# Parallel Sparse Matrix Vector Product with OpenMP for SMP in Code Saturne

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*Higher-order DG methods and finite element software for modern architectures*

*Bath 31 May - 2 Jun*

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# Code Saturne (http://code-saturne.org)

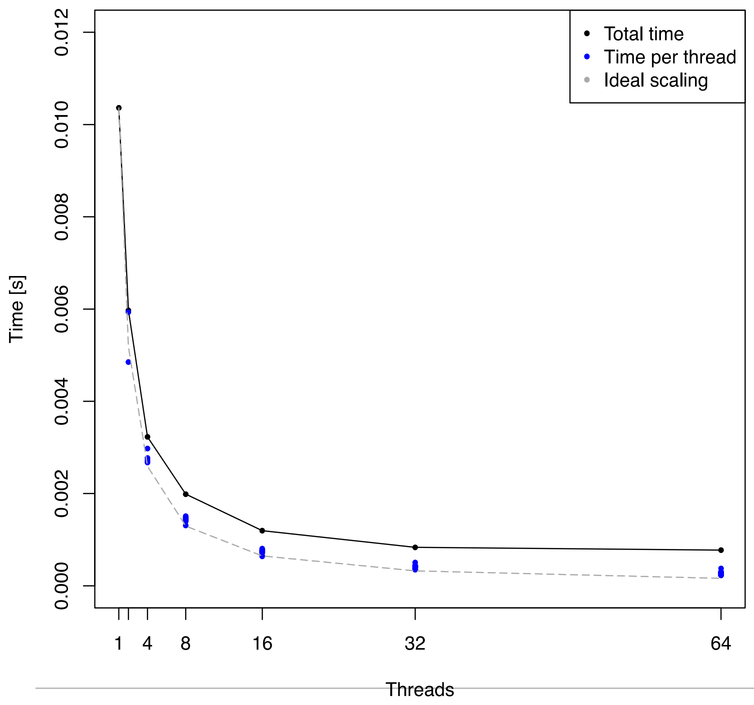
- open-source CFD code
  - 2D,3D flows, steady or unsteady, laminar or turbulent, incompressible or weakly dilatable, isothermal or not, scalar transport,…
  - Physical models modules: gas, coal, heavy fuel combustion, particle tracking, etc,
- mainly developed by EDF (France)
- Fortran, C, Python, ~350k lines of code
- fully validated production versions with long-term support released every two years
- Part of restricted PRACE Unified European Applications benchmark Suite (UEABS, http://www.prace-ri.eu/ueabs/)

# Motivation

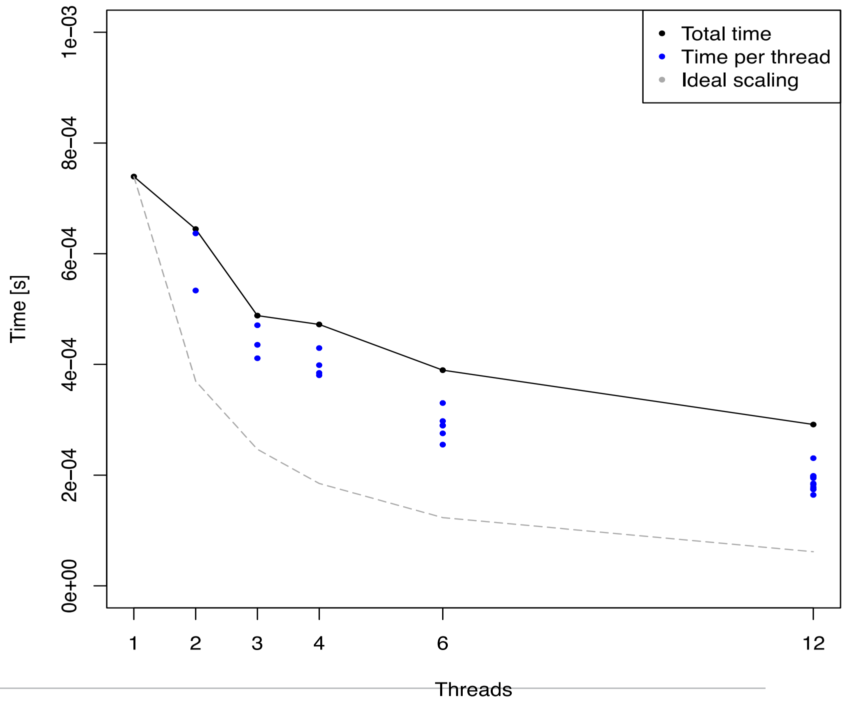
- **In general, optimisation of scientific apps is periodically required in order to take advantage of the evolving hardware architectures**
  - multi/many cores (+GPUs)
  - hyperthreads
  - Vector processing
  - Cache layout
  - interconnect
  - I/O
- **Specifically, the CS project was defined to explore ways to improve the OpenMP scaling**
  - CS run time in incompressible flow simulations is dominated by the pressure solver
    - sparse matrix vector product

# Native OpenMP: BQG vs Intel

Matrix vector (Cavity 145k, Blue Joule)




Matrix vector (Cavity 145k, ARCHER)



# Sparse Matrix Vector product in Code Saturne

Code_Saturne formats for sparse matrix storage and associated MV product algorithms:

- **Native –** using Code_Saturne native sparse matrix storage format
- **Native OpenMP –** multiple groups, with threads having non-overlapping regions within a group
- **CSR –** compressed sparse row; rows divided between threads
- **MSR –** modified compressed

# Native MV (symmetric)

```
for (face_id = 0; face_id < ms->n_faces; face_id++) {
  ii = face_cel_p[2*face_id] -1;
  jj = face_cel_p[2*face_id + 1] -1;
  y[ii] += xa[face_id] * x[jj];
  y[jj] += xa[face_id] * x[ii];
}
```

# Native OpenMP MV

```
for (g_id = 0; g_id < n_groups; g_id++) {
# pragma omp parallel for private(face_id, ii, jj)
  for (t_id = 0; t_id < n_threads; t_id++) {
    for (face_id = group_index[(t_id*n_groups + g_id)*2];
      face_id < group_index[(t_id*n_groups + g_id)*2 + 1];
      face_id++) {
      ii = face_cel_p[2*face_id] -1;
      jj = face_cel_p[2*face_id + 1] -1;
      y[ii] += xa[face_id] * x[jj];
      y[jj] += xa[face_id] * x[ii];
    }
  }
}
```

# Native OpenMP: time tracing

- Extrae/Paraver trace of native sparse matrix vector
- product used within PCG showing synchronisation
  - Top: executed function; Middle: useful work; Bottom: OpenMP loop

# Blocked Native Algorithm

- faces are grouped into blocks:
  - Each block is guaranteed to update cells in selected cell index range
  - Can be parallelized with OpenMP
    - synchronization free
    - better cache utilisation
- different block types to handle:
  - diagonal: y[ii] and y[jj]
  - off-diagonal: either y[ii] or y[jj]
- however: additional work with increasing number of blocks
- corresponding matrix vector product alogrithms are integrated into Code_Saturne, including the autotuning framework
- algorithmic variations for better load balance

# Blocked Native Code

```
for (g_id = 0; g_id < n_groups; g_id++) {
# pragma omp parallel for
private(face_id, ii, jj)
  for (t_id = 0; t_id < n_threads;
t_id++) {
    for (face_id =
group_index[(t_id*n_groups + g_id)*2];
      face_id <
group_index[(t_id*n_groups + g_id)*2 +
1];
      face_id++) {
       ii = face_cel_p[2*face_id] -1;
       jj = face_cel_p[2*face_id + 1] -1;
       y[ii] += xa[face_id] * x[jj];
       y[jj] += xa[face_id] * x[ii];
    }
  }
}
```

```
# pragma omp parallel private ( ii, jj, faceid )
{
  int ith = omp_get_threadnum( ) ;
  int jb,fs,fe, fst ,fet ;
  for ( jb =0; jb < nthreads ; ++jb ){
    fs = ms->th_blk[ith][jb].s;
    fe = ms->th_blk[ith][jb].s +
            ms->th_blk[ith][jb].n;
    if ( jb == ith){
      for (face_id = fs ; face_id < fe;
            face_id++){
        ii = face_cel_p [2 * face_id ] -1;
        jj = face_cel_p [2 * face_id + 1] -1;
         y[ii] += xa [face_id ] * x[jj] ;
         y[jj] += xa [face_id ] * x[ii] ;
     }
  }
  else{
….
```

# Blocked Native Code (cont'd)

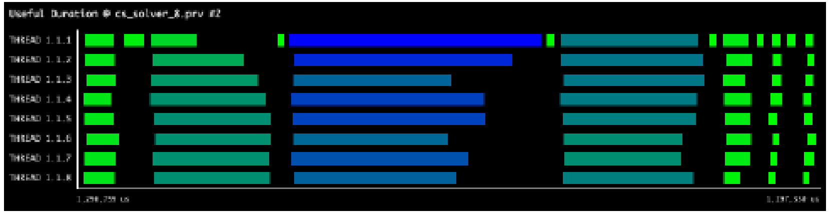
```
if ( jb > ith){
        for (face_id = fs; face_id < fe;
face_id++) {
          ii = face_cel_p[2*face_id] -1;
          jj = face_cel_p[2*face_id + 1] -1;
          y[ii] += xa2[face_id] * x[jj];
        }
      }
      else{
        for ( face_id = fs; face_id < fe;
face_id++) {
          ii = face_cel_p[2*face_id] -1;
          jj = face_cel_p[2*face_id + 1] -1;
          y[jj] += xa2[face_id] * x[ii];
...
```

# Blocked native: Variations

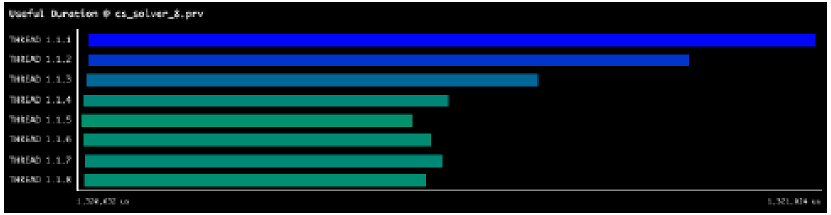
- **Blocked** – split faces into blocks, each thread works on a separate range in the y vector; diagonal blocks and off-diagonal blocks
- **SECO / PACO** – serial / parallel setting of coefficients
- **BAL / UNB** – setting blocks boundaries so that: number of rows are equally distributed (UNB) or number of faces are equally distributed (BAL)
- **INCDIAG** – include diagonal handling and zeroing of y in the processing of the diagonal blocks
- **EXHA** – exclude halo region in the y vector calculation
- **MULTIBLOCKS fixed block size: 1k, 2k, etc.** - dynamic scheduled OpenMP loop for load balance
- **MULTIBLOCKS fixed number of blocks: 2TT, 3TT** - blocks split between static and dynamic scheduled OpenMP loop for load balance

# Qualitative Comparison

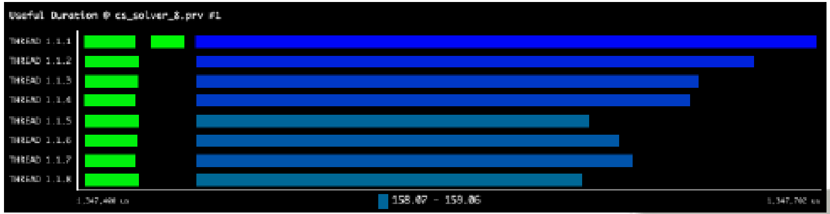
- Native



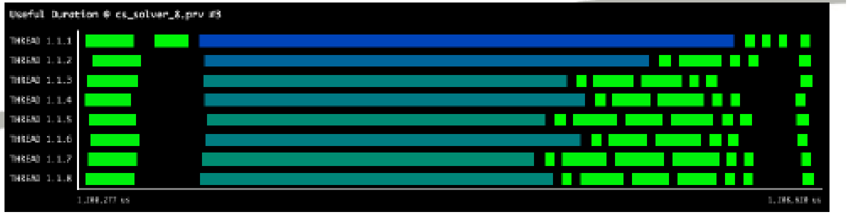

- MSR
  (modified compressed sparse row)




- Blocked
  one row block per thread




- Blocked
  with mixed static/ dynamic scheduling



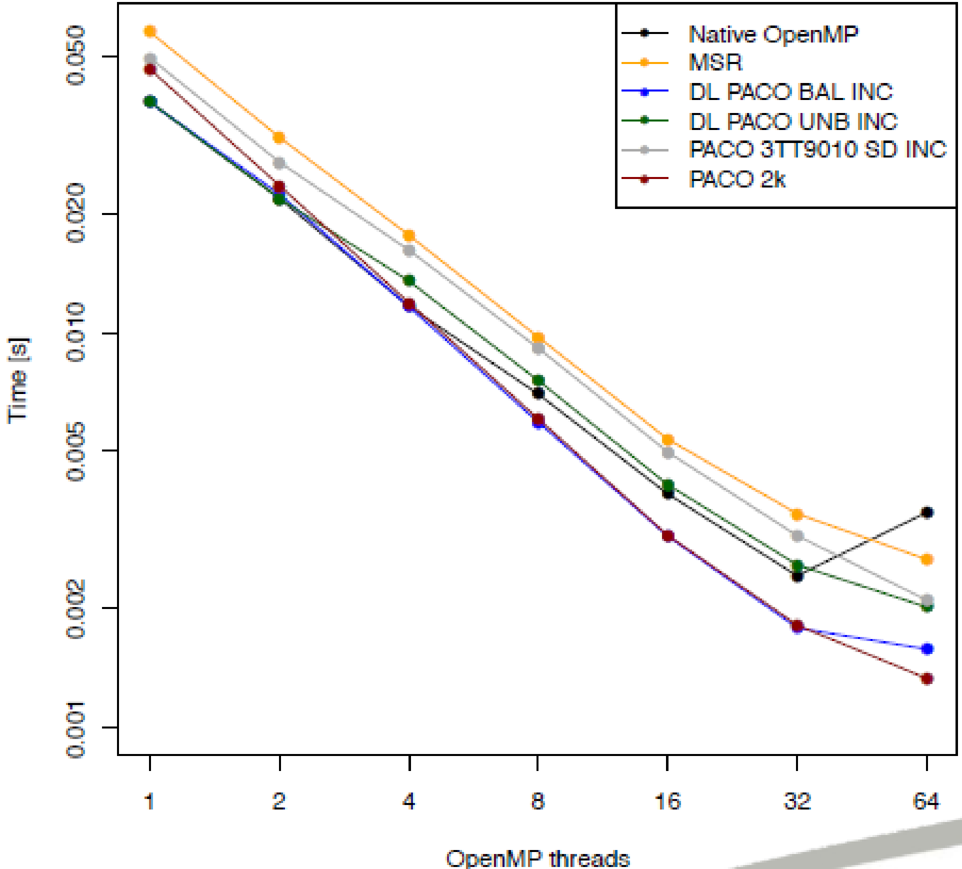
# Test setup

- cavity test case
  - laminar lid-driven cavity flow
  - tetrahedral cells
- number of cells: 145k, 500k, 1800k, (13M)
- time taken from autotuning framework

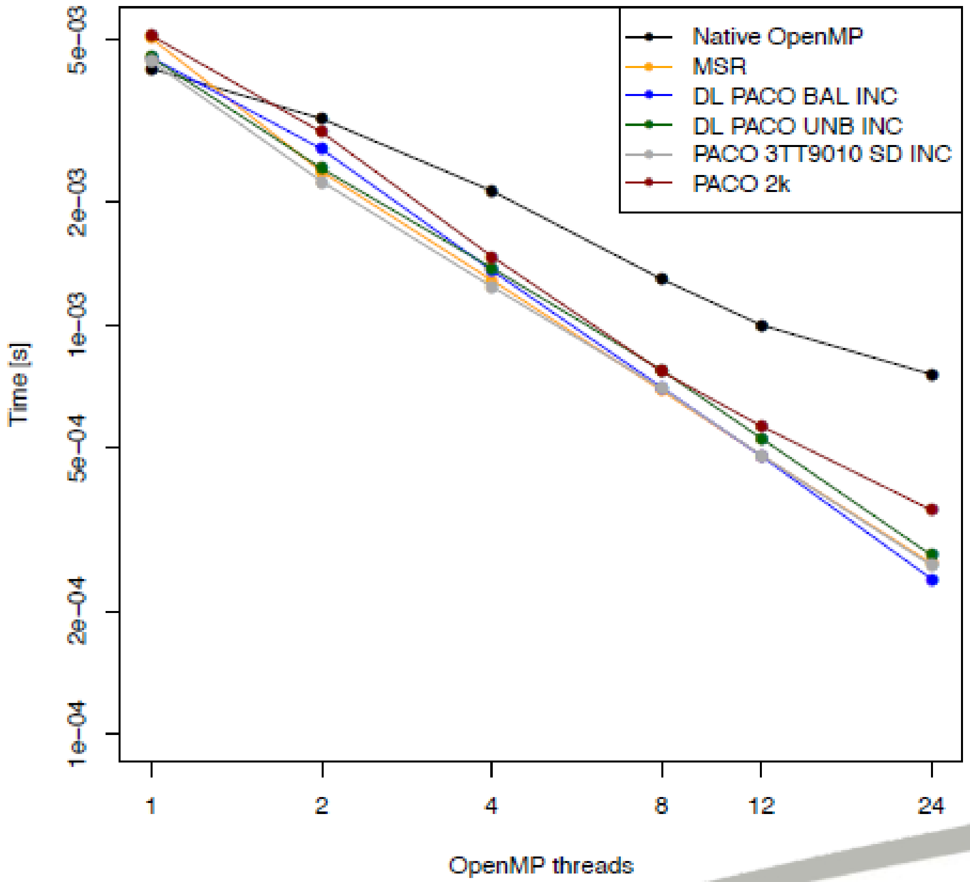
# Test Setup (cont'd)

- Blue Joule
  - Blue Gene/Q, 1x 16-core 1.60 GHz A2 PowerPC
- Blue Wonder
  - iDataPlex, 2x 8-core 2.6 GHz Intel Xeon (Sandybridge)
- Phase 2 Wonder
  - NextScale, 2x 12-core 2.7 GHz Intel Xeon E5-2697 v2 (Ivybridge)
- ARCHER
  - Cray XC30, 2x 12-core 2.7 GHz Intel Xeon E5-2697 v2(Ivybridge)

# Results: Blue Joule, cavity test, 500k

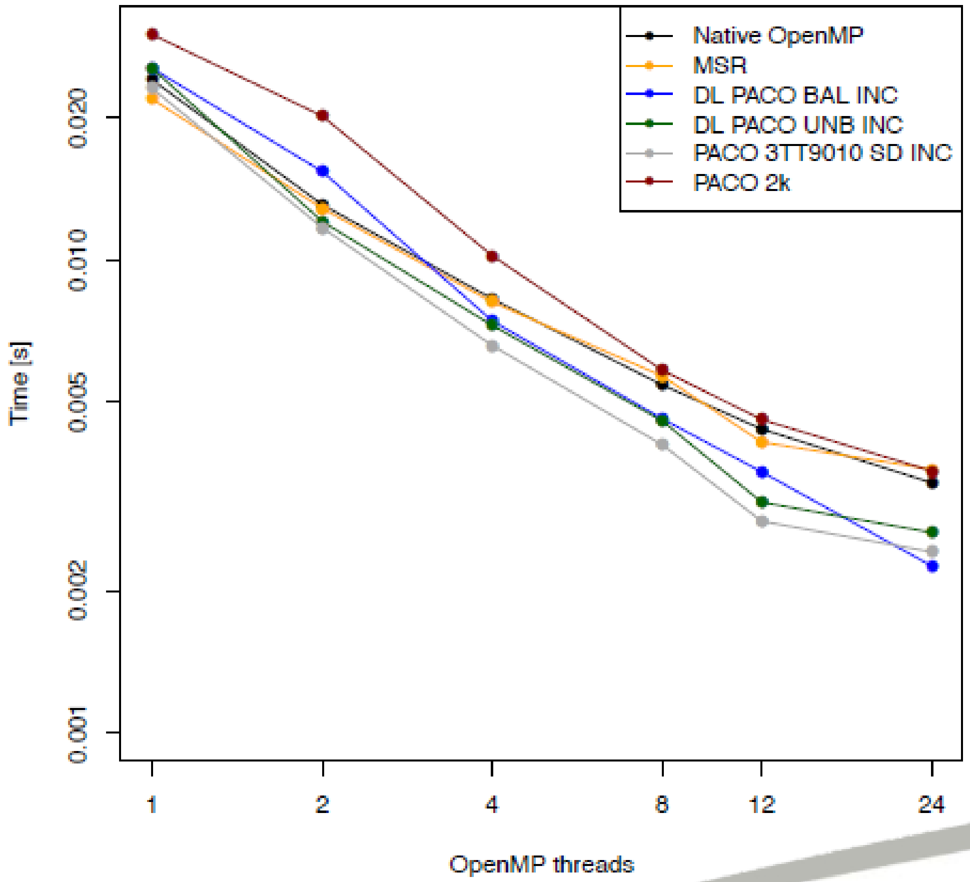


# Results: Ivybridge cavity test, 500K

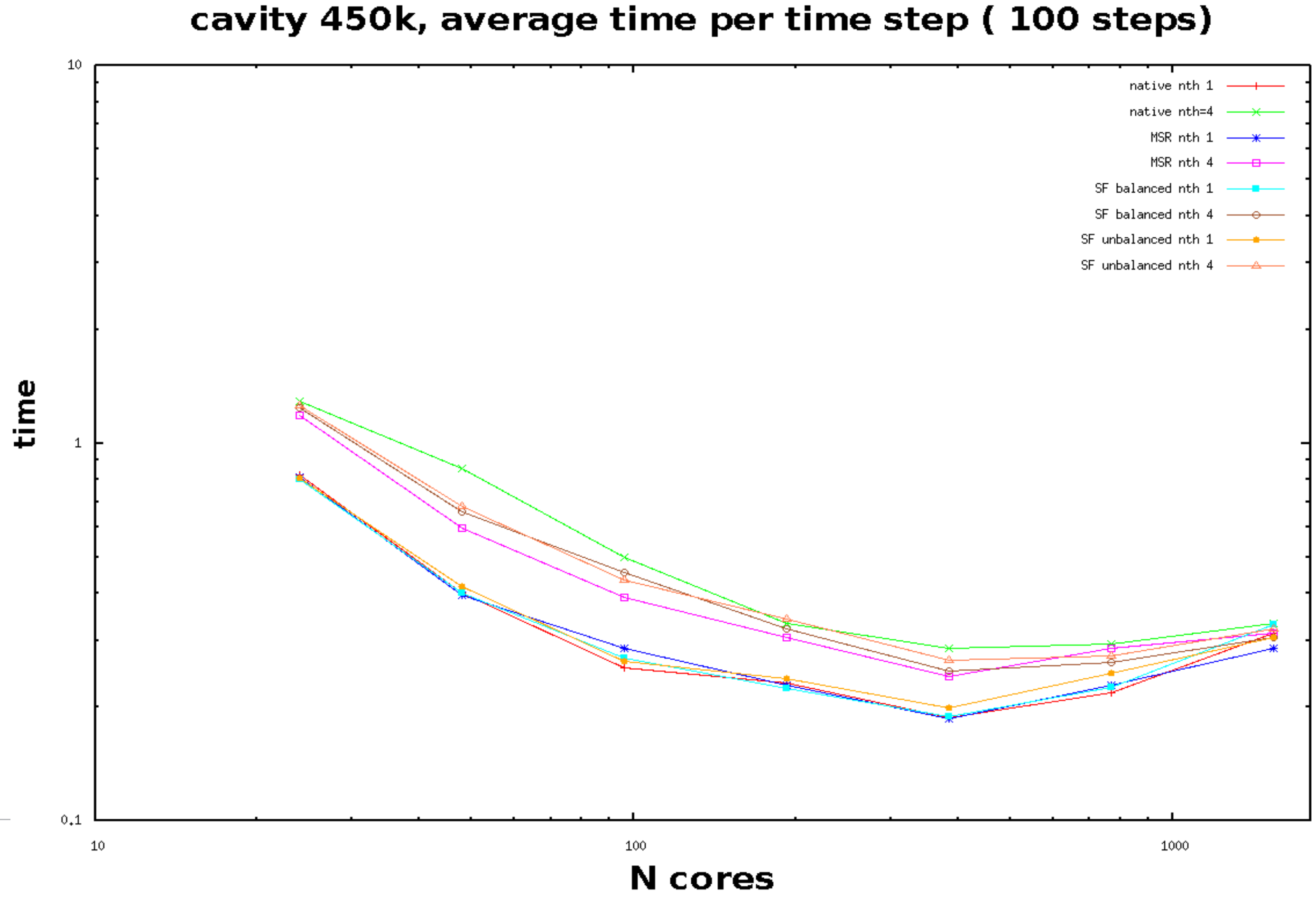



ALYZE

# Results: IvyBridge, cavity test 1800k



# Result: MPI+OpenMP, cavity 450k (ARCHER)



# Conclusions

- we propose a blocked native storage and matrix vector product implementation
  - synchronisation free
  - Imporves load balancing & cache
  - Good performance on BGQ and Intel processors
- algorithm variations for improved load balance
  - Performance depends on CPU architecture and mesh size
- implemented in Code_Saturne, including autotuning framework
  - tests on cavity case using autotuning framework

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archer

This work used the ARCHER UK National Supercomputing Service (http://www.archer.ac.uk).

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# Q&A

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