

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?

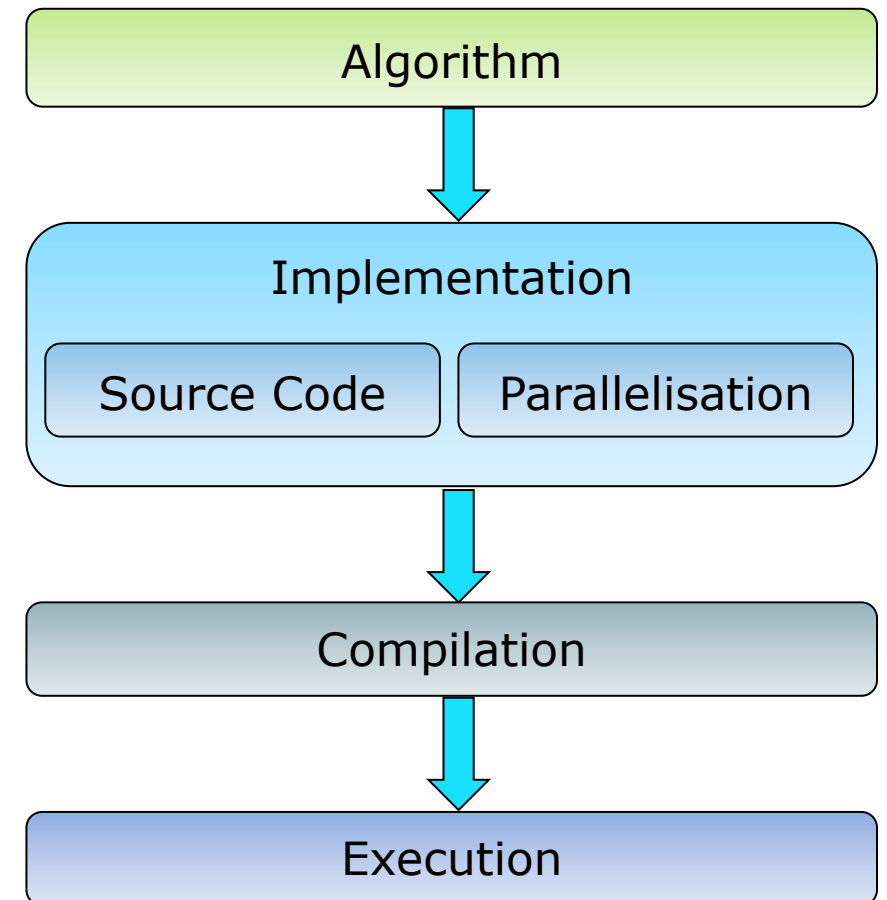
- Algorithm, implementation, runtime or hardware?
- Data access or computation?

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

```

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

```

1) High number of statements

2) Non-unit stride accesses

3) Indirect accesses

4) DIV/SQRT

5) Reductions

6) Variable number of iterations

2) Non-unit stride accesses

- 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 transforms (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:

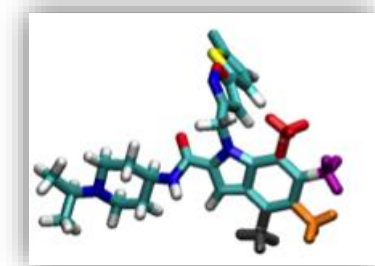
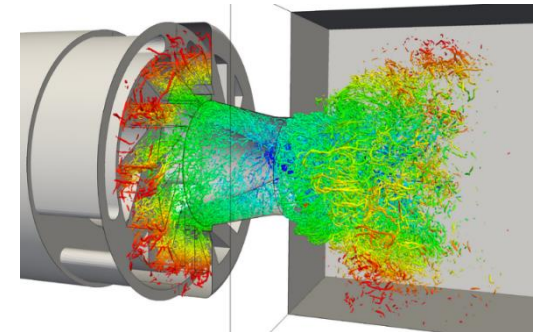
- **Modular tool** offering complementary views
- Support for **Intel x86-64** and **Aarch64** (beta version)
 - Work in progress on GPU support
- LGPL3 Open Source software
- Developed at UVSQ since 2004
- Binary release available as a **static executable**



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 Ibmamar, 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
 - Δ 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

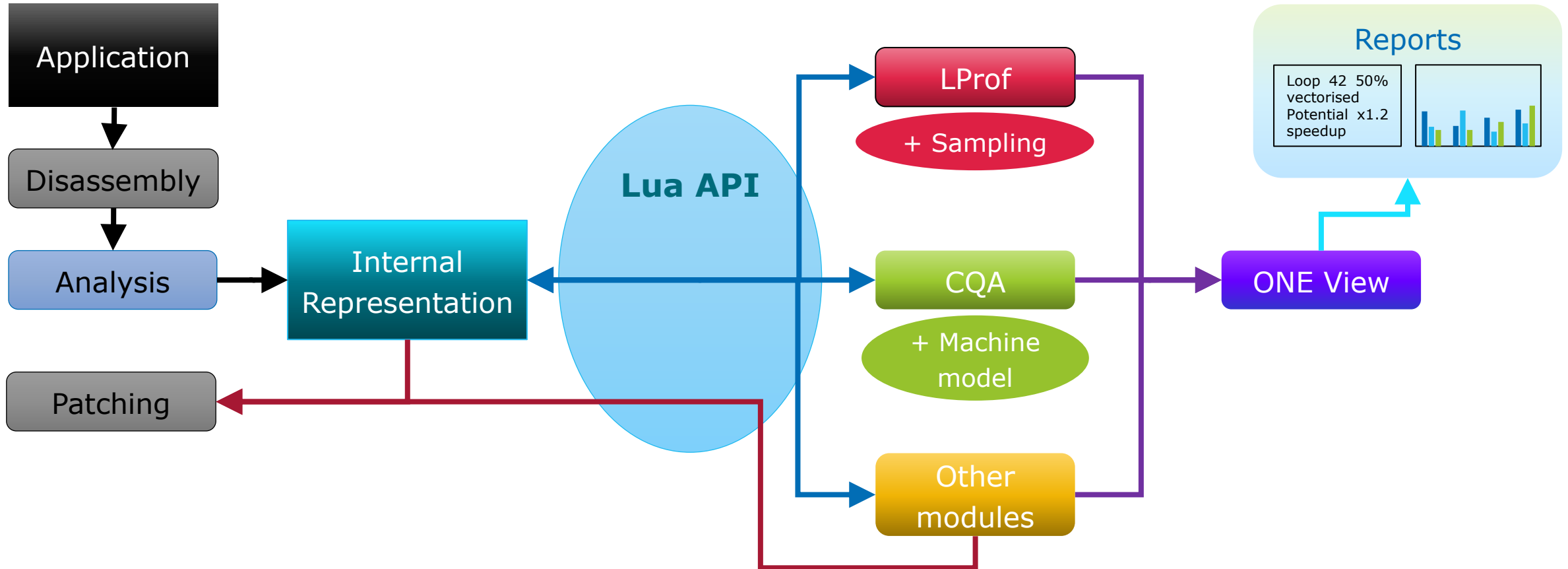
Static analysis

- 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
- Automates 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

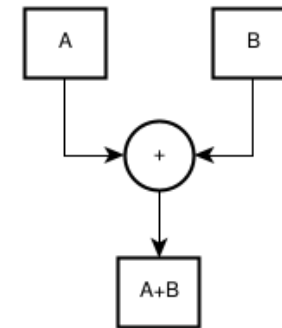
SIMD/Vectorization/Data Parallelism

- 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

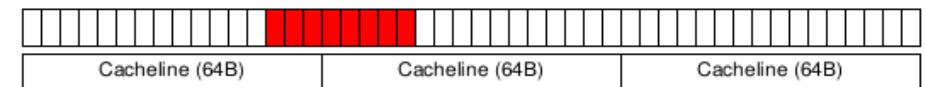
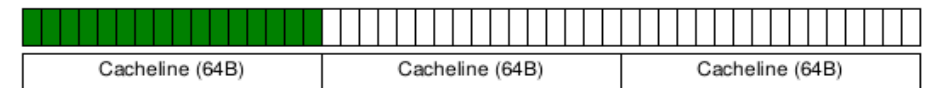
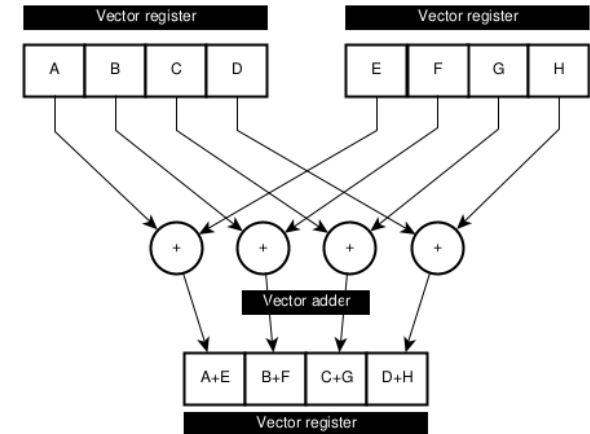
Memory and caches

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

Scalar addition



Vector addition



Crossing cacheline boundary

MAQAO LProf: Lightweight Profiler

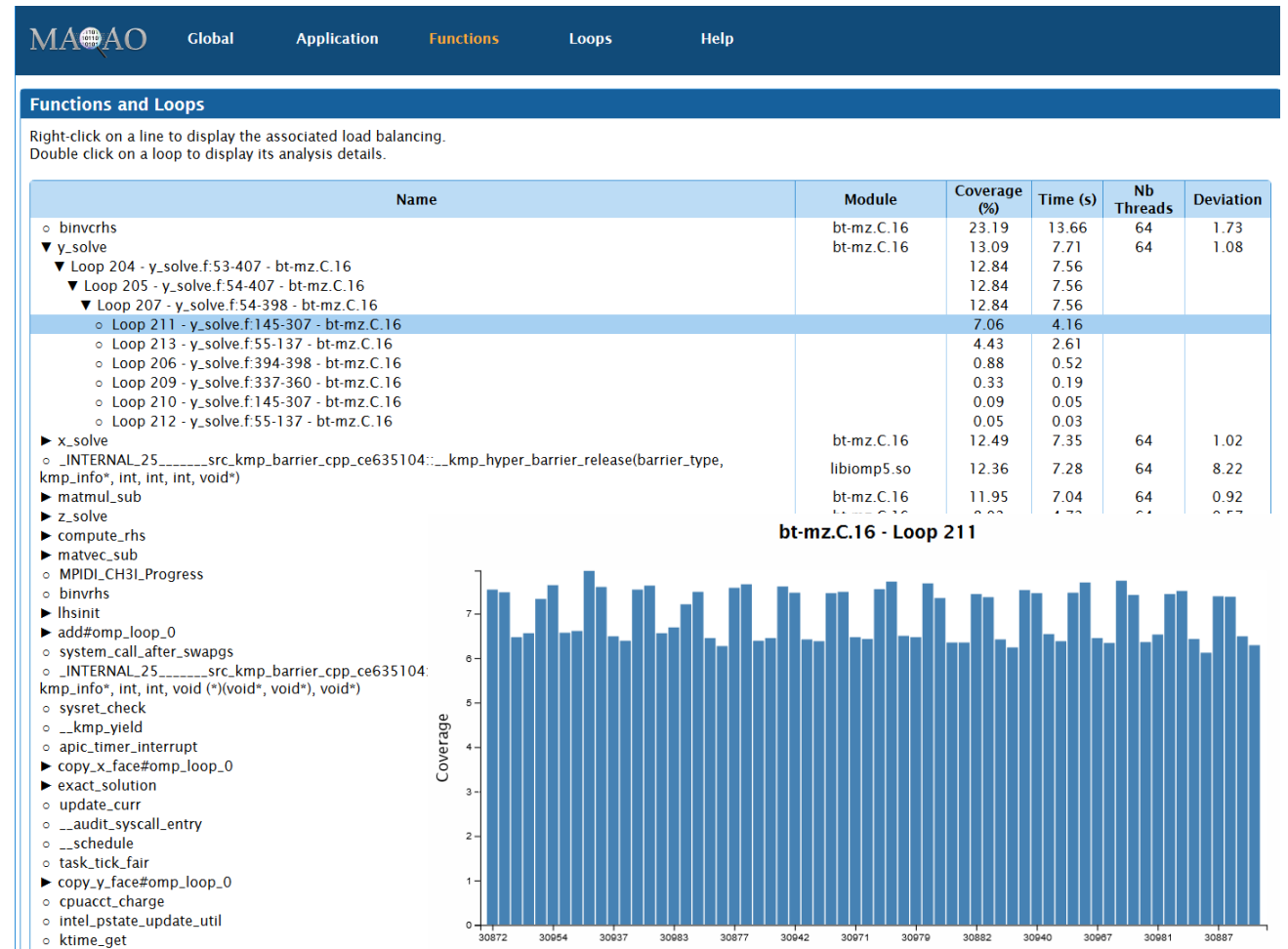
Goal: Lightweight localization of application hotspots

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

Static Reports

▼ **CQA Report**

The loop is defined in /tmp/NPB3.3.1-MZ/NPB3.3-MZ-MPI/BT-MZ/z_solve.f:415-423

▼ **Path 1**

2% of peak computational performance is used (0.77 out of 32.00 FLOP per cycle (GFLOPS @ 1GHz))

gain potential hint expert

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 65.00 to 57.00 cycles (1.14x speedup).

Workaround

- Try to reorganize arrays of structures to structures of arrays
- Consider to permute loops (see vectorization gain report)
- 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

Your loop is not vectorized. 8 data elements could be processed at once in vector registers. By vectorizing your loop, you can lower the cost of an iteration from 65.00 to 8.12 cycles (8.00x speedup).

Workaround

- Try another compiler or update/tune your current one:
 - use the vec-report option to understand why your loop was not vectorized. If "existence of vector dependences", try the IVDEP directive. If, using IVDEP, "vectorization possible but seems inefficient", try the VECTOR ALWAYS directive.
- 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)

Execution units bottlenecks

Found no such bottlenecks but see expert reports for more complex bottlenecks.

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

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

Same instruction – Same cost



**Process up to
8X data**

“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

```

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
  
```

6) Variable number of iterations

2) Non-unit stride accesses

1) High number of statements

7) Vector vs scalar

4) DIV/SQRT

3) Indirect accesses

5) Reductions

2) Non-unit stride accesses

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

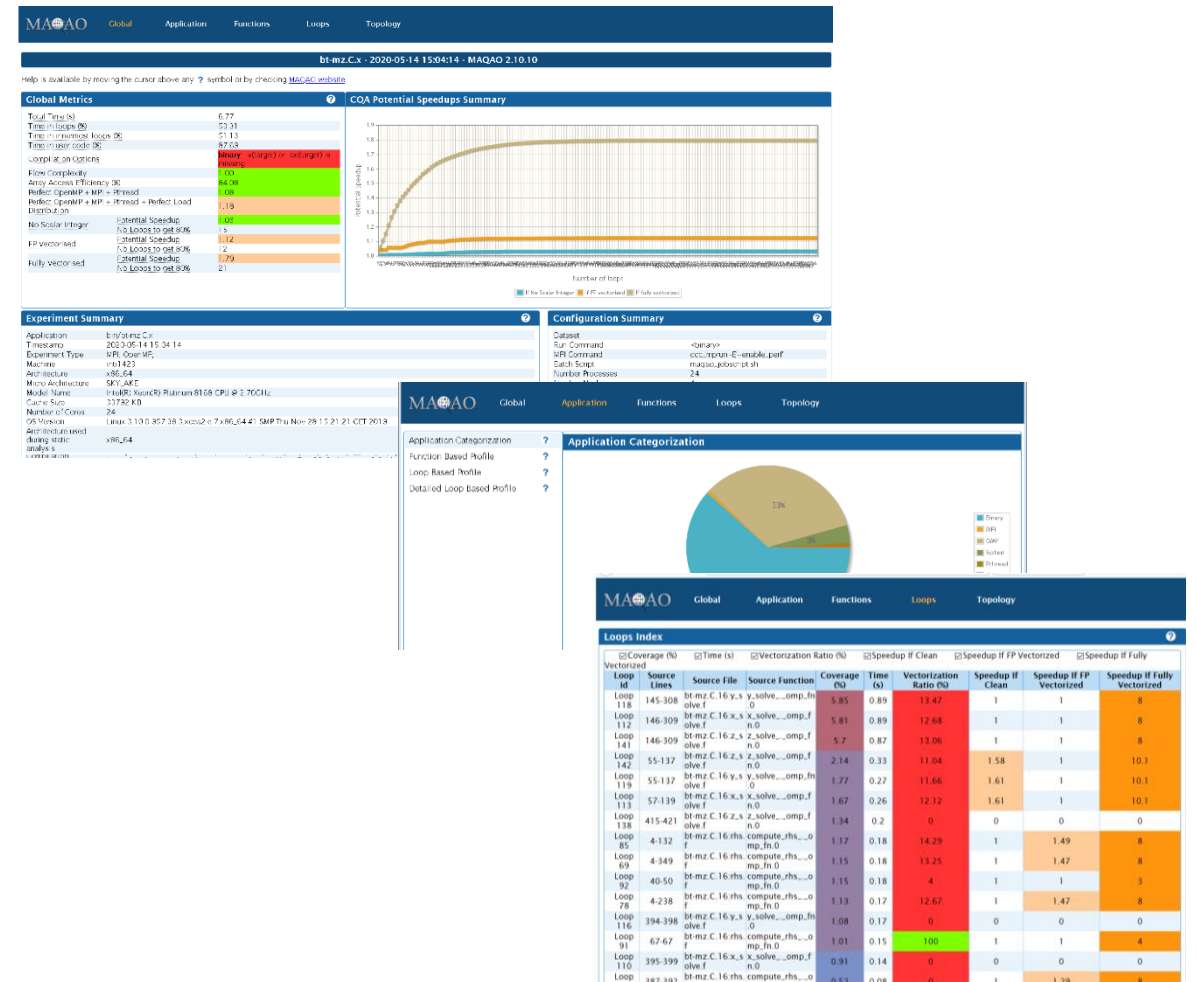
- Invoke multiple MAQAO modules
- Generate **aggregated performance views**
- Generate a report in HTML format

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

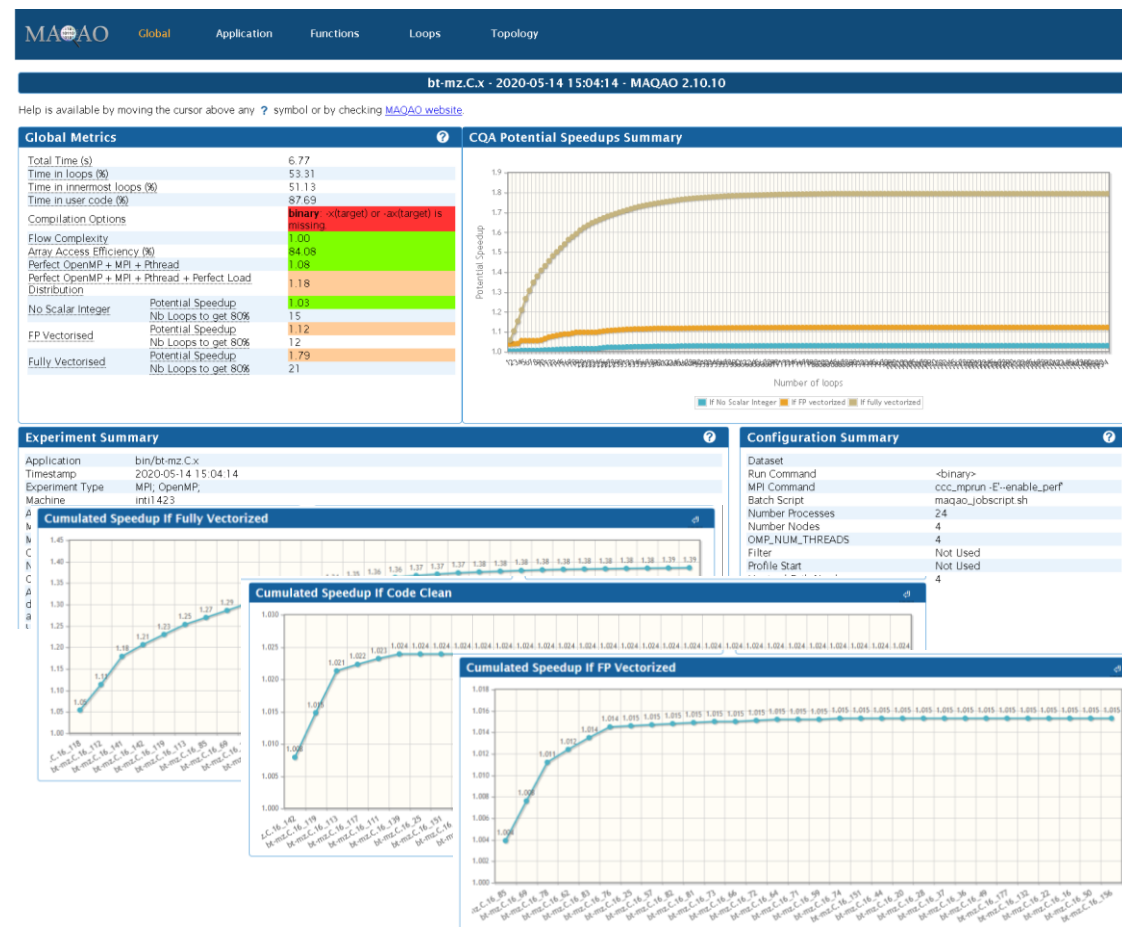
Global summary

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

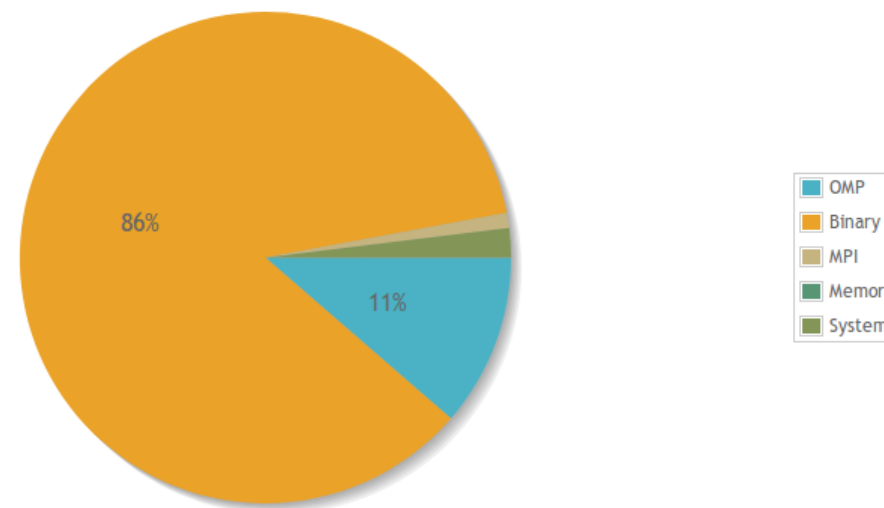


Time Categorisation

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

Application Categorization



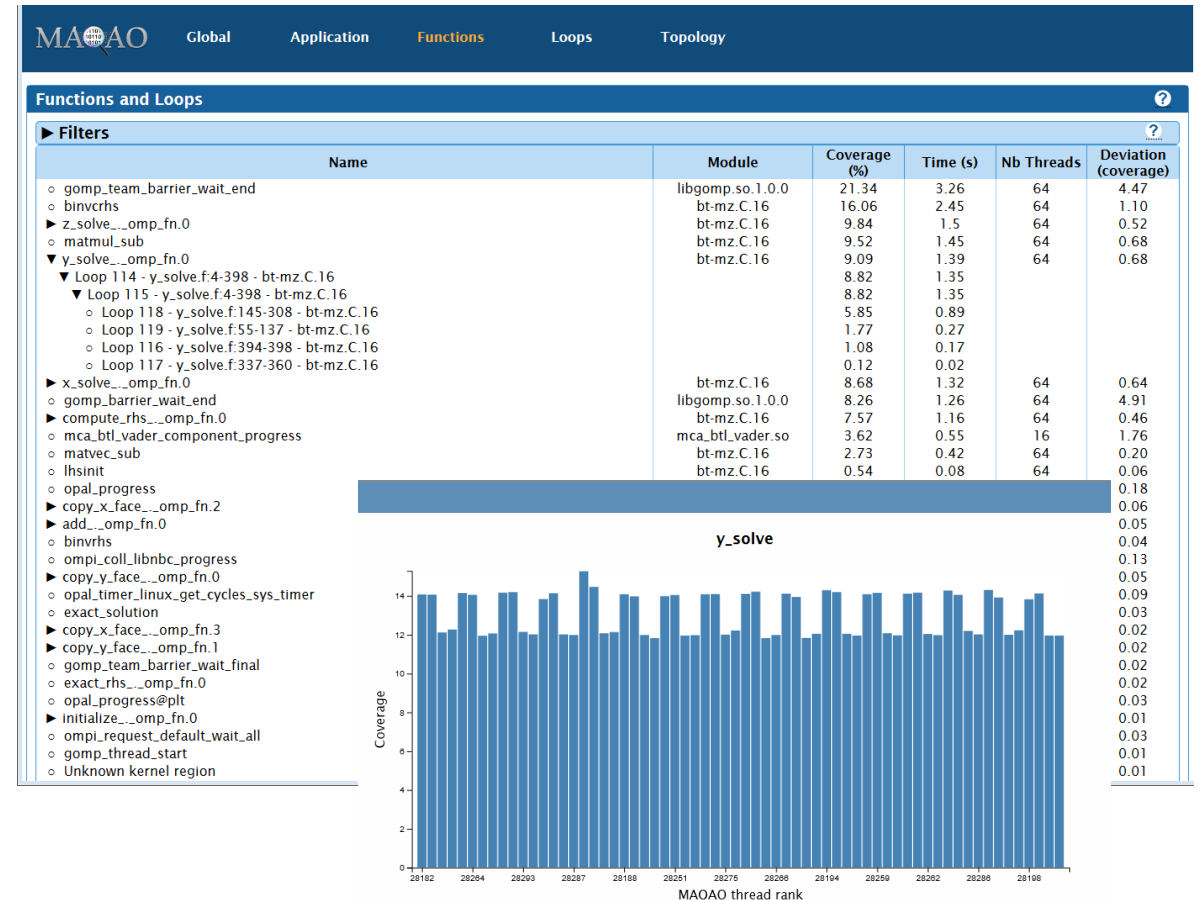
Functions Profiling

Identifying hotspots

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

- ▼ matmul_sub
 - Loop 230 - solve_subs.f:71-175 - bt-mz.C.16
 - Loop 231 - solve_subs.f:71-175 - bt-mz.C.16
- ▼ z_solve
 - ▼ Loop 232 - z_solve.f:53-423 - bt-mz.C.16
 - ▼ Loop 233 - z_solve.f:54-423 - bt-mz.C.16
 - ▼ Loop 236 - z_solve.f:54-423 - bt-mz.C.16
 - Loop 239 - z_solve.f:146-308 - bt-mz.C.16
 - Loop 235 - z_solve.f:55-137 - bt-mz.C.16
 - Loop 234 - z_solve.f:415-423 - bt-mz.C.16

Single
 Outermost
 Inbetween
 Inbetween
 Innermost



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

MAAO 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 additional 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

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_e.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_e.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:115-121	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

The screenshot displays the MAOAO Loop Analysis Report interface. The top navigation bar includes 'Global', 'Application', 'Functions', 'Loops', and 'Topology'. The main header shows 'Loop Id: 224', 'Module: bt-mz.C.16', 'Source: solve_subs.f:71-175', and 'Coverage: 4.79%'.

The source code is shown in a window with the following content:

```

71:  >  cblock(1,1) = cblock(1,1) - ablock(1,1) %bblock(1,1)
72:  >  - ablock(1,2) %bblock(2,1)
73:  >  - ablock(1,3) %bblock(3,1)
74:  >  - ablock(1,4) %bblock(4,1)
75:  >  - ablock(1,5) %bblock(5,1)
76:  >  cblock(2,1) = cblock(2,1) - ablock(2,1) %bblock(1,1)
77:  >  - ablock(2,2) %bblock(2,1)
78:  >  - ablock(2,3) %bblock(3,1)
79:  >  - ablock(2,4) %bblock(4,1)
80:  >  - ablock(2,5) %bblock(5,1)
81:  >  cblock(3,1) = cblock(3,1) - ablock(3,1) %bblock(1,1)
82:  >  - ablock(3,2) %bblock(2,1)
83:  >  - ablock(3,3) %bblock(3,1)
84:  >  - ablock(3,4) %bblock(4,1)
85:  >  - ablock(3,5) %bblock(5,1)
86:  >  cblock(4,1) = cblock(4,1) - ablock(4,1) %bblock(1,1)
87:  >  - ablock(4,2) %bblock(2,1)
88:  >  - ablock(4,3) %bblock(3,1)
89:  >  - ablock(4,4) %bblock(4,1)
90:  >  - ablock(4,5) %bblock(5,1)
91:  >  cblock(5,1) = cblock(5,1) - ablock(5,1) %bblock(1,1)
92:  >  - ablock(5,2) %bblock(2,1)
93:  >  - ablock(5,3) %bblock(3,1)
94:  >  - ablock(5,4) %bblock(4,1)
95:  >  - ablock(5,5) %bblock(5,1)
96:  >  cblock(1,2) = cblock(1,2) - ablock(1,2) %bblock(1,1)
97:  >  - ablock(1,3) %bblock(2,1)
98:  >  - ablock(1,4) %bblock(3,1)
99:  >  - ablock(1,5) %bblock(4,1)
100: >  - ablock(1,6) %bblock(5,1)
101: >  cblock(2,2) = cblock(2,2) - ablock(2,2) %bblock(1,1)
102: >  - ablock(2,3) %bblock(2,1)
103: >  - ablock(2,4) %bblock(3,1)
104: >  - ablock(2,5) %bblock(4,1)
  
```

The analysis results are displayed in a sidebar on the right, categorized by hint type:

- Gain:** Coverage 4.79%, Function `matmul_sub`, Source file and lines `solve_subs.f:71-175`, Module `bt-mz.C.16`. The loop is defined in `/ccc/dsku/nfs-server/user/cont001/ocre/valensic/NPB3.3.1-MZ/NPB3.3-MZ-MPI/BT-MZ/solve_subs.f:71-175`. It is the main loop of related source loop which is unrolled by 2 (including vectorization).
- Potential:** 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 27.00 to 25.00 cycles (1.08x speedup).
- Hint:** FMA: Presence of both ADD/SUB and MUL operations. Workaround: Use parentheses in arithmetic expressions to enable your compiler to use a valid FMA (MUL then ADD then MUL).
- Expert:** Workaround: Unroll your loop if trip count is significantly higher than target unroll factor and if some data references are common to consecutive iterations. This can be done manually. Or by recompiling with `-funroll-loops` and/or `-floop-unroll-and-jam`.

Additional text in the expert section mentions: 'them with the "contiguous" attribute', 'b set to `ab` before this loop', 'it unit-stride: elements are accessed regularly: Fortran storage order 1) => do i do j', and 'structures of arrays of I a%x(i) = b%x(i)'. It also notes: 'is a bottleneck. By power the cost of an iteration from 204.00 to 141.33' and 'compiler: responding "for" loop'.

Application to Motivating Example

The image shows a screenshot of a compiler optimization report with several sections and annotations. A list of seven optimization goals is on the right, with arrows pointing to specific parts of the report.

Vectorization

Your loop is partially vectorized.
Only 28% of vector register length is used (average across all SSE/AVX instructions).
By fully vectorizing your loop, you can lower the cost of an iteration from 57.00 to 21.50 cycles (2.65x speedup).
51% of SSE/AVX instructions are used in vector version (process two or more data elements in vector registers):

- 24% of SSE/AVX loads are used in vector version.
- 0% of SSE/AVX stores are used in vector version.

Since your execution units are vector units, only a fully vectorized loop can use their full power.

Proposed solution(s):

- Try another compiler or update/tune your current one:
 - use the `vec-report` option to understand why your loop was not vectorized. If "existence of vector dependences", try the `IVDEF` directive. If, using `IVDEF`, "vectorization possible but seems inefficient", try the `VECTOR ALWAYS` directive.
- 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(j,i)` (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)

Execution units bottlenecks

Performance is limited by:

- execution of divide and square root operations (the divide/square root unit is a bottleneck)
- execution of INT/FP operations in vector registers (the VPU is a bottleneck)

By removing all these bottlenecks, you can lower the cost of an iteration from 57.00 to 48.00 cycles (1.19x speedup).

Proposed solution(s):

- Reduce the number of division or square root instructions.
If denominator is constant over iterations, use reciprocal (replace `x/y` with `x*(1/y)`). Check precision impact. This will be done by your compiler with `no-prec-div` or `Ofast`.
Check whether you really need double precision. If not, switch to single precision to speedup execution.
- Reduce arithmetical operations on array elements

FMA

Detected 48 FMA (fused multiply-add) operations.
Presence of both ADD/SUB and MUL operations.

Proposed solution(s):

Try to change order in which elements are evaluated (using parentheses) in arithmetic expressions containing both ADD/SUB and MUL operations to enable your compiler to generate FMA instructions wherever possible.
For instance `a + b*c` is a valid FMA (MUL then ADD). However `(a+b)*c` cannot be translated into FMA.

Slow data structures access

Detected data structures (typically arrays) that cannot be efficiently read/written:

- Constant non-unit stride: 1 occurrence(s)
- Irregular (variable stride) or indirect: 1 occurrence(s)

Optimization Goals:

- 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

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

Gain Potential gain Hints Experts only

ASM code

In the binary file, the address of the loop is: 421409

Instruction	Nb	FU	P0	P1	P2	P3	P4	P5	P6	Latency	Recip. throughput
MOVAPS %XMM13,%XMM5	1	0.50	0.50	0	0	0	0	0	0	2	0.50
INC %RDI	1	0	0	0	0	0	1.50	0.50	0	1	1
DIVSD 0x28(%R10,%RDX,1),%XMM5	4	1	0	0.50	0.50	0	0	0	0	40-42	12-32
MOVAPS %XMM5,%XMM15	1	0.50	0.50	0	0	0	0	0	0	2	0.50
MULSD %XMM5,%XMM15	1	0.50	0.50	0	0	0	0	0	0	6	0.50
MOVSD %XMM5,0x12890(%R14)	1	0	0	0.50	0.50	0	0	0	1	2	1
MULSD %XMM15,%XMM5	1	0.50	0.50	0	0	0	0	0	0	6	0.50

Loop Id: 224 Module: bt-mz.C.16

Assembly Code

Hide groups analysis

Source: solve_subs.f:71-175 Coverage: 4.79%

CQA Advanced

Path 1 / 1

Metric	Value
Coverage (% app. time)	4.79
Time (s)	0.23
CQA speedup if clean	1.08
CQA speedup if FP arith vectorized	1.65
CQA speedup if fully vectorized	2.00
CQA speedup if no inter-iteration dependency	NA
CQA speedup if next bottleneck killed	1.08
Source	solve_subs.f:71-175
Source loop unroll info	unrolled by 2
Source loop unroll confidence level	max
Unroll/vectorization loop type	main
Unroll factor	2
CQA cycles	27.00
CQA cycles if clean	25.00
CQA cycles if FP arith vectorized	16.32
CQA cycles if fully vectorized	13.50
Front-end cycles	22.50
P0 cycles	25.00
P1 cycles	27.00
P2 cycles	13.00
P3 cycles	13.00

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

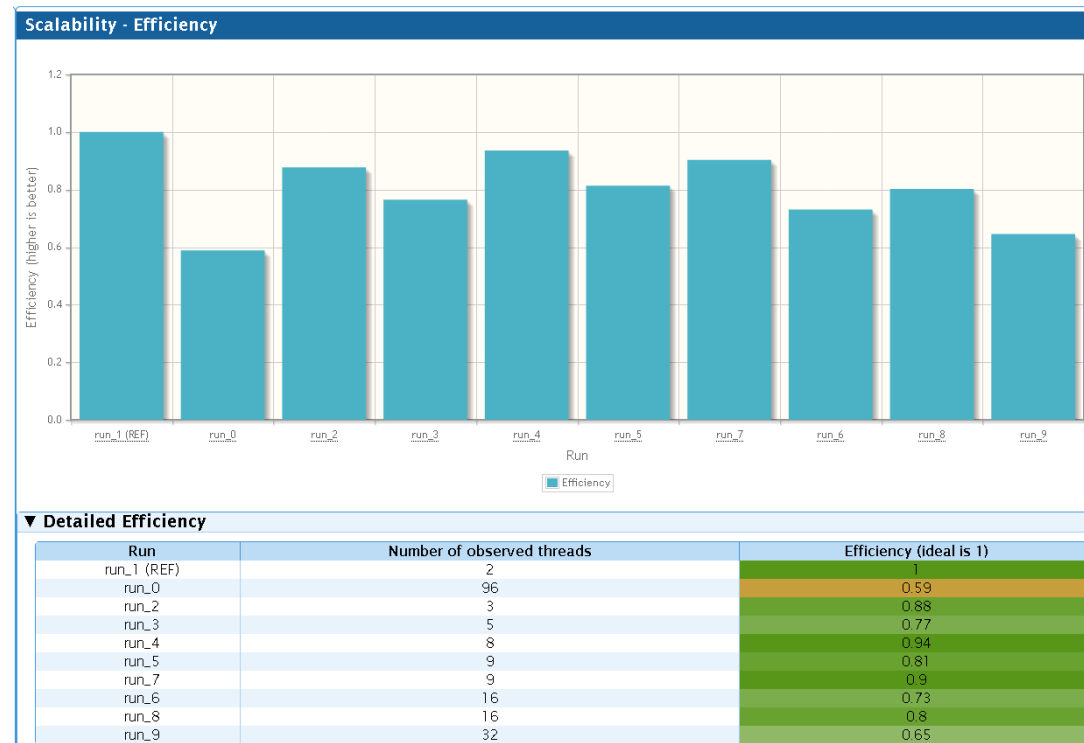
Profiling node c251-109.wrangler.tacc.utexas.edu - process 145897 - thread 145897

Name	Module	Coverage (%)	Time (s)
○ binvcrhs	bt-mz_B.16	24.34	1.3
○ _INTERNAL_25_____src_kmp_barrier_cpp_fa608613::__kmp_hy_per_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



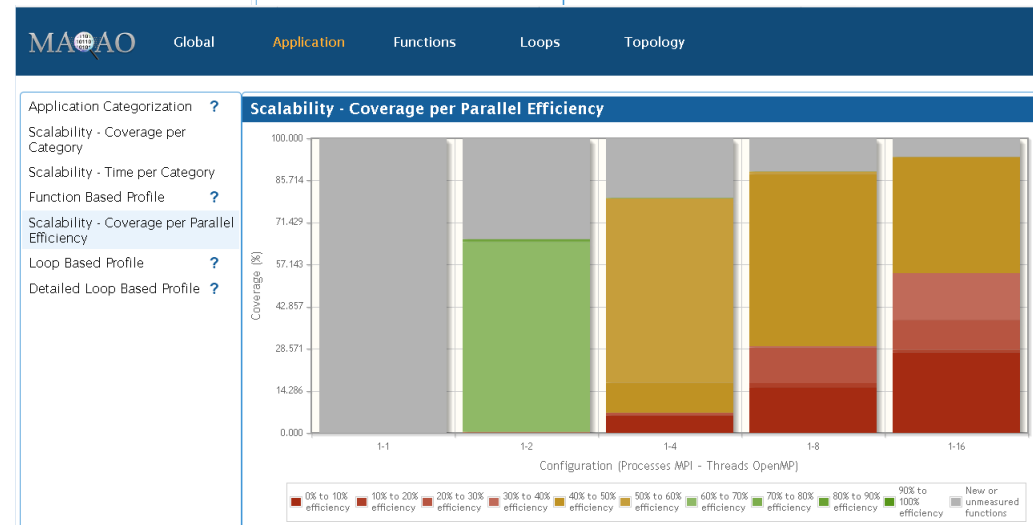
MAQAO ONE View Scalability Reports – Application View

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

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, void*)	libiomp5.so	24.02	15.38	16	18.62		1	0	0.04	5.49	0.01	14.35	0.01	23
o binvrchs	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

Loops Index

Filters: 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_subsf	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_subsf	matmul_sub	0.77	0.23	0.62	0.41	0.48	0.54	0.4	0.62
Loop 171	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 ?