# MAQAO
# Performance Analysis and Optimization Framework

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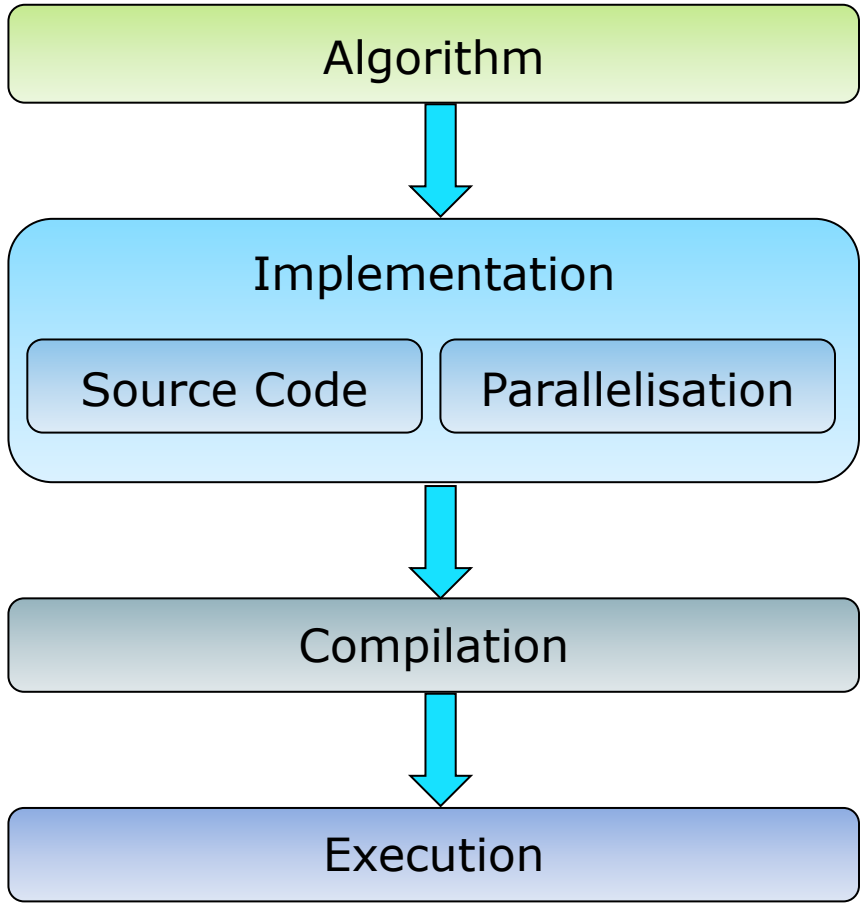
# Performance analysis and optimisation

**Where** is the application spending most execution time and resources?

**Why** is the application spending time there?
- Algorithm, implementation, runtime or hardware?
- Data access or computation?

**How** to improve the application?
- At which step(s) of the workflow or dev process?
- What additional information is needed?

**How much** gain can be expected?
- At what cost?



# Motivating example

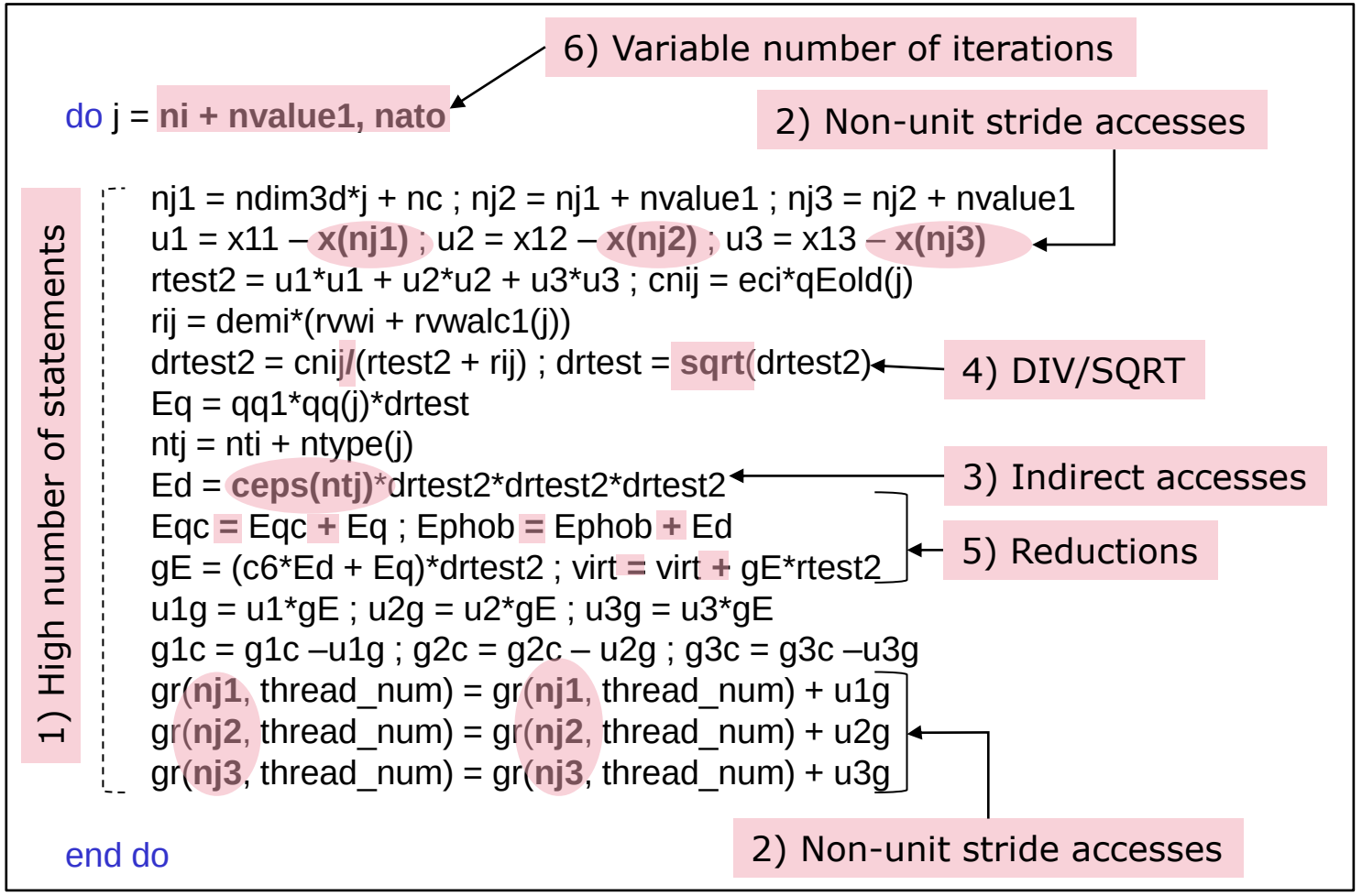
## Code of a loop representing ~10% walltime

```
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
```

**Where are the bottlenecks?**

# Motivating example

## Code of a loop representing ~10% walltime




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

***Which is the dominant one?***

➔ **Need analysis tools to identify performance issues**

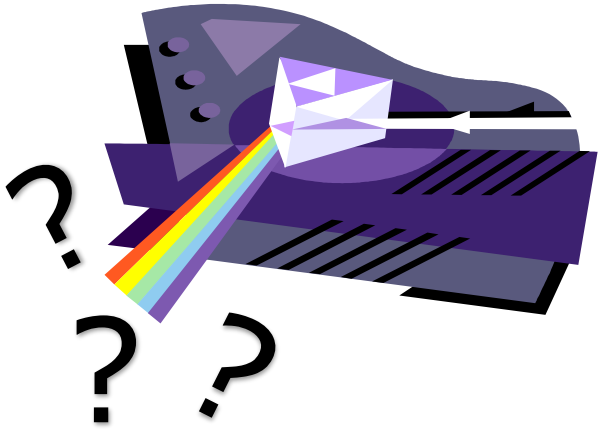
# A multifaceted problem

**What type of problems are we facing?**

- CPU or data access problems
- Identifying the dominant issues: Algorithms, implementation, parallelisation, …

**What transformations to apply?**

- Compiler switches, Partial/full vectorization
- Loop blocking/array restructuring, If removal, Full unroll
- Binary tranforms (prefetch),
- …




Making the **best use** of the machine features

Finding the **most rewarding** issues to be fixed

- **40%** total time, expected **10%** speedup
  - ➔ TOTAL IMPACT: **4%** speedup

- **20%** total time, expected **50%** speedup
  - ➔ TOTAL IMPACT: **10%** speedup

➔ **Need for dedicated and complementary tools**

# Our Approach

**Nobody wants problems everybody wants solutions ☺**

- Focusing on the knobs that code developers can operate:
  - Compiler flags and runtime settings
  - Code restructuring
  - Data restructuring
- Helping the user in using these knobs

➔ **Instead of pinpointing problems, guiding the user towards a way to address them.**

**Philosophy: Analysis at Binary Level**

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

➔ **What You Analyse Is What You Run**

# MAQAO: Modular Assembly Quality Analyzer and Optimizer

**Objectives:**

- Characterizing performance of HPC applications
- Focusing on performance at the **core level**
- **Guiding users** through the optimization process
- Estimating return on investment (**R.O.I.**)

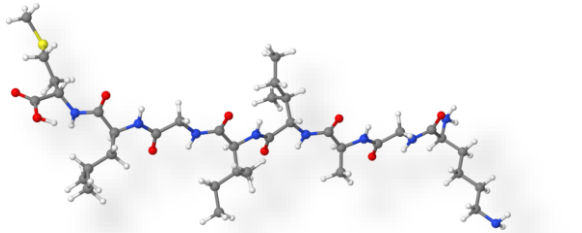
**Characteristics:**

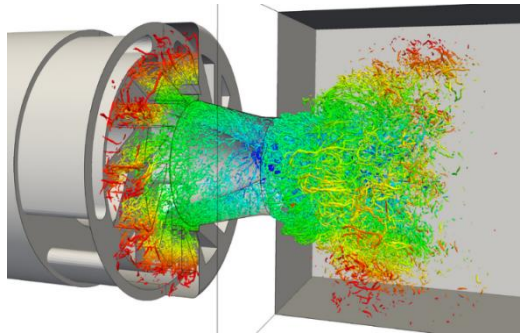
- **Modular tool** offering complementary views
- Support for **Intel x86-64** and **Aarch64** (beta version)
  - Work in progress on GPU support
- LGPL3 Open Source software
- Developed at UVSQ since 2004
- Binary release available as a **static executable**

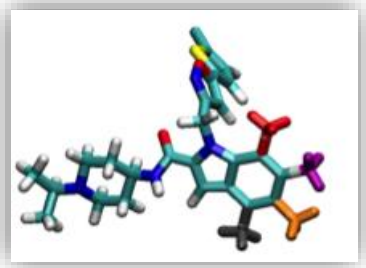
# Success stories

Optimizing industrial and academic HPC applications:

- QMC=CHEM (IRSAMC)
  - Quantum chemistry
  - Speedup: **> 3x**
    - Optimization: moved invocations of functions with identical parameters out of the loop body
- Yales2 (CORIA)
  - Computational fluid dynamics
  - Speedup: **up to 2.8x**
    - Optimization: removing double structure indirections
- Polaris (CEA)
  - Molecular dynamics
  - Speedup: **1.5x – 1.7x**
    - Optimization: enforcing loop vectorization through compiler directives
- AVBP (CERFACS)
  - Computational fluid dynamics
  - Speedup: **1.08x – 1.17x**
    - Replaced divisions by reciprocal multiplications
    - Complete unrolling of loops with a small number of iterations







# Partnerships

MAQAO is part of the POP Centre of Excellence

- Provides performance optimisation and productivity services for academic and industrial codes
- https://pop-coe.eu/


MAQAO has been funded by UVSQ, Intel and CEA (French department of energy) through Exascale Computing Research (ECR) and through various European projects (FUI/ITEA: H4H, COLOC, PerfCloud, ELCI, POP2 CoE, TREX CoE, etc...)




Provided core binary analysis and instrumentation capabilities and features for other tools:

- TAU performance tools with MADRAS patcher through MIL (MAQAO Instrumentation Language)
  - X86_64 only, aarch64 under development
- Intel Advisor

# MAQAO team and collaborators

**MAQAO Team**

- William Jalby, Prof.
- Cédric Valensi, Ph.D.
- Emmanuel Oseret, Ph.D.
- Mathieu Tribalat, M.Sc.Eng.
- Jäsper Salah Ibnamar, M.Sc.Eng.
- Hugo Bolloré , M.Sc.Eng
- Kévin Camus, Eng.
- Aurélien Delval, Eng.
- Max Hoffer, Eng.

**Collaborators**

- David J. Kuck, Prof. (Intel US)
- Pablo de Oliveira, Prof. (UVSQ)
- Eric Petit, Ph.D. (Intel US)
- David C. Wong, Ph.D. (Intel US)
- Othman Bouizi, Ph.D. (Intel US)
- AbdelHafid Mazouz Ph.D.(Intel)
- Jeongnim Kim (Intel)

**Past Collaborators or Team Members**

- *Andrés S. Charif-Rubial, Ph.D.*
- Denis Barthou, Prof. (Univ. Bordeaux)
- Jean-Thomas Acquaviva, Ph.D. (DDN)
- Stéphane Zuckerman, Ph.D. (ENSEA)
- Julien Jaeger, Ph.D. (CEA DAM)
- Souad Koliaï, Ph.D. (CELOXICA)
- Zakaria Bendifallah, Ph.D. (ATOS)
- Tipp Moseley, Ph.D. (Google)
- Jean-Christophe Beyler, Ph.D. (Google)
- Hugo Bolloré, M.Sc.Eng. (ATOS)
- Jean-Baptiste Le Reste, M.Sc.Eng. (start-up)
- Sylvain Henry, Ph.D. (start-up)
- José Noudohouenou, Ph.D. (Intel US)
- Aleksandre Vardoshvili, M.Sc.Eng.
- Romain Pillot, Eng
- Youenn Lebras, Ph.D. (start-up)

# More on MAQAO

MAQAO website: www.maqao.org

- Mirror: maqao.liparad.uvsq.fr
- Documentation: www.maqao.org/documentation.html
  - Tutorials for ONE View, LProf and CQA
  - Lua API documentation
- Latest release: http://www.maqao.org/downloads.html
  - Binary releases (2-3 per year)
  - Source code
- Publications around MAQAO: http://www.maqao.org/publications.html
- Repository of MAQAO analyses: http://datafront.exascale-computing.eu/public/
- Email: contact@maqao.org

# MAQAO Main Features

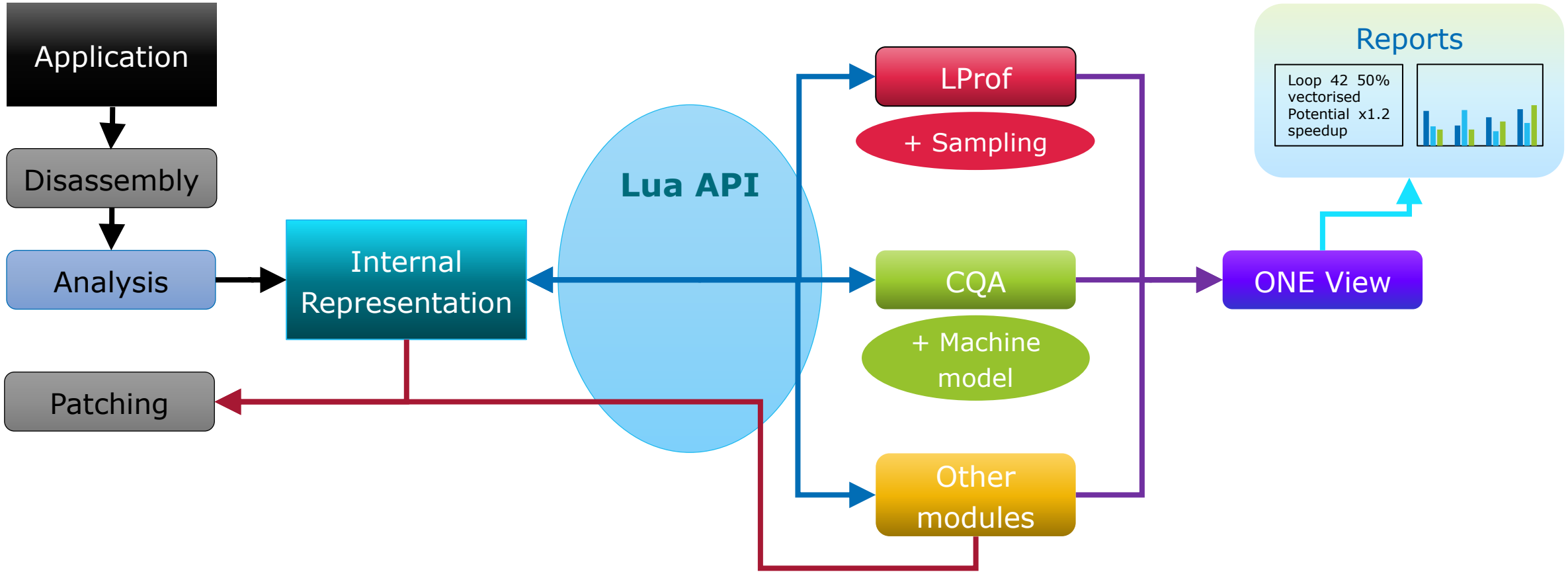
**Binary layer**
- Builds internal representation from binary
  - Construct high level structures (CFG, DDG, SSA, …)
  - Links binary instructions to source code
  - ⚠ A single source loop can be compiled as multiple assembly loops → Affecting unique identifiers to loops
- Allows patching through binary rewriting

**Profiling**
- LProf: Lightweight sampling-based Profiler operating at process, thread, function and loops level

**Static analysis**
- CQA (Code Quality Analyzer): Evaluates the quality of the binary code and offers hints for improving it

**Performance view aggregation module: ONE View**
- Goal: Guiding the user through the analysis & optimization process.
- Synthesizes information provided by different MAQAO modules
- Automatizes execution of experiments invoking other MAQAO modules and aggregates their results to produce high-level reports in HTML or XLSX format

# MAQAO Main structure



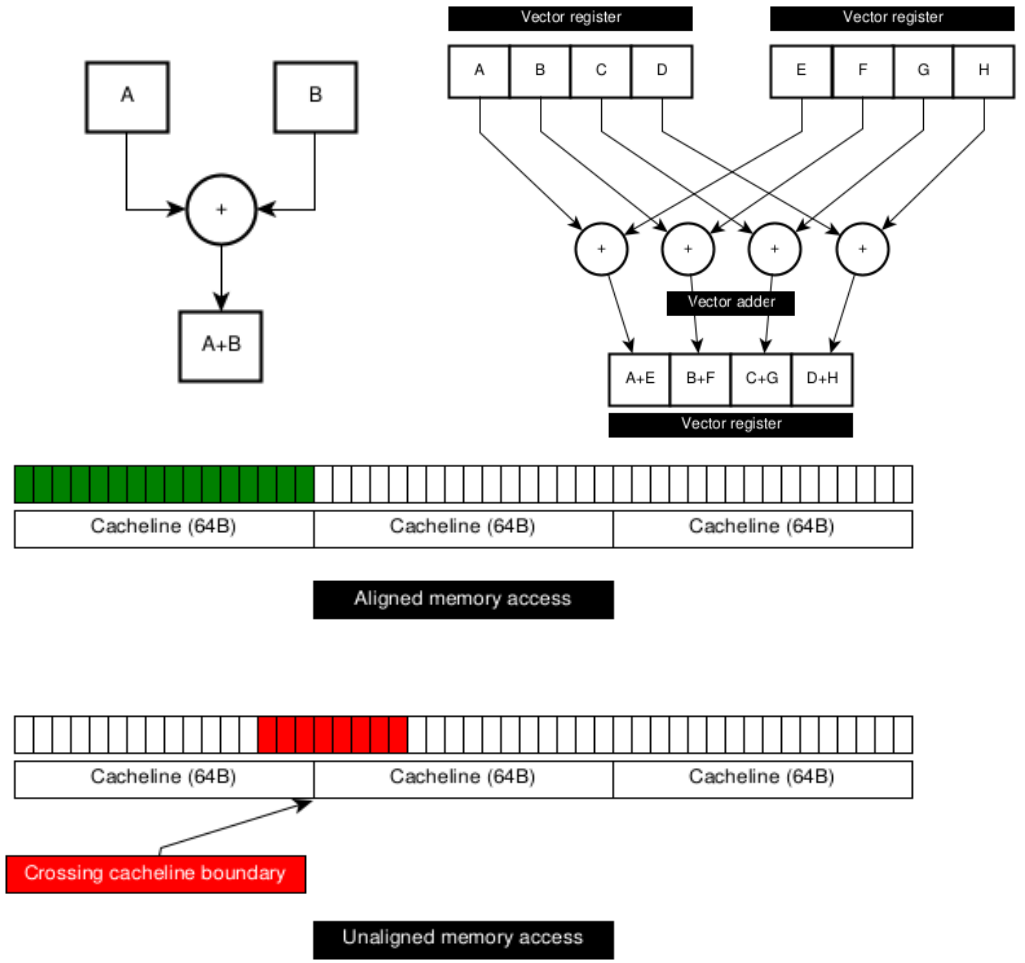
# Useful notions

## SIMD/Vectorization/Data Parallelism

- Scalar pattern: a[i] = b[i] + c[i]
- Vector pattern: a(i, i + 8) = b(i, i + 8) + c(i, i + 8)
- Benefits : increases memory bandwidth and **IPC**
- Example implementations :
  - ARM : Neon, SVE
  - x86 : SSE, AVX, AVX512

## Memory and caches

- Computations are in general faster than memory accesses
- Alignment/Contiguity of memory (x86) :
  **posix_memalign**, **aligned_alloc**, …
- Caches: L1, L2, L3, …



# MAQAO LProf: Lightweight Profiler

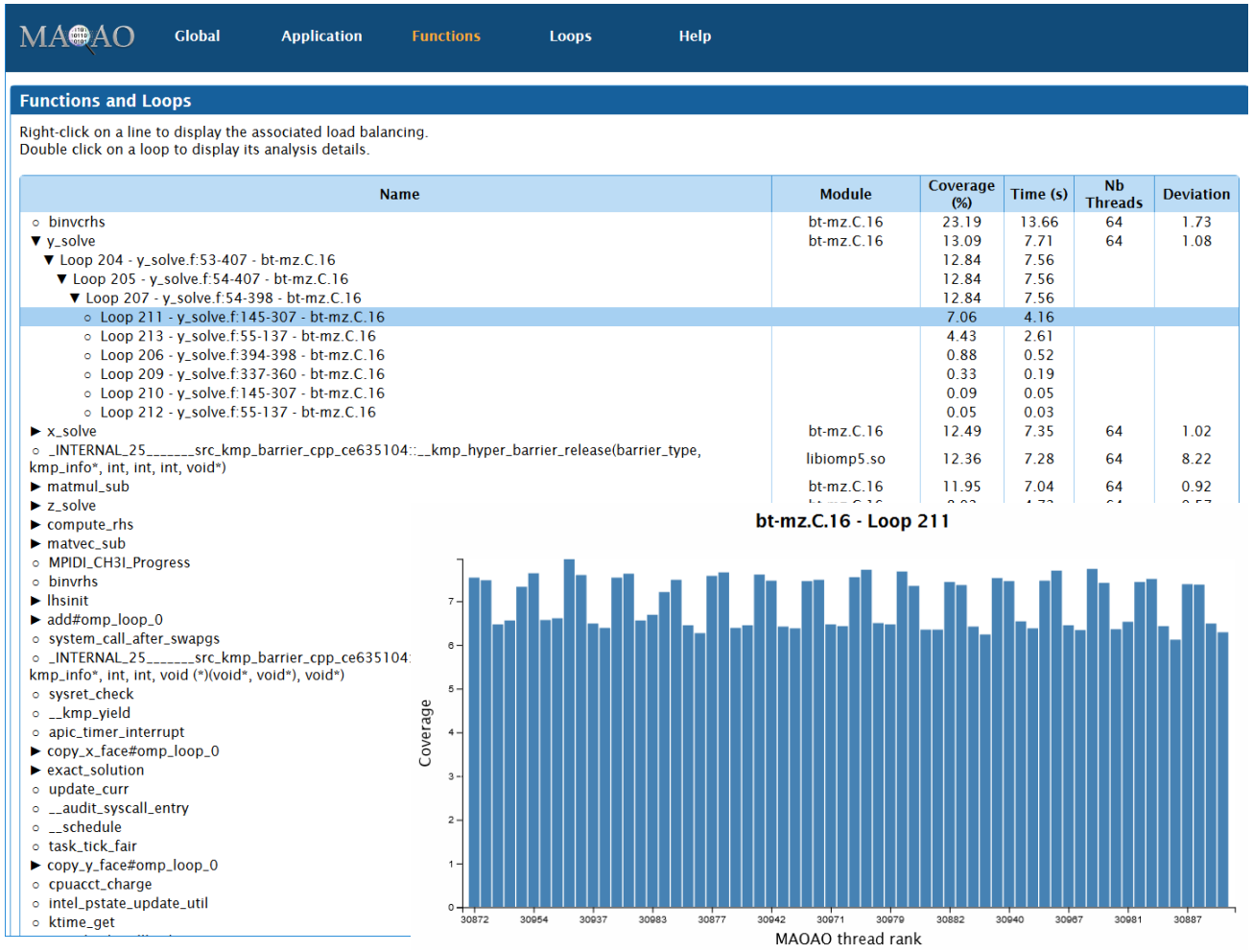
**Goal**: Lightweight localization of application hotspots

Features:

- **Lightweight**
- **Sampling** based
- Access to hardware counters
- Analysis at **function** and **loop** granularity

Strengths:

- **Non intrusive**: No recompilation necessary
- **Low overhead**
- Agnostic with regard to parallel runtime

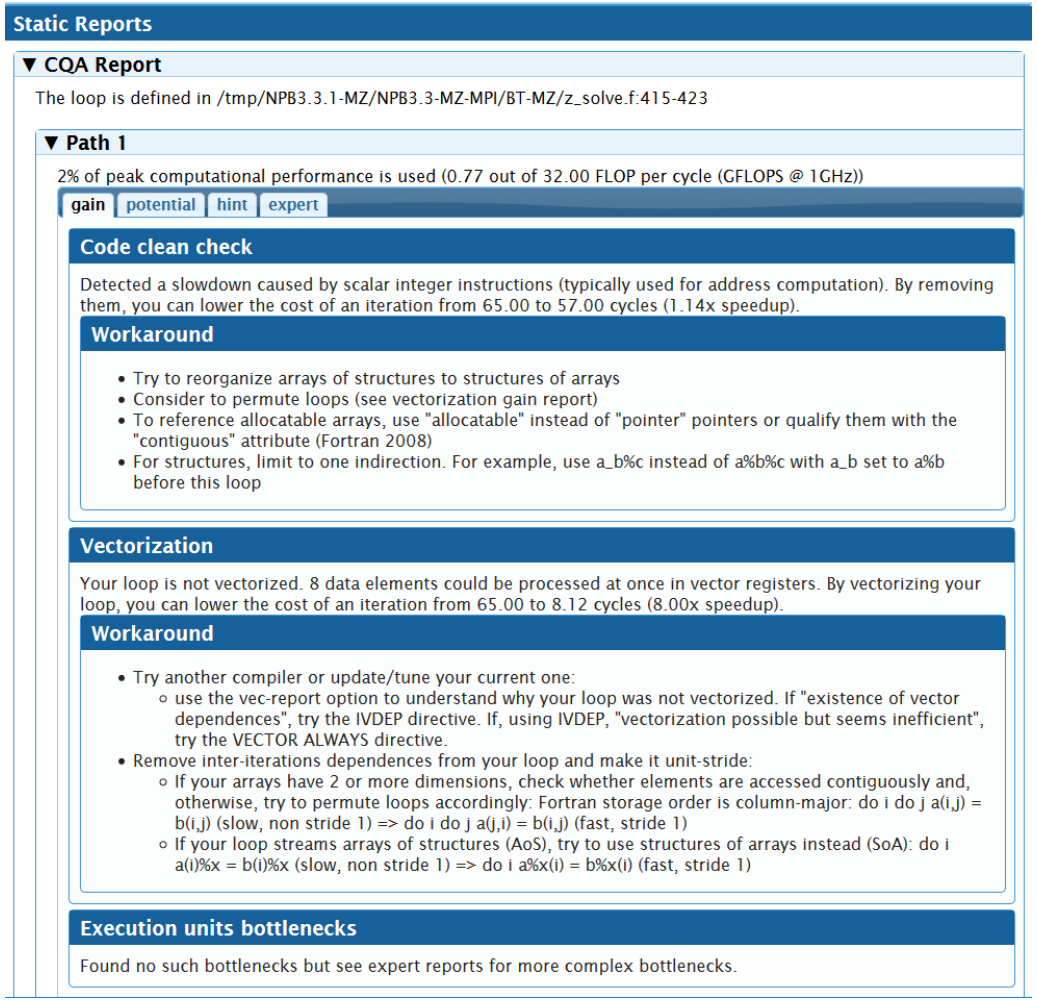


# MAQAO CQA: Code Quality Analyzer

Goal: **Assist developers** in improving code performance

Features:

- Static analysis: **no execution** of the application
- Allows **cross-analysis** of/on multiple architectures
- Evaluates the **quality** of compiler generated code
- Proposes **hints and workarounds** to improve quality/performance
- **Loops centric**
  - In HPC, loops cover most of the processing time
- Targets **compute-bound** codes



# MAQAO CQA: Main Concepts

Applications exploit at best 5 to 10% of the peak performance.

Main elements of analysis:

- Peak performance
- Execution pipeline
- Resources/Functional units

**Same instruction – Same cost**

**Process up to 8X data**

Key performance levers for core level efficiency:

- Vectorization
- Avoiding high latency instructions if possible (DIV/SQRT)
- Guiding the compiler code optimization
- Reorganizing memory and data structures layout

# "What If" Scenarios: Vectorization

Code "Clean"

- Generate an Assembly "Clean" variant : **keep only FP Arithmetic and Memory operations, suppress all other**
- Generate a CQA Performance estimate on the "Clean" Variant

Code "FP Vector"

- Generate an Assembly "FP Vector" variant : **only replace scalar FP Arithmetic by Vector FP Arithmetic equivalent**. Generate additional instructions to fill in Vector Registers.
- Generate a CQA Performance estimate

Code "Full Vector"

- Generate an Assembly "Full Vector" variant **: replace both scalar FP Arithmetic and FP Load/Store by their Vector equivalent**.
- Generate a CQA Performance estimate

All of these "What If Scenarios" are generated in a fully static manner.

# MAQAO CQA: Guiding the compiler and implementation hints

Compilers can be driven using flags, pragmas, and keywords:

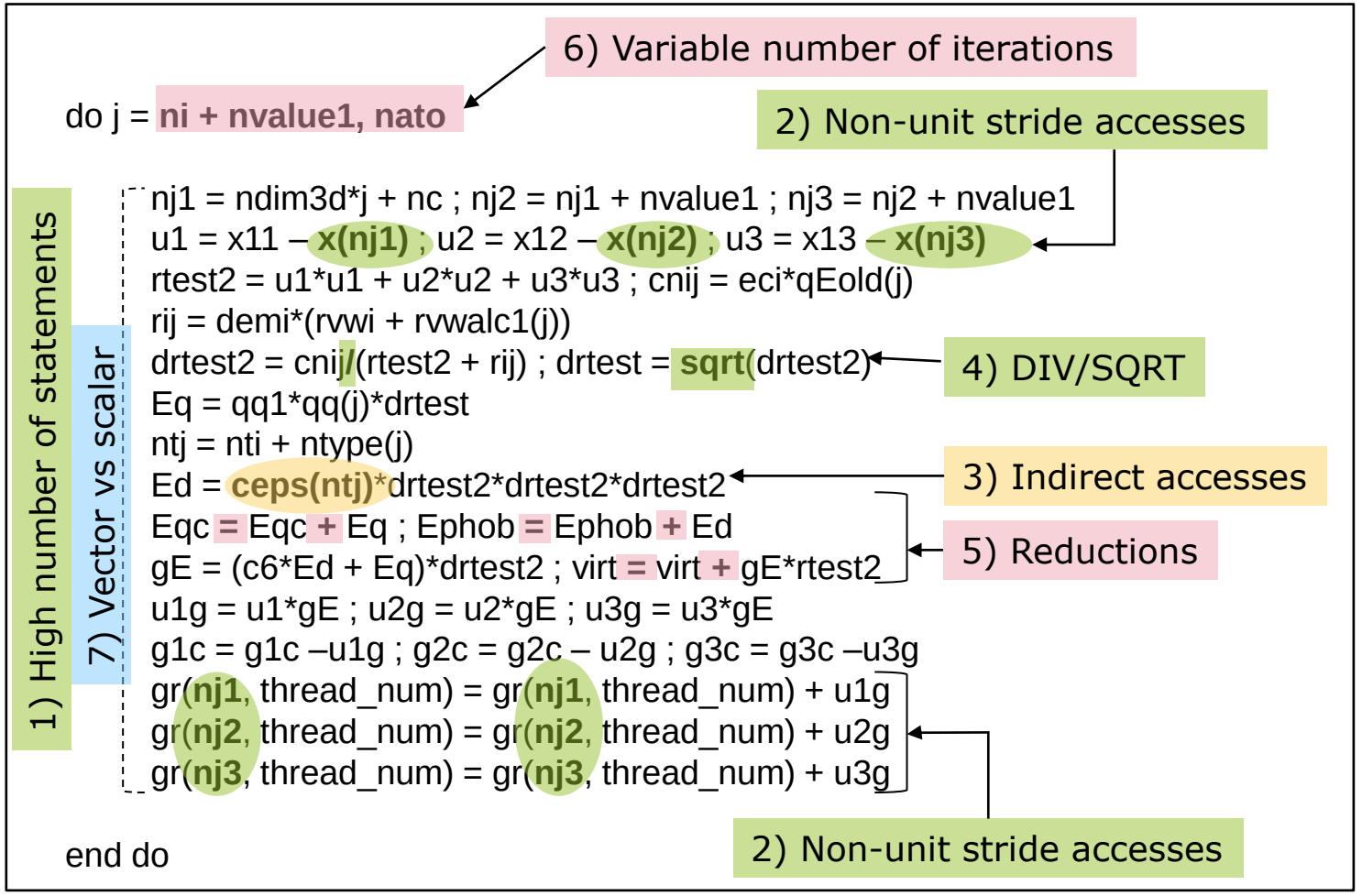
- Ensuring full use of architecture capabilities (e.g. using flag -xHost on AVX capable machines)
- Forcing optimizations (unrolling, vectorization, alignment, …)
- Bypassing conservative behaviour when possible (e.g. 1/X precision)

Hints for implementation changes:

- Improve data access patterns
  - Memory alignment
  - Loop interchange
  - Changing loop strides
  - Reshaping arrays of structures
- Avoid instructions with high latency (SQRT, DIV, GATHER, SCATTER, …)

# Application to Motivating Example

## Issues identified by CQA




CQA can detect and provide hints to resolve most of the identified issues:

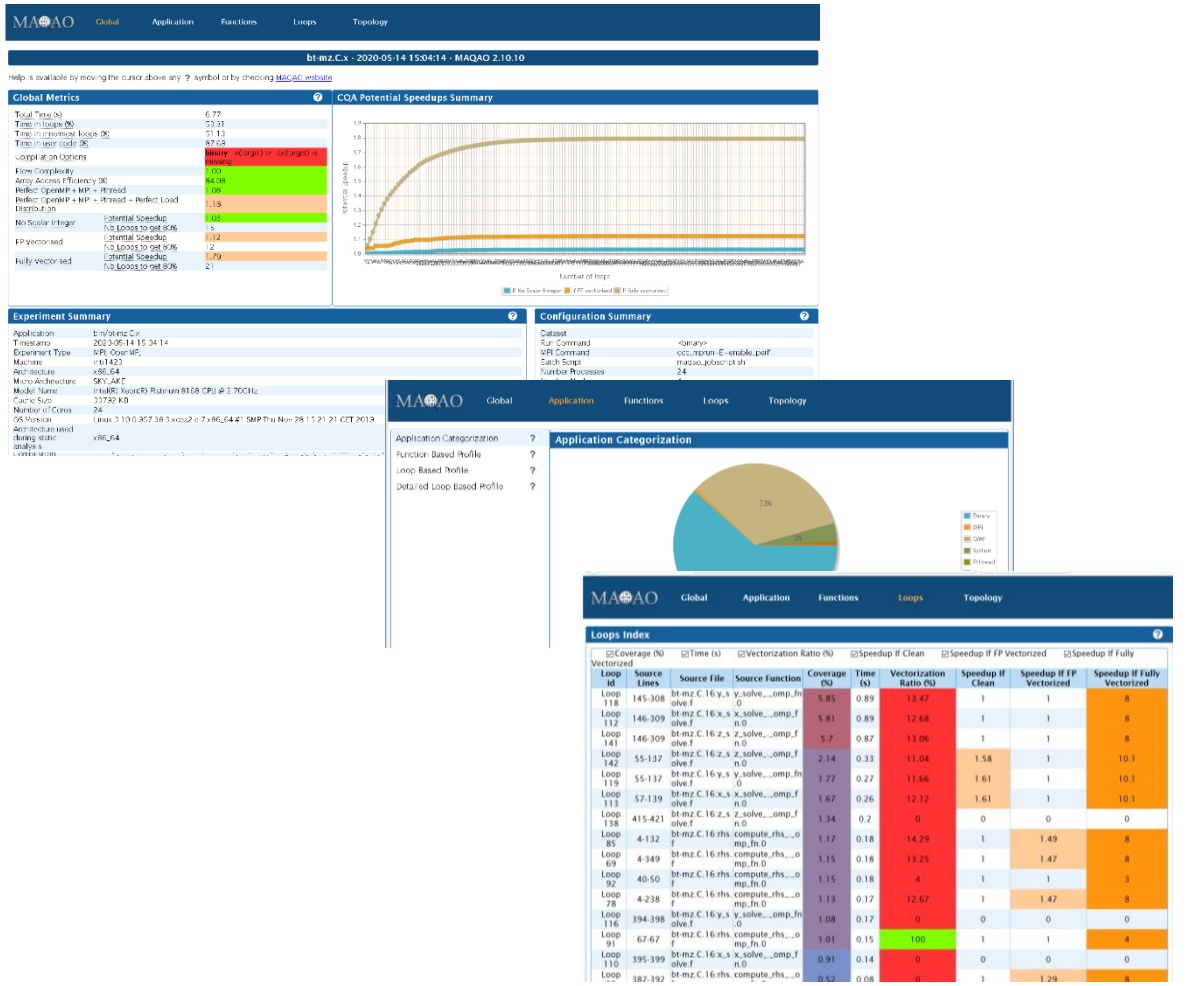
1) **High number of statements**
2) **Non-unit stride accesses**
3) **Indirect accesses**
4) **DIV/SQRT**
5) Reductions
6) Variable number of iterations
7) **Vector vs scalar**

# MAQAO ONE View: Performance View Aggregator

**Automating** the whole analysis process
- Invoke multiple MAQAO modules
- Generate **aggregated performance views**
- Generate a report in HTML format

Main steps:
- Invokes LProf to **identify hotspots**
- Invokes CQA on **hotspots**

Available results:
- **Speedup** predictions
- **High-level** summary
- Global **code quality** metrics
- **Hints** for improving performance
- Parallel **efficiency** analysis



# ONE View Reports Levels

**ONE VIEW ONE**
- Requires a single run of the application
- Profiling of the application using LProf
- Static analysis using CQA

**Scalability mode**
- Multiple executions with varying parallel configurations
- Allows to evaluate scalability or parallel behaviour of applications

**Comparison mode**
- Comparison of multiple runs (iso-binary or iso-source)
- Allows to compare performance across different datasets, compilers, or hardware platforms

**Stability mode**
- Multiple runs with identical parameters
- Allows to assess the stability of execution time

# Analysing an application with MAQAO

ONE View execution

- Provide all parameters necessary for executing the application
  - Parameters can be passed on the command line or as a configuration file
  - Parameters include binary name, MPI commands, dataset directory, …

```
$ maqao oneview --create-report=one --executable=bt-mz.C.16 --mpi_command="mpirun -n 16"
```

```
$ maqao oneview --create-report=one --config=my_config.json"
```

- Analyses can be tweaked if necessary
  - Report level **one** corresponds to lightweight profiling (**LProf**) and code quality analysis (**CQA**)
- ONE View can reuse an existing experiment directory to perform further analyses
- Results available in HTML format by default
  - XLS spreadsheets and textual output generation are also available

Online help is available:

```
$ maqao oneview --help
```

# Analysing an application with MAQAO

MAQAO modules can be invoked separately for advanced analyses

- LProf
  - Profiling

```
$ maqao lprof xp=exp_dir --mpi-command="mpirun -n 16 -ppn 4" ppn=4 -- ./bt-mz.C.16
```

  - Display functions profile

```
$ maqao lprof xp=exp_dir –df
```

  - Displaying the results from a ONE View run

```
$ maqao lprof xp=oneview_xp_dir/tools/lprof_npsu –df
```

- CQA

```
$ maqao cqa loop=42 bt-mz.C.16
```

Online help is available:

```
$ maqao lprof --help
```

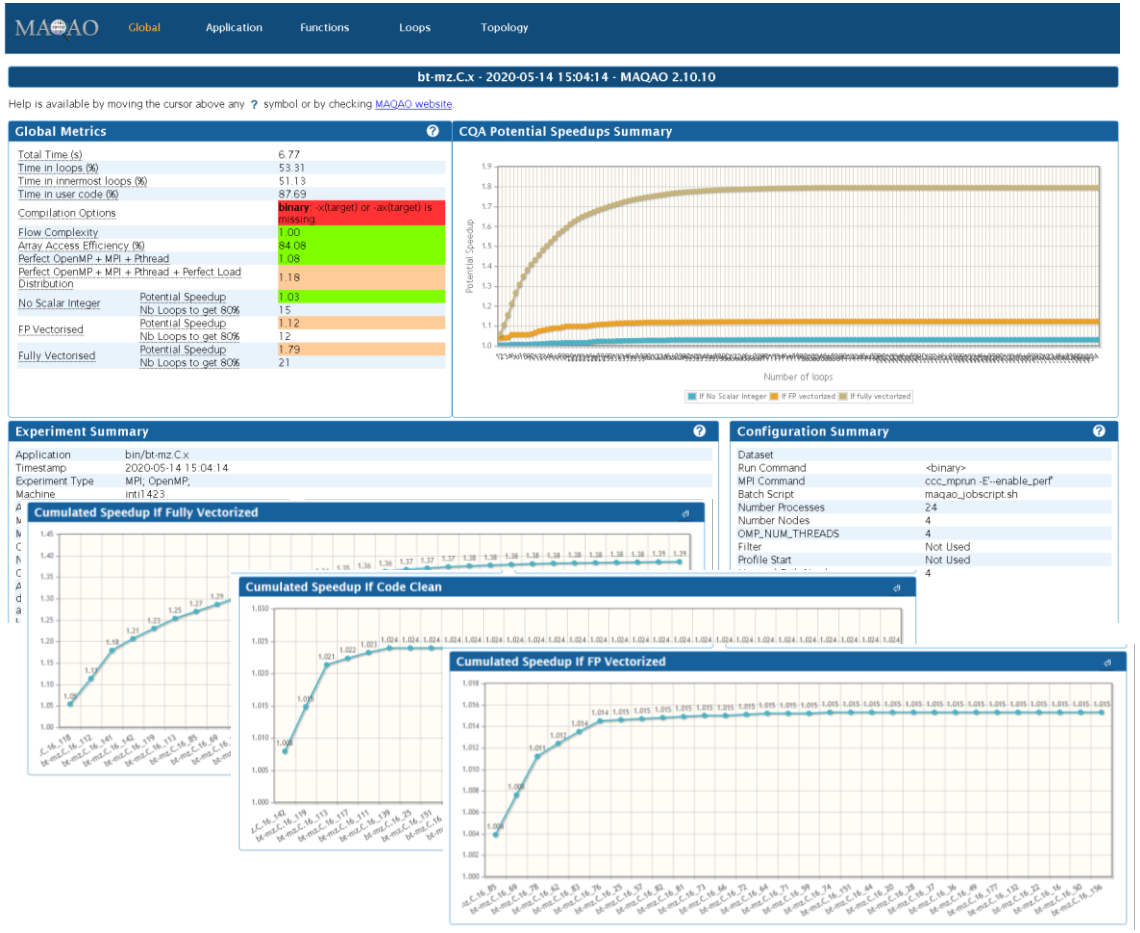
```
$ maqao cqa --help
```

# Navigating ONE View Reports

# Global summary

Experiment summary
- Machine characteristics and configuration

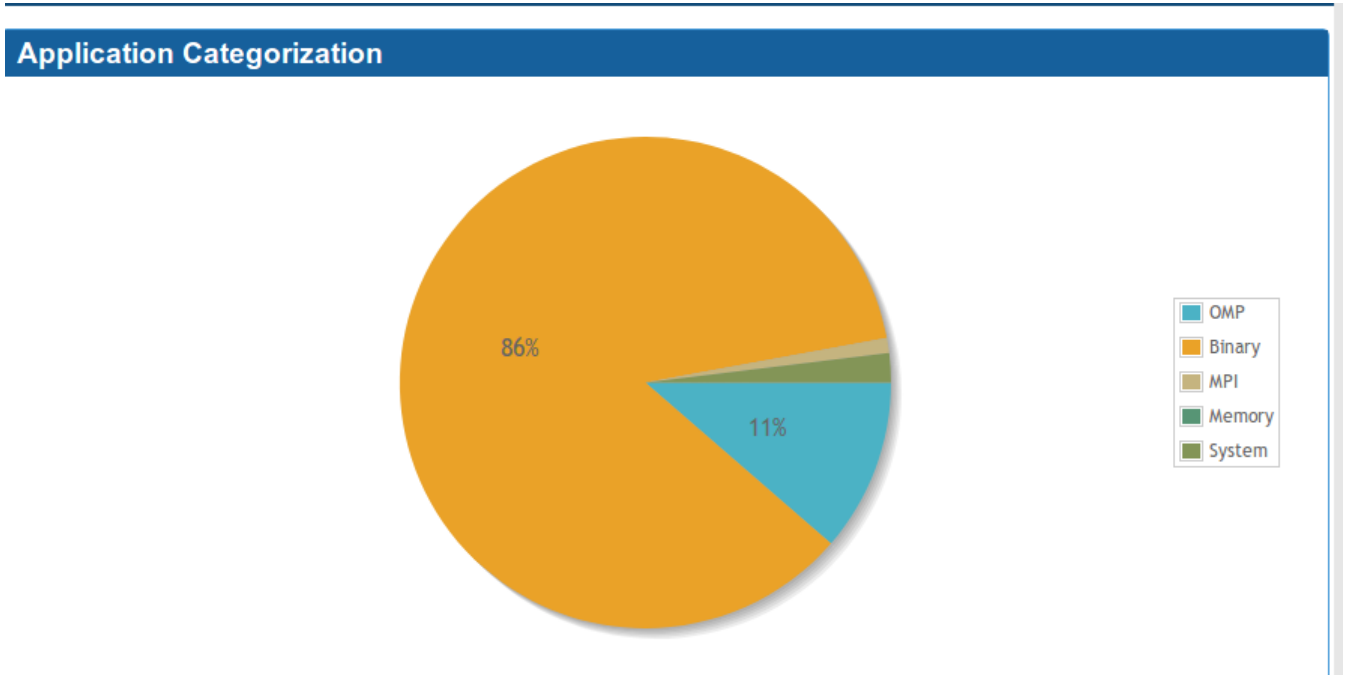
Global metrics
- General quality metrics derived from MAQAO analyses
- Global speedup predictions
  - Speedup prediction depending on the number of vectorised loops
  - Ordered speedups to identify the loops to optimise first



# Time Categorisation

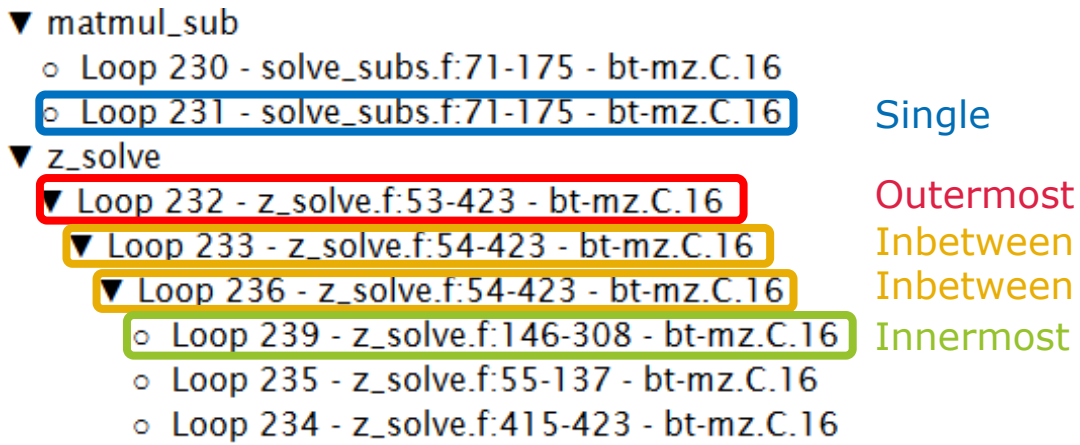
Identifying at a glance where time is spent

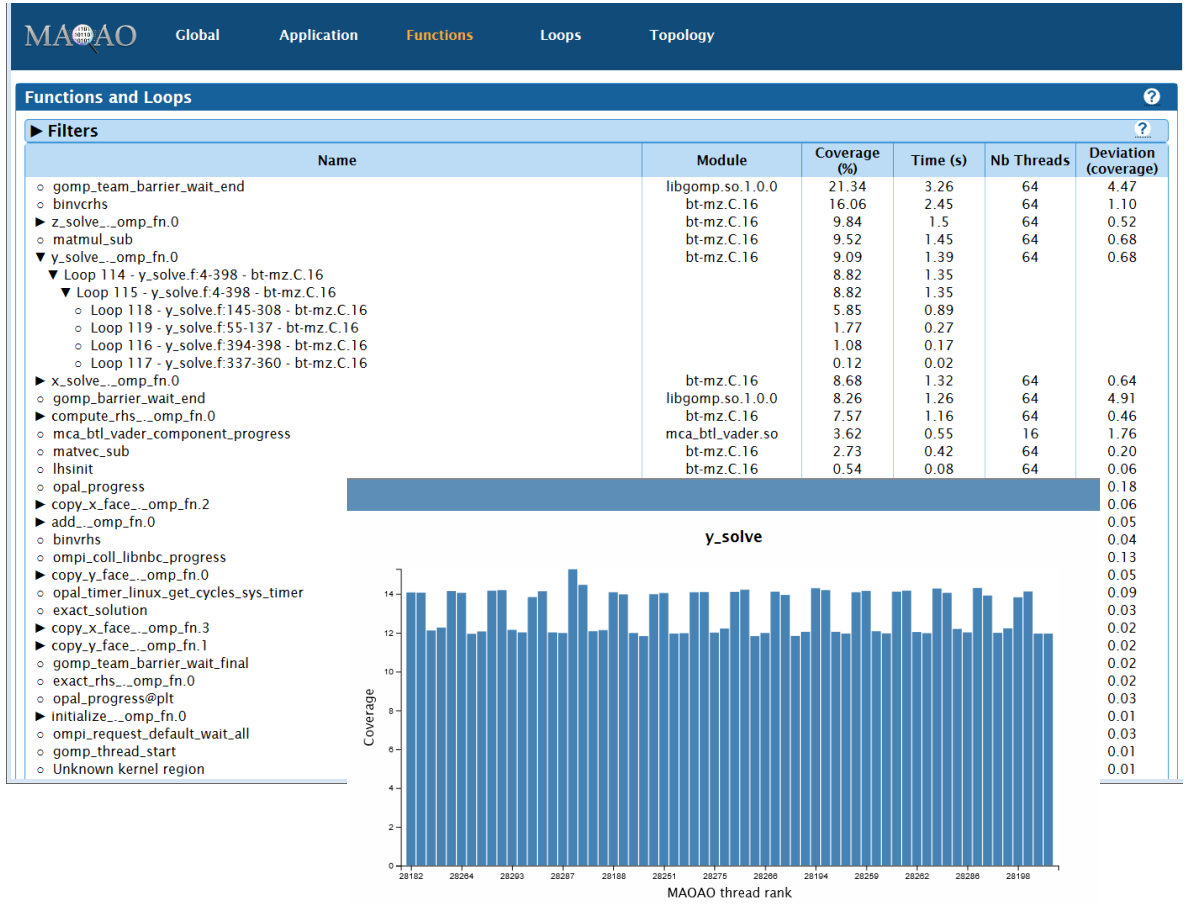
- Application
  - Main executable
- Parallelization
  - Threads
  - OpenMP
  - MPI
- System libraries
  - I/O operations
  - String operations
  - Memory management functions
- External libraries
  - Specialised libraries such as libm / libmkl
  - Application code in external libraries



# Functions Profiling

Identifying hotspots
- Exclusive coverage
- Load balancing across threads
- Loops nests by functions



# Loops Profiling Summary

Identifying loop hotspots

- Vectorisation information
- Potential speedup by optimisation
  - No scalar integer: Removing address computations
  - FP Vectorised: Vectorising floating-point computations
  - Fully Vectorised: Vectorising floating-point computations and memory accesses
  - Perfect Load Balancing: Optimal balance across all threads

MAQAO Global Application Functions Loops Topology

Show Full Profile | Open Expert Summary

**Loops Index**

73 loops have been discarded from the report because their coverage is lower than the threshold set by *object_coverage_threshold* (0.01%). It represents about 0% of the application. To include them, change the value of *object_coverage_threshold* in the experiment directory configuration file, then rerun the command with the additionnal parameter *--force-static-analysis*

▶ Filters

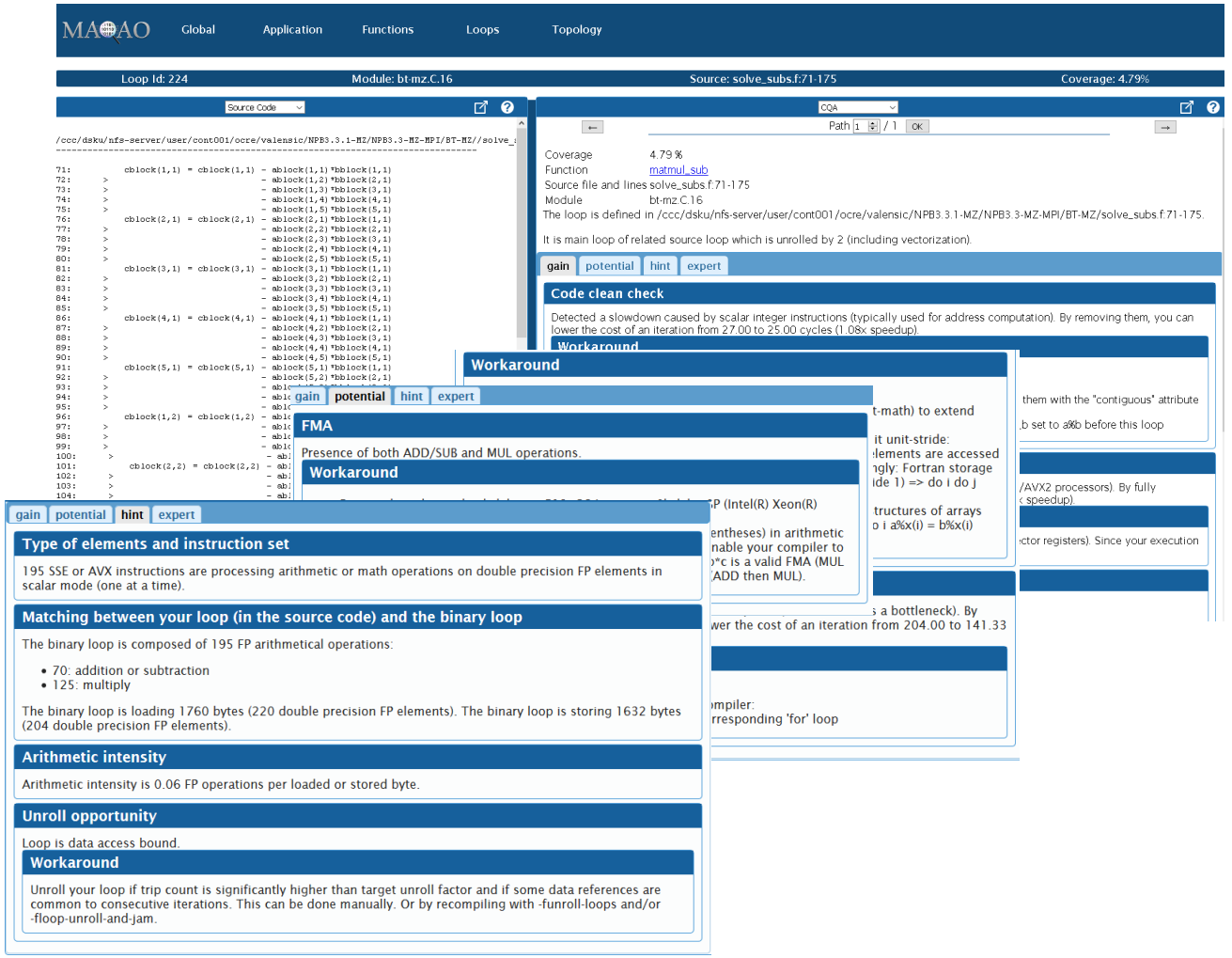
☑Coverage (%) ☑Level ☑Time (s) ☑Vectorization Ratio (%) ☑Speedup If No Scalar Integer ☑Speedup If FP Vectorized ☑Speedup If Fully Vectorized ☑Speedup If Perfect Load Balancing Select none

| Loop id | Source Location | Source Function | Coverage (%) | Level | Time (s) | Vectorization Ratio (%) | Speedup If No Scalar Integer | Speedup If FP Vectorized | Speedup If Fully Vectorized | Speedup If Perfect Load Balancing |
|---|---|---|---|---|---|---|---|---|---|---|
| 179 | bt-mz_C.8 - x_solve.f:146-309 | x_solve_._omp_fn.0 | 7.67 | Innermost | 1.29 | 5.02 | 1.04 | 1 | 2.06 | 1.22 |
| 207 | bt-mz_C.8 - z_solve.f:146-309 | z_solve_._omp_fn.0 | 7.67 | Innermost | 1.29 | 5.31 | 1.02 | 1 | 2.06 | 1.15 |
| 185 | bt-mz_C.8 - y_solve.f:145-308 | y_solve_._omp_fn.0 | 7.35 | Innermost | 1.24 | 5.17 | 1.03 | 1 | 2.06 | 1.22 |
| 208 | bt-mz_C.8 - z_solve.f:55-137 | z_solve_._omp_fn.0 | 3.48 | Innermost | 0.59 | 7.09 | 1 | 1.13 | 2.26 | 1.17 |
| 180 | bt-mz_C.8 - x_solve.f:57-139 | x_solve_._omp_fn.0 | 3.09 | Innermost | 0.52 | 7.04 | 1 | 1.11 | 2.23 | 1.25 |
| 186 | bt-mz_C.8 - y_solve.f:55-137 | y_solve_._omp_fn.0 | 3.06 | Innermost | 0.52 | 7.09 | 1 | 1.11 | 2.23 | 1.21 |
| 156 | bt-mz_C.8 - rhs.f:40-50 | compute_rhs_._omp_fn.0 | 2.41 | Innermost | 0.41 | 0 | 1 | 2 | 2 | 1.15 |
| 133 | bt-mz_C.8 - rhs.f:4-349 | compute_rhs_._omp_fn.0 | 1.84 | Innermost | 0.31 | 0 | 1 | 1.65 | 3.41 | 1.29 |
| 150 | bt-mz_C.8 - rhs.f:4-132 | compute_rhs_._omp_fn.0 | 1.77 | Innermost | 0.3 | 0 | 1 | 1.71 | 3.68 | 1.27 |
| 142 | bt-mz_C.8 - rhs.f:4-238 | compute_rhs_._omp_fn.0 | 1.76 | Innermost | 0.3 | 0 | 1 | 1.65 | 3.41 | 1.27 |
| 204 | bt-mz_C.8 - z_solve.f:415-421 | z_solve_._omp_fn.0 | 1.7 | Innermost | 0.29 | 0 | 1 | 1 | 2.83 | 1.17 |

# Loop Analysis Reports

High level reports

- Reference to the source code
- Bottleneck description
- Hints for improving performance
- Reports categorized by probability that applying hints will yield predicted gain
  - Gain: Good probability
  - Potential gain: Average probability
  - Hints: Lower probability



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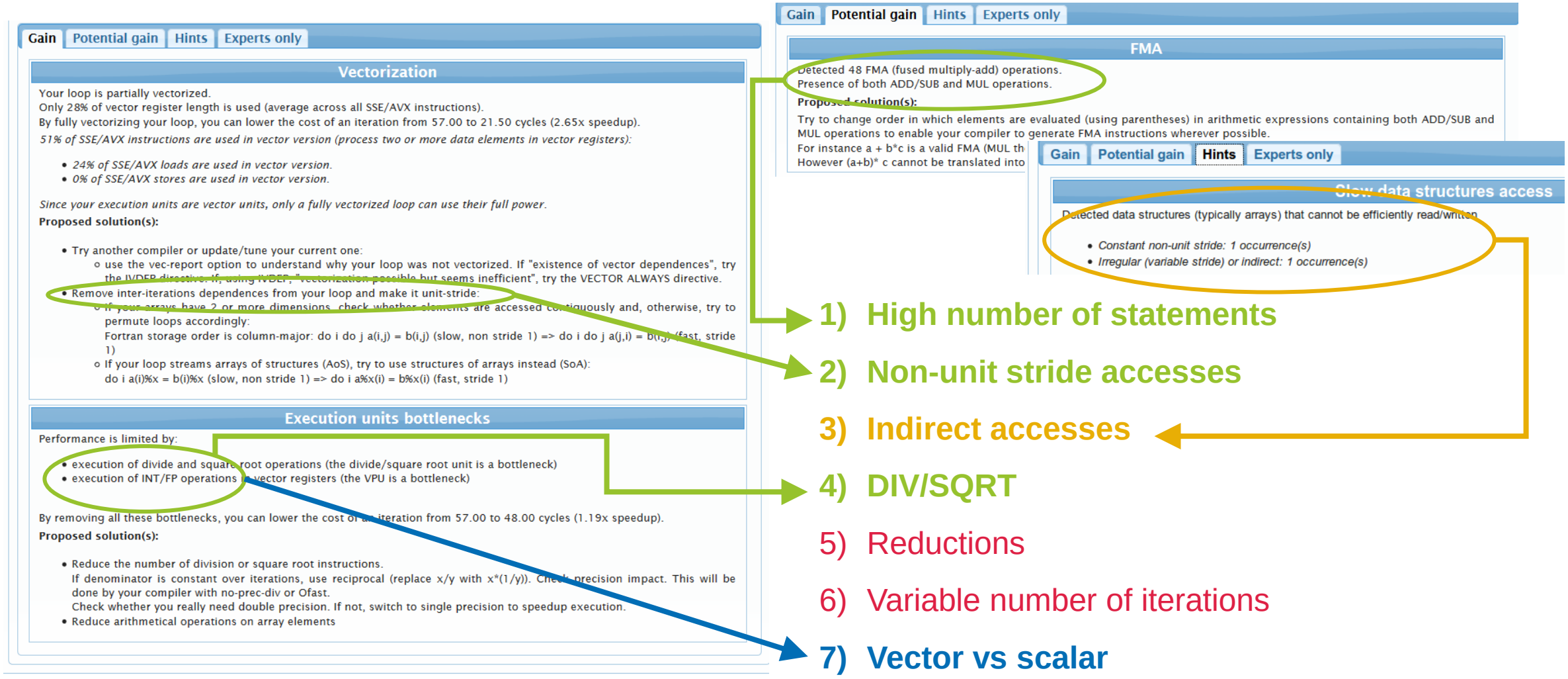
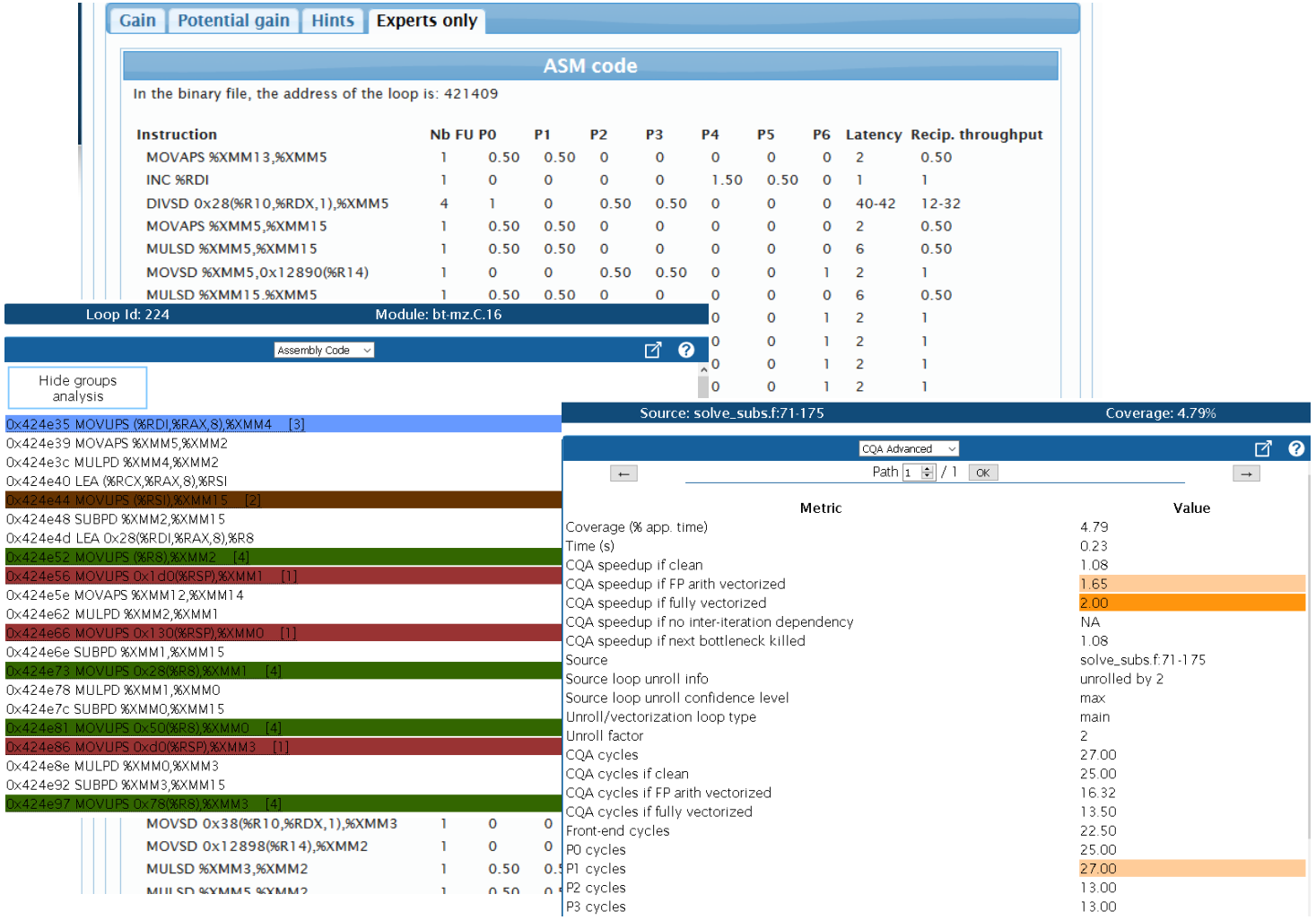


# Loop Analysis Reports – Expert View

Low level reports for performance experts
- Assembly-level
- Instructions cycles costs
- Instructions dispatch predictions
- Memory access analysis

Assembly code
- Highlights groups of instructions accessing the same memory addresses

CQA internal metrics



# MAQAO ONE View Thread/Process View

Software Topology
- List of nodes
- Processes by node
- Thread by process

View by thread
- Function profile at the thread or process level

MAQAO Global Application Functions Loops Topology

**Software Topology**

| ID | Processes | Threads | Time(s) |
|---|---|---|---|
| ▼ Node c251-109.wrangler.tacc.utexas.edu | 8 | 32 | 5.34 |
| ▼ Process 145897 | | 4 | 5.34 |
| ○ Thread 145897 | | | 5.34 |
| ○ Thread 145933 | | | 5.32 |
| ○ Thread 145952 | | | 5.32 |
| ○ Thread 145969 | | | 5.3 |
| ▶ Process 145899 | | 4 | 5.34 |
| ▶ Process 145901 | | 4 | 5.34 |
| ▶ Process 145903 | | 4 | 5.34 |
| ▶ Process 145898 | | 4 | 5.34 |
| ▶ Process 145900 | | 4 | 5.34 |
| ▶ Process 145895 | | 4 | 5.34 |
| ▶ Process 145896 | | 4 | 5.34 |
| ▶ Node c251-110.wrangler.tacc.utexas.edu | 8 | 32 | 5.36 |
| ○ AVERAGE | | | 5.36 |

MAQAO Global

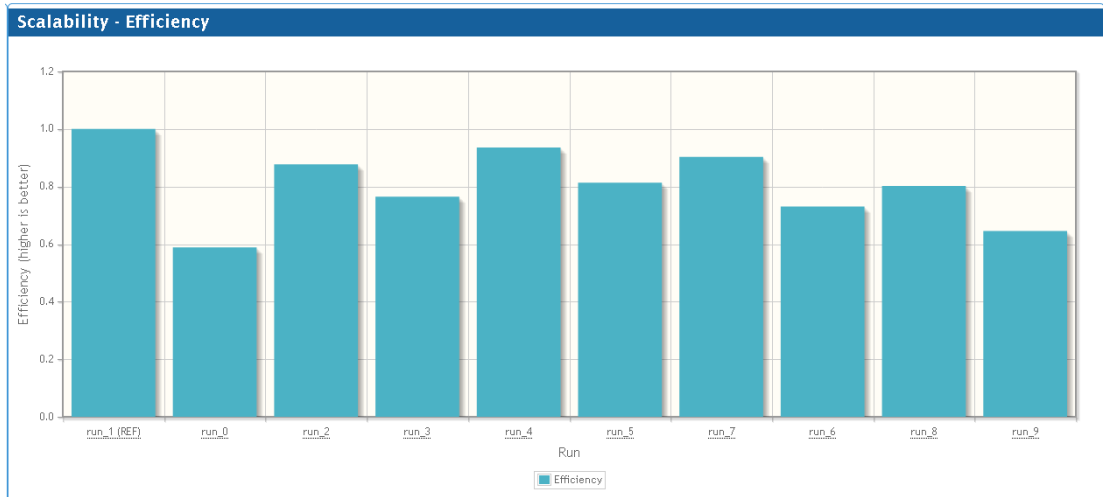
**Profiling node c251-109.wrangler.tacc.utexas.edu - process 145897 - thread 145897**

| Name | Module | Coverage (%) | Time (s) |
|---|---|---|---|
| ○ binvcrhs | bt-mz_B.16 | 24.34 | 1.3 |
| ○ _INTERNAL_25_____src_kmp_barrier_cpp_fa608613::__kmp_hyper_barrier_gather(barrier_type, kmp_info*, int, int, void (*)(void*, void*), void*) | libiomp5.so | 17.6 | 0.94 |
| ▶ matmul_sub | bt-mz_B.16 | 12.73 | 0.68 |
| ▶ y_solve | bt-mz_B.16 | 7.87 | 0.42 |
| ▶ compute_rhs | bt-mz_B.16 | 7.49 | 0.4 |
| ▶ x_solve | bt-mz_B.16 | 7.12 | 0.38 |
| ▶ z_solve | bt-mz_B.16 | 6.74 | 0.36 |

# MAQAO ONE View Scalability Reports

Goal: Provide a view of the application scalability

- Profiles with different numbers of threads/processes
- Displays efficiency metrics for application




▼ Detailed Efficiency

| Run | Number of observed threads | Efficiency (ideal is 1) |
|---|---|---|
| run_1 (REF) | 2 | 1 |
| run_0 | 96 | 0.59 |
| run_2 | 3 | 0.88 |
| run_3 | 5 | 0.77 |
| run_4 | 8 | 0.94 |
| run_5 | 9 | 0.81 |
| run_7 | 9 | 0.9 |
| run_6 | 16 | 0.73 |
| run_8 | 16 | 0.8 |
| run_9 | 32 | 0.65 |

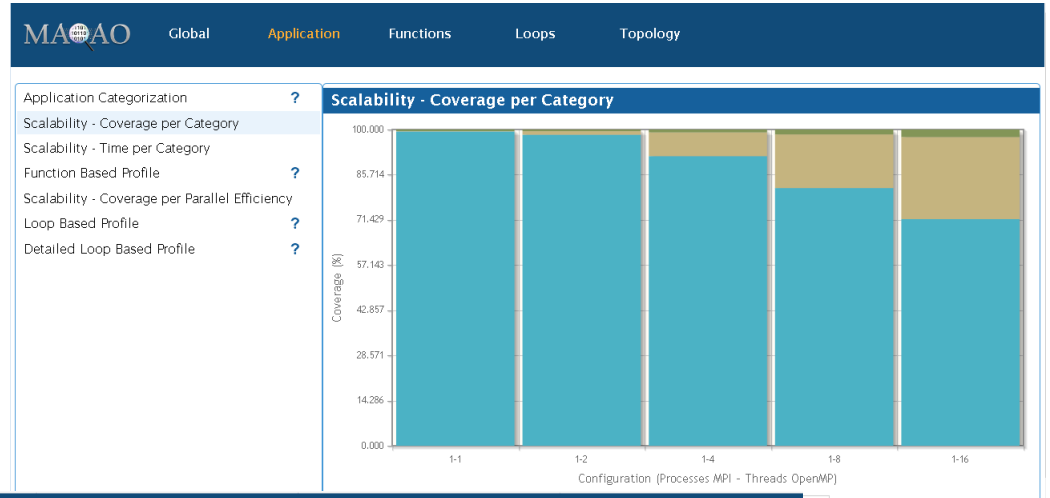
# MAQAO ONE View Scalability Reports – Application View

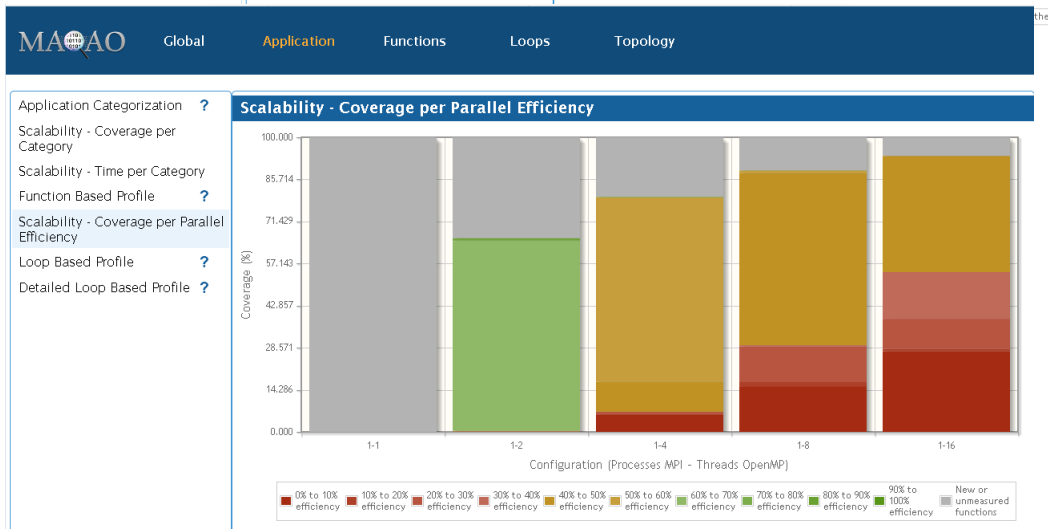
Coverage per category

- Comparison of categories for each run

Coverage per parallel efficiency

- $Efficiency = \frac{T_{sequential}}{T_{parallel} * N_{threads}}$
  - Distinguishing functions only represented in parallel or sequential
- Displays efficiency by coverage



# MAQAO ONE View Scalability Reports – Functions and Loops Views

Displays metrics for each function/loop

- Efficiency
- Potential speedup if efficiency=1

MAQAO Global Application Functions Loops Topology

**Functions and Loops**

▶ Filters

☑(1-1) Efficiency ☐(1-1) Potential Speed-Up (%) ☑(1-2) Efficiency ☑(1-2) Potential Speed-Up (%) ☑(1-4) Efficiency ☑(1-4) Potential Speed-Up (%) ☑(1-8) Efficiency ☑(1-8) Potential Speed-Up (%) ☑(1-16) Efficiency ☑(1-16) Potential Speed-Up (%) ☐Select none

| Name | Module | Coverage (%) | Time (s) | Nb Threads | Deviation (coverage) | (1-1) Efficiency | (1-2) Efficiency | (1-2) Potential Speed-Up (%) | (1-4) Efficiency | (1-4) Potential Speed-Up (%) | (1-8) Efficiency | (1-8) Potential Speed-Up (%) | (1-16) Efficiency | (1-16) Potential Speed-Up (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| o _INTERNAL_25_____src_kmp_barrier_cpp_ac7c2c73::__kmp_hyper_barrier_release(barrier_type, kmp_info*, int, int, int, void*) | libiomp5.so | 24.02 | 15.38 | 16 | 18.62 | | 1 | 0 | 0.04 | 5.49 | 0.01 | 14.35 | 0.01 | 23 |
| o binvcrhs | bt-mz.C.1 | 20.71 | 13.27 | 16 | 6.22 | 1 | 0.7 | 6.14 | 0.55 | 10.2 | 0.45 | 11.58 | 0.41 | 11.43 |
| ▶ compute_rhs | bt-mz.C.1 | 10.76 | 6.9 | 16 | 2.45 | 1 | 0.63 | 2.68 | 0.42 | 5.39 | 0.26 | 8.47 | 0.25 | 7.57 |
| | | | | | | | | 2.91 | 0.57 | 4.44 | 0.44 | 5.75 | 0.41 | 5.45 |
| | | | | | | | | 2.69 | 0.55 | 4.24 | 0.42 | 5.43 | 0.37 | 5.61 |
| | | | | | | | | 2.48 | 0.55 | 3.73 | 0.46 | 4.09 | 0.41 | 4.18 |
| | | | | | | | | 2.06 | 0.54 | 3.56 | 0.45 | 3.92 | 0.39 | 4.11 |
| | | | | | | | | 0.91 | 0.57 | 1.31 | 0.45 | 1.62 | 0.41 | 1.59 |
| | | | | | | | | 0.12 | 0.44 | 0.22 | 0.25 | 0.41 | 0.09 | 1.17 |
| | | | | | | | | 0 | 0.45 | 0.08 | 0.17 | 0.23 | 0.06 | 0.62 |
| | | | | | | | | 0.1 | 0.57 | 0.27 | 0.53 | 0.24 | 0.42 | 0.31 |
| | | | | | | | | 0.11 | 0.56 | 0.2 | 0.51 | 0.19 | 0.44 | 0.21 |
| | | | | | | | | | 1 | 0 | 0.07 | 0.24 | 0.04 | 0.34 |
| | | | | | | | | 0.06 | 0.27 | 0.15 | 0.14 | 0.27 | 0.11 | 0.3 |
| | | | | | | | | 0.01 | 0.02 | 0.07 | 0.01 | 0.18 | 0 | 0.28 |
| | | | | | | | | 0.03 | 0.28 | 0.16 | 0.17 | 0.22 | 0.17 | 0.18 |
| | | | | | | | | 0.07 | 0.48 | 0.1 | 0.31 | 0.16 | 0.37 | 0.1 |
| | | | | | | | | 0.07 | 0.21 | 0.16 | 0.14 | 0.2 | 0.13 | 0.18 |
| | | | | | | | | 0 | 0.04 | 0.04 | 0.01 | 0.13 | 0.01 | 0.19 |
| | | | | | | | | | | | 1 | 0 | 0.01 | 0.16 |
| | | | | | | | | 0.03 | 0.64 | 0.03 | 0.39 | 0.07 | 0.43 | 0.05 |
| | | | | | | | | 0.01 | 0.08 | 0.02 | 0.06 | 0.02 | 0.01 | 0.12 |
| | | | | | | | | 0 | 0.06 | 0.02 | 0.02 | 0.06 | 0.01 | 0.07 |
| | | | | | | | | 0 | 0.06 | 0.02 | 0.02 | 0.05 | 0.01 | 0.07 |
| | | | | | | | | 0 | | | 0.06 | 0.02 | 0.02 | 0.06 |
| | | | | | | | | 0 | 0.12 | 0.01 | 0.03 | 0.04 | 0.02 | 0.06 |
| | | | | | | | | 0 | 0.25 | 0.01 | 0.06 | 0.02 | 0.01 | 0.07 |
| | | | | | | | | 0 | 0.25 | 0.01 | 0.06 | 0.02 | 0.02 | 0.06 |
| | | | | | | | | 0 | 0.06 | 0.02 | 0.04 | 0.03 | 0.02 | 0.06 |

MAQAO Global Application Functions Loops Topology

**Loops Index**

☐Coverage (%) ☐Time (s) ☐Vectorization Ratio (%) ☐Speedup If Clean ☐Speedup If FP Vectorized ☐Speedup If Fully Vectorized ☐(1-1) Efficiency ☐(1-1) Potential Speed-Up (%) ☑(1-2) Efficiency ☑(1-2) Potential Speed-Up (%) ☑(1-4) Efficiency ☑(1-4) Potential Speed-Up (%) ☑(1-8) Efficiency ☑(1-8) Potential Speed-Up (%) ☑(1-16) Efficiency ☑(1-16) Potential Speed-Up (%) ☐Select none

| Loop id | Source Lines | Source File | Source Function | (1-2) Efficiency | (1-2) Potential Speed-Up (%) | (1-4) Efficiency | (1-4) Potential Speed-Up (%) | (1-8) Efficiency | (1-8) Potential Speed-Up (%) | (1-16) Efficiency | (1-16) Potential Speed-Up (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Loop 215 | 71-175 | bt-mz.C.1 :solve_subs.f | matmul_sub | 0.71 | 1.51 | 0.56 | 2.49 | 0.45 | 2.99 | 0.41 | 2.96 |
| Loop 224 | 146-308 | bt-mz.C.1 :z_solve.f | z_solve | 0.7 | 1.34 | 0.57 | 2.07 | 0.43 | 2.73 | 0.4 | 2.62 |
| Loop 192 | 146-308 | bt-mz.C.1 :x_solve.f | x_solve | 0.66 | 1.22 | 0.52 | 1.91 | 0.45 | 1.92 | 0.39 | 2.04 |
| Loop 199 | 145-307 | bt-mz.C.1 :y_solve.f | y_solve | 0.69 | 1.09 | 0.54 | 1.81 | 0.45 | 1.99 | 0.39 | 2.11 |
| Loop 169 | 40-50 | bt-mz.C.1 :rhs.f | compute_rhs | 0.52 | 0.49 | 0.23 | 1.59 | 0.11 | 2.95 | 0.11 | 2.3 |
| Loop 221 | 55-137 | bt-mz.C.1 :z_solve.f | z_solve | 0.66 | 0.92 | 0.54 | 1.32 | 0.43 | 1.56 | 0.37 | 1.66 |
| Loop 189 | 57-139 | bt-mz.C.1 :x_solve.f | x_solve | 0.71 | 0.7 | 0.57 | 1.14 | 0.47 | 1.28 | 0.43 | 1.26 |
| Loop 196 | 55-137 | bt-mz.C.1 :y_solve.f | y_solve | 0.73 | 0.52 | 0.55 | 1.01 | 0.44 | 1.18 | 0.41 | 1.12 |
| Loop 165 | 65-67 | bt-mz.C.1 :rhs.f | compute_rhs | 0.45 | 0.55 | 0.24 | 1.22 | 0.11 | 2.31 | 0.13 | 1.64 |
| Loop 227 | 26-28 | bt-mz.C.1 :add.f | add#omp_loop_0 | 0.64 | 0.12 | 0.44 | 0.22 | 0.25 | 0.4 | 0.09 | 1.14 |
| Loop 220 | 415-423 | bt-mz.C.1 :z_solve.f | z_solve | 0.67 | 0.34 | 0.49 | 0.62 | 0.34 | 0.87 | 0.3 | 0.88 |
| Loop 188 | 395-399 | bt-mz.C.1 :x_solve.f | x_solve | 0.62 | 0.5 | 0.56 | 0.57 | 0.44 | 0.69 | 0.41 | 0.65 |
| Loop 216 | 71-175 | bt-mz.C.1 :solve_subs.f | matmul_sub | 0.77 | 0.23 | 0.62 | 0.41 | 0.48 | 0.54 | 0.4 | 0.62 |
| Loop | 304-349 | bt-mz.C.1 :rhs.f | compute_rhs | 0.71 | 0.29 | 0.65 | 0.34 | 0.46 | 0.56 | 0.44 | 0.5 |

# Thank you for your attention !

# Questions ?