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# Optimization of Preconditioned Parallel Iterative Solvers for Finite-Element Applications using Hybrid Parallel Programming Models on "T2K Open Supercomputer (Tokyo)"


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The 11th International Specialist Meeting on Next Generation Models on Climate Change and Sustainability for High Performance Computing Facilities

March 16-18, 2009 Oak Ridge National Laboratory, Oak Ridge, TN, USA

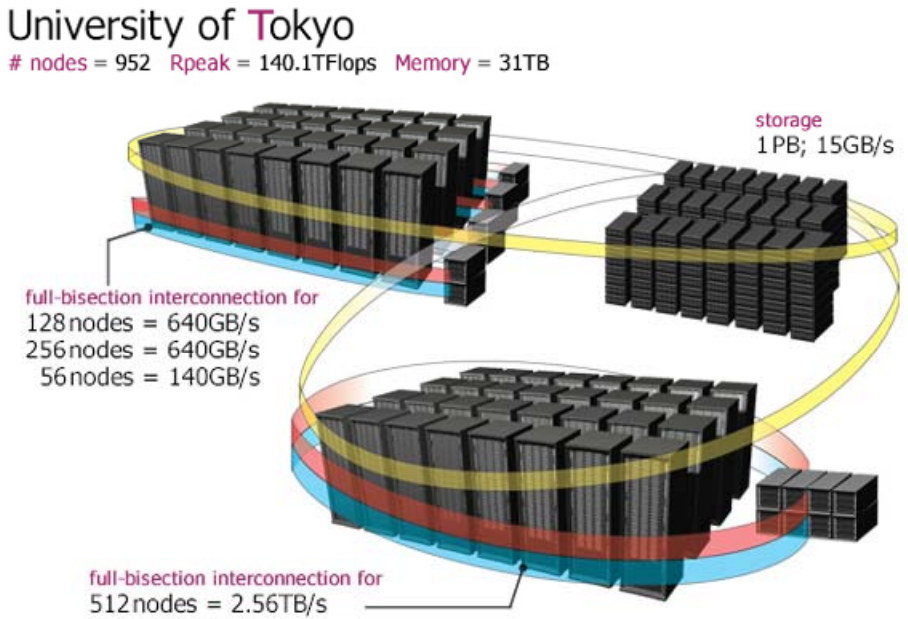
# Goal of this Study

- Parallel FEM Applications with Sparse Matrices on T2K Open Supercomputer (Tokyo) (T2K/Tokyo)
- Hybrid vs. Flat MPI Parallel Programming Models
- Optimization of Hybrid Parallel Programming Models
  - NUMA Control
  - First Touch
  - Further Reordering of Data

# T2K/Tokyo (1/2)

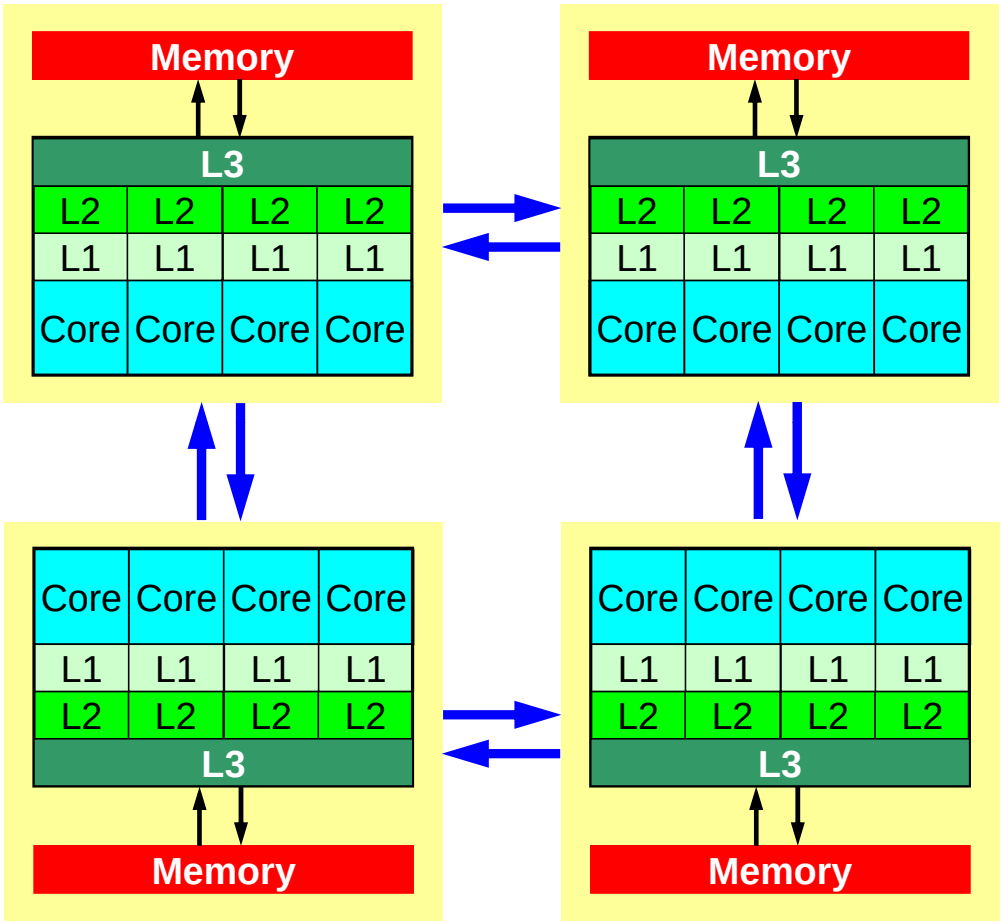
- "T2K Open Supercomputer Alliance"
  - http://www.open-supercomputer.org/
  - Tsukuba, Tokyo, Kyoto

- "T2K Open Supercomputer (Todai Combined Cluster)"
  - by Hitachi
  - op. started June 2008
  - Total 952 nodes (15,232 cores), 141 TFLOPS peak
    - Quad-core Opteron (Barcelona)
  - 27th in TOP500 (NOV 2008) (fastest in Japan)



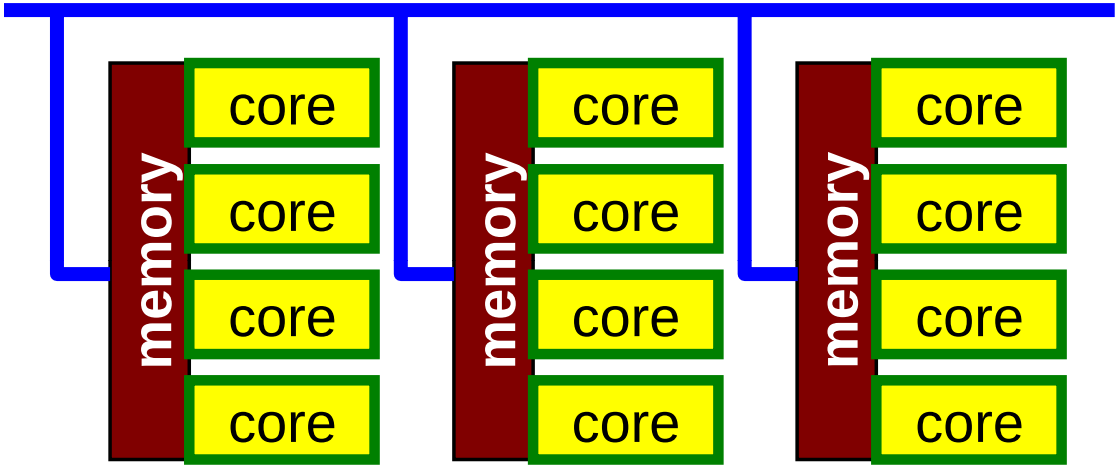
# T2K/Tokyo (2/2)

- AMD Quad-core Opteron (Barcelona) 2.3GHz
- 4 “sockets” per node
  - 16 cores/node
- Multi-core, multi-socket system
- cc-NUMA architecture
  - careful configuration needed
    - local data ~ local memory
  - To reduce memory traffic in the system, it is important to keep the data close to the cores that will work with the data (e.g. NUMA control).

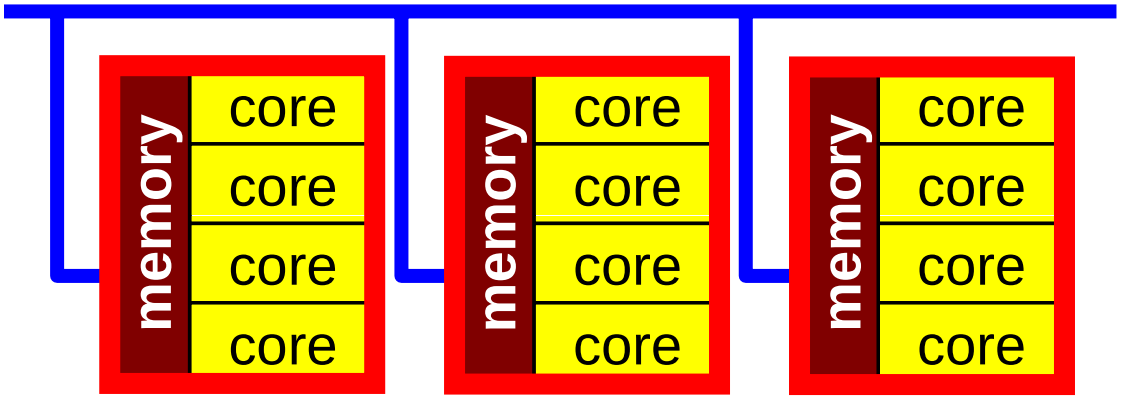


# Flat MPI vs. Hybrid

## Flat-MPI：Each PE -> Independent




## Hybrid：Hierarchal Structure



# Flat MPI vs. Hybrid

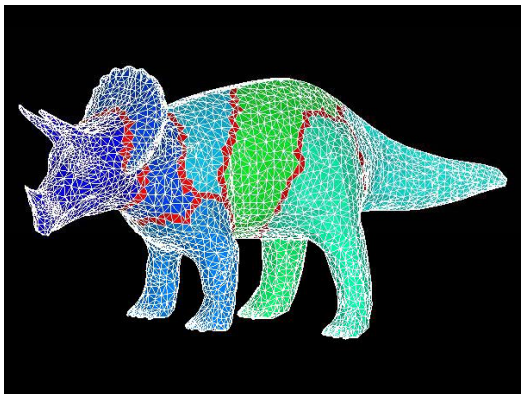
- Performance is determined by various parameters

- Hardware
  - core architecture itself
  - peak performance
  - memory bandwidth, latency
  - network bandwidth, latency
  - their balance
- Software
  - types: memory or network/communication bound
  - problem size

# Sparse Matrix Solvers by FEM, FDM …

```
for (i=0; i<N; i++) {
  for (j=Index(i-1); j<Index(i); j++{
    Y[i]= Y[i] + AMAT[k]*X[Item[k]];
  }
}
```

- Memory-Bound
  - indirect accesses
  - Hybrid (OpenMP) is more memory-bound
- Latency-Bound for Parallel Computations
  - comm.'s occurs only at domain boundaries
  - small amount of messages
- Exascale Systems
  - O($10^8$) cores
  - Terrible Communication Overhead by MPI Latency for > $10^8$-way MPI's
  - **Expectations for Hybrid**
    - **1/16 MPI processes for T2K/Tokyo**

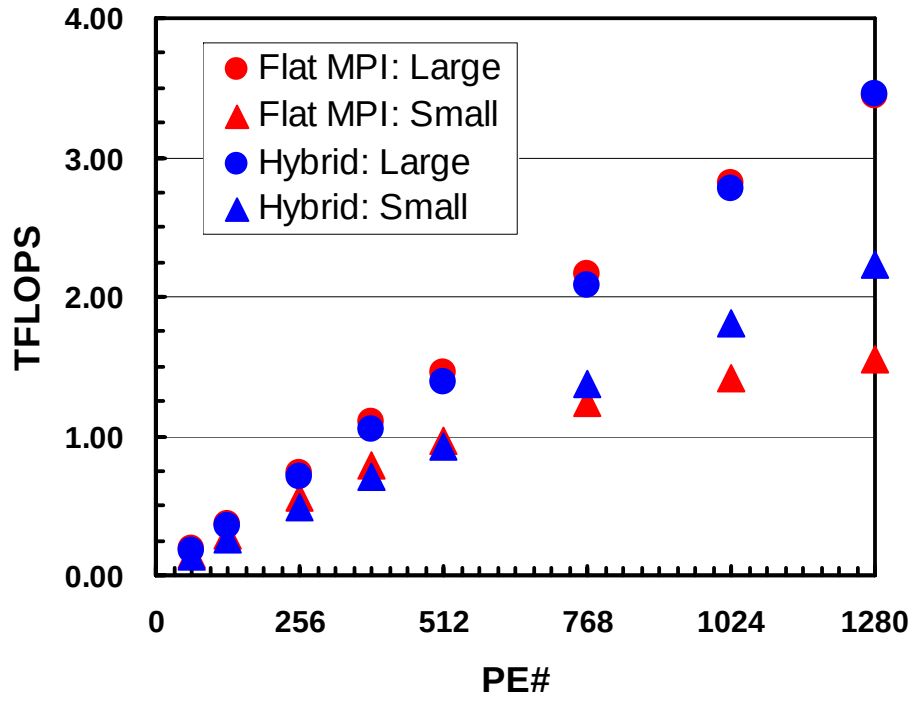


```
for (i=0; i<N; i++) {
```

# Weak Scaling Results on ES

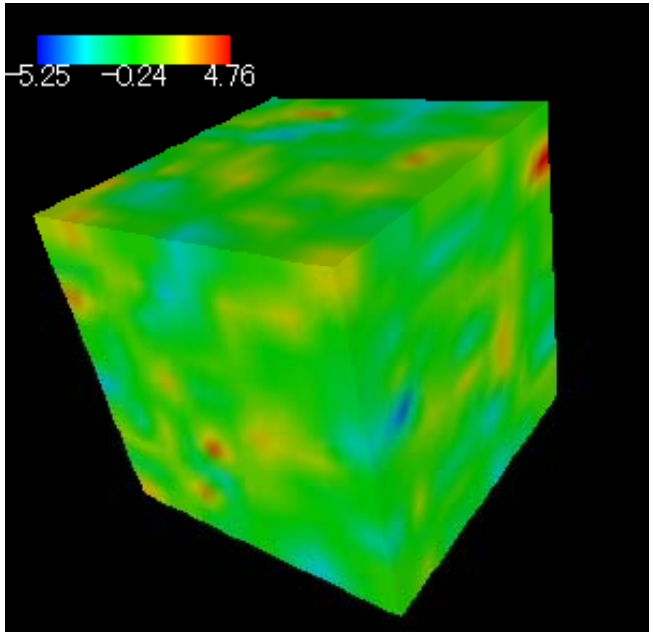
## GeoFEM Benchmarks [KN 2003]

- Generally speaking, hybrid is better for large number of nodes
- especially for small problem size per node
  - “less” memory bound



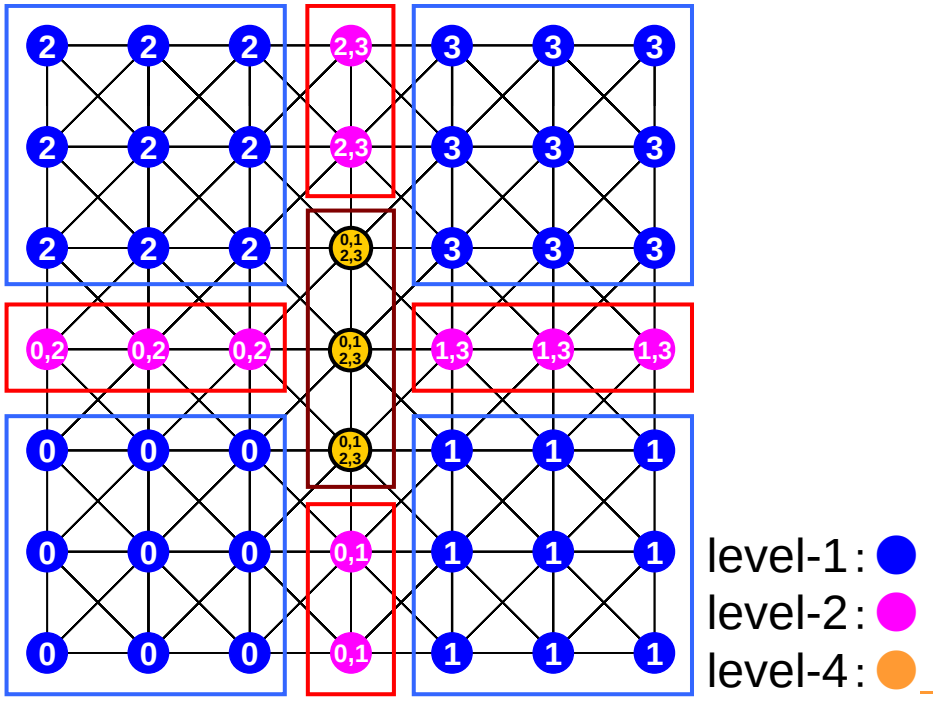
# Target Application

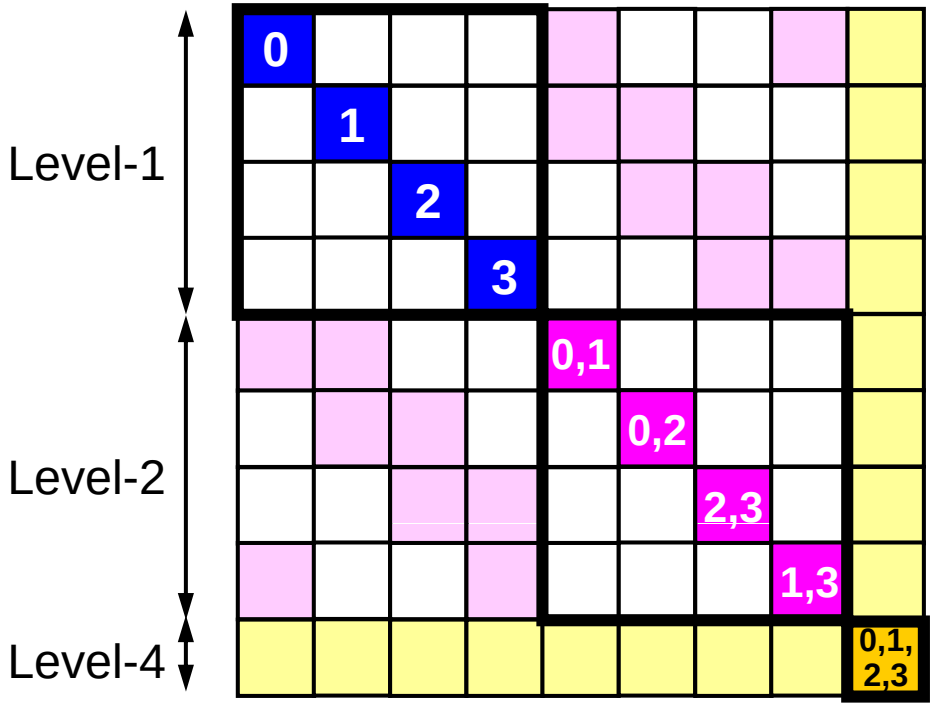
- 3D Elastic Problems with Heterogeneous Material Property
  - $E_{max}=10^{3}$, $E_{min}=10^{-3}$, $\nu=0.25$
    - generated by “sequential Gauss” algorithm for geo-statistics [Deutsch & Journel, 1998]
  - $128^{3}$ tri-linear hexahedral elements, 6,291,456 DOF
    - Strong Scaling
- (SGS+CG) Iterative Solvers
  - Symmetric Gauss-Seidel
  - HID-based domain decomposition
- T2K/Tokyo
  - 512 cores (32 nodes)
- FORTARN90 (Hitachi) + MPI
  - Flat MPI, Hybrid (4x4, 8x2, 16x1)



# HID: Hierarchical Interface Decomposition [Henon & Saad 2007]

- Multilevel Domain Decomposition
  - Extension of Nested Dissection
- Non-overlapped Approach: Connectors, Separators
- Suitable for Parallel Preconditioning Method

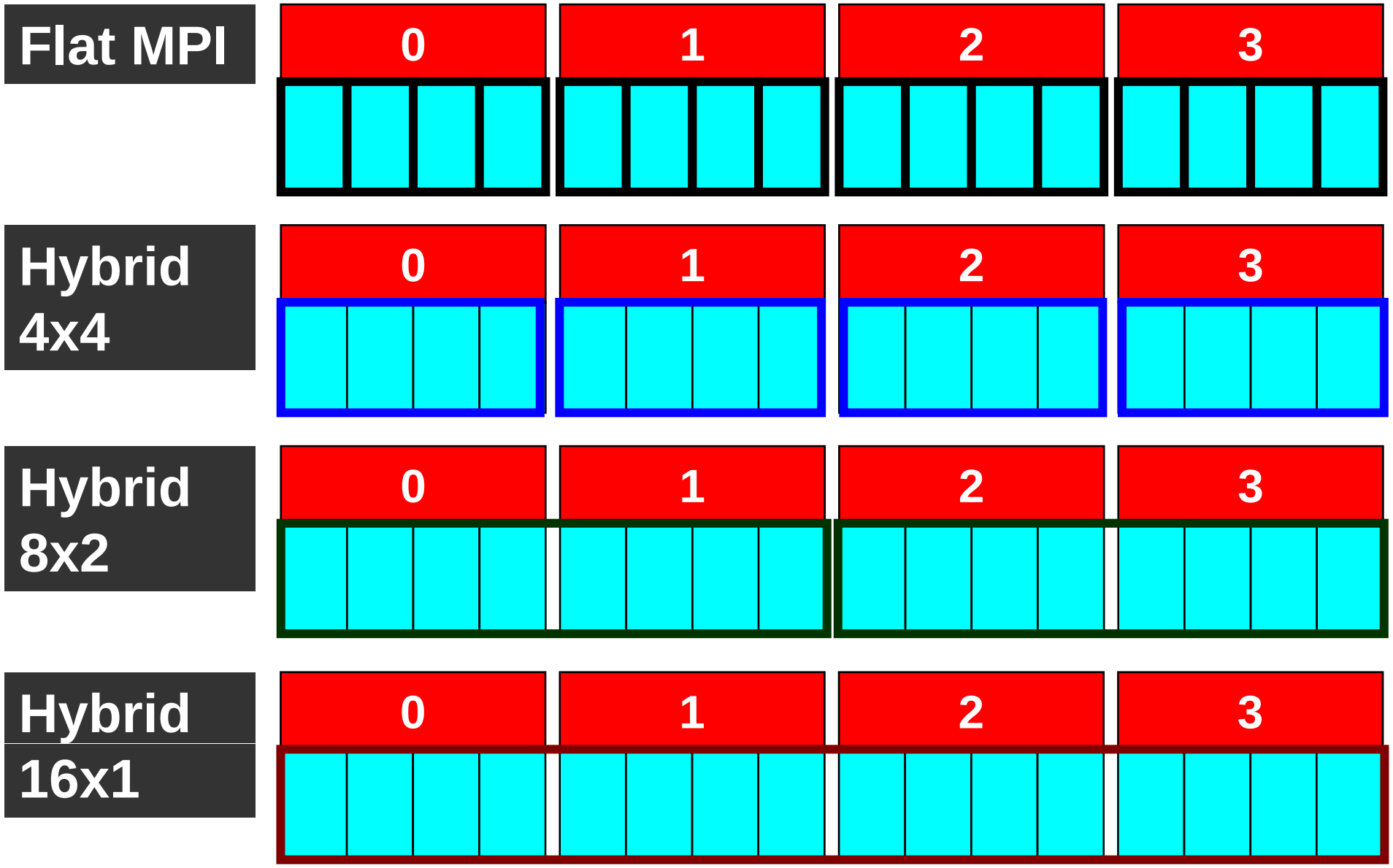


# Parallel Preconditioned Iterative Solvers on an SMP/Multicore node by OpenMP

- DAXPY, SMVP, Dot Products
  - Easy
- Factorization, Forward/Backward Substitutions in Preconditioning Processes
  - Global dependency
  - Reordering for parallelism required: forming independent sets
  - Multicolor Ordering (MC), Reverse-Cuthill-Mckee (RCM)
  - Works on “Earth Simulator” [KN 2002,2003]
    - both for parallel/vector performance
- CM-RCM (Cyclic Multi Coloring + RCM)
  - robust and efficient
  - elements on each color are independent

# Flat MPI, Hybrid (4x4, 8x2, 16x1)



# CASES for Evaluation

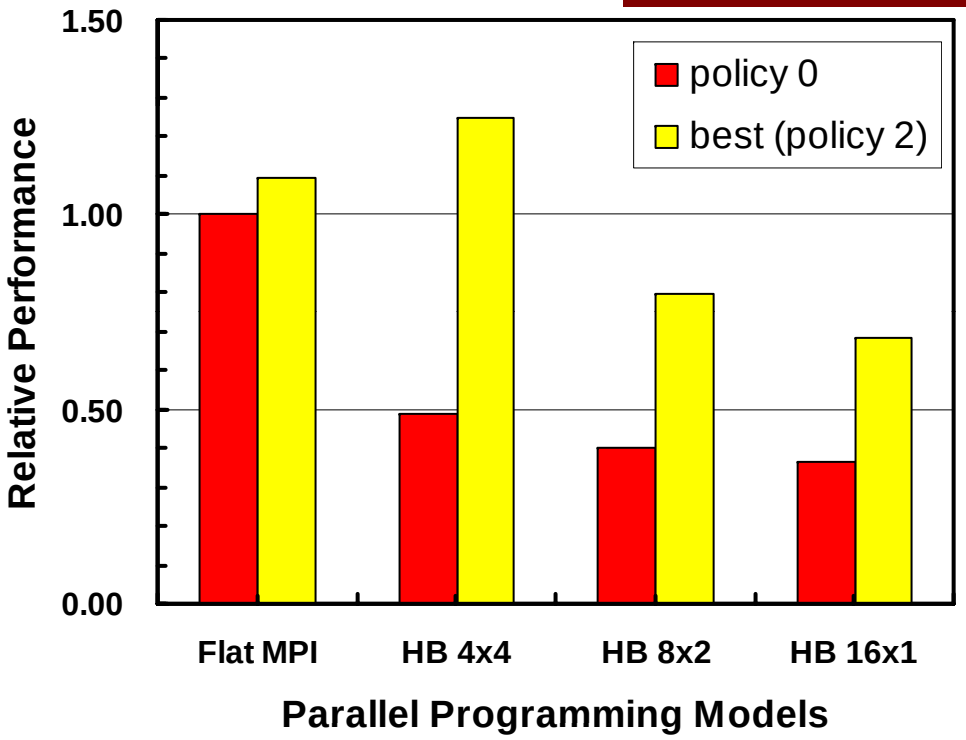
- CASE-1
  - initial case (CM-RCM)
  - for evaluation of NUMA control effect
    - specifies local core-memory configulation
- CASE-2 (Hybrid only)
  - First-Touch
- CASE-3 (Hybrid only)
  - Further Data Reordering + First-Touch
- NUMA policy (0-5) for each case

# Results of CASE-1, 32 nodes/512cores

## computation time for linear solvers

| Policy ID | Command line switches |
|---|---|
| 0 | no command line switches |
| 1 | `--cpunodebind=$SOCKET --interleave=all` |
| 2 | `--cpunodebind=$SOCKET --interleave=$SOCKET` |
| 3 | `--cpunodebind=$SOCKET --membind=$SOCKET` |
| 4 | `--cpunodebind=$SOCKET --localalloc` |
| 5 | `--localalloc` |

**Normalized by Flat MPI (Policy 0)**




| Method | Iterations | Best Policy CASE-1 |
|---|---|---|
| Flat MPI | 1264 | 2 |
| HB 4x4 | 1261 | 2 |
| HB 8x2 | 1216 | 2 |
| HB 16x1 | 1244 | 2 |

e.g. mpirun –np 64 –cpunodebind 0,1,2,3 a.out

# First Touch Data Placement

ref. “Patterns for Parallel Programming” Mattson, T.G. et al.

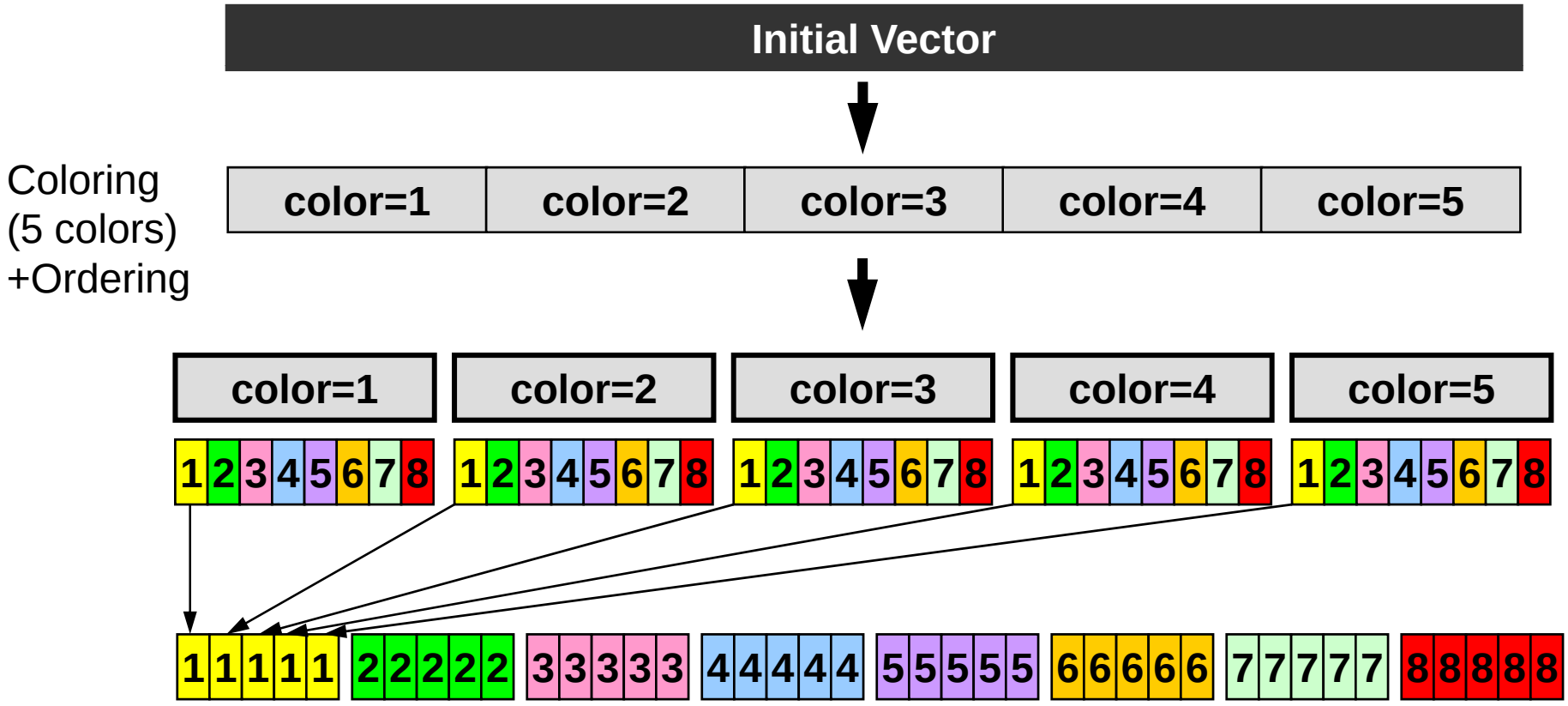
To reduce memory traffic in the system, it is important to keep the data close to the PEs that will work with the data (e.g. NUMA control).

On NUMA computers, this corresponds to making sure the pages of memory are allocated and “owned” by the PEs that will be working with the data contained in the page.

The most common NUMA page-placement algorithm is the “first touch” algorithm, in which the PE first referencing a region of memory will have the page holding that memory assigned to it.

A very common technique in OpenMP program is to initialize data in parallel using the same loop schedule as will be used later in the computations.

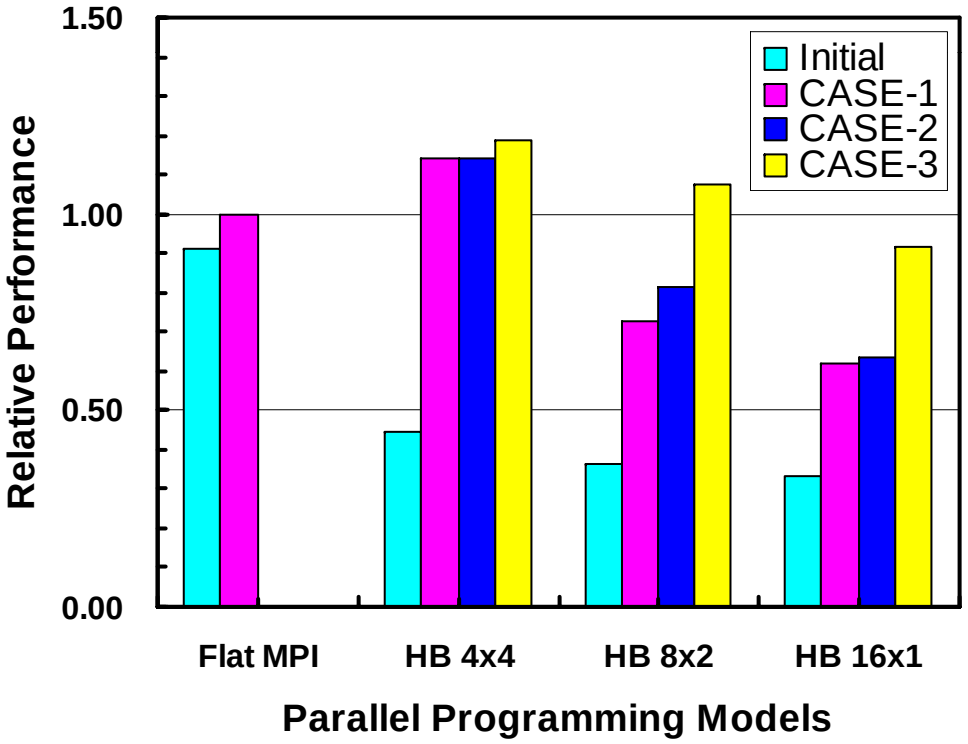
# Further Re-Ordering for Continuous Memory Access 5 colors, 8 threads



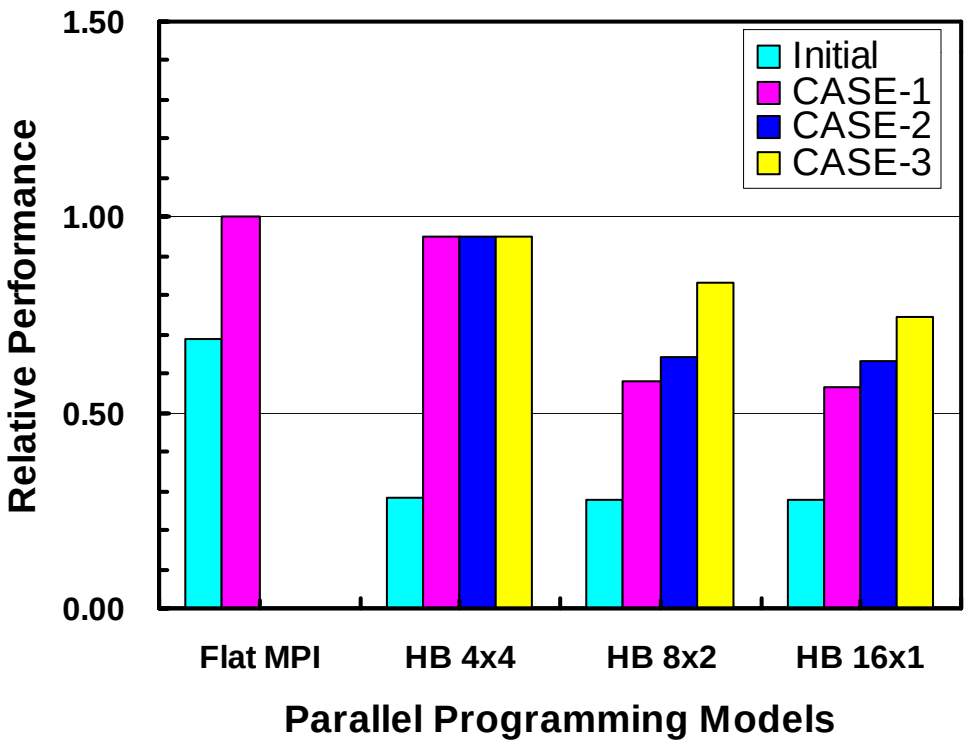
# Improvement: CASE-1 ⇒ CASE-3

## Normalized by the Best Performance of Flat MPI

**32nodes, 512cores**
**196,608 DOF/node**

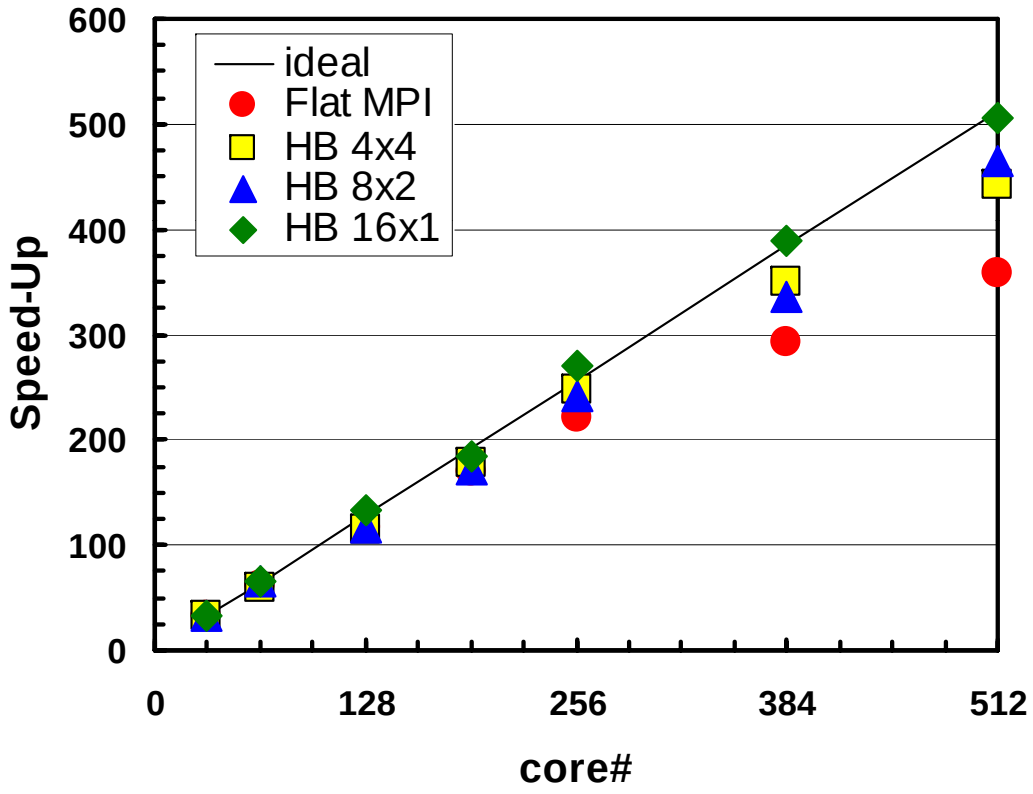



**8nodes, 128cores**
**786,432 DOF/node**



# Strong Scalability (Best Cases)

## 32~512 cores



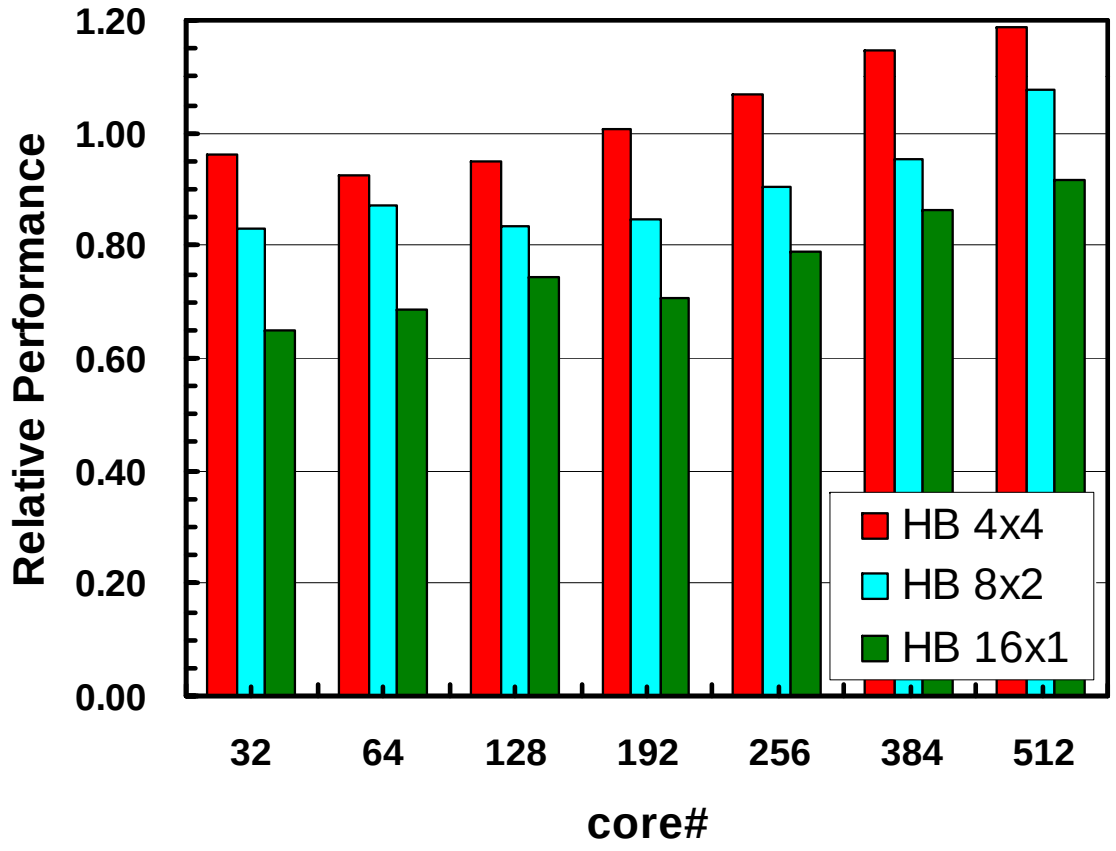

| 2 nodes, 32 cores | | |
|---|---|---|
| Method | ITERATIONS | sec. |
| Flat MPI | 1284 | 335.2 |
| HB 4x4 | 1186 | 348.9 |
| HB 8x2 | 1232 | 403.5 |
| HB 16x1 | 1353 | 515.8 |

| 32 nodes, 512 cores | | |
|---|---|---|
| Method | ITERATIONS | sec. |
| Flat MPI | 1264 | 29.9 |
| HB 4x4 | 1261 | 25.2 |
| HB 8x2 | 1216 | 27.8 |
| HB 16x1 | 1244 | 32.7 |

# Relative Performance for Strong Scaling (Best Cases)

32~512 cores

Normalized by BEST Flat MPI at each core#



# Summary & Future Works

- HID for Ill-Conditioned Problems on T2K/Tokyo
  - Hybrid/Flat MPI, CM-RCM reordering
- Hybid 4x4 and Flat MPI are competitive
- Data locality and continuous memory access by (further re-ordering + F.T.) provide significant improvement on Hybrid 8x2/16x1.
- Performance of Hybrid is improved when,
  - many cores, smaller problem size/core (strong scaling)
- Future Works
  - Extension to Atmospheric & Ocean Simulations
    - Multigrid Solvers for Poisson Equations