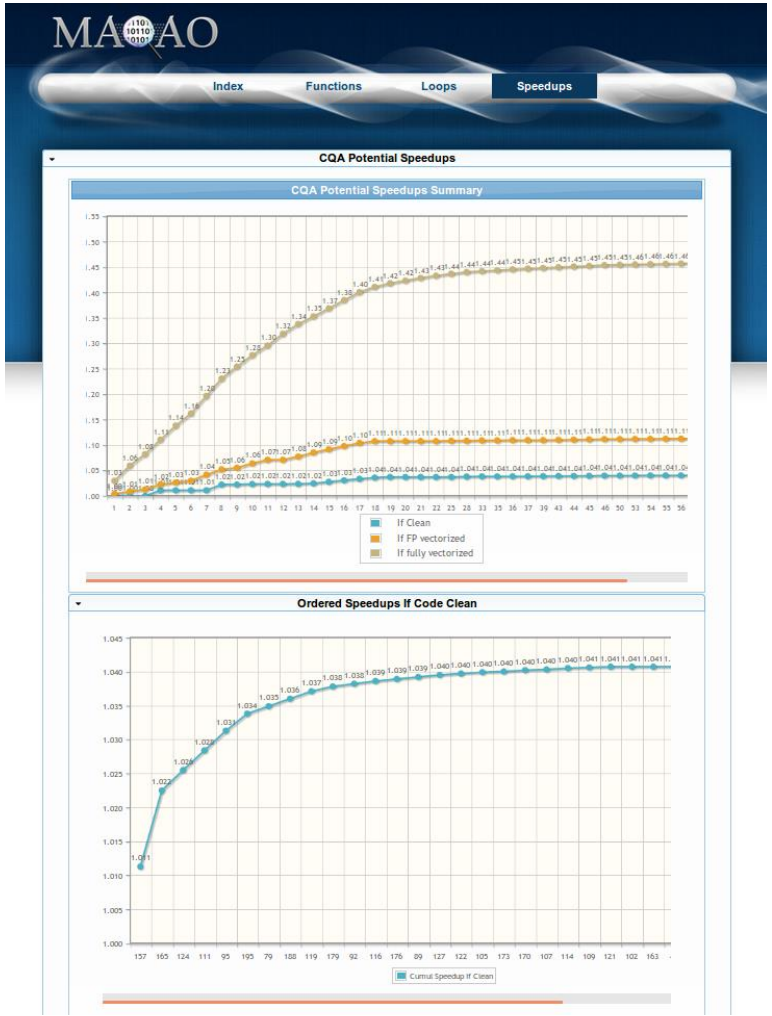
Workaround

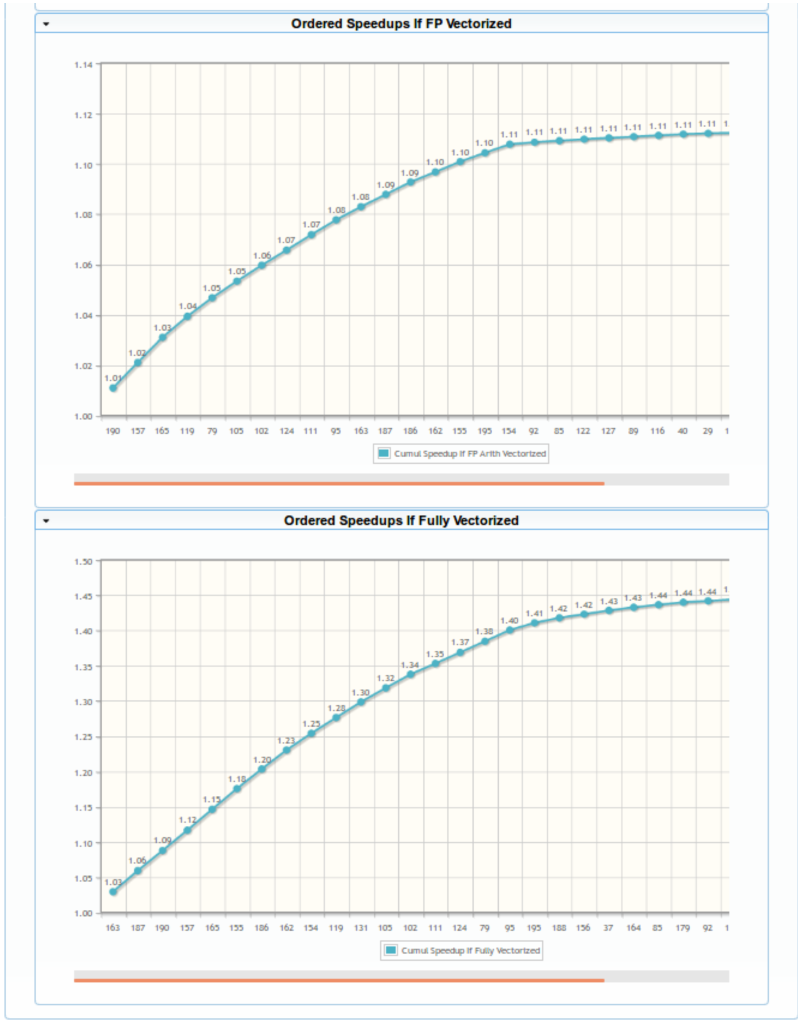
- Try another compiler or update/tune your current one:
  - if not already done, recompile with O3 to enable the compiler vectorizer. In case of reduction loop, use Ofast instead of O3 or add ffast-math.
- Remove inter-iterations dependences from your loop and make it unit-stride:
  - If your arrays have 2 or more dimensions, check whether elements are accessed contiguously and, otherwise, try to permute loops accordingly: Fortran storage order is column-major: do i do j a(i,j) = b(i,j) (slow, non stride 1) => do i do j a(j,i) = b(i,j) (fast, stride 1)
  - If your loop streams arrays of structures (AoS), try to use structures of arrays instead (SoA): do i a(i)%x = b(i)%x (slow, non stride 1) => do i a%x(i) = b%x(i) (fast, stride 1)

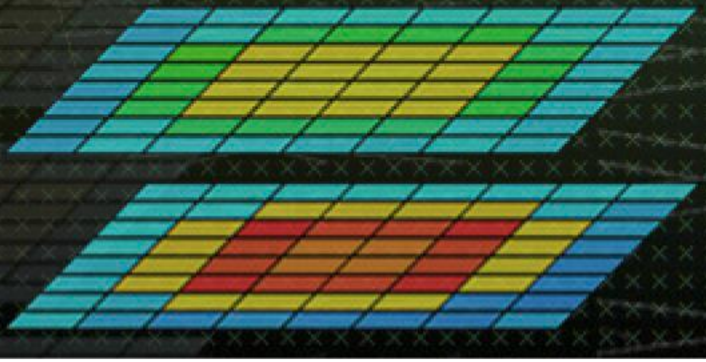
Bottlenecks

Performance is bounded by instruction throughput (loading/decoding program instructions to execution core) (front-end is a bottleneck).

MAQAO ONE View: Performance View Aggregator
GUI sample (3/3)




Ordered Speedups If FP Vectorized
Cumul Speedup If FP Arith Vectorized
Ordered Speedups If Fully Vectorized
Cumul Speedup If Fully Vectorized



Thank you for your attention !

Questions ?