MAQAO
Performance Analysis and Optimization Tool

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arm
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Universität Stuttgart

Performance analysis and optimisation

How much can I optimise my application?

- Can it actually be done?
- What would the effort/gain ratio be?

Where can I gain time?

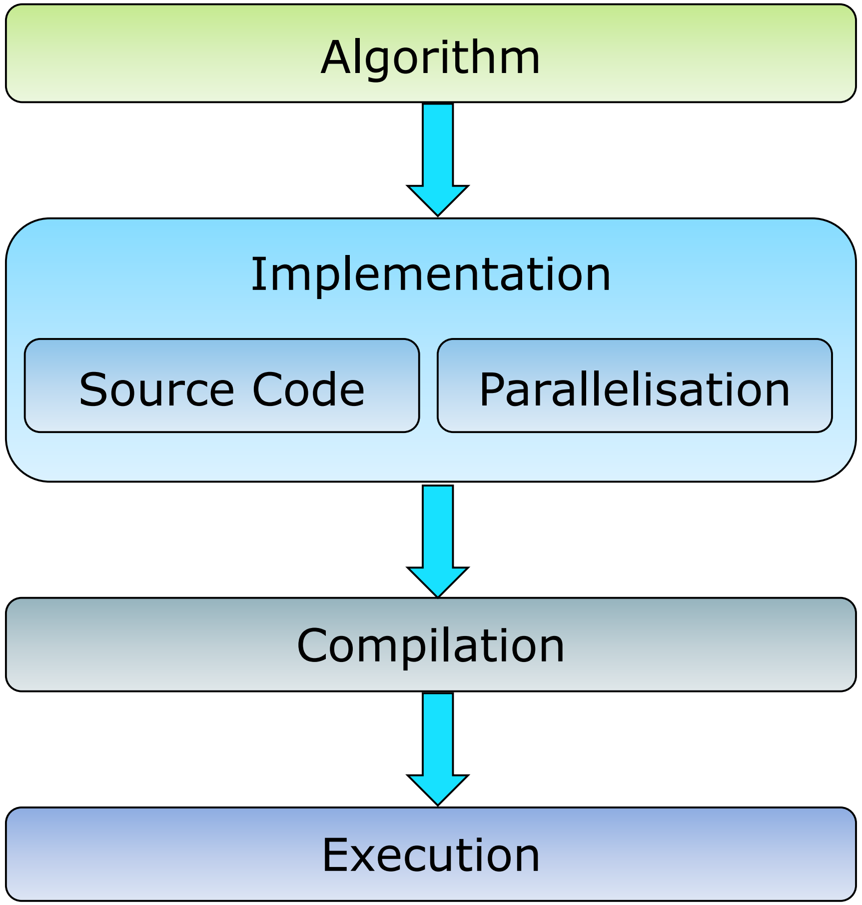
- Where is my application wasting time?

Why is the application spending time there?

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

How can I improve the situation?

- In which step(s) of the design process?
- What additional information do I need?



Algorithm

Implementation

Source Code

Parallelisation

Compilation

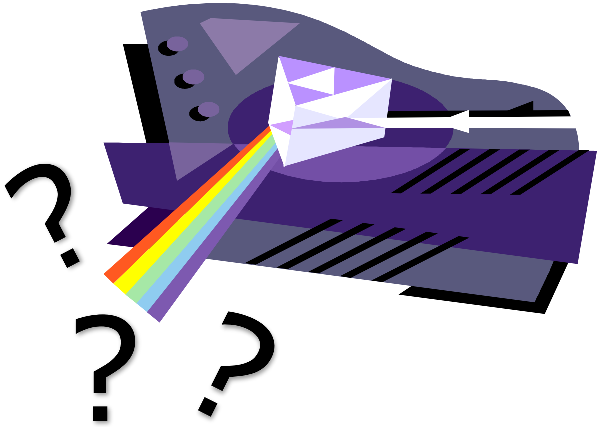
Execution

A multifaceted problem

Pinpointing the performance bottlenecks

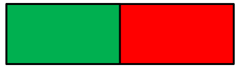
Identifying the dominant issues
- Algorithms, implementation, parallelisation, …

Making the **best use** of the machine features
- Complex multicore and manycore CPUs
- Complex memory hierarchy



Finding the **most rewarding** issues to be fixed
- **40%** total time, expected **10%** speedup
  - ➔ TOTAL IMPACT: **4%** speedup

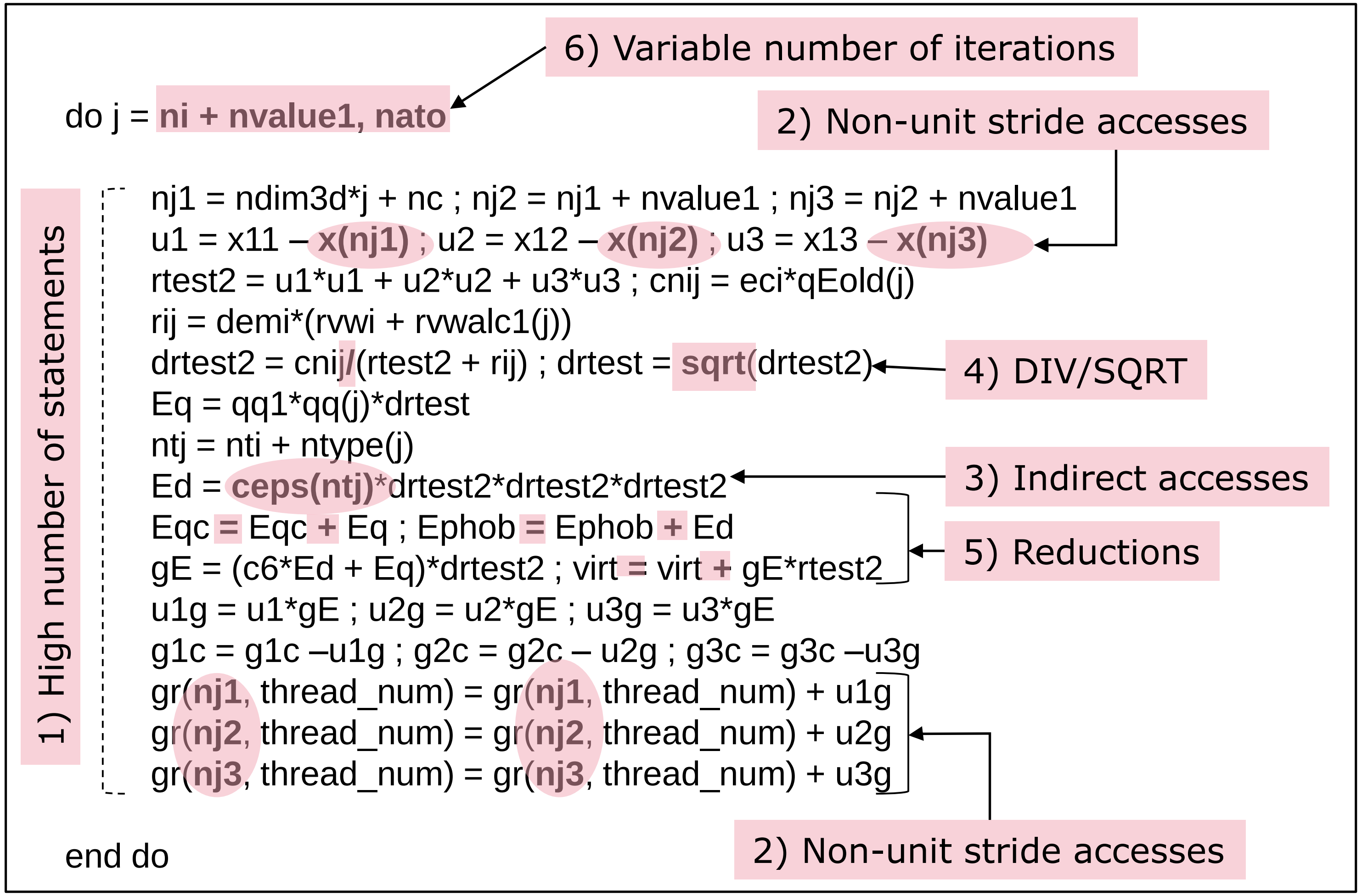
- **20%** total time, expected **50%** speedup
  - ➔ TOTAL IMPACT: **10%** speedup



➔ **Need for dedicated and complementary tools**

Motivating example

Code of a loop representing ~10% walltime



6) Variable number of iterations

2) Non-unit stride accesses

1) High number of statements

```
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
```

4) DIV/SQRT

3) Indirect accesses

5) Reductions

2) Non-unit stride accesses

Source code and associated issues:

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

MAQAO: Modular Assembly Quality Analyzer and Optimizer

Objectives:

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

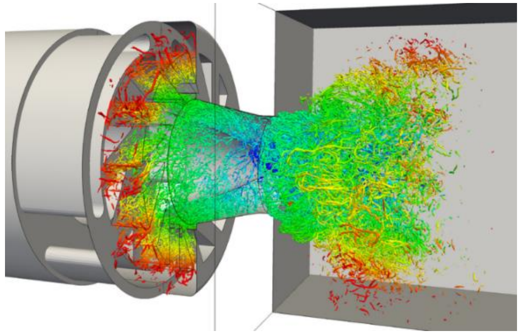
Characteristics:

- **Modular tool** offering complementary views
- Support for **Intel x86-64** and **Xeon Phi**
  - ARM under development
- LGPL3 Open Source software
- Developed at UVSQ since 2004
- Binary release available as **static executable**

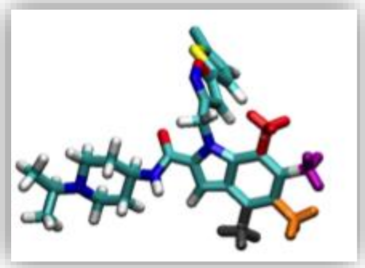
Success stories

MAQAO was used for optimizing industrial and academic HPC applications:

- QMC=CHEM (IRSAMC)
  - Quantum chemistry
  - Speedup: **> 3x**
    - Moved invocation of function with identical parameters out of loop body



- Yales2 (CORIA)
  - Computational fluid dynamics
  - Speedup: **up to 2.8x**
    - Removed double structure indirections
- Polaris (CEA)
  - Molecular dynamics
  - Speedup: **1.5x – 1.7x**
    - Enforced loop vectorisation through compiler directives



- AVBP (CERFACS)
  - Computational fluid dynamics
  - Speedup: **1.08x – 1.17x**
    - Replaced division with multiplication by reciprocal
    - Complete unrolling of loops with small number of iterations

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 Advisor
- INRIA Bordeaux HWLOC

PeXL ISV also contributes to MAQAO:

- Commercial performance optimization expertise
- Training and software development
- www.pexl.eu

Analysis at binary level

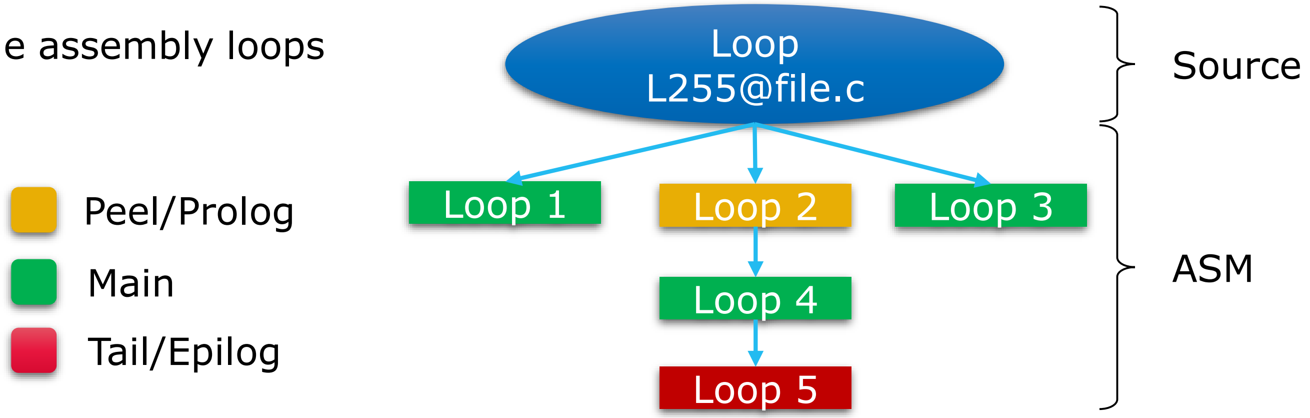
Advantages of binary analysis:

- 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 Analyse 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
  - Affecting unique identifiers to loops



🟨 Peel/Prolog

🟩 Main

🟥 Tail/Epilog

Loop L255@file.c

Loop 1

Loop 2

Loop 3

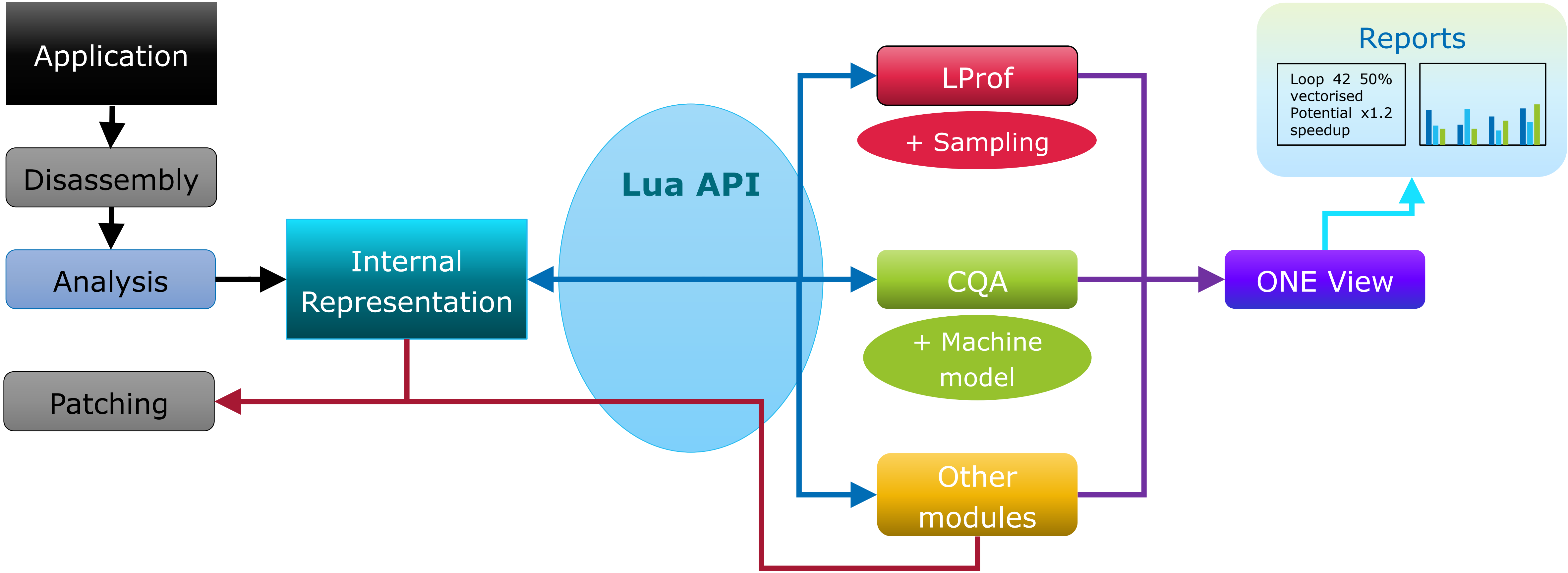
Loop 4

Loop 5

Source

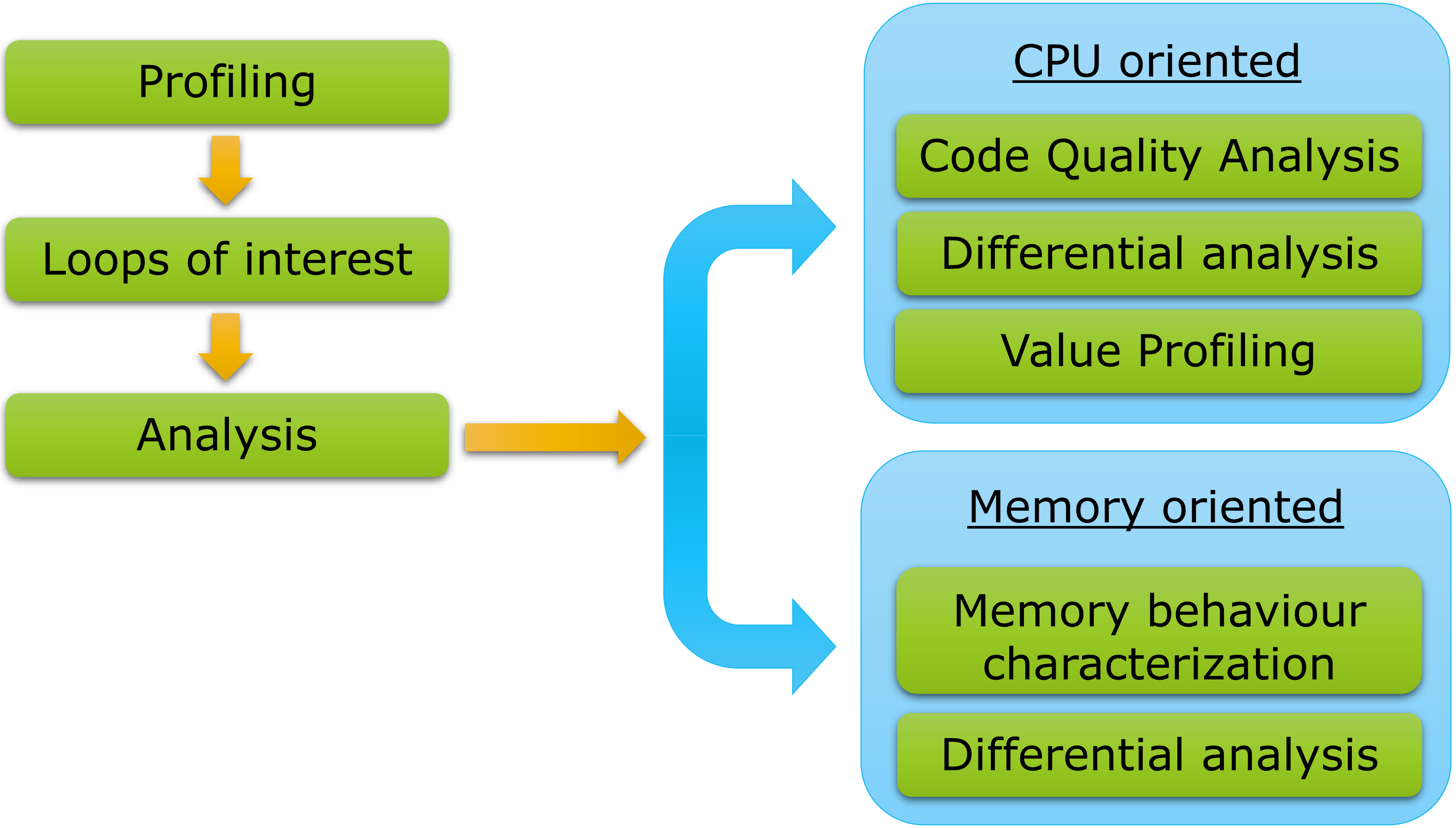
ASM

MAQAO Main structure



MAQAO Methodology

Decision tree



Profiling

Loops of interest

Analysis

CPU oriented

- Code Quality Analysis
- Differential analysis
- Value Profiling

Memory oriented

- Memory behaviour characterization
- Differential analysis

MAQAO LProf: Lightweight Profiler

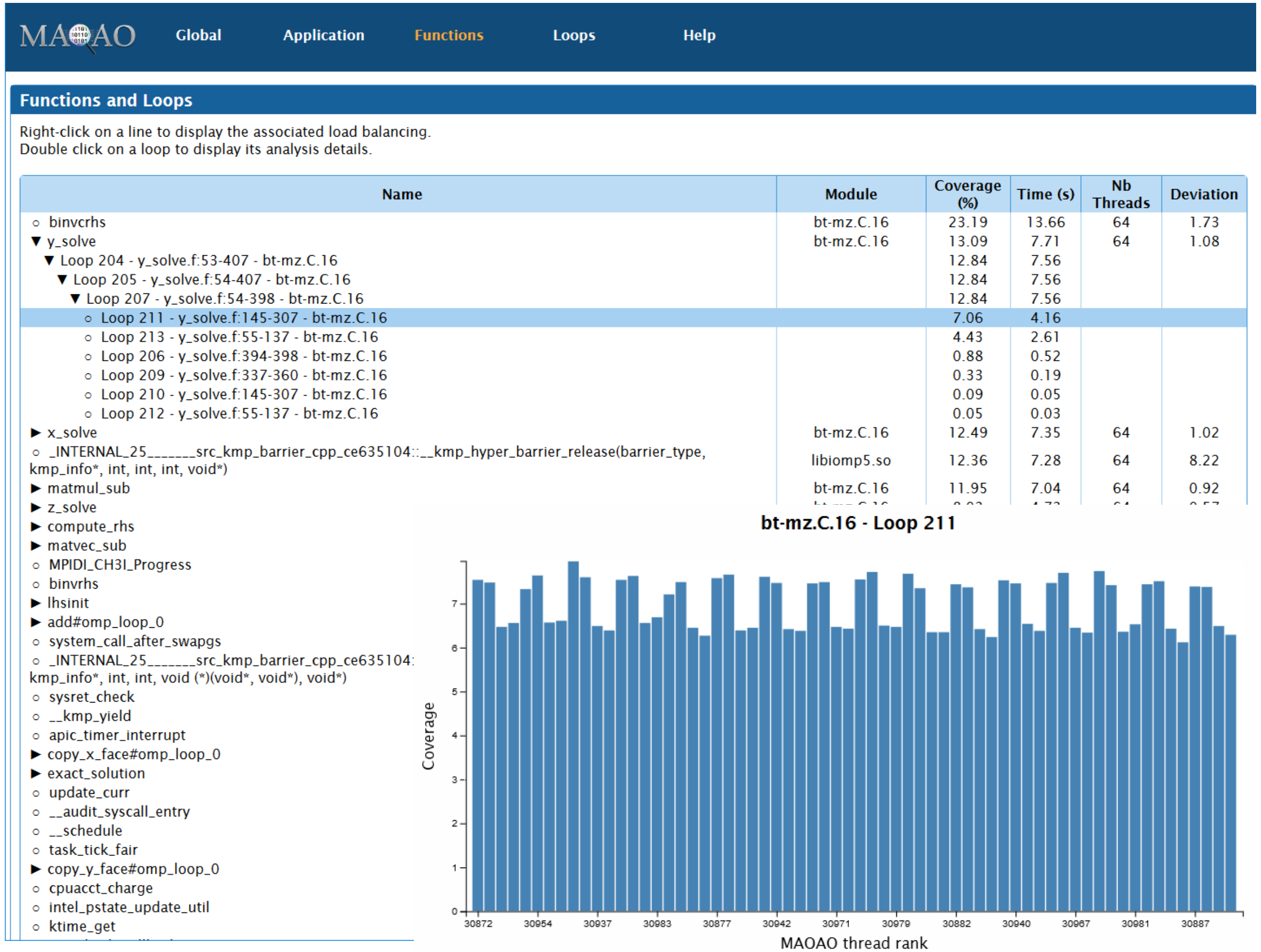
Goal: Lightweight localization of application hotspots

Features:

- **Sampling** based
- Access to hardware counters for additional information
- Results at function and loop granularity

Strengths:

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



Functions and Loops

Right-click on a line to display the associated load balancing.
Double click on a loop to display its analysis details.

Name	Module	Coverage (%)	Time (s)	Nb Threads	Deviation
○ binvcrhs	bt-mz.C.16	23.19	13.66	64	1.73
▼ y_solve	bt-mz.C.16	13.09	7.71	64	1.08
▼ Loop 204 - y_solve.f:53-407 - bt-mz.C.16		12.84	7.56		
▼ Loop 205 - y_solve.f:54-407 - bt-mz.C.16		12.84	7.56		
▼ Loop 207 - y_solve.f:54-398 - bt-mz.C.16		12.84	7.56		
○ Loop 211 - y_solve.f:145-307 - bt-mz.C.16		7.06	4.16		
○ Loop 213 - y_solve.f:55-137 - bt-mz.C.16		4.43	2.61		
○ Loop 206 - y_solve.f:394-398 - bt-mz.C.16		0.88	0.52		
○ Loop 209 - y_solve.f:337-360 - bt-mz.C.16		0.33	0.19		
○ Loop 210 - y_solve.f:145-307 - bt-mz.C.16		0.09	0.05		
○ Loop 212 - y_solve.f:55-137 - bt-mz.C.16		0.05	0.03		
▶ x_solve	bt-mz.C.16	12.49	7.35	64	1.02
○ _INTERNAL_25_______src_kmp_barrier_cpp_ce635104::__kmp_hyper_barrier_release(barrier_type, kmp_info*, int, int, int, void*)	libiomp5.so	12.36	7.28	64	8.22
▶ matmul_sub	bt-mz.C.16	11.95	7.04	64	0.92
▶ z_solve					
▶ compute_rhs					
▶ matvec_sub					
○ MPIDI_CH3I_Progress					
○ binvrhs					
▶ lhsinit					
▶ add#omp_loop_0					
○ system_call_after_swapgs					
○ _INTERNAL_25_______src_kmp_barrier_cpp_ce635104: kmp_info*, int, int, void (*)(void*, void*), void*)					
○ sysret_check					
○ __kmp_yield					
○ apic_timer_interrupt					
▶ copy_x_face#omp_loop_0					
▶ exact_solution					
○ update_curr					
○ __audit_syscall_entry					
○ __schedule					
○ task_tick_fair					
▶ copy_y_face#omp_loop_0					
○ cpuacct_charge					
○ intel_pstate_update_util					
○ ktime_get					

MAQAO CQA: Code Quality Analyzer

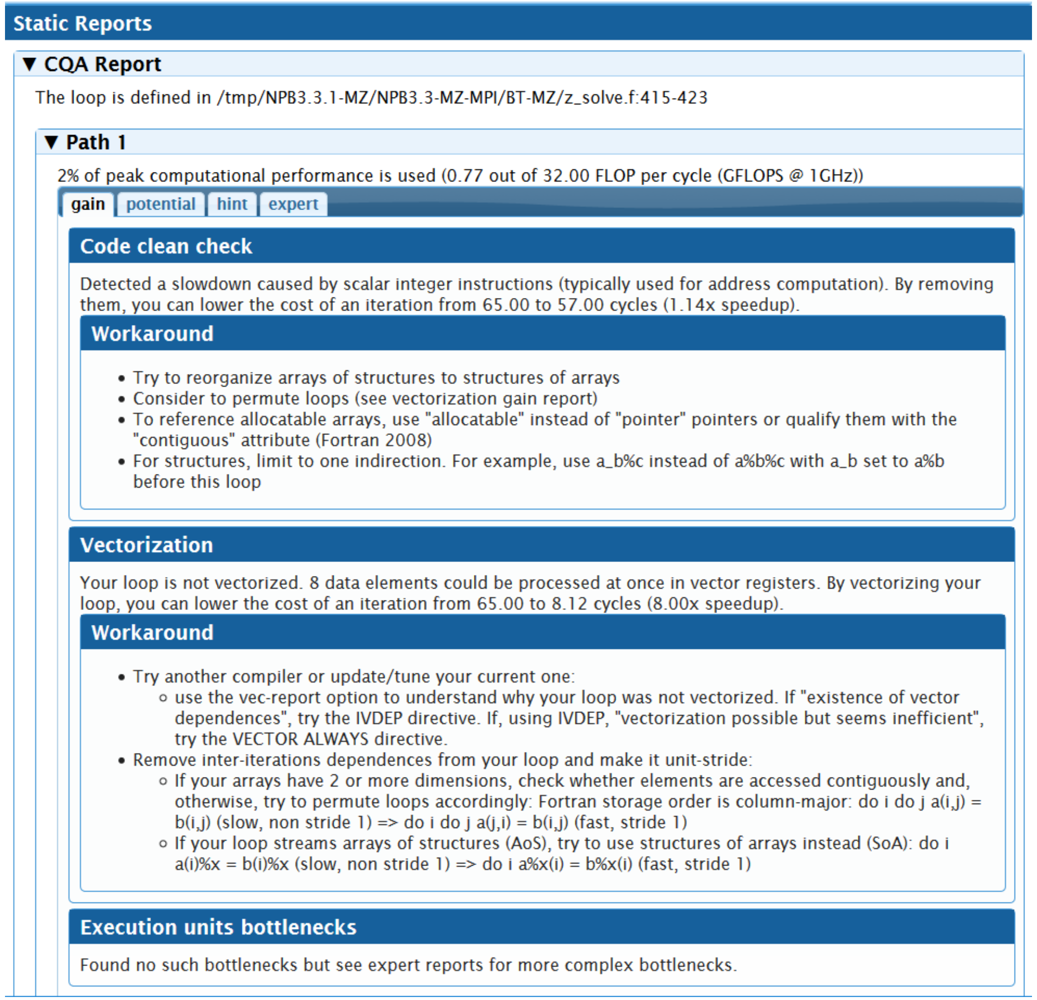
Goal: **Assist developers** in improving code performance

Features:

- Evaluates the **quality** of the compiler generated code
- Returns **hints and workarounds** to improve quality
- Focuses on **loops**
  - In HPC most of the time is spent in loops
- Targets **compute-bound** codes

Static analysis:

- Requires **no execution** of the application
- Allows **cross-analysis**



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))

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

Most of the time, applications only 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:
- Vectorizing
- Avoiding high latency instructions if possible
- Having the compiler generate an efficient code
- Reorganizing memory layout

Same instruction – Same cost

Process up to 8X data

MAQAO CQA: 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 behaviour when possible (e.g. 1/X precision)

Implementation changes:

- Improve data access
  - Loop interchange
  - Changing loop strides
  - Reshaping arrays of structures
- Avoid instructions with high latency

MAQAO ONE View: Performance View Aggregator

Automating the whole analysis process

- Invocation of the required MAQAO modules
- Generation of **aggregated performance views** available as HTML files

Main steps:

- Invokes LProf to **identify hotspots**
- Invokes CQA on **loop hotspots**

Available results:

- **Speedup** predictions
- Global code **quality** metrics
- **Hints** for improving performance
- Parallel **efficiency**

Experiment Summary

Application	bin/bt-mz.C.16
Timestamp	2018-10-09 16:40:18
Experiment Type	MPI; OpenMP;
Machine	skl01.intel.ecr
Architecture	x86_64
Micro Architecture	SKYLAKE
Model Name	Intel(R) Xeon(R) Platinum 8180 CPU @ 2.50GHz
Cache Size	39424 KB
Number of Cores	28
Compilation Options	binary: GNU 7.3.0 -ffixed-form -mtune=generic -march=x86-64 -g -O3 -fopenmp -fintrinsic-modules-path /opt/gnu/gcc/7.3.0/lib/gcc/x86_64-pc-linux-gnu/7.3.0/finclude

Configuration Summary

Dataset	
Run Command	<binary>
Number Processes	1
Number Nodes	1
Number Tasks per Nodes	1
OMP_NUM_THREADS	4

Global Metrics

Total Time (s)		20.15
Compilation Options		binary: -funroll-loops is missing.
Flow Complexity		1.00
Array Access Efficiency (%)		70.57
Clean	Potential Speedup	1.02
	Nb Loops to get 80%	3
FP Vectorised	Potential Speedup	1.02
	Nb Loops to get 80%	31
Fully Vectorised	Potential Speedup	1.39
	Nb Loops to get 80%	10

Loop id	Source Lines	Source File	Source Function	Coverage (%)	Time (s)	Vectorization Ratio (%)	Speedup If Clean	Speedup If FP Vectorized	Speedup If Fully Vectorized
Loop 118	145-308	bt-mz.C.16:y_solve.f	y_solve_._omp_fn.0	5.85	0.89	13.47	1	1	8
Loop 112	146-309	bt-mz.C.16:x_solve.f	x_solve_._omp_fn.0	5.81	0.89	12.68	1	1	8
Loop 141	146-309	bt-mz.C.16:z_solve.f	z_solve_._omp_fn.0	5.7	0.87	13.06	1	1	8
Loop 142	55-137	bt-mz.C.16:z_solve.f	z_solve_._omp_fn.0	2.14	0.33	11.04	1.58	1	10.1
Loop 119	55-137	bt-mz.C.16:y_solve.f	y_solve_._omp_fn.0	1.77	0.27	11.66	1.61	1	10.1
Loop 113	57-139	bt-mz.C.16:x_solve.f	x_solve_._omp_fn.0	1.67	0.26	12.12	1.61	1	10.1
Loop 138	415-421	bt-mz.C.16:z_solve.f	z_solve_._omp_fn.0	1.34	0.2	0	0	0	0
Loop 85	4-132	bt-mz.C.16:rhs.f	compute_rhs_._omp_fn.0	1.17	0.18	14.29	1	1.49	8
Loop 69	4-349	bt-mz.C.16:rhs.f	compute_rhs_._omp_fn.0	1.15	0.18	13.25	1	1.47	8
Loop 92	40-50	bt-mz.C.16:rhs.f	compute_rhs_._omp_fn.0	1.15	0.18	4	1	1	3
Loop 78	4-238	bt-mz.C.16:rhs.f	compute_rhs_._omp_fn.0	1.13	0.17	12.67	1	1.47	8
Loop 116	394-398	bt-mz.C.16:y_solve.f	y_solve_._omp_fn.0	1.08	0.17	0	0	0	0
Loop 91	67-67	bt-mz.C.16:rhs.f	compute_rhs_._omp_fn.0	1.01	0.15	100	1	1	4
Loop 110	395-399	bt-mz.C.16:x_solve.f	x_solve_._omp_fn.0	0.91	0.14	0	0	0	0
Loop	387-392	bt-mz.C.16:rhs.	compute_rhs_._o	0.52	0.08	0	1	1.29	8

Analysing an application with MAQAO

Execute ONE View

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

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

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

- Analyses can be tweaked if necessary
  - Report one corresponds to profiling and code quality analysis
- ONE View can reuse an existing experiment directory to perform further analyses
- Results available in HTML by default
  - XLS files or console output available

Online help 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" -- ./bt-mz.C.16
```

  - Display

```
$ maqao lprof xp=exp_dir -df
```

  - Displaying the results from a ONE View run

```
$ maqao lprof xp=oneview_xp_dir/lprof_npsu -df
```

- CQA

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

Online help available:

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

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

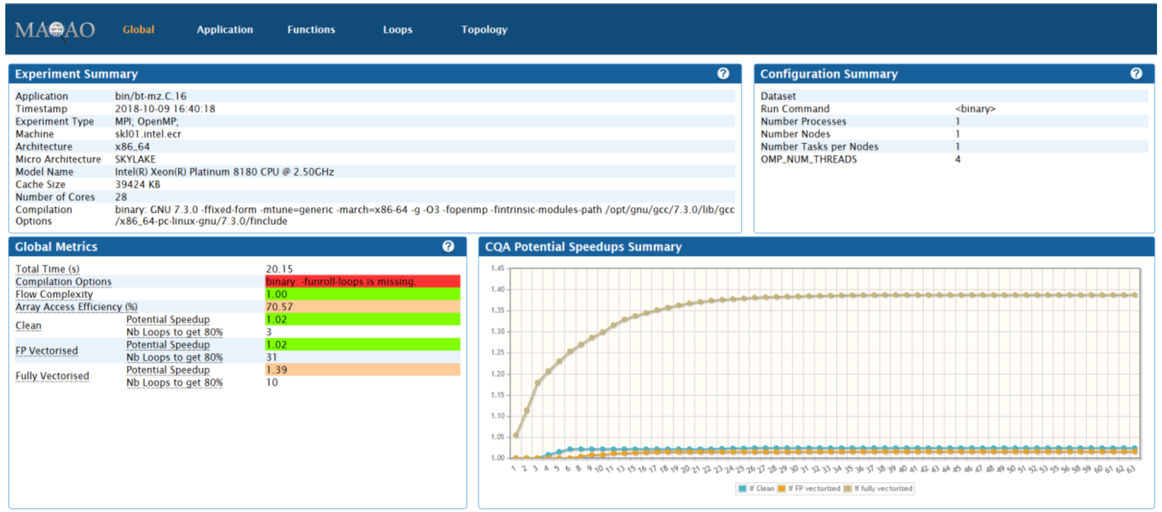
Global summary

Experiment summary

- Characteristics of the machine where the experiment took place

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 in priority



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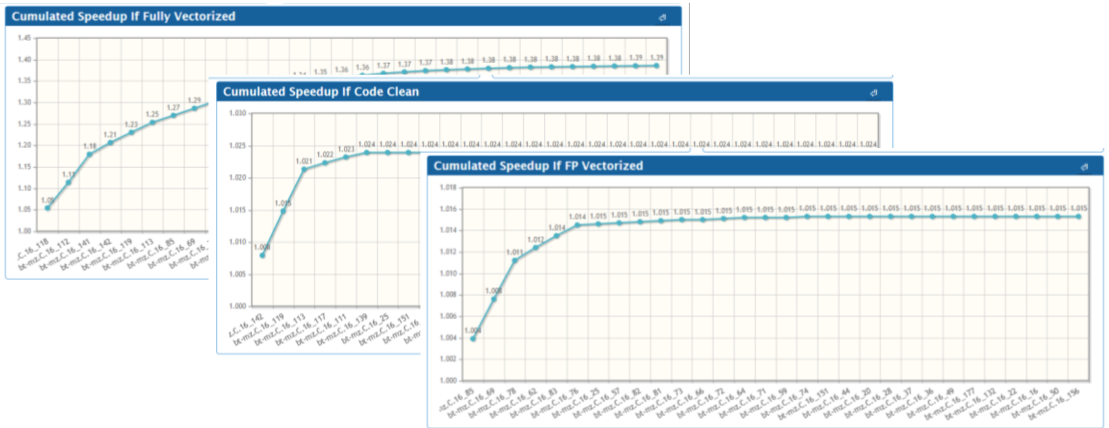
CQA Potential Speedups Summary



Cumulated Speedup If Fully Vectorized

Cumulated Speedup If Code Clean

Cumulated Speedup If FP Vectorized

Application Characteristics

Application categorisation
- Time spent in different regions of code

Function based profile
- Functions by coverage ranges

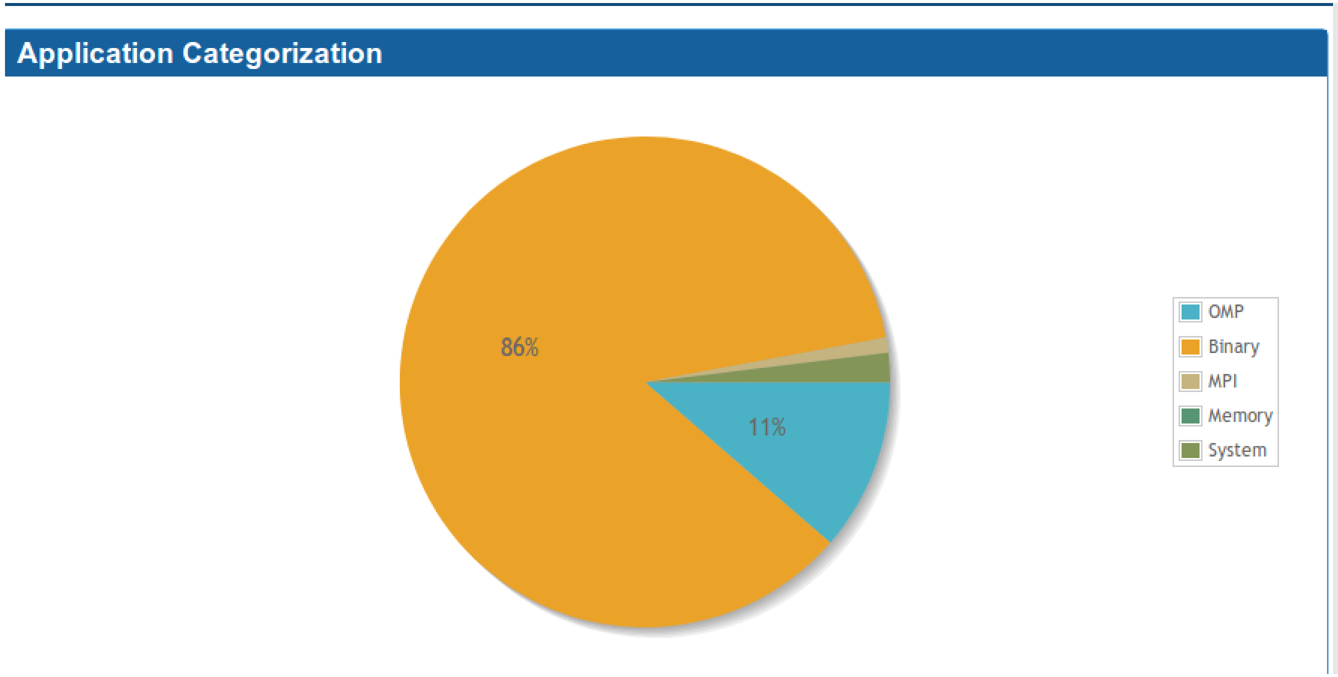
Loop based profile
- Loops by coverage ranges

Detailed loop based profile
- Loop types by coverage ranges

Application Characteristics: Time Categorisation

Identifying at a glance where time is spent

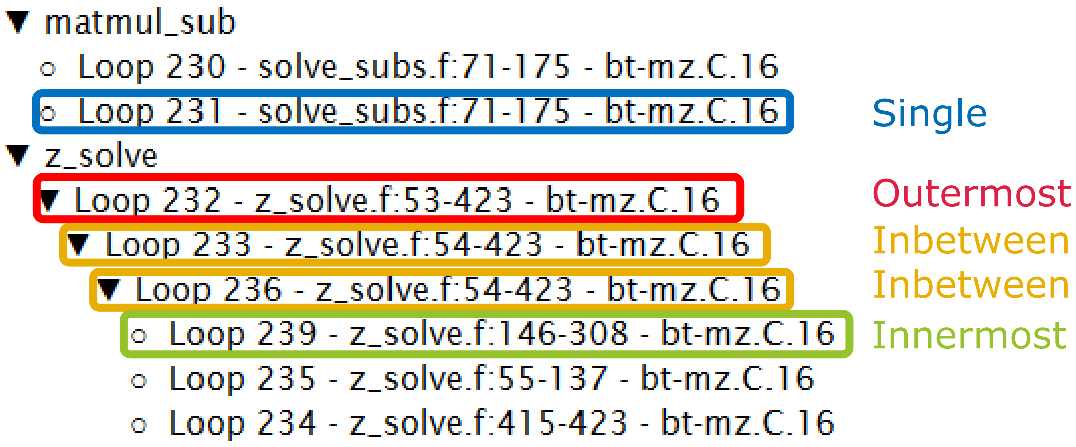
- Application
  - Main executable
- Parallelization
  - Threads
  - OpenMP
  - MPI
- System libraries
  - I/O operations
  - String operations
  - Memory management functions
- External libraries
  - Specialised libraries such as libm / libmkl
  - Application code in external libraries



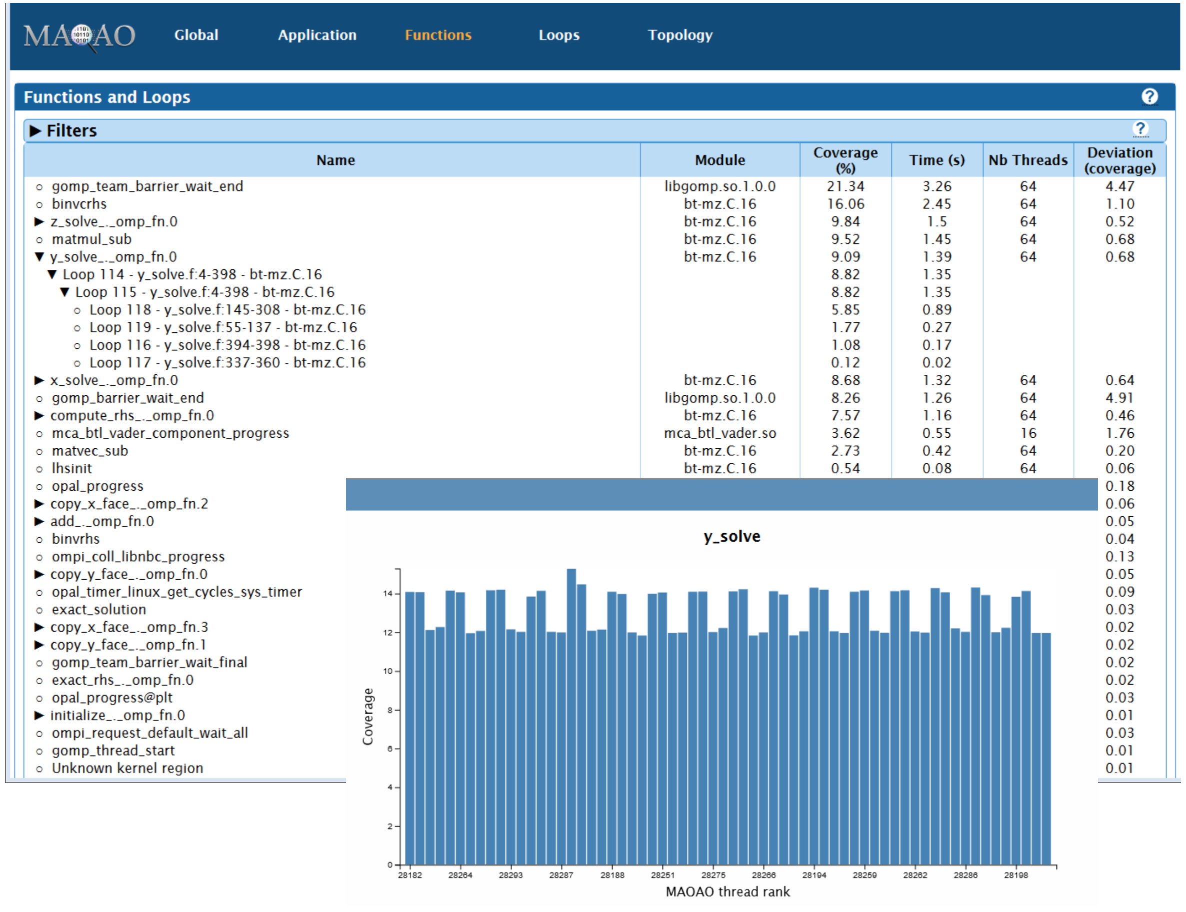
Functions Profiling

Identifying hotspots

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



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



Functions and Loops

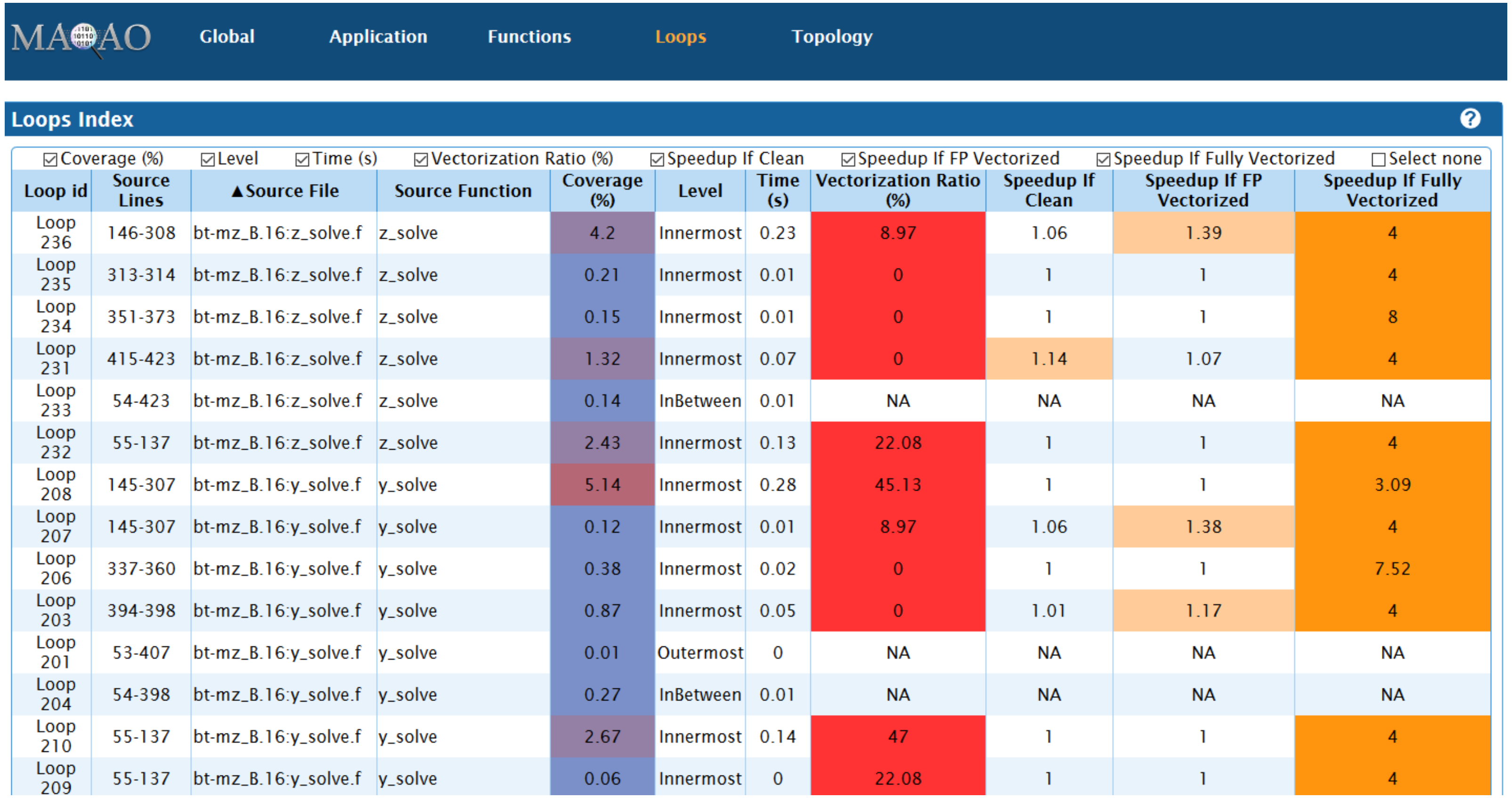
▶ Filters

Name	Module	Coverage (%)	Time (s)	Nb Threads	Deviation (coverage)
○ gomp_team_barrier_wait_end	libgomp.so.1.0.0	21.34	3.26	64	4.47
○ binvcrhs	bt-mz.C.16	16.06	2.45	64	1.10
▶ z_solve_._omp_fn.0	bt-mz.C.16	9.84	1.5	64	0.52
○ matmul_sub	bt-mz.C.16	9.52	1.45	64	0.68
▼ y_solve_._omp_fn.0	bt-mz.C.16	9.09	1.39	64	0.68
▼ Loop 114 - y_solve.f:4-398 - bt-mz.C.16		8.82	1.35		
▼ Loop 115 - y_solve.f:4-398 - bt-mz.C.16		8.82	1.35		
○ Loop 118 - y_solve.f:145-308 - bt-mz.C.16		5.85	0.89		
○ Loop 119 - y_solve.f:55-137 - bt-mz.C.16		1.77	0.27		
○ Loop 116 - y_solve.f:394-398 - bt-mz.C.16		1.08	0.17		
○ Loop 117 - y_solve.f:337-360 - bt-mz.C.16		0.12	0.02		
▶ x_solve_._omp_fn.0	bt-mz.C.16	8.68	1.32	64	0.64
○ gomp_barrier_wait_end	libgomp.so.1.0.0	8.26	1.26	64	4.91
▶ compute_rhs_._omp_fn.0	bt-mz.C.16	7.57	1.16	64	0.46
○ mca_btl_vader_component_progress	mca_btl_vader.so	3.62	0.55	16	1.76
○ matvec_sub	bt-mz.C.16	2.73	0.42	64	0.20
○ lhsinit	bt-mz.C.16	0.54	0.08	64	0.06
○ opal_progress					0.18
▶ copy_x_face_._omp_fn.2					0.06
▶ add_._omp_fn.0					0.05
○ binvrhs					0.04
○ ompi_coll_libnbc_progress					0.13
▶ copy_y_face_._omp_fn.0					0.05
○ opal_timer_linux_get_cycles_sys_timer					0.09
○ exact_solution					0.03
▶ copy_x_face_._omp_fn.3					0.02
▶ copy_y_face_._omp_fn.1					0.02
○ gomp_team_barrier_wait_final					0.02
○ exact_rhs_._omp_fn.0					0.02
○ opal_progress@plt					0.03
▶ initialize_._omp_fn.0					0.01
○ ompi_request_default_wait_all					0.03
○ gomp_thread_start					0.01
○ Unknown kernel region					0.01

Loops Profiling Summary

Identifying loop hotspots

- Vectorisation information
- Potential speedup by optimisation
  - Clean: Removing address computations
  - FP Vectorised: Vectorising floating-point computations
  - Fully Vectorised: Vectorising floating-point computations and memory accesses



Loops Index

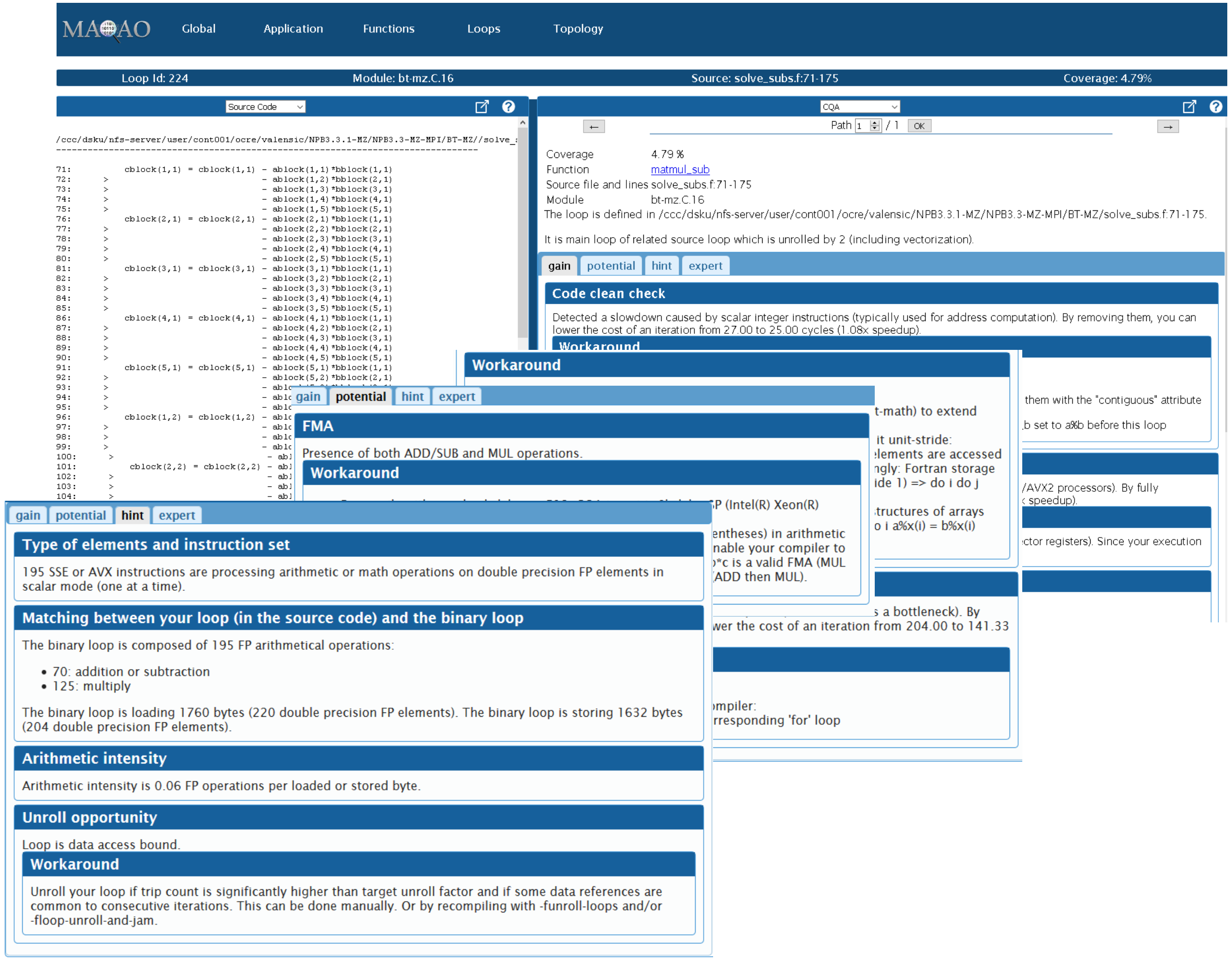
☑ Coverage (%) ☑ Level ☑ Time (s) ☑ Vectorization Ratio (%) ☑ Speedup If Clean ☑ Speedup If FP Vectorized ☑ Speedup If Fully Vectorized ☐ Select none

Loop id	Source Lines	▲Source File	Source Function	Coverage (%)	Level	Time (s)	Vectorization Ratio (%)	Speedup If Clean	Speedup If FP Vectorized	Speedup If Fully Vectorized
Loop 236	146-308	bt-mz_B.16:z_solve.f	z_solve	4.2	Innermost	0.23	8.97	1.06	1.39	4
Loop 235	313-314	bt-mz_B.16:z_solve.f	z_solve	0.21	Innermost	0.01	0	1	1	4
Loop 234	351-373	bt-mz_B.16:z_solve.f	z_solve	0.15	Innermost	0.01	0	1	1	8
Loop 231	415-423	bt-mz_B.16:z_solve.f	z_solve	1.32	Innermost	0.07	0	1.14	1.07	4
Loop 233	54-423	bt-mz_B.16:z_solve.f	z_solve	0.14	InBetween	0.01	NA	NA	NA	NA
Loop 232	55-137	bt-mz_B.16:z_solve.f	z_solve	2.43	Innermost	0.13	22.08	1	1	4
Loop 208	145-307	bt-mz_B.16:y_solve.f	y_solve	5.14	Innermost	0.28	45.13	1	1	3.09
Loop 207	145-307	bt-mz_B.16:y_solve.f	y_solve	0.12	Innermost	0.01	8.97	1.06	1.38	4
Loop 206	337-360	bt-mz_B.16:y_solve.f	y_solve	0.38	Innermost	0.02	0	1	1	7.52
Loop 203	394-398	bt-mz_B.16:y_solve.f	y_solve	0.87	Innermost	0.05	0	1.01	1.17	4
Loop 201	53-407	bt-mz_B.16:y_solve.f	y_solve	0.01	Outermost	0	NA	NA	NA	NA
Loop 204	54-398	bt-mz_B.16:y_solve.f	y_solve	0.27	InBetween	0.01	NA	NA	NA	NA
Loop 210	55-137	bt-mz_B.16:y_solve.f	y_solve	2.67	Innermost	0.14	47	1	1	4
Loop 209	55-137	bt-mz_B.16:y_solve.f	y_solve	0.06	Innermost	0	22.08	1	1	4

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



Loop Id: 224 Module: bt-mz.C.16 Source: solve_subs.f:71-175 Coverage: 4.79%

```
/ccc/dsku/nfs-server/user/cont001/ocre/valensic/NPB3.3.1-MZ/NPB3.3-MZ-MPI/BT-MZ//solve_s
--------------------------------------------------------------------------------

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:     >                            - ablc
94:     >                            - ablc
95:     >                            - ablc
96:        cblock(1,2) = cblock(1,2) - ablc
97:     >                            - ablc
98:     >                            - ablc
99:     >                            - ablc
100:     >                            - abl
101:        cblock(2,2) = cblock(2,2) - abl
102:     >                            - abl
103:     >                            - abl
104:     >                            - abl
```

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 main loop of related source loop which is unrolled by 2 (including vectorization).

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).

Workaround

them with the "contiguous" attribute

b set to a%b before this loop

/AVX2 processors). By fully

speedup).

ctor registers). Since your execution

Workaround

t-math) to extend

it unit-stride:
elements are accessed
ngly: Fortran storage
ide 1) => do i do j

tructures of arrays
o i a%x(i) = b%x(i)

s a bottleneck). By
wer the cost of an iteration from 204.00 to 141.33

mpiler:
rresponding 'for' loop

FMA

Presence of both ADD/SUB and MUL operations.

Workaround

P (Intel(R) Xeon(R)

entheses) in arithmetic
nable your compiler to
*c is a valid FMA (MUL
ADD then MUL).

Type of elements and instruction set

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

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

The binary loop is composed of 195 FP arithmetical operations:

- 70: addition or subtraction
- 125: multiply

The binary loop is loading 1760 bytes (220 double precision FP elements). The binary loop is storing 1632 bytes (204 double precision FP elements).

Arithmetic intensity

Arithmetic intensity is 0.06 FP operations per loaded or stored byte.

Unroll opportunity

Loop is data access bound.

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.

Loop Analysis Reports – Expert View

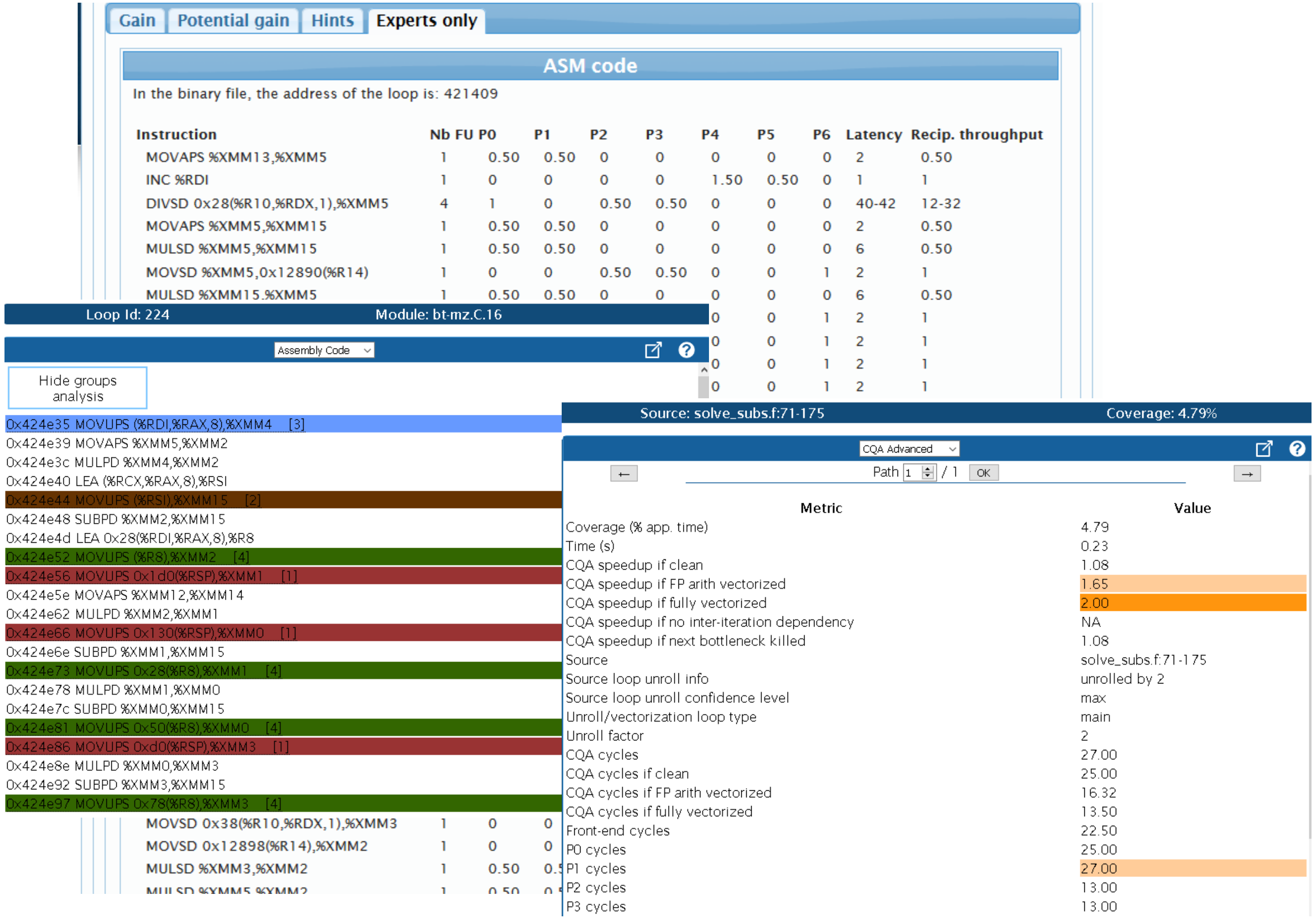
Low level reports for performance experts

- 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



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	2	0.50
INC %RDI	1	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	40-42	12-32
MOVAPS %XMM5,%XMM15	1	0.50	0.50	0	0	0	0	0	2	0.50
MULSD %XMM5,%XMM15	1	0.50	0.50	0	0	0	0	0	6	0.50
MOVSD %XMM5,0x12890(%R14)	1	0	0	0.50	0.50	0	0	1	2	1
MULSD %XMM15.%XMM5	1	0.50	0.50	0	0	0	0	0	6	0.50
						0	0	1	2	1
						0	0	1	2	1
						0	0	1	2	1
						0	0	1	2	1
MOVSD 0x38(%R10,%RDX,1),%XMM3	1	0	0							
MOVSD 0x12898(%R14),%XMM2	1	0	0							
MULSD %XMM3,%XMM2	1	0.50	0.5							

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

```
0x424e35 MOVUPS (%RDI,%RAX,8),%XMM4    [3]
0x424e39 MOVAPS %XMM5,%XMM2
0x424e3c MULPD %XMM4,%XMM2
0x424e40 LEA (%RCX,%RAX,8),%RSI
0x424e44 MOVUPS (%RSI),%XMM15    [2]
0x424e48 SUBPD %XMM2,%XMM15
0x424e4d LEA 0x28(%RDI,%RAX,8),%R8
0x424e52 MOVUPS (%R8),%XMM2    [4]
0x424e56 MOVUPS 0x1d0(%RSP),%XMM1    [1]
0x424e5e MOVAPS %XMM12,%XMM14
0x424e62 MULPD %XMM2,%XMM1
0x424e66 MOVUPS 0x130(%RSP),%XMM0    [1]
0x424e6e SUBPD %XMM1,%XMM15
0x424e73 MOVUPS 0x28(%R8),%XMM1    [4]
0x424e78 MULPD %XMM1,%XMM0
0x424e7c SUBPD %XMM0,%XMM15
0x424e81 MOVUPS 0x50(%R8),%XMM0    [4]
0x424e86 MOVUPS 0xd0(%RSP),%XMM3    [1]
0x424e8e MULPD %XMM0,%XMM3
0x424e92 SUBPD %XMM3,%XMM15
0x424e97 MOVUPS 0x78(%R8),%XMM3    [4]
```

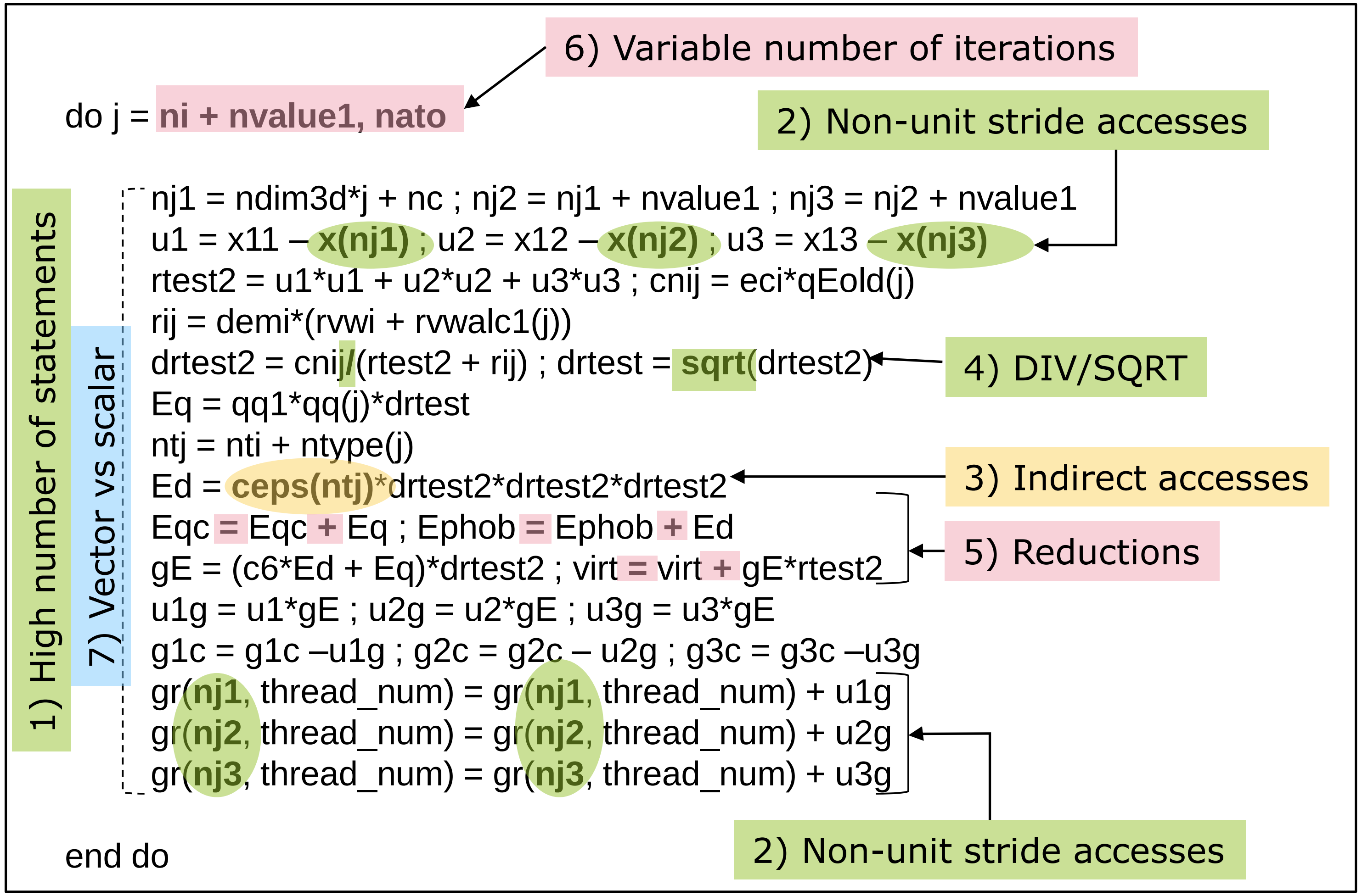
Source: solve_subs.f:71-175 Coverage: 4.79%

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

Application to Motivating Example

Issues identified by CQA

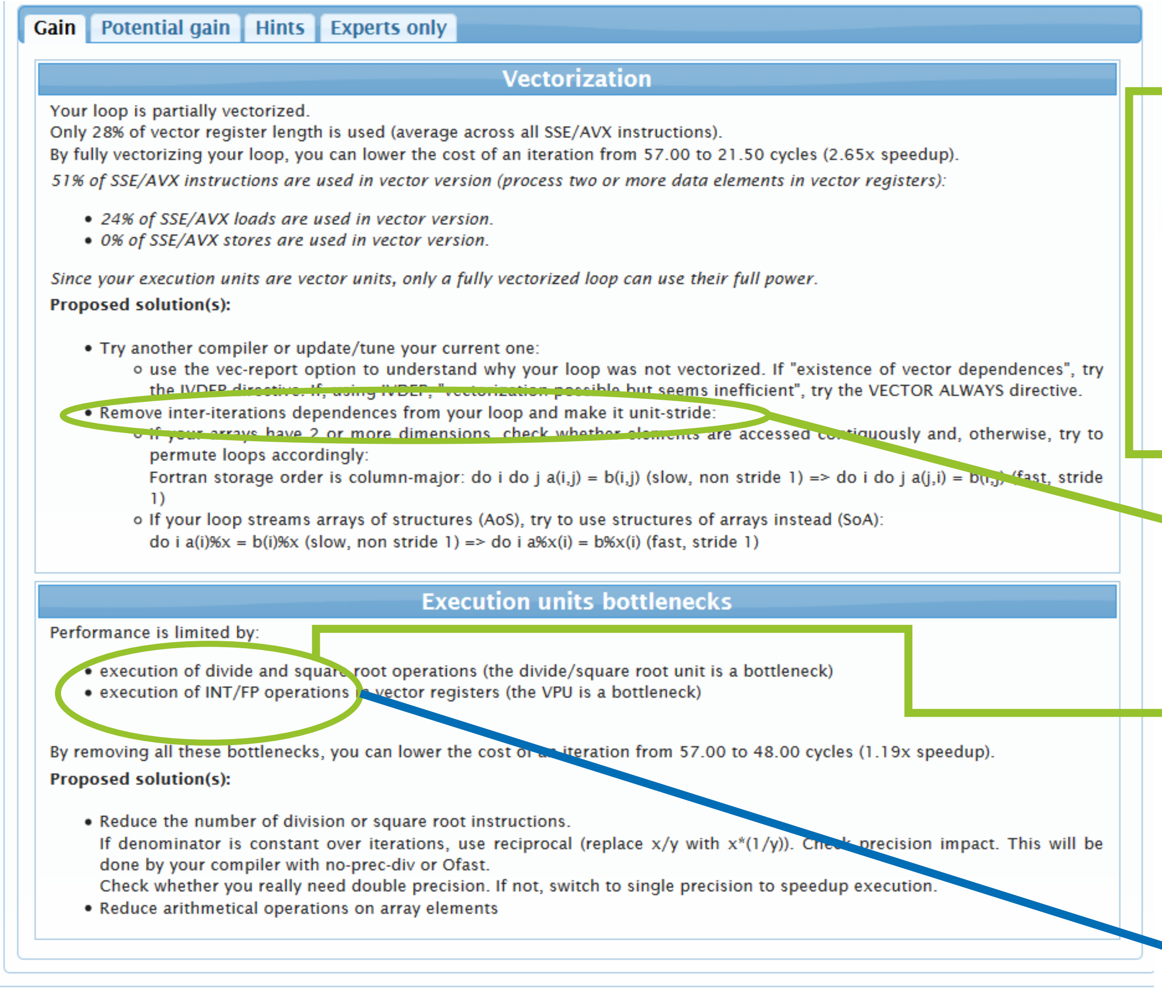


```
do j = ni + nvalue1, nato

   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
```

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**

Application to Motivating Example



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 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

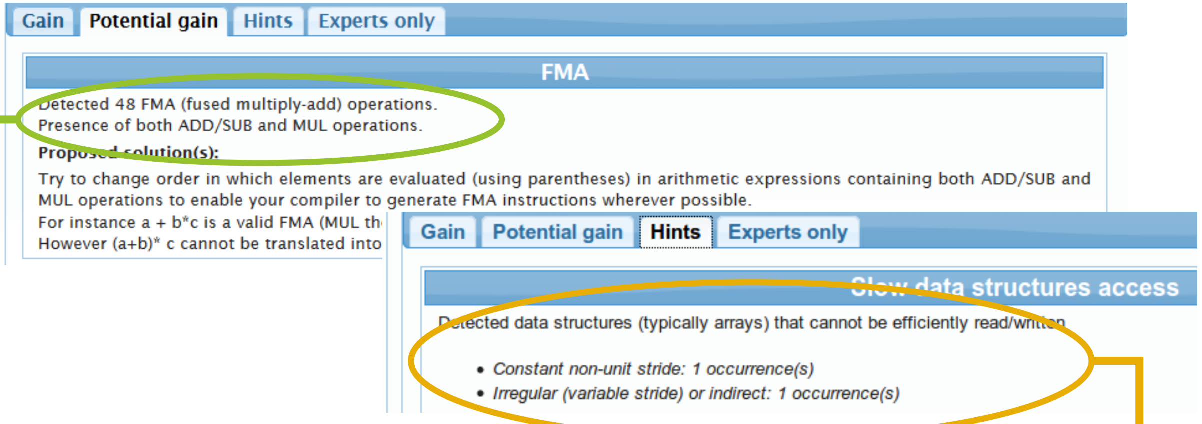
Performance is limited by:

- execution of divide and square root operations (the divide/square root unit is a bottleneck)
- execution of INT/FP operations on 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 th
However (a+b)* c cannot be translated into

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)*

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**

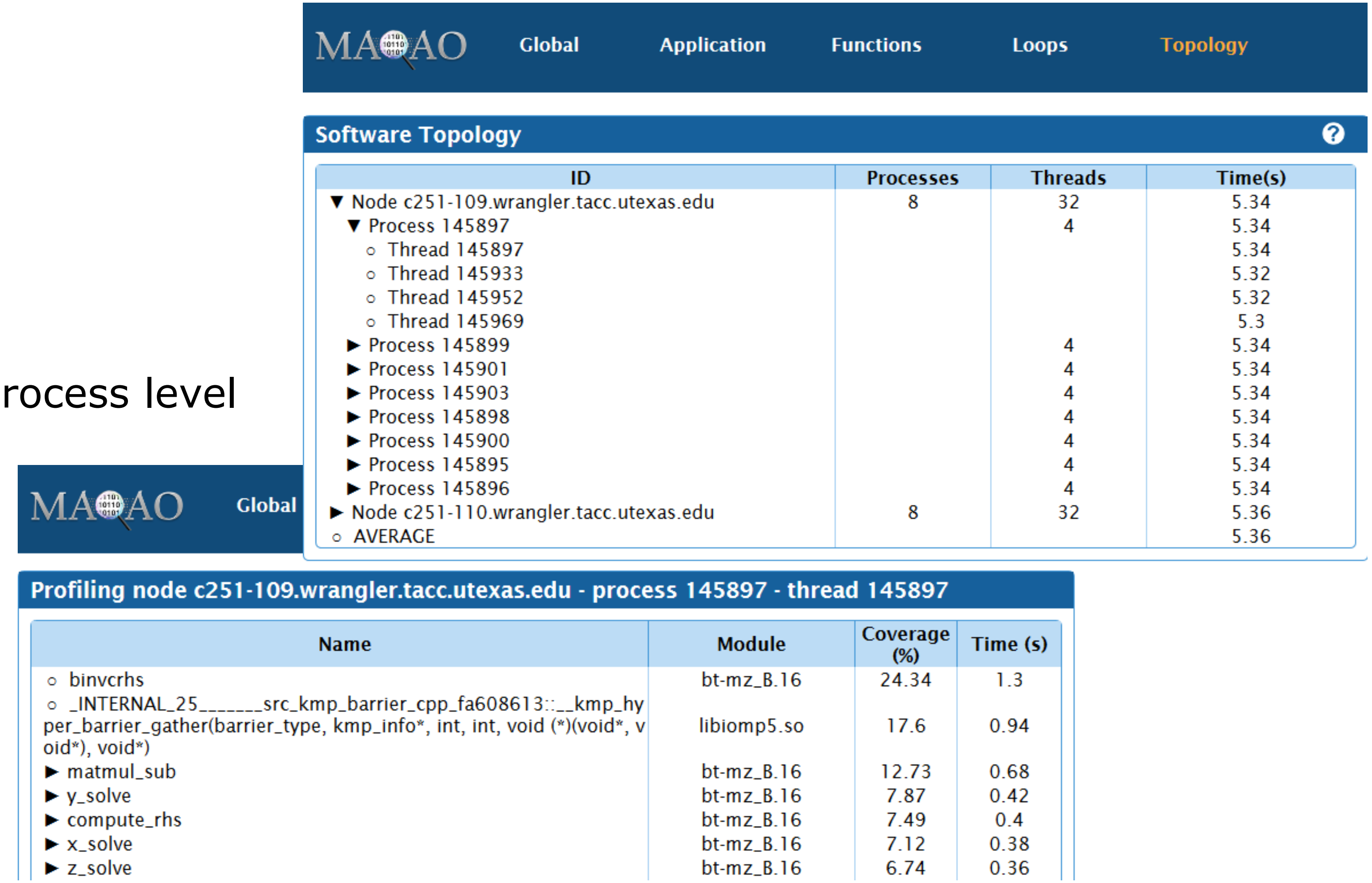
MAQAO ONE View Thread/Process View

Software Topology

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

View by thread

- Function profile at the thread or process level



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

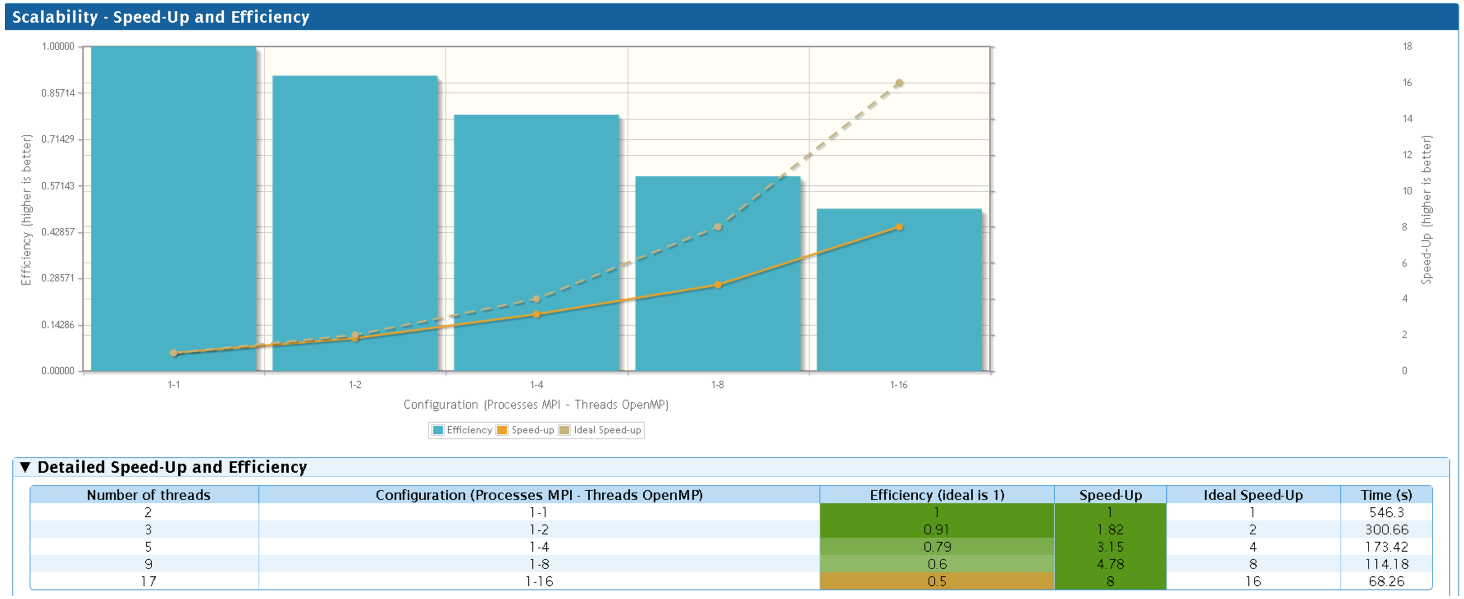
Profiling node c251-109.wrangler.tacc.utexas.edu - process 145897 - thread 145897

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 Speed-Up and Efficiency

Number of threads	Configuration (Processes MPI - Threads OpenMP)	Efficiency (ideal is 1)	Speed-Up	Ideal Speed-Up	Time (s)
2	1-1	1	1	1	546.3
3	1-2	0.91	1.82	2	300.66
5	1-4	0.79	3.15	4	173.42
9	1-8	0.6	4.78	8	114.18
17	1-16	0.5	8	16	68.26

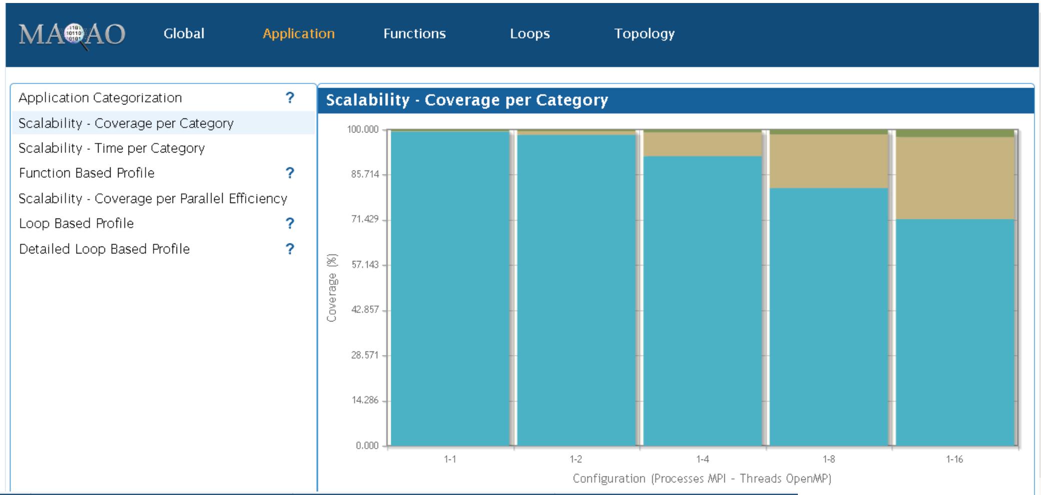
MAQAO ONE View Scalability Reports – Application View

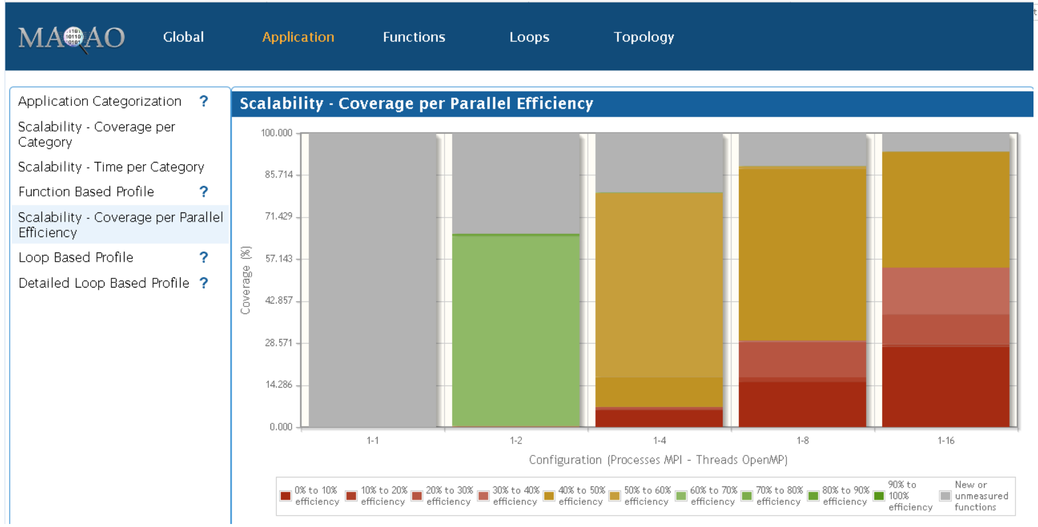
Coverage per category

- 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

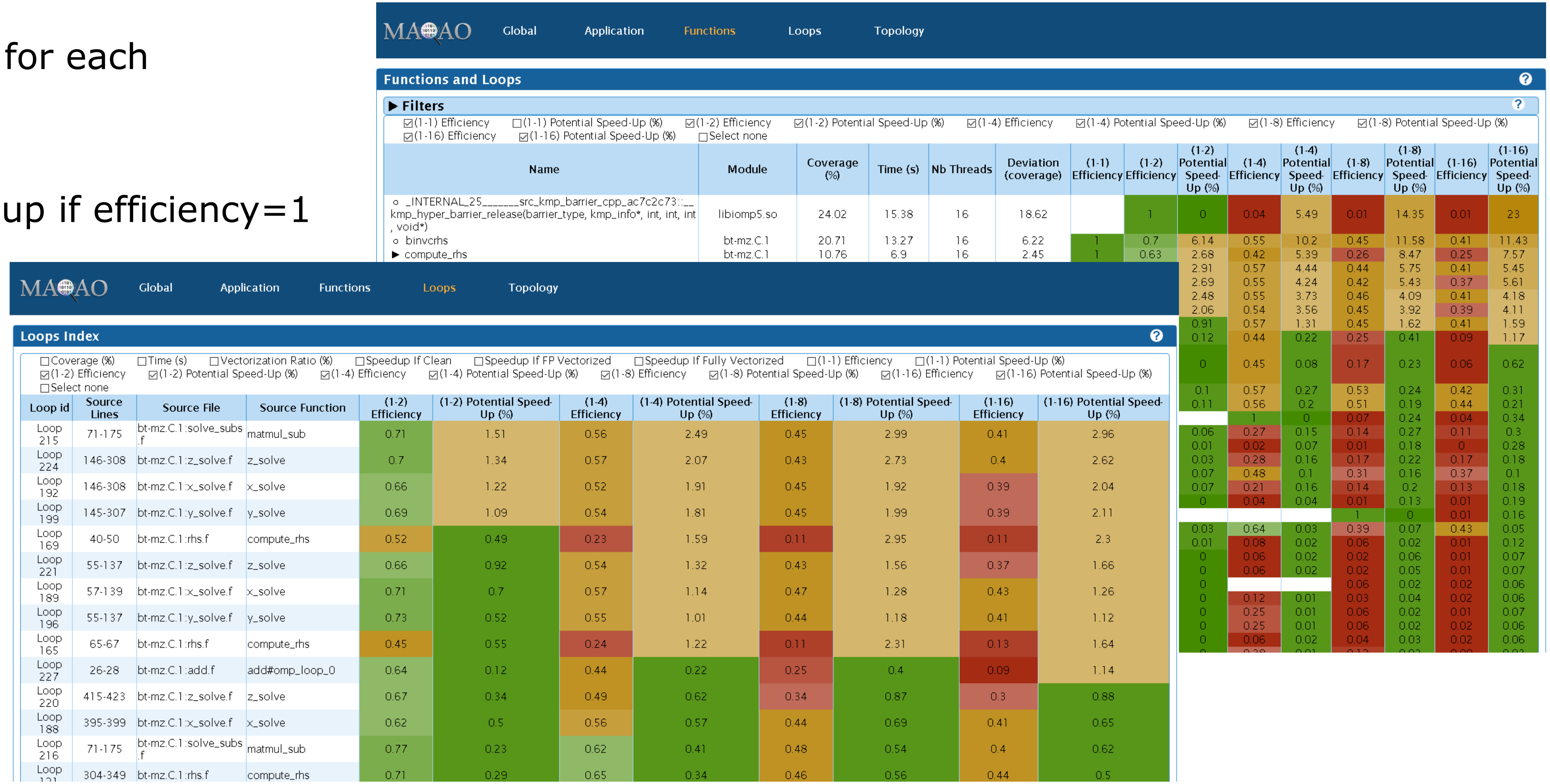




MAQAO ONE View Scalability Reports – Functions and Loops Views

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 (%)
○ _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
○ 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

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

More on MAQAO

MAQAO website: www.maqao.org

- 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)
  - Core sources
- Publications around MAQAO: http://www.maqao.org/publications.html

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Thank you for your attention !

Questions ?

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