

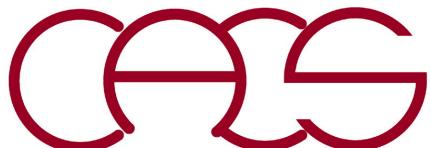
Parallel Molecular Dynamics

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Parallel-computing basics using MD as an example



Parallel Computing

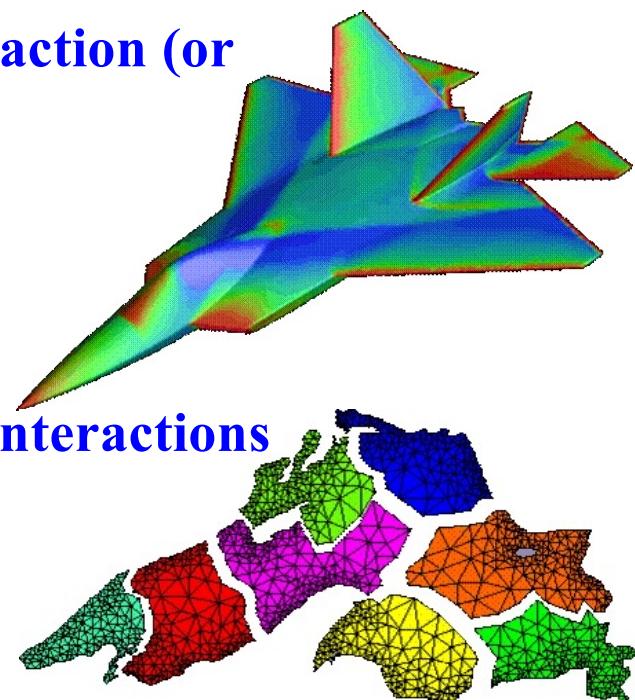
Glossary

- **Parallel algorithm design = decomposition (who does what?)**
 - Task: Units of computation into which the main computation is subdivided
 - Decomposition: Dividing a computation into subsets of tasks that may be executed in parallel
- **Goal of parallel algorithm design = maximize concurrency & minimize task dependency/interaction**
 - Concurrency: The maximum number of tasks that can be executed simultaneously in parallel (limited by task dependency/interaction)
 - Task dependency: A task depends on another task, if the former uses data produced by the latter; represented by a directed acyclic graph called **task-dependency graph**
 - Task interaction: Tasks share inputs, outputs or intermediate data
- **Granularity: Size of decomposed tasks:** **fine-grained** = a large number of small tasks; **coarse-grained** = a small number of large tasks
- **Mapping:** Assign tasks (or processes = running programs to perform the tasks) to processors

A. Grama, A. Gupta, G. Karypis, & V. Kumar,
Introduction to Parallel Computing, 2nd Ed. (Addison-Wesley, '03) Chap. 3

Parallel Algorithm Design

- **Decomposition** (example: molecular dynamics)
 - Spatial decomposition (\approx domain decomposition)—coarse-grained
 - Particle decomposition—single-instruction multiple-data (SIMD) computers
 - Force decomposition—fine-grained
- **Maximal-concurrency algorithm:** Expose data locality in the problem (e.g. divide-&-conquer)
- **Scalability:** Achieve a large fraction of perfect speed-up (= number of processors) on a large number of processors
- **Load balancing:** Keep all processors equally busy
- **Optimization:** Optimal mapping to minimize task interaction (or communication between processes)
 - Owner-computes rule
 - Minimize the volume & frequency of data exchanges
 - Computation-communication overlapping
 - Data & computation replication
- **Issues:** Regular vs. irregular & static vs. dynamic task interactions



Parallel Supercomputers

Rank	System	Cores	Rmax (PFlop/s)	Rpeak (PFlop/s)	Power (kW)
1	Frontier - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot-11, HPE DOE/SC/Oak Ridge National Laboratory United States	8,730,112	1,102.00	1,685.65	21,100
2	Supercomputer Fugaku - Supercomputer Fugaku, A64FX 48C 2.2GHz, Tofu interconnect D, Fujitsu RIKEN Center for Computational Science Japan	7,630,848	442.01	537.21	29,899
3	LUMI - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot-11, HPE EuroHPC/CSC Finland	1,110,144	151.90	214.35	2,942
4	Summit - IBM Power System AC922, IBM POWER9 22C 3.07GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband, IBM DOE/SC/Oak Ridge National Laboratory United States	2,414,592	148.60	200.79	10,096
5	Sierra - IBM Power System AC922, IBM POWER9 22C 3.1GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband, IBM / NVIDIA / Mellanox DOE/NNSA/LLNL United States	1,572,480	94.64	125.71	7,438

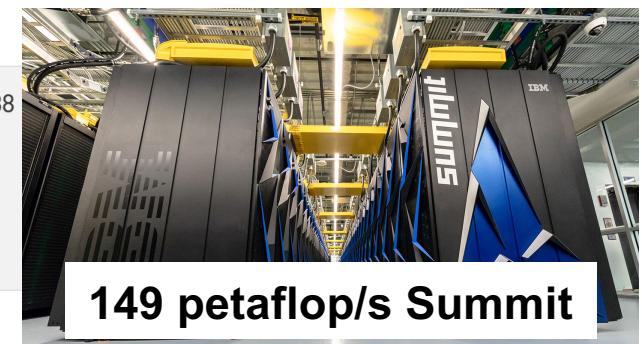
Measured performance
(in Tflop/s)

Theoretical
performance

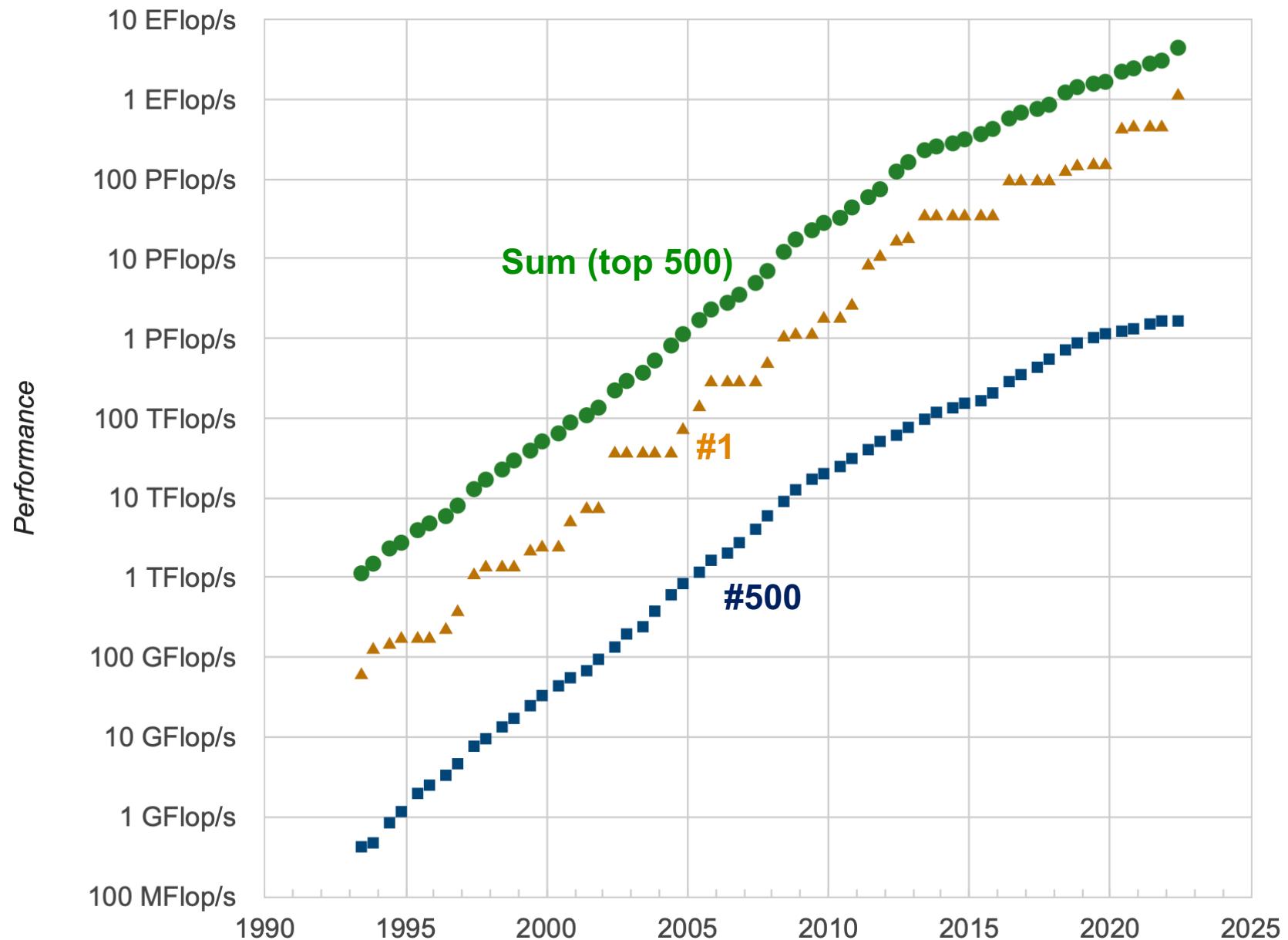
<http://www.top500.org> (June '22)

**flops =
floating-point
operations/second**

M (mega) = 10^6
G (giga) = 10^9
T (Tera) = 10^{12}
P (Peta) = 10^{15}
E (Exa) = 10^{18}
Z (Zetta) = 10^{21}
Y (Yotta) = 10^{24}



Performance Development



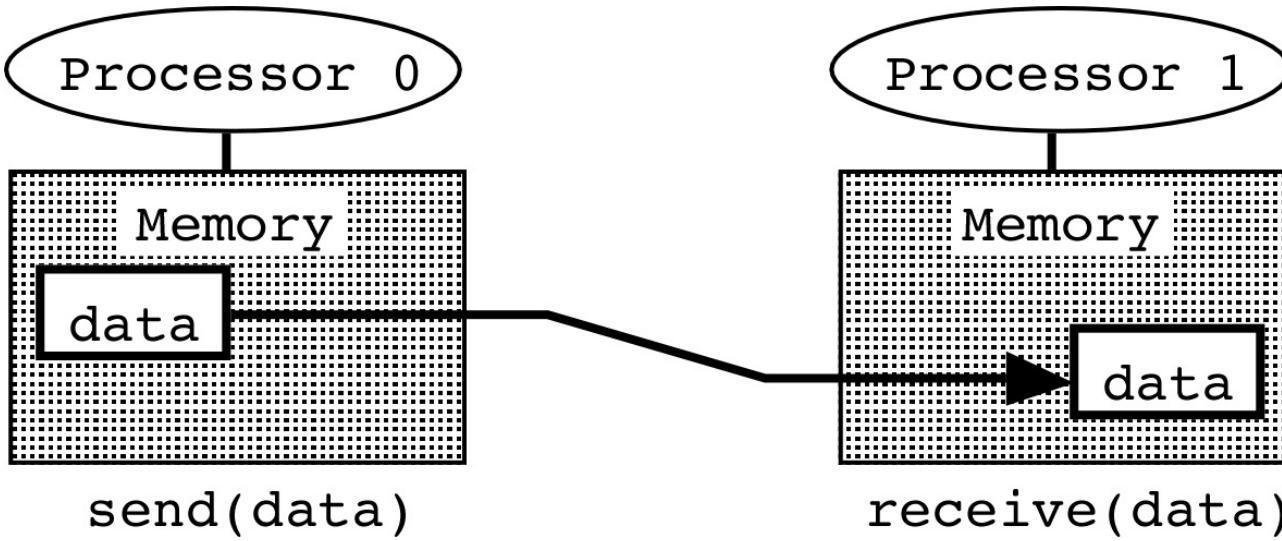
Message Passing Interface

MPI (Message Passing Interface): A standard message passing system that enables us to write & run applications on parallel computers (<http://www.mcs.anl.gov/mpi>).

```
#include "mpi.h"
#include <stdio.h>
main(int argc, char *argv[ ]) {
    MPI_Status status;
    int myid;
    int n;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &myid);
    if (myid == 0) {
        n = 777;
        MPI_Send(&n, 1, MPI_INT, 1, 10, MPI_COMM_WORLD);
    } else {
        MPI_Recv(&n, 1, MPI_INT, 0, 10, MPI_COMM_WORLD, &status);
        printf("n = %d\n", n);
    }
    MPI_Finalize();
}
```

The diagram illustrates the MPI message exchange between two MPI ranks, P0 and P1. Rank P0 is shown at the top, and rank P1 is shown at the bottom. An arrow labeled "send to 1" points from P0 to P1, indicating that P0 is sending a message to P1. Another arrow labeled "recv from 0" points from P1 to P0, indicating that P1 is receiving a message from P0. The MPI code on the left shows the specific MPI calls used for this exchange: MPI_Send and MPI_Recv. The MPI_Send call is annotated with "Data triplet" under the argument &n, "To/from whom" under the argument 1, and "Matching message labels" under the argument 10. The MPI_Recv call is annotated with "Data triplet" under the argument &n, "To/from whom" under the argument 0, and "Matching message labels" under the argument 10. Arrows point from these annotations to the corresponding arguments in the MPI code.

Single Program Multiple Data (SPMD)



Process 0

```
if (myid == 0) {  
    n = 777;  
    MPI_Send(&n,...);  
}  
else {  
    MPI_Recv(&n,...);  
    printf(...);  
}
```

Process 1

```
if (myid == 0) {  
    n = 777;  
    MPI_Send(&n,...);  
}  
else {  
    MPI_Recv(&n,...);  
    printf(...);  
}
```

```
cSCI653_to_do()  
{  
    if (I == student)  
    {  
        do_assignment();  
        MPI_Send(...);  
    }  
    else if (I == teacher)  
    {  
        MPI_Recv(...);  
        grade();  
    }  
}
```

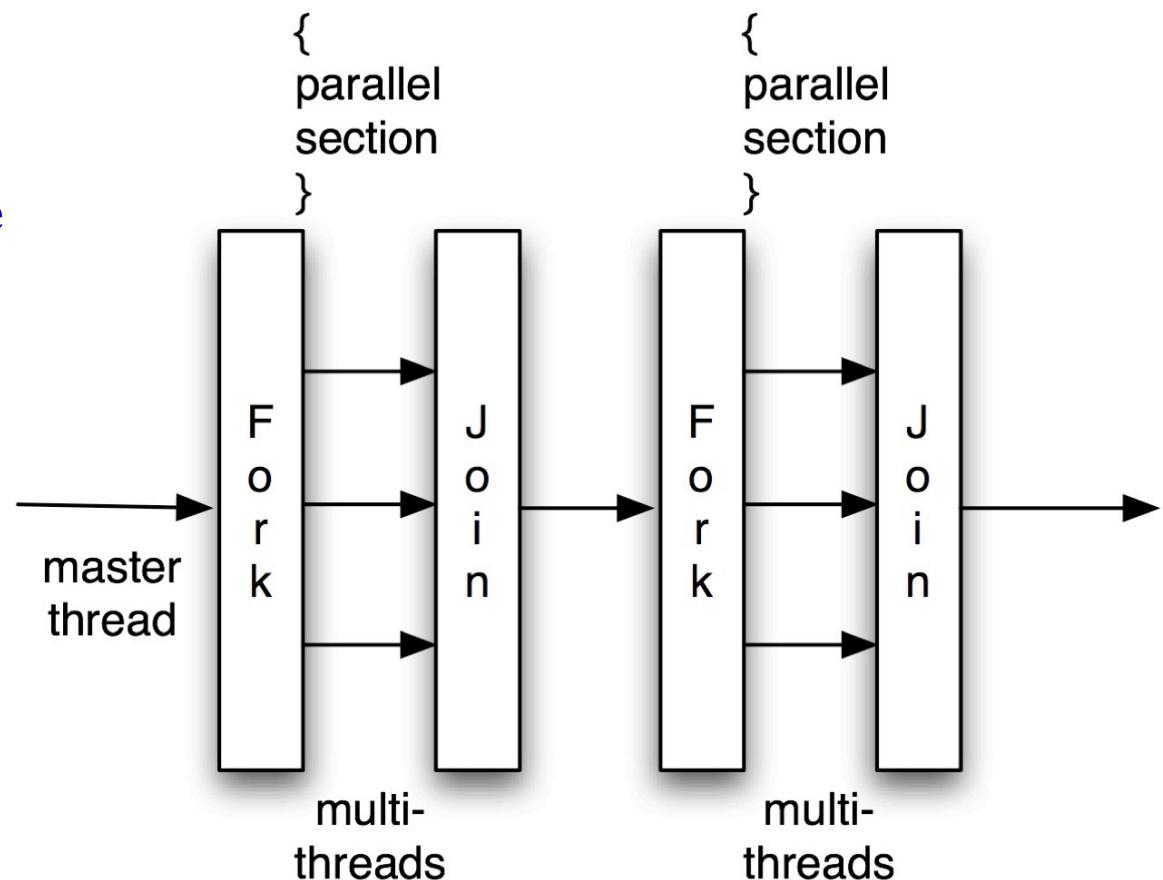
Parallel programming = choreography of “who does what”?

OpenMP

- OpenMP (Open specifications for Multi Processing): Portable application program interface (API) for shared-memory parallel programming based on multi-threading by compiler directives (<http://www.openmp.org>)
processes (= running programs) sharing resources
- Fork-join parallelism:
 - > Fork: Master thread spawns a team of threads as needed
 - > Join: When the team of threads complete the statements in the parallel section, they terminate synchronously, leaving only the master thread
- OpenMP is typically used to parallelize loops
- OpenMP threads communicate by sharing variables

On HPC, compile as

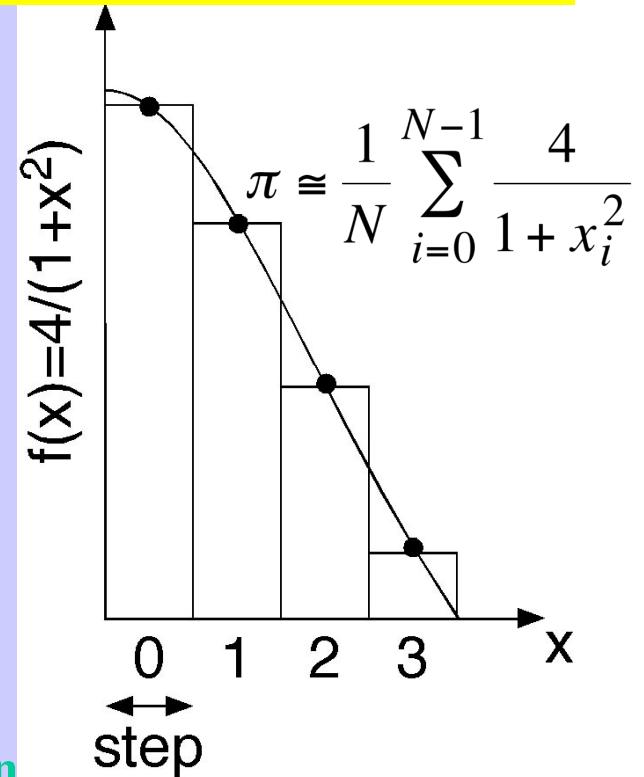
```
> cc ... -fopenmp  
> mpicc ... -fopenmp
```



OpenMP Programming

```
#include <stdio.h>
#include <omp.h>
#define NBIN 100000
#define MAX_THREADS 8
void main() {
    int nthreads,tid;
    double step,sum[MAX_THREADS]={0.0},pi=0.0;
    step = 1.0/NBIN;
#pragma omp parallel private(tid)
{
    int i;
    double x;
    nthreads = omp_get_num_threads();
    tid = omp_get_thread_num();
    for (i=tid; i<NBIN; i+=nthreads) {
        x = (i+0.5)*step;
        sum[tid] += 4.0/(1.0+x*x);}
    } data privatization to avoid race condition
    for(tid=0; tid<nthreads; tid++) pi += sum[tid]*step;
    printf("PI = %f\n",pi);
}
```

Array of partial sums
for multi-threads



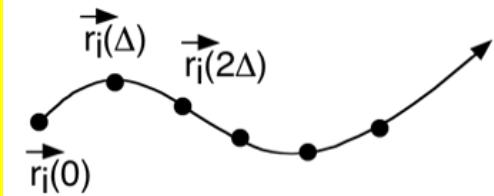
parallel section

- Obtain the number of threads & my thread ID
- By default, all variables are shared unless selectively changing storage attributes using private clauses

Molecular Dynamics Algorithm

Time discretization

$$\begin{cases} \vec{r}_i(t + \Delta) = \vec{r}_i(t) + \vec{v}_i(t)\Delta + \frac{1}{2}\vec{a}_i(t)\Delta^2 \\ \vec{v}_i(t + \Delta) = \vec{v}_i(t) + \frac{\vec{a}_i(t) + \vec{a}_i(t + \Delta)}{2}\Delta \end{cases} \quad \vec{a}_i = -\frac{1}{m}\frac{\partial V}{\partial \vec{r}_i}$$



Time stepping: Velocity Verlet algorithm

Given $(\vec{r}_i(t), \vec{v}_i(t))$,

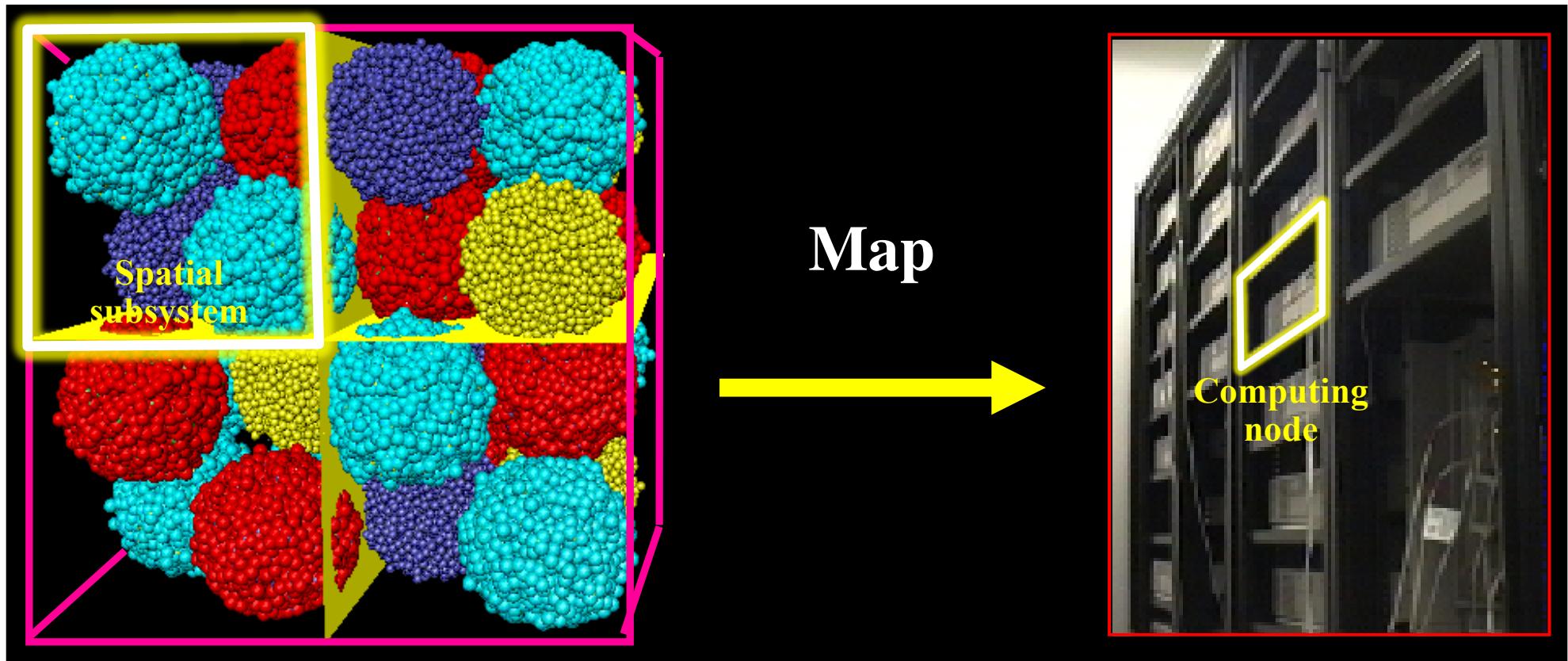
1. (Compute $\vec{a}_i(t)$ as a function of $\{\vec{r}_i(t)\}$)
2. $\vec{v}_i\left(t + \frac{\Delta}{2}\right) \leftarrow \vec{v}_i(t) + \frac{\Delta}{2}\vec{a}_i(t)$
3. $\vec{r}_i(t + \Delta) \leftarrow \vec{r}_i(t) + \vec{v}_i\left(t + \frac{\Delta}{2}\right)\Delta$
4. Compute $\vec{a}_i(t + \Delta)$ as a function of $\{\vec{r}_i(t + \Delta)\}$
5. $\vec{v}_i(t + \Delta) \leftarrow \vec{v}_i\left(t + \frac{\Delta}{2}\right) + \frac{\Delta}{2}\vec{a}_i(t + \Delta)$

Parallel Molecular Dynamics

Spatial decomposition (short ranged):

1. Divide the physical space into subspaces of equal volume
2. Assign each subspace to a compute node (more generally, to a process) in a parallel computer
3. Each node computes forces on the atoms in its subspace & updates their positions & velocities

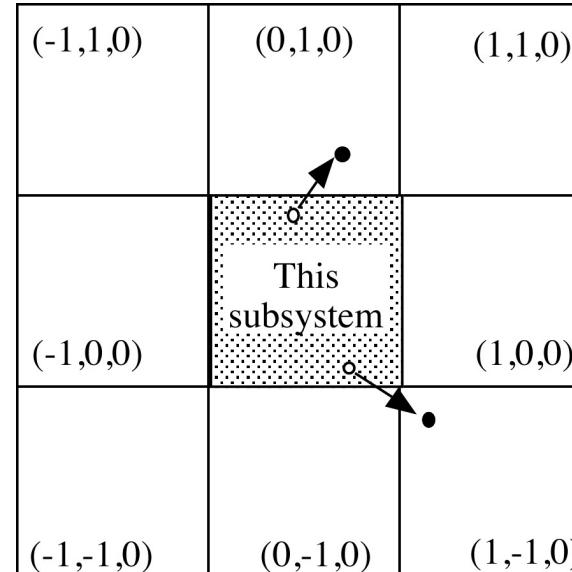
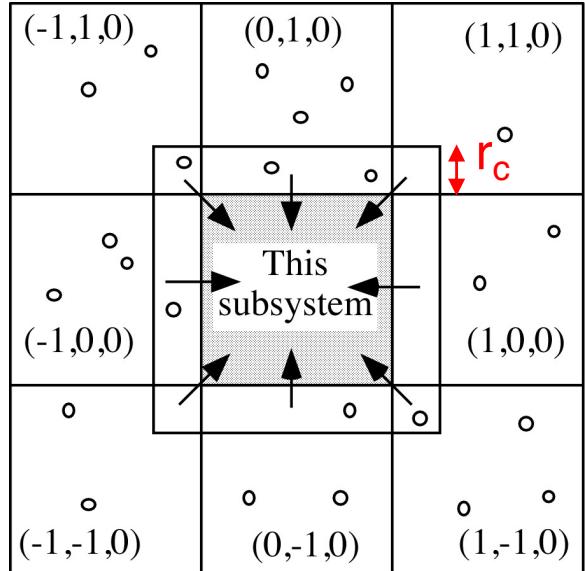
or MPI rank



Parallel MD Algorithm

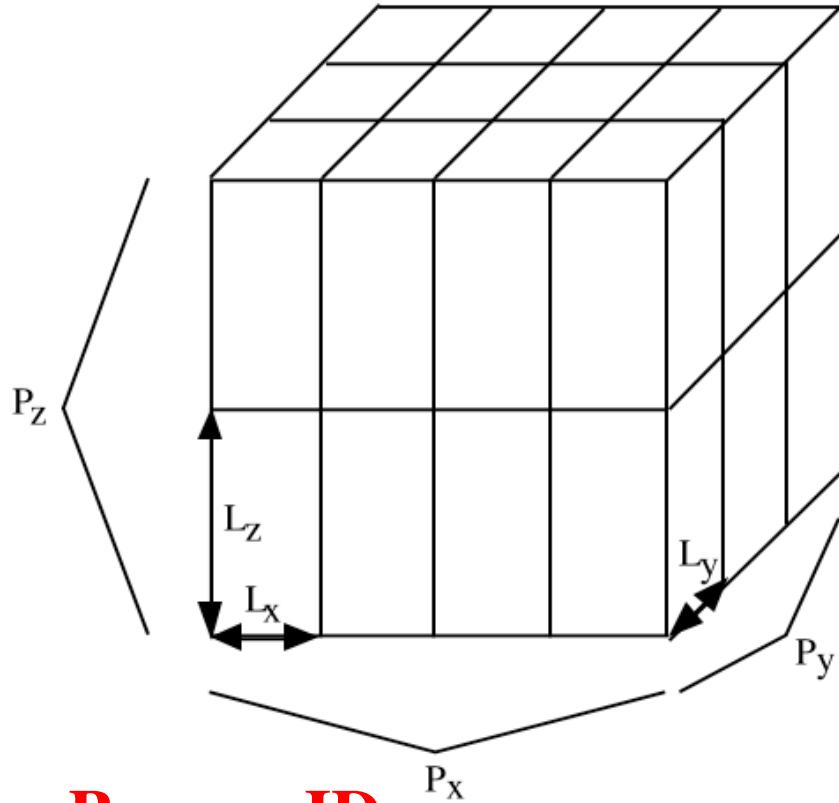
1. $\vec{v}_i\left(t + \frac{\Delta}{2}\right) \leftarrow \vec{v}_i(t) + \frac{\Delta}{2} \vec{a}_i(t)$
2. $\vec{r}_i(t + \Delta) \leftarrow \vec{r}_i(t) + \vec{v}_i\left(t + \frac{\Delta}{2}\right) \Delta$
3. **atom_move()** // migrate moved-out atoms
4. **atom_copy()** // cache surface atoms
5. Compute $\vec{a}_i(t + \Delta)$ as a function of $\{\vec{r}_i(t + \Delta)\}$
6. $\vec{v}_i(t + \Delta) \leftarrow \vec{v}_i\left(t + \frac{\Delta}{2}\right) + \frac{\Delta}{2} \vec{a}_i(t + \Delta)$

atom_copy()



atom_move()

Spatial Decomposition



- Process ID

Vector

$$p_x = p / (P_y P_z)$$

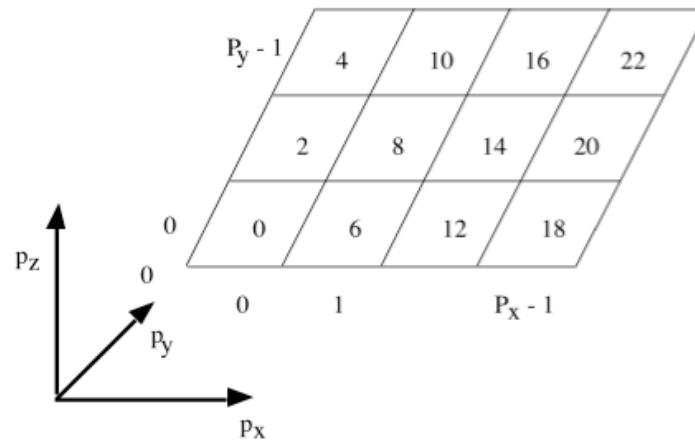
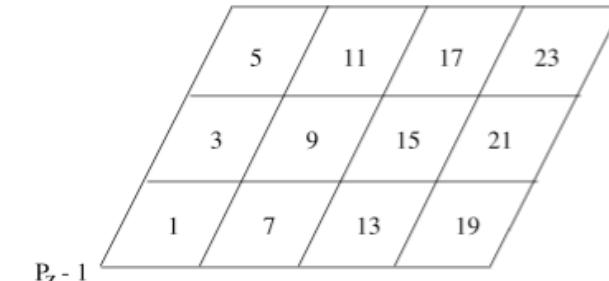
$$p_y = (p / P_z) \bmod P_y$$

$$p_z = p \bmod P_z$$

Scalar

$$p = p_x \times P_y P_z + p_y \times P_z + p_z \text{ Rank}$$

Which 3D
subspace?



$$\text{nproc} = \text{vproc}[0] \times \text{vproc}[1] \times \text{vproc}[2]$$

In **pmd.h**

$P_x \quad P_y \quad P_z$

```
int vproc[3] = {1, 1, 2}, nproc = 2;
```

In **pmd.c**

```
MPI_Comm_rank(MPI_COMM_WORLD, &sid);
vid[0] = sid / (vproc[1] * vproc[2]);
vid[1] = (sid / vproc[2]) % vproc[1];
vid[2] = sid % vproc[2];
```

Neighbor Process ID

$$p'_\alpha(\kappa) = [p_\alpha + \delta_\alpha(\kappa) + P_\alpha] \bmod P_\alpha \quad (\kappa = 0, \dots, 5; \alpha = x, y, z)$$

$$p'(\kappa) = p'_x(\kappa) \times P_y P_z + p'_y(\kappa) \times P_z + p'_z(\kappa)$$

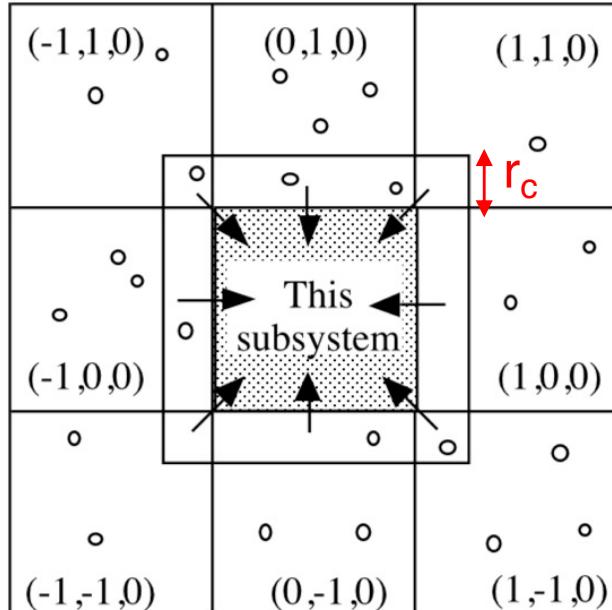
Neighbor ID, κ	$\vec{\delta} = (\delta_x, \delta_y, \delta_z)$	$\vec{\Delta} = (\Delta_x, \Delta_y, \Delta_z)$
0 (east)	(-1, 0, 0)	($-L_x$, 0, 0)
1 (west)	(1, 0, 0)	(L_x , 0, 0)
2 (north)	(0, -1, 0)	(0, $-L_y$, 0)
3 (south)	(0, 1, 0)	(0, L_y , 0)
4 (up)	(0, 0, -1)	(0, 0, $-L_z$)
5 (down)	(0, 0, 1)	(0, 0, L_z)

- L_x, L_y & L_z are the box lengths *per process* in the x, y & z directions
 - Atom coordinates are in the range $[0, L_\alpha]$ ($\alpha = x, y, z$) in each process

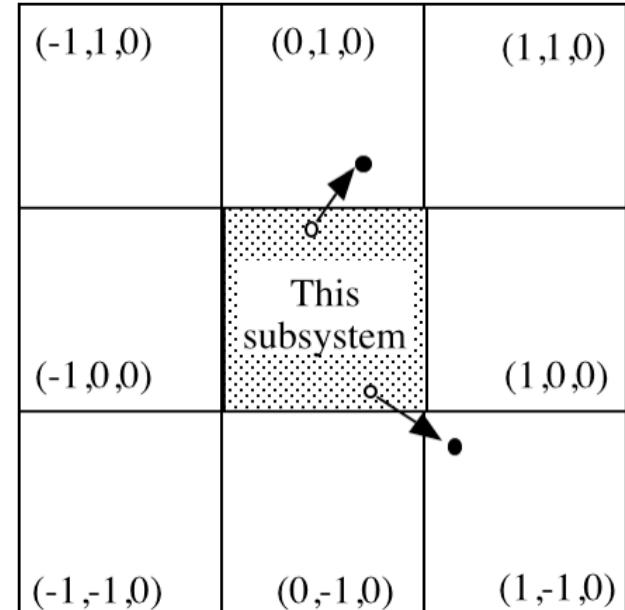
In pmd.c

Parallel MD Concepts

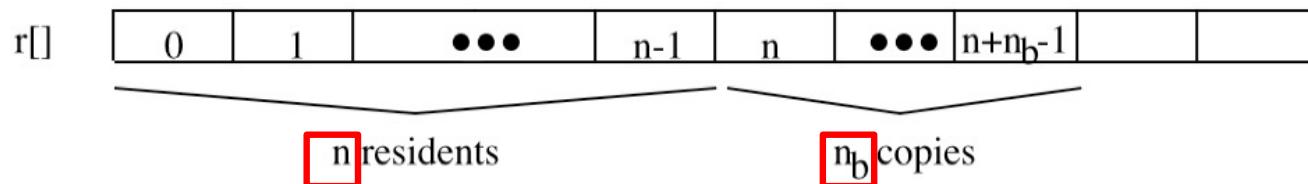
Atom caching



Atom migration



1. First half kick to obtain $v_i(t+Dt/2)$
2. Update atomic coordinates to obtain $r_i(t+Dt)$
3. **`atom_move()`:** Migrate the moved-out atoms to the neighbor processes
4. **`atom_copy()`:** Copy the surface atoms within distance r_c from the neighbors
5. **`compute_accel()`:** Compute new accelerations, $a_i(t+Dt)$, including the contributions from the cached atoms
6. Second half kick to obtain $v_i(t+Dt)$



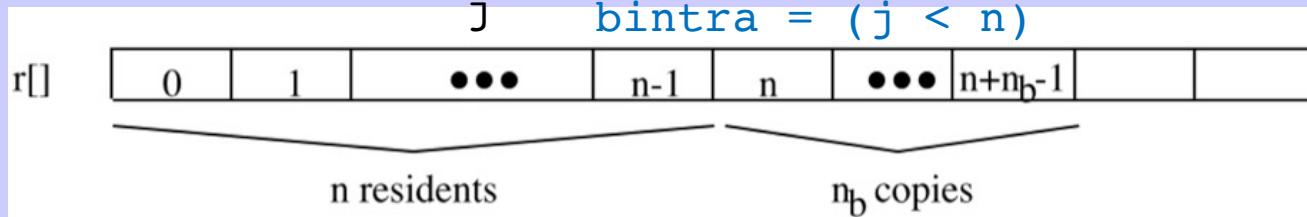
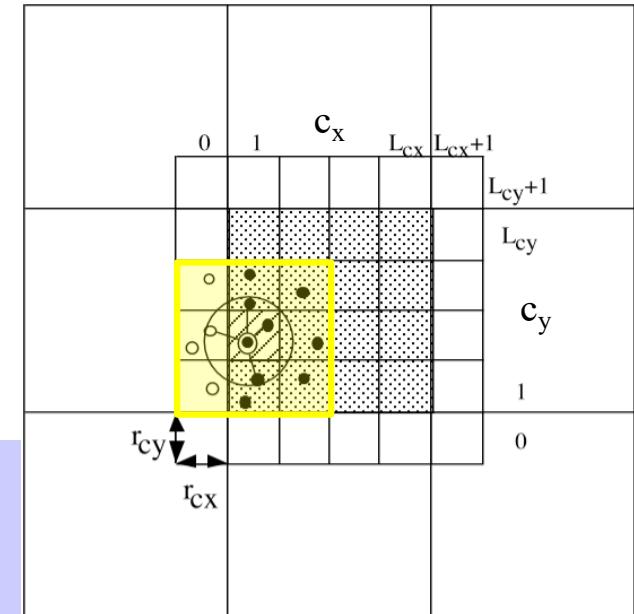
Parallel Interaction Computation

SPMD: Who does what?

Each process computes:

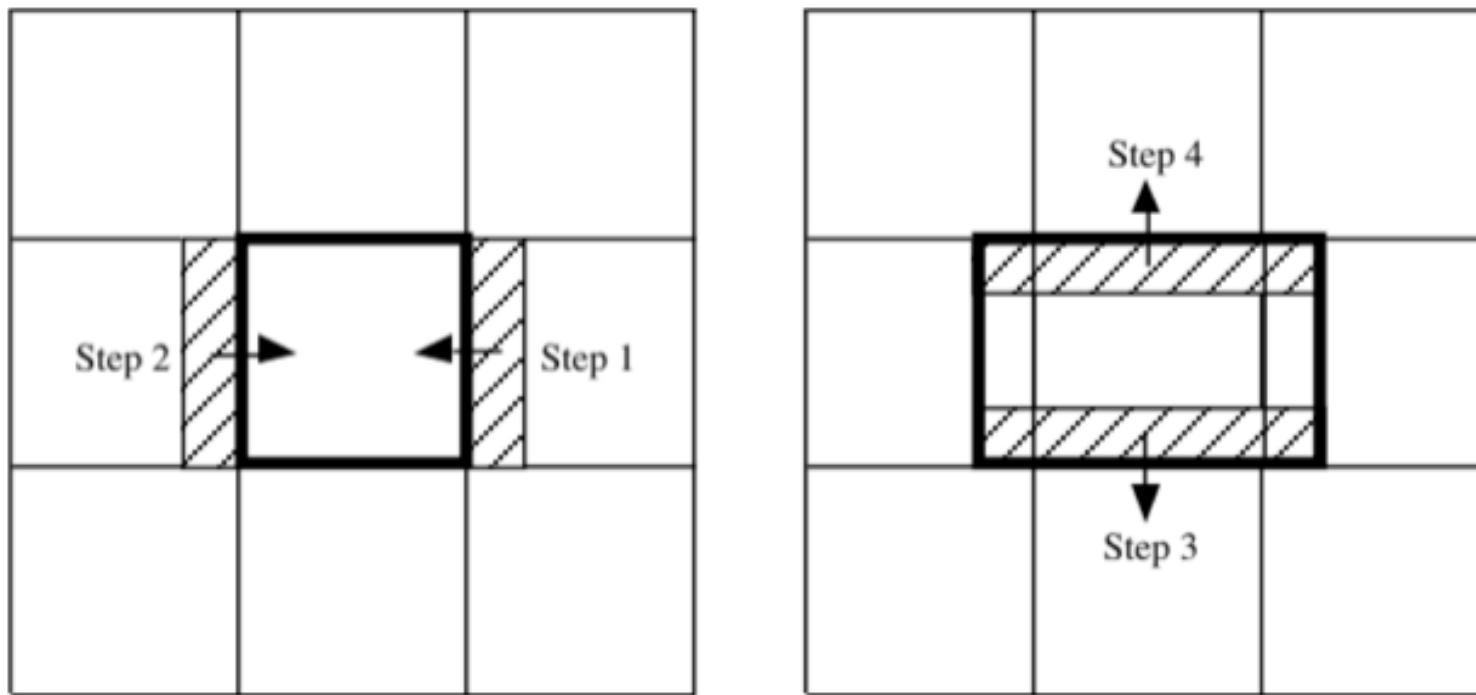
1. The forces on its resident atoms
2. The potential energy between resident pairs & 1/2 of that between resident-cached pairs

```
for resident cells, c {  
    for neighbor (resident or cached) cells, c1 {  
        scan atom i in cell c using c's linked list {  
            scan atom j in cell c1 using c1's linked list {  
                ...  
                if (i<j && rij<rc2) {  
                    compute pair force aij & potential u(rij)  
                    bintra = j < n; /* j is resident? */  
                    ai += aij; if (bintra) aj -= aij;  
                    if (bintra) lpe += u(rij); else lpe += u(rij)/2;  
                }  
            }  
        }  
    }  
}  
MPI_Allreduce(&lpe, &potEnergy,...,MPI_SUM,...);
```



global reduction over MPI ranks

Atom Caching: atom_copy()



26-step → 6-step communication by message forwarding

Reset the number of received cache atoms, nbnew = 0

for x, y, and z directions

 Make boundary-atom lists, lsb, for lower and higher directions

including both resident, n, and cache, nbnew, atoms

 for lower and higher directions

 Send/receive boundary-atom coordinates to/from the neighbor

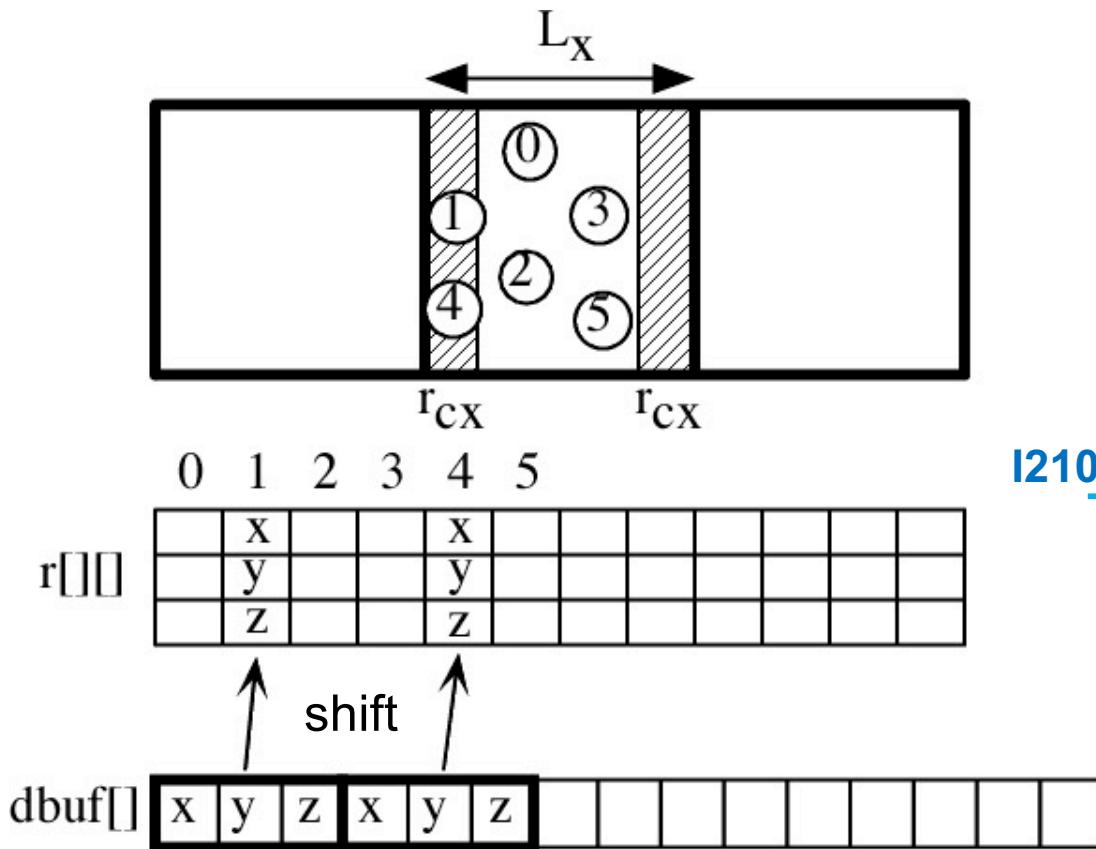
 Increment nbnew

 endfor

endfor

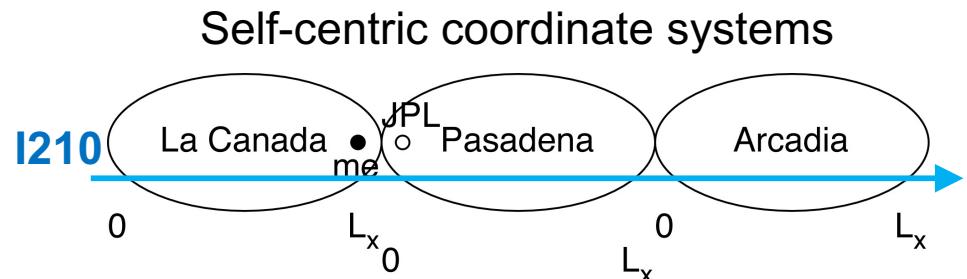
nb = nbnew

Implementing Atom Caching



Copying condition

```
bbd(ri[],ku) {  
    kd = ku / 2 (= 0|1|2) xlylz  
    kdd = ku % 2 (= 0|1) lowerhigher  
    if (kdd == 0)  
        return ri[kd] < RCUT  
    else  
        return al[kd] - RCUT < ri[kd]  
}
```

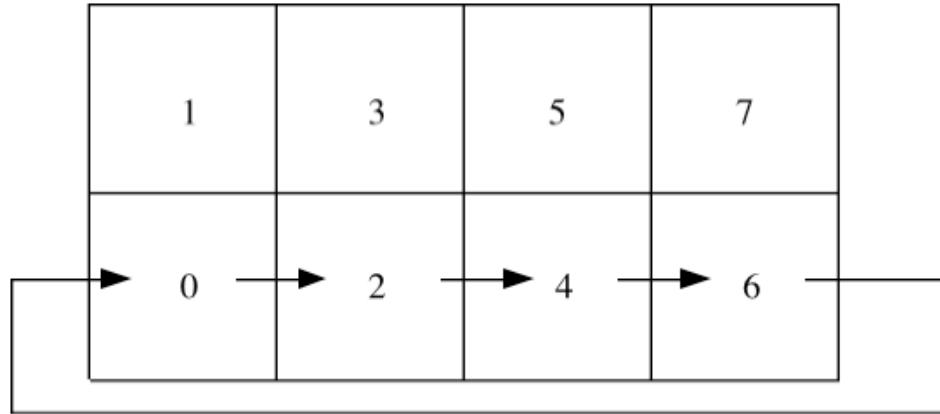


3 phases of message passing

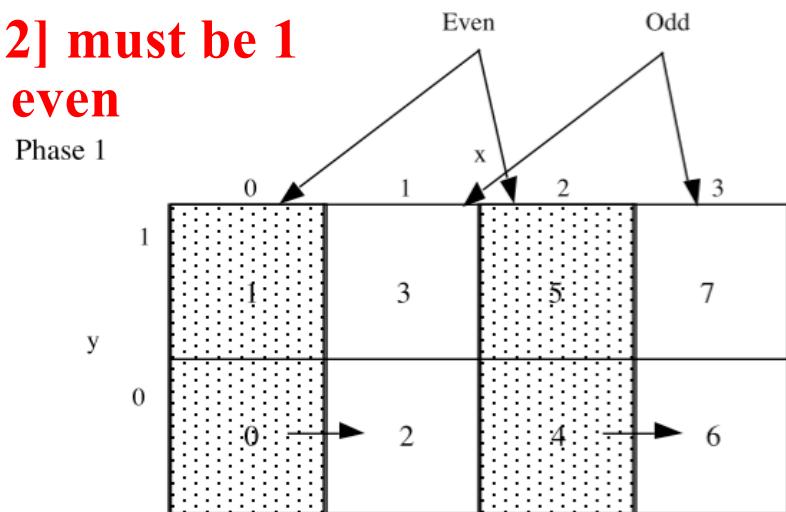
1. Message buffering: $\text{dbuf} \leftarrow r\text{-sv}(\text{shift})$, gather
2. Message passing: $\text{dbufr} \leftarrow \text{dbuf}$
Send dbuf
Receive dbufr
3. Message storing: $r \leftarrow \text{dbufr}$, append after the residents

Deadlock Avoidance

Cyclic dependence



vproc[0|1|2] must be 1
or even

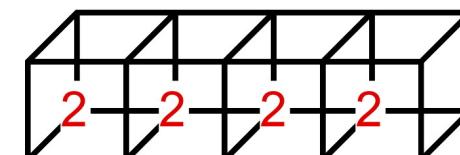
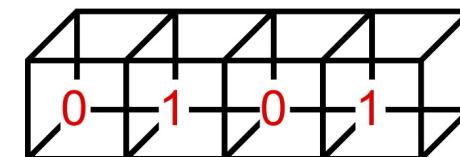
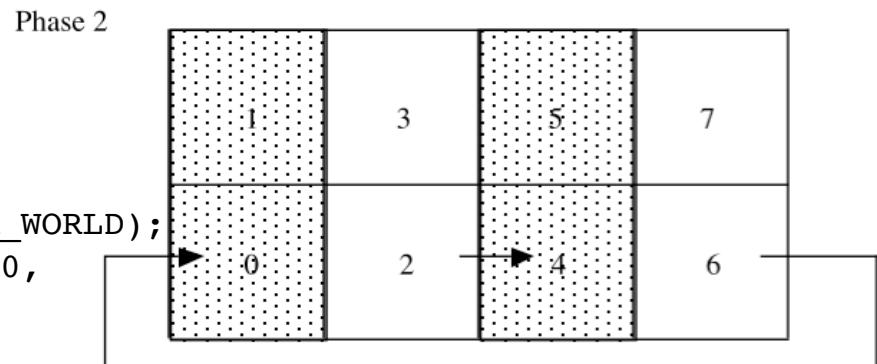


3-phase (deadlock-free) message passing

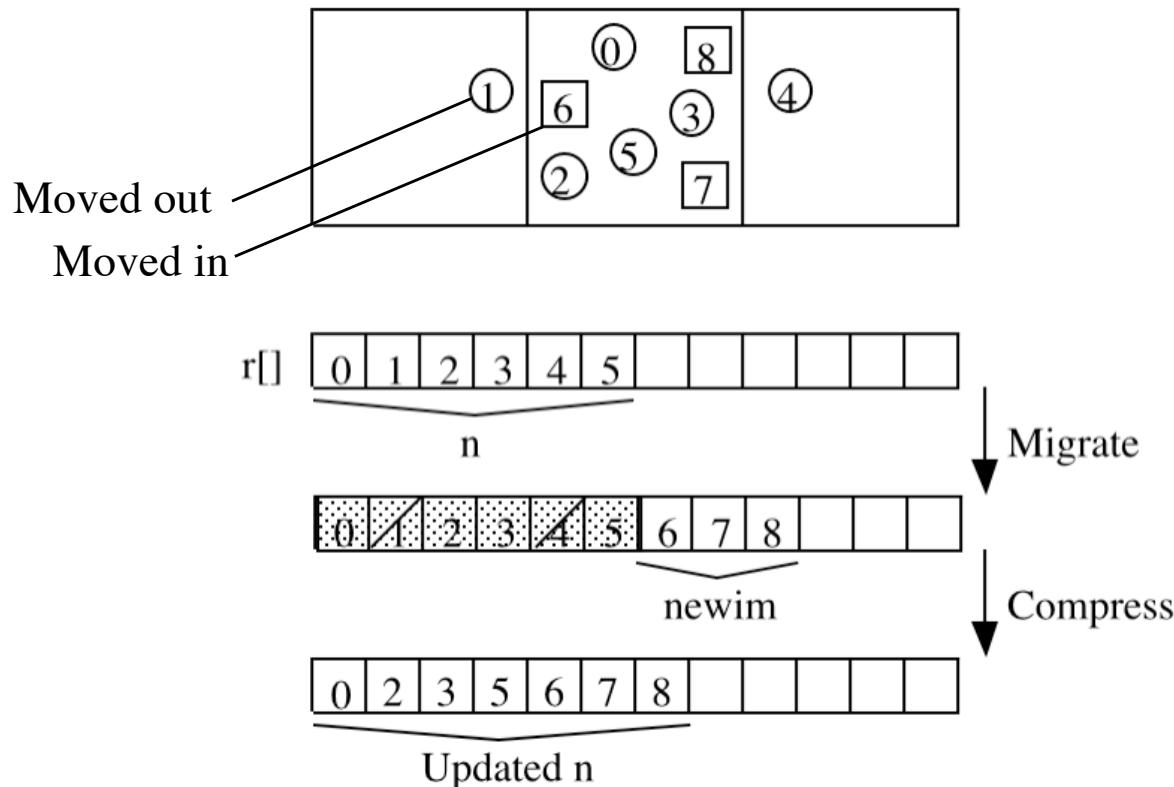
```

1. Message buffering: dbuf <- r, gather
2. Message passing: dbufr <- dbuf
/* Even node: send & recv, if not empty */
if (myparity[kd] == 0) {
    MPI_Send(dbufr, 3*nsd, MPI_DOUBLE, inode, 120, MPI_COMM_WORLD);
    MPI_Recv(dbufr, 3*nrc, MPI_DOUBLE, MPI_ANY_SOURCE, 120,
             MPI_COMM_WORLD, &status);
}
/* Odd node: recv & send, if not empty */
else if (myparity[kd] == 1) {
    MPI_Recv(dbufr, 3*nrc, MPI_DOUBLE, MPI_ANY_SOURCE, 120,
             MPI_COMM_WORLD, &status);
    MPI_Send(dbufr, 3*nsd, MPI_DOUBLE, inode, 120, MPI_COMM_WORLD);
}
/* Single layer: Exchange information with myself */
else
    for (i=0; i<3*nrc; i++) dbufr[i] = dbufr[i];
3. Message storing: r <- dbufr, append

```



Atom Migration: atom_move()



Reset the number of received new immigrants, $newim = 0$

for x, y, and z directions

Make moving-atom lists, $mvque$, for lower and higher directions **including both resident, n, and immigrant, newim, atoms but excluding those already moved out for lower and higher directions**

Send/receive moving-atom coordinates to/from the neighbor

(When moving, $r[0] \leftarrow MOVED_OUT = -10^{10}$)

Increment $newim$

endfor

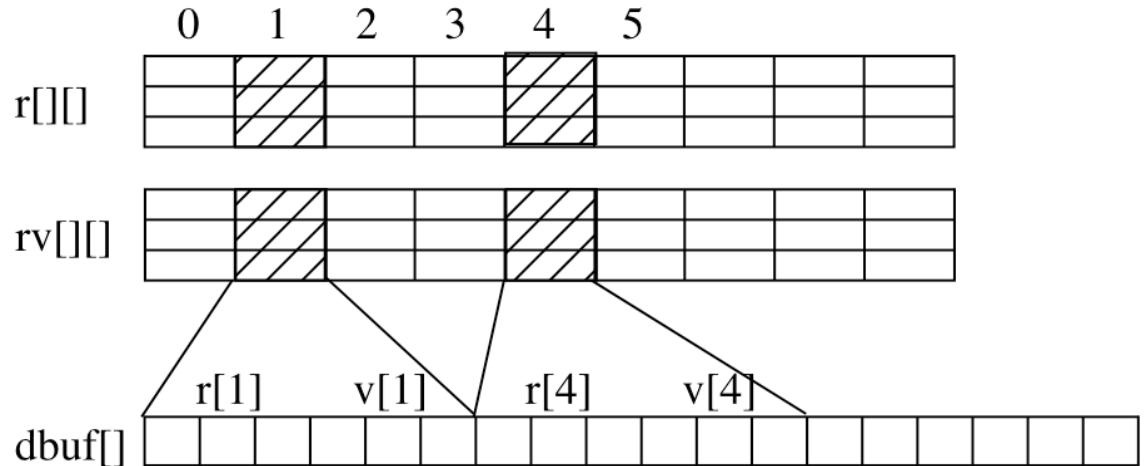
endfor

Compress the r array to eliminate the moved-out atoms

Implementing Atom Migration

Moving condition

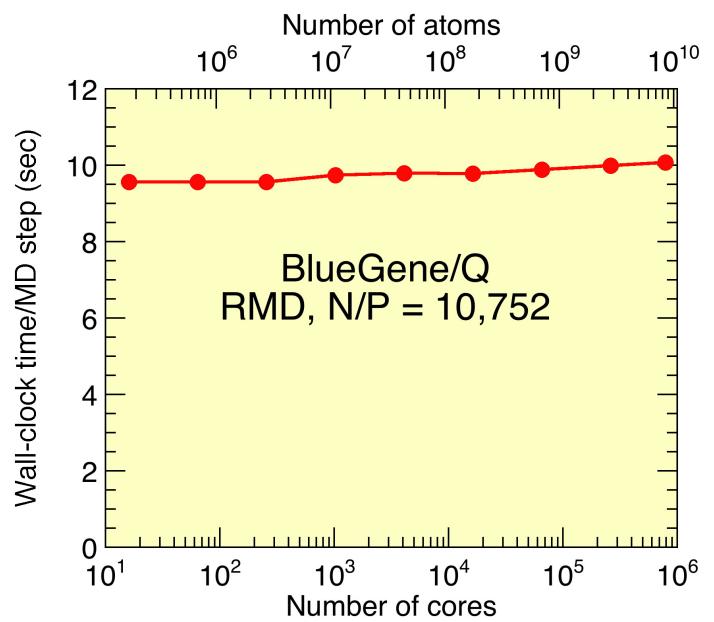
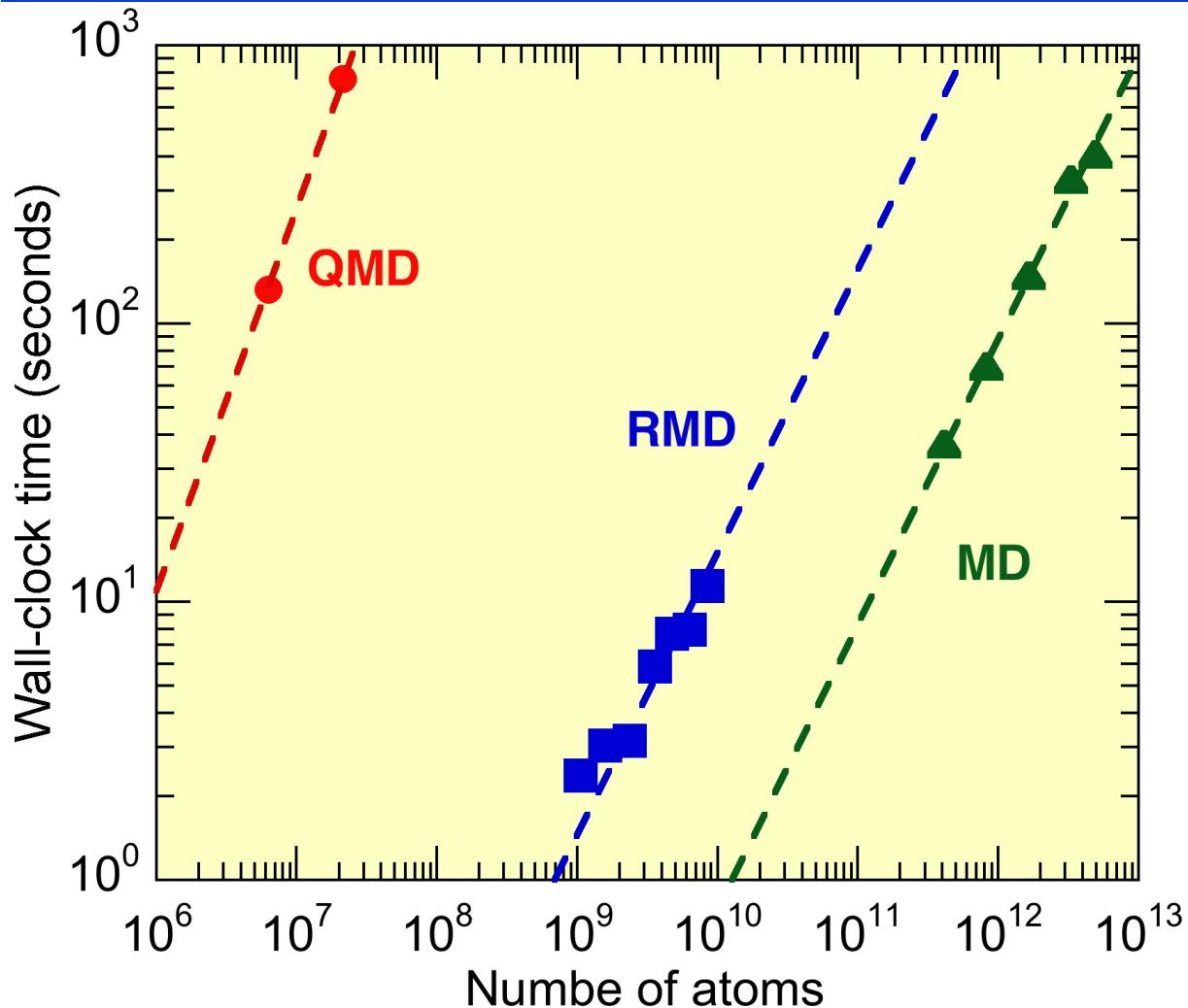
```
bmv(ri[],ku) {  
    kd = ku / 2 (= 0|1|2)  
    kdd = ku % 2 (= 0|1)  
    if (kdd == 0)  
        return ri[kd] < 0.0  
    else  
        return al[kd] < ri[kd]  
}
```



3 phases of message passing

1. Message buffering: $\text{dbuf} \leftarrow \text{r-sv}$ (shift) & rv , gather
Mark **MOVED_OUT** in r
2. Message passing: $\text{dbufr} \leftarrow \text{dbuf}$
Send dbuf
Receive dbufr
3. Message storing: $\text{r} \& \text{rv} \leftarrow \text{dbufr}$, append after the residents

Spatial Decomposition Benchmark



QMD (quantum molecular dynamics): DC-DFT

RMD (reactive molecular dynamics): F-ReaxFF

MD (molecular dynamics): MRMD

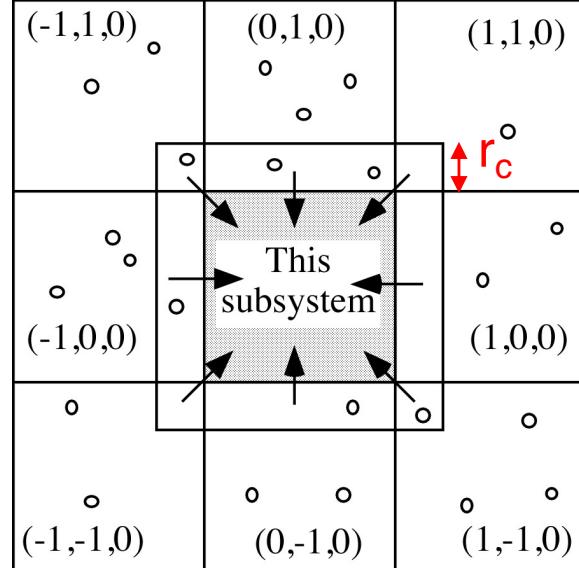
- 4.9 trillion-atom space-time multiresolution MD (MRMD) of SiO_2
 - 8.5 billion-atom fast reactive force-field (F-ReaxFF) RMD of RDX
 - 1.9 trillion grid points (21.2 million-atom) DC-DFT QMD of SiC
- parallel efficiency 0.98 on 786,432 BlueGene/Q cores

Cost of Spatial Decomposition MD

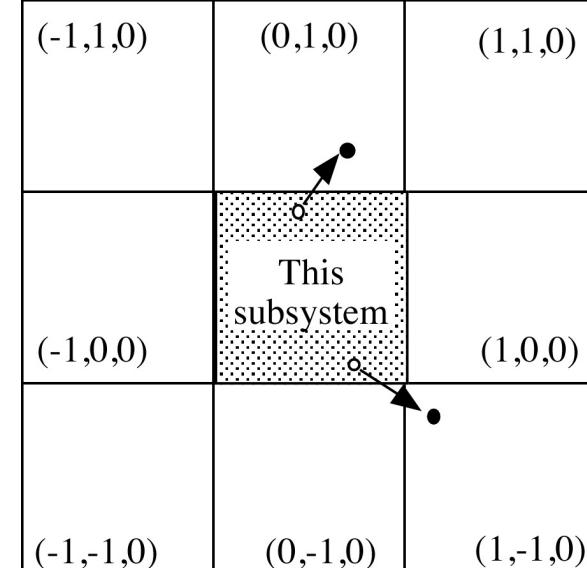
Spatial decomposition (short ranged): $O(N/P)$ computation



Atom caching: $O((N/P)^{2/3})$



Atom migration



Large overhead & lack of parallelism for small N/P

Parallel Efficiency

Parallel computing = solving a big problem (W) in a short time (T) using many processors (P)

- Execution time: $T(W,P)$; W : Workload, P : Number of processors

- Speed: $S(W,P) = \frac{W}{T(W,P)}$

- Speedup: $S_P = \frac{S(W_P,P)}{S(W_1,1)} = \frac{W_P T(W_1,1)}{W_1 T(W_P,P)}$

See Grama'03, Chap. 5

- Efficiency: $E_P = \frac{S_P}{P} = \frac{W_P T(W_1,1)}{P W_1 T(W_P,P)}$

- How to scale W_P with P ?

- > Isogranular (weak) scaling:

$W_P = Pw$; w = constant workload per processor (granularity)

- > Constant problem-size (strong) scaling:

$W_P = W$ — constant

Analysis of Parallel MD

- Parallel execution time:

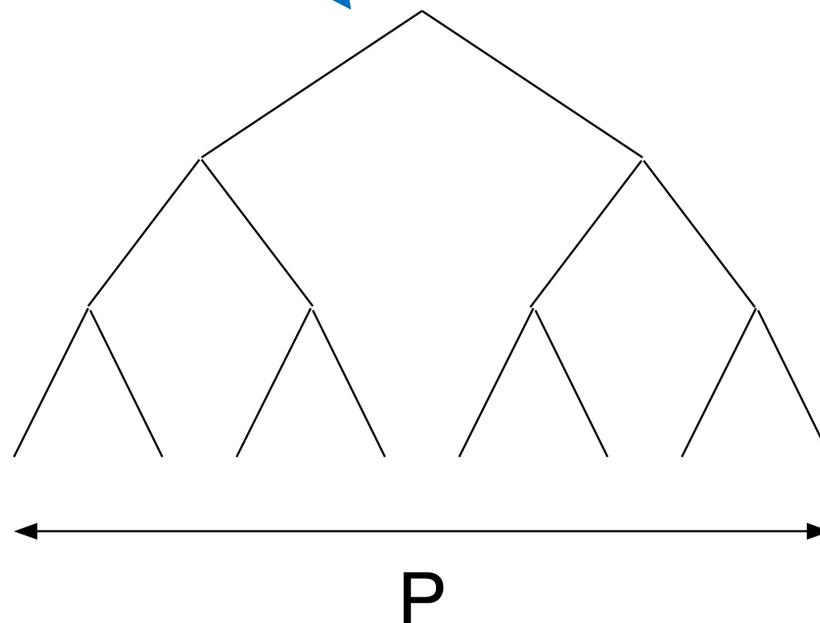
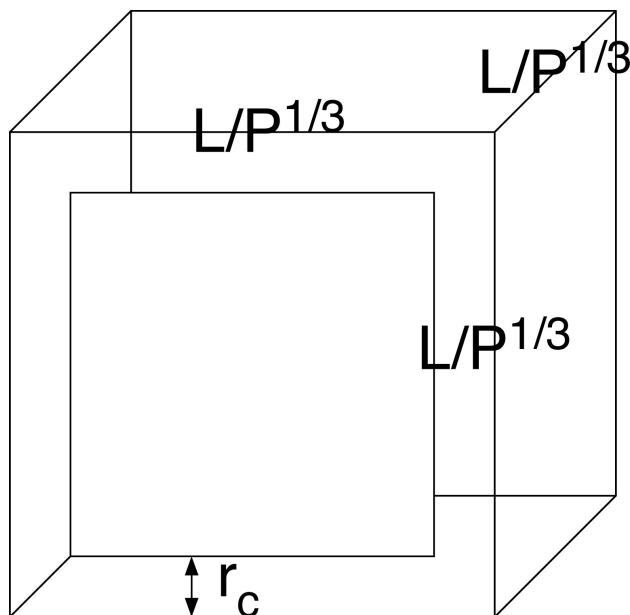
Workload \propto Number of atoms, N (linked-list cell algorithm)

$$T(N, P) = T_{\text{comp}}(N, P) + T_{\text{comm}}(N, P) + T_{\text{global}}(P)$$

$$= a \frac{N}{P} + b \left(\frac{N}{P} \right)^{2/3} + c \log P$$

`MPI_Allreduce()`

$$\begin{aligned} & \text{facets } \overbrace{6}^{\text{cached volume}} \times \overbrace{\frac{L^2}{P^{2/3}} r_c}^{\text{atom density}} \\ & = 6r_c \frac{N^{2/3}/\rho^{2/3}}{P^{2/3}} \rho \\ & = 6r_c \rho^{1/3} \left(\frac{N}{P} \right)^{2/3} \end{aligned}$$



Fixed Problem-Size Scaling

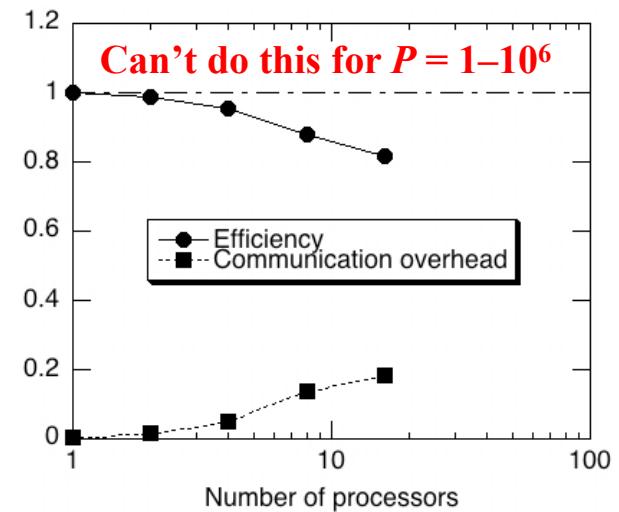
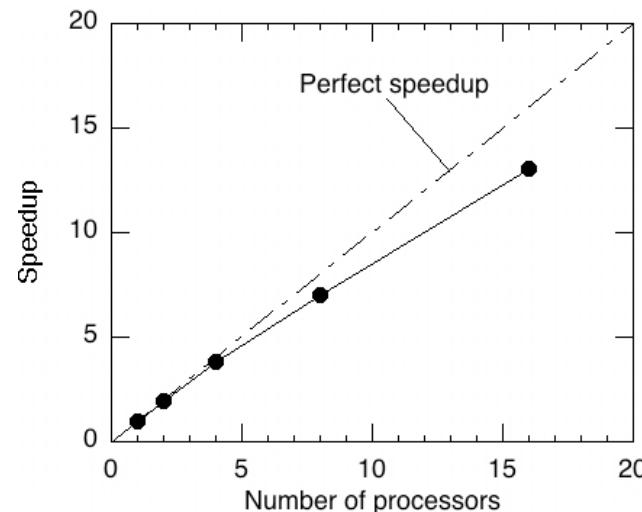
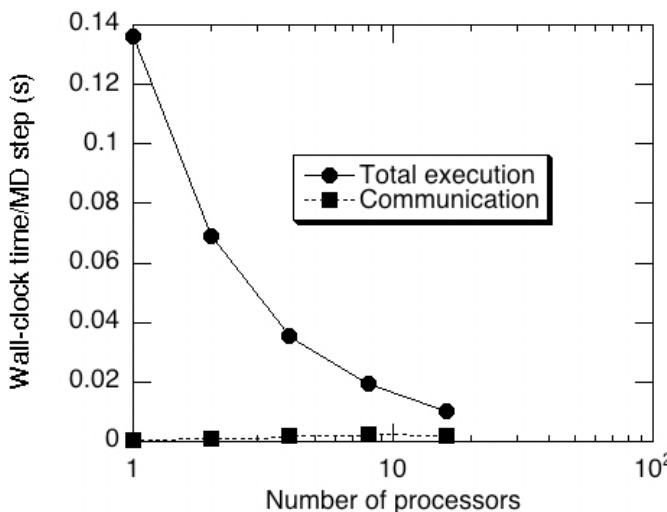
- Speedup:

$$S_P = \frac{T(N,1)}{T(N,P)} = \frac{\frac{aN}{P + b(N/P)^{2/3} + c \log P}}{P} = \frac{1 + \frac{b(P)^{1/3}}{a(N)} + \frac{c P \log P}{N}}{1 + \frac{b(P)^{1/3}}{a(N)} + \frac{c P \log P}{N}}$$

$$S_P = \frac{S(W_P, P)}{S(W_1, 1)} = \frac{\mathbb{W}_R T(W_1, 1)}{\mathbb{W}_R T(W_P, P)}$$

- Efficiency:

$$E_P = \frac{S_P}{P} = \frac{1}{1 + \frac{b(P)^{1/3}}{a(N)} + \frac{c P \log P}{N}}$$



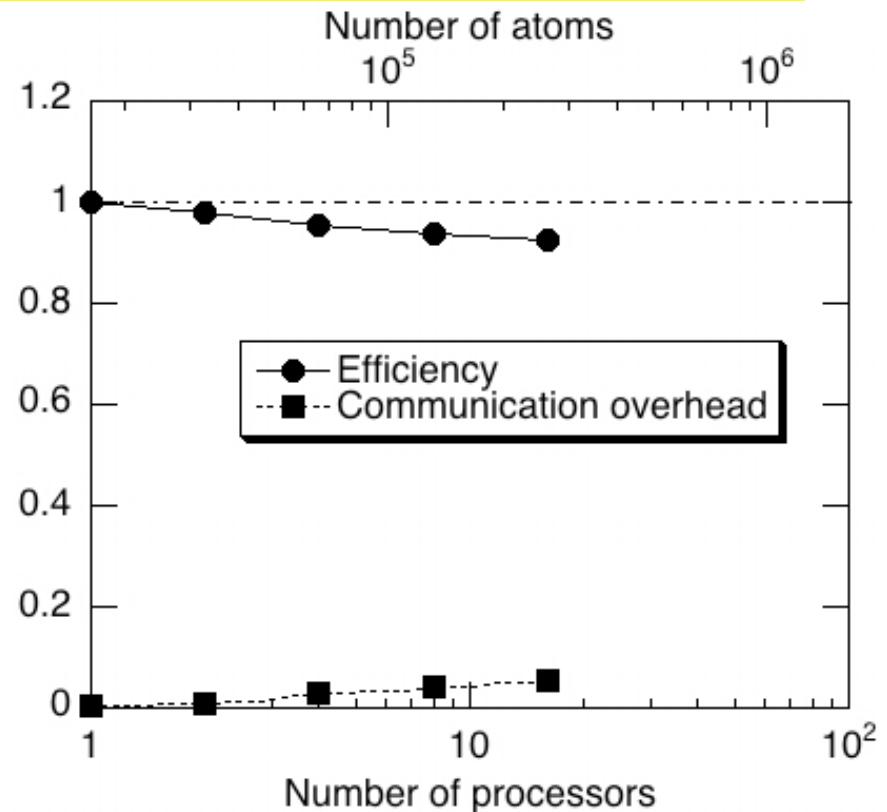
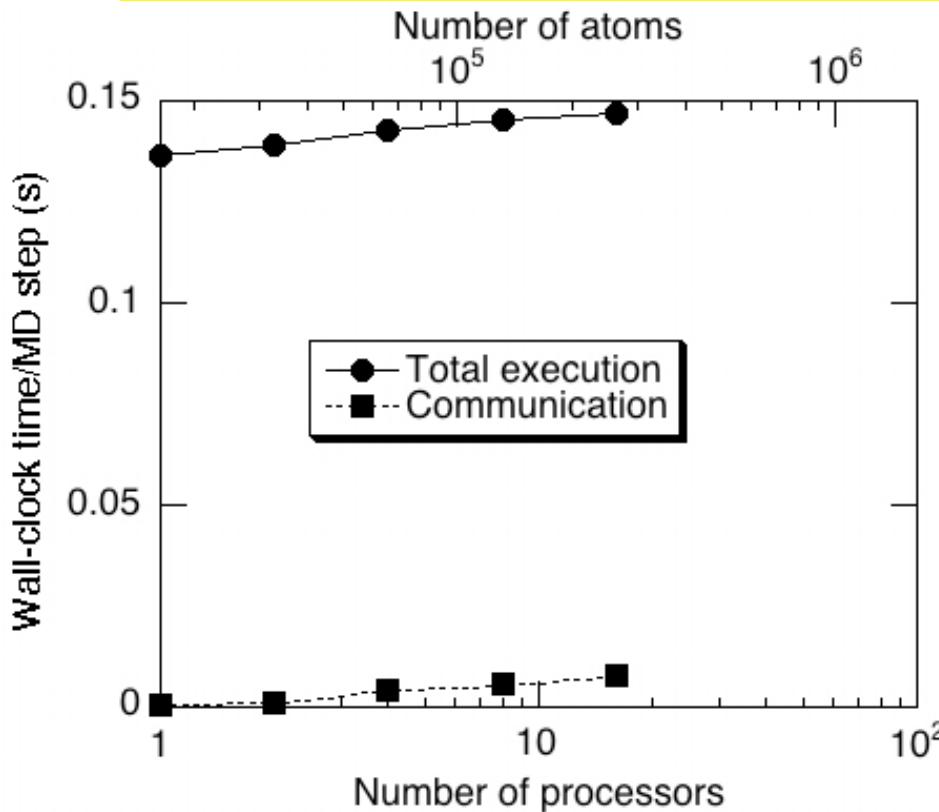
pmd.c: $N = 16,384$, on CARC

Isogranular Scaling of Parallel MD

- $n = N/P = \text{constant}$: doable for arbitrarily large P

- Efficiency:

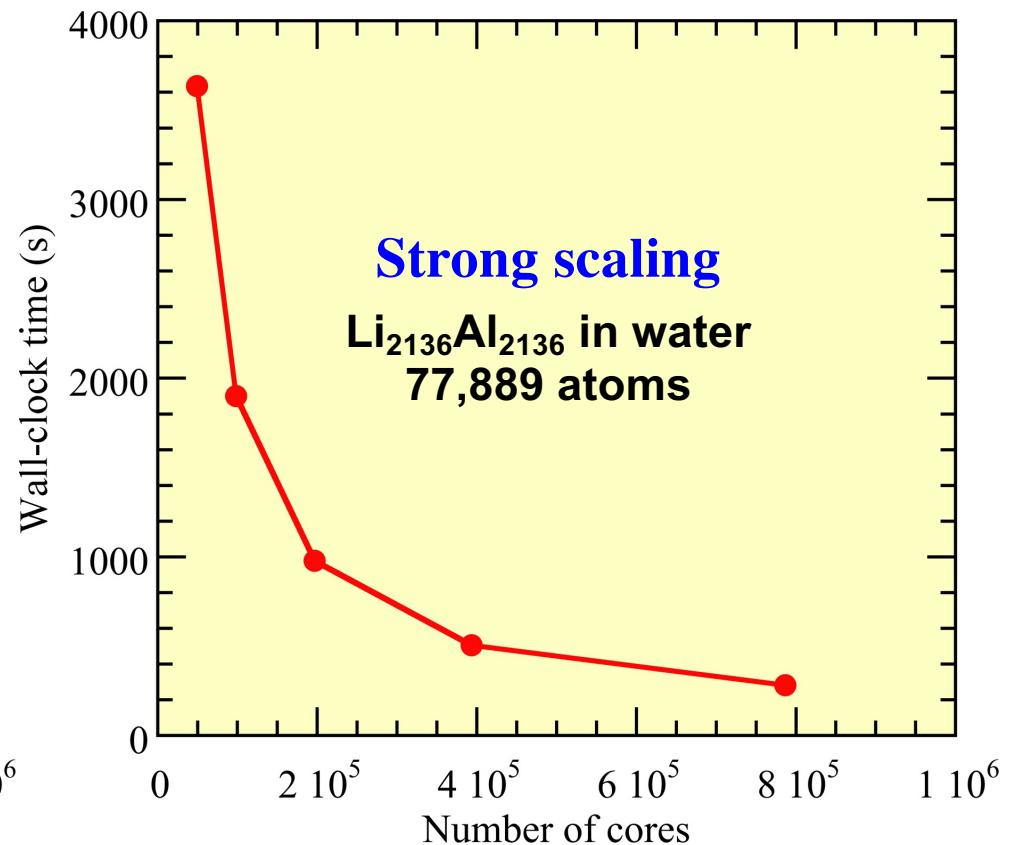
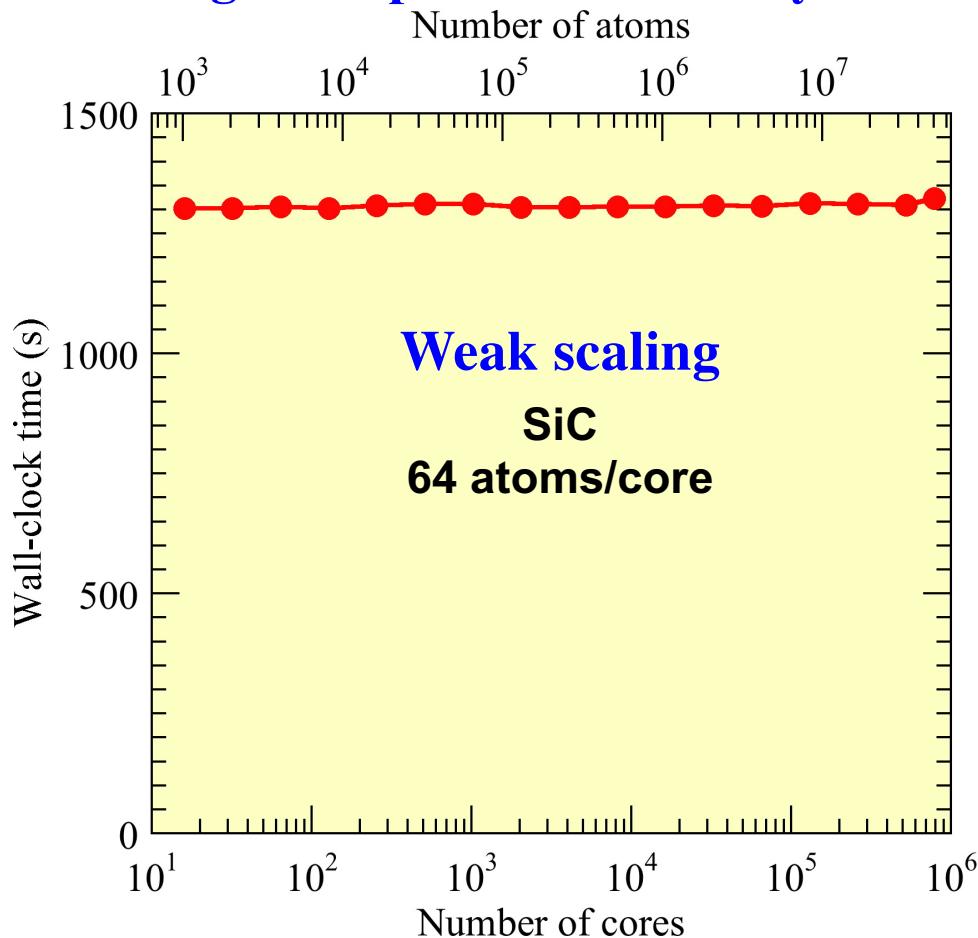
$$E_P = \frac{T(n,1)}{T(nP,P)} = \frac{an}{an + bn^{2/3} + c \log P} = \frac{1}{1 + \frac{b}{a} n^{-1/3} + \frac{c}{an} \log P}$$



pmd.c: $N/P = 16,384$, on CARC

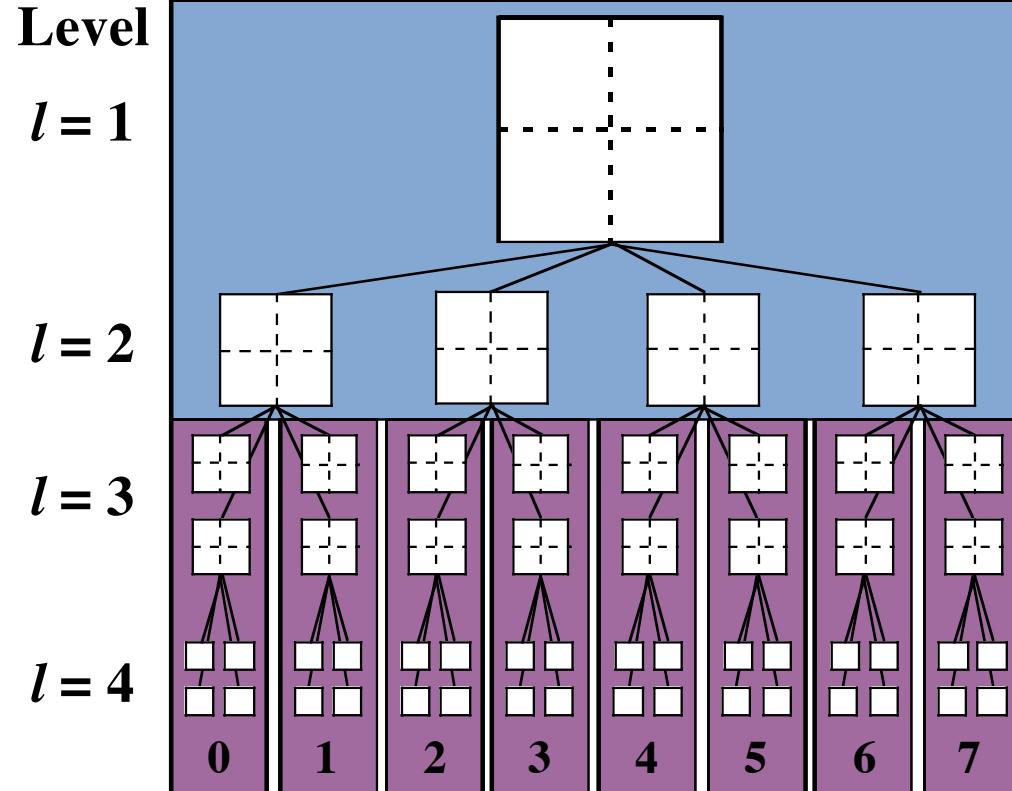
Parallel Performance of Quantum MD

- Weak-scaling parallel efficiency is 0.984 on 786,432 Blue Gene/Q cores for a 50,331,648-atom SiC system
- Strong-scale parallel efficiency is 0.803 on 786,432 Blue Gene/Q cores



- 62-fold reduction of time-to-solution [441 s/SCF-step for 50.3M atoms] from the previous state-of-the-art [55 s/SCF-step for 102K atoms, Osei-Kuffuor *et al.*, PRL '14]

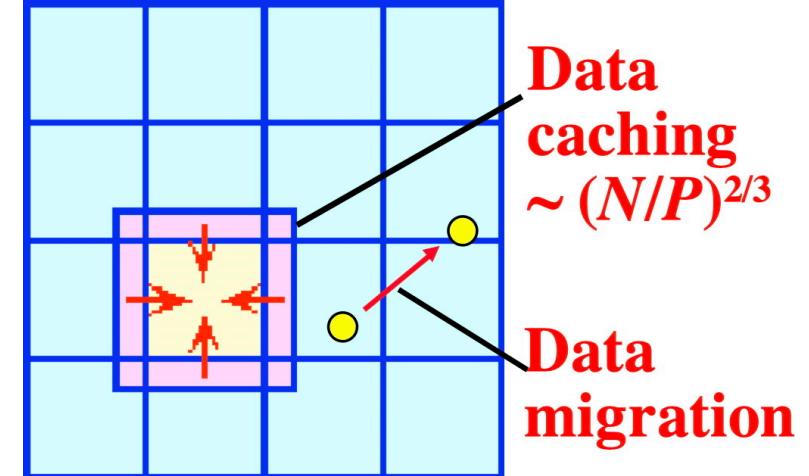
Parallel Fast Multipole Method



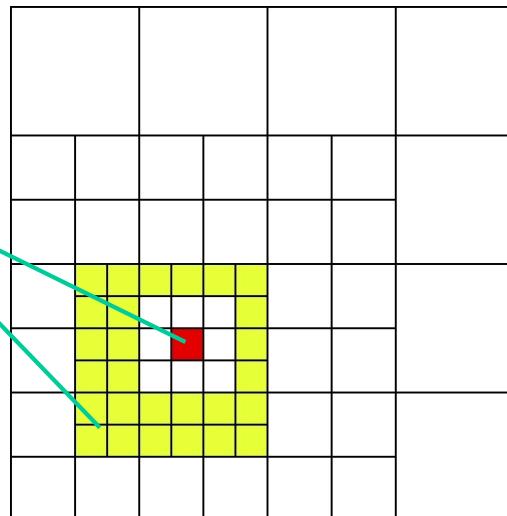
Upper levels:
Global to all processors
Overhead: $O(\log P)$

A. Nakano *et al.*, *Comput. Phys. Commun.* 83, 197 (1994)

Lower levels:
Spatial decomposition
Computation: $O(N/P)$



Level-by-level
short-ranged (M-to-L)
interaction with cousins



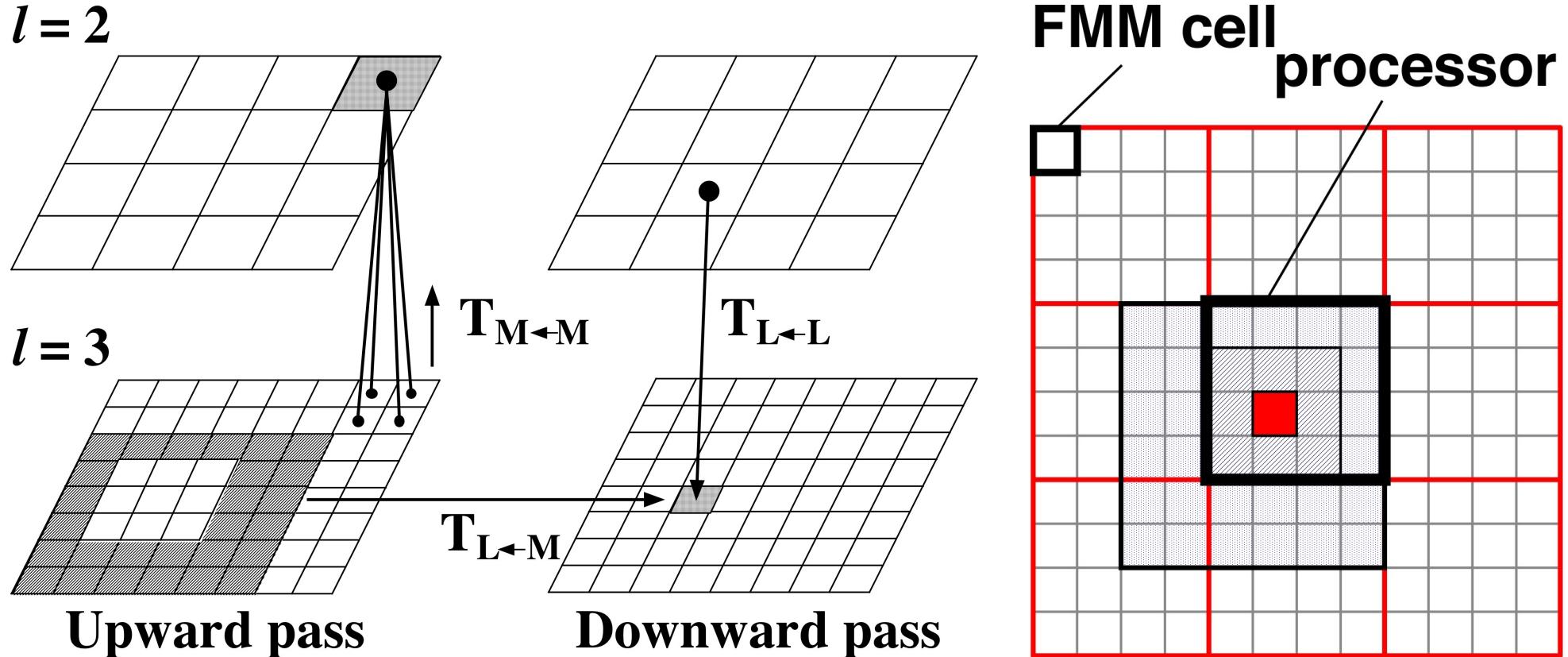
Coarse grain:
 $N/P \sim 10^6; P \leq 10^3$



$N/P \gg \log P, (N/P)^{2/3}$

S. Ogata *et al.*,
Comput. Phys. Commun.
153, 445 ('03)

Caching Interactive Cells



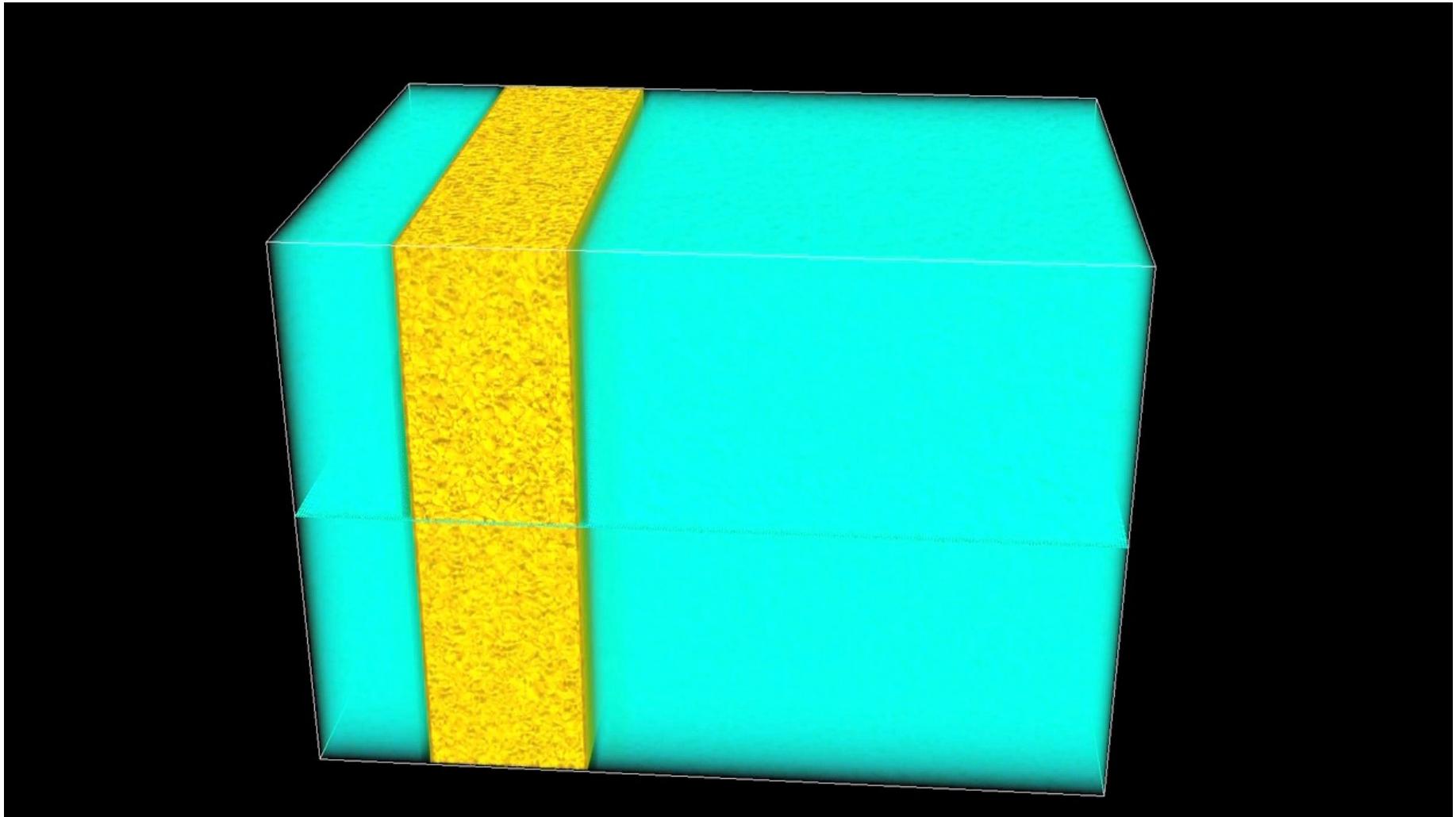
- $T_{M \leftarrow M}$ & $T_{L \leftarrow L}$: local at lower octree levels
- $T_{L \leftarrow M}$: cache 2 boundary layers of cells at each level

See lecture note on “scalability analysis of parallel molecular-dynamics
& fast-multipole-method algorithms ”

<http://cacs.usc.edu/education/cs653/02-2Scalability.pdf>

Billion-Atom Molecular Dynamics

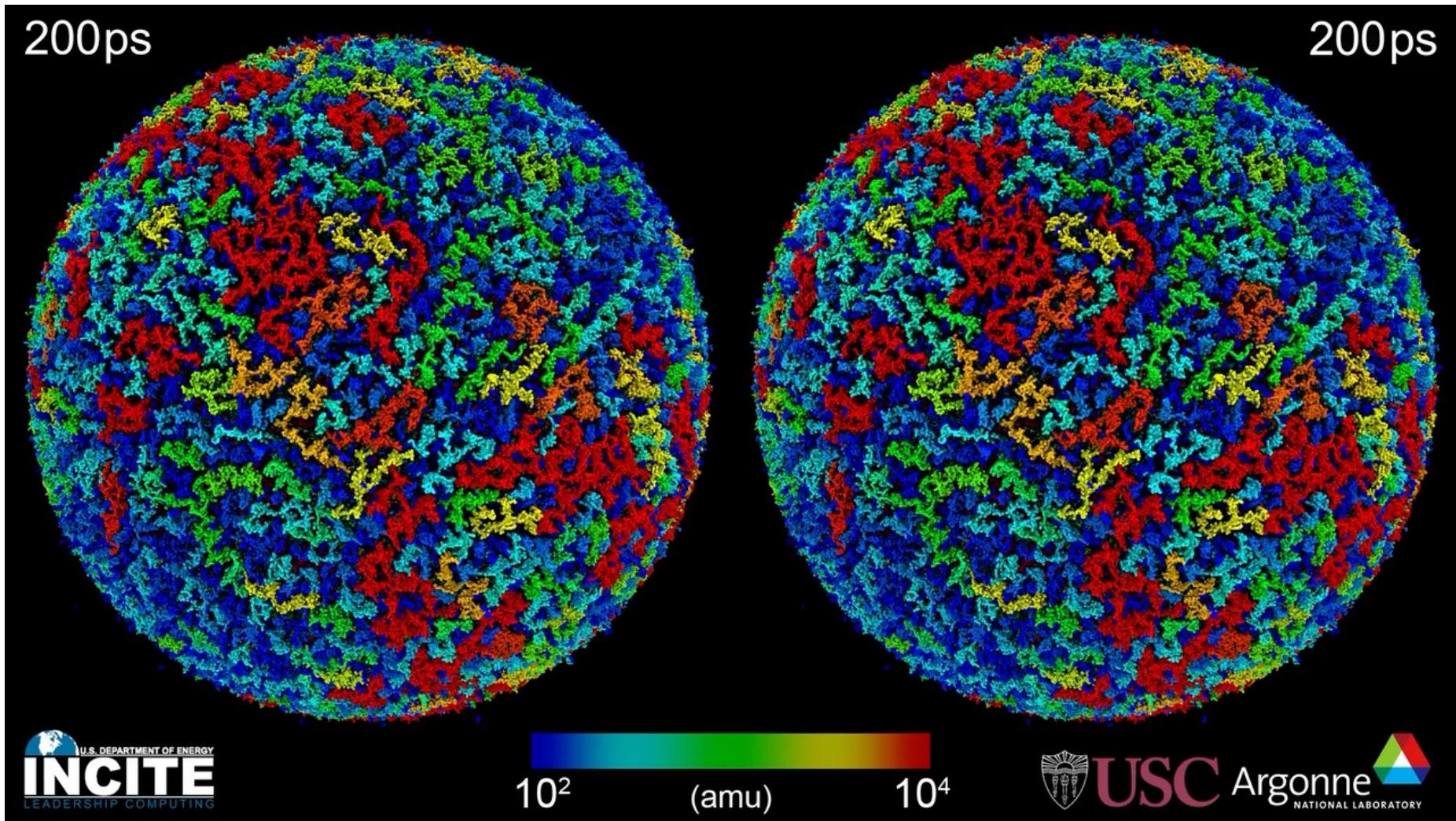
- Billion-atom MD simulation of shock-induced nanobubble collapse in water near silica surface (67 million core-hours on 163,840 Blue Gene/P cores)



- Water nanojet formation and its collision with silica surface

112 Million-Atom Reactive MD

- 112 million-atom reactive MD simulation to study nanocarbon synthesis by high-temperature oxidation of SiC nanoparticle (410 million core-hours on 786,432 Blue Gene/Q cores)



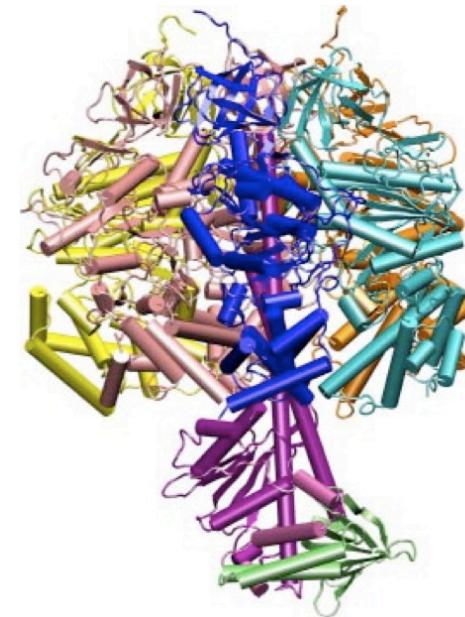
Fine-Grained Parallel MD

Pathways to a Protein Folding Intermediate Observed in a 1-Microsecond Simulation in Aqueous Solution

Yong Duan and Peter A. Kollman*

An implementation of classical molecular dynamics on parallel computers of increased efficiency has enabled a simulation of protein folding with explicit representation of water for 1 microsecond, about two orders of magnitude longer than the longest simulation of a protein in water reported to date. Starting with an unfolded state of villin headpiece subdomain, hydrophobic collapse and helix formation occur in an initial phase, followed by conformational readjustments. A marginally stable state, which has a lifetime of about 150 nanoseconds, a favorable solvation free energy, and shows significant resemblance to the native structure, is observed; two pathways to this state have been found.

Science 282, 740 ('98)

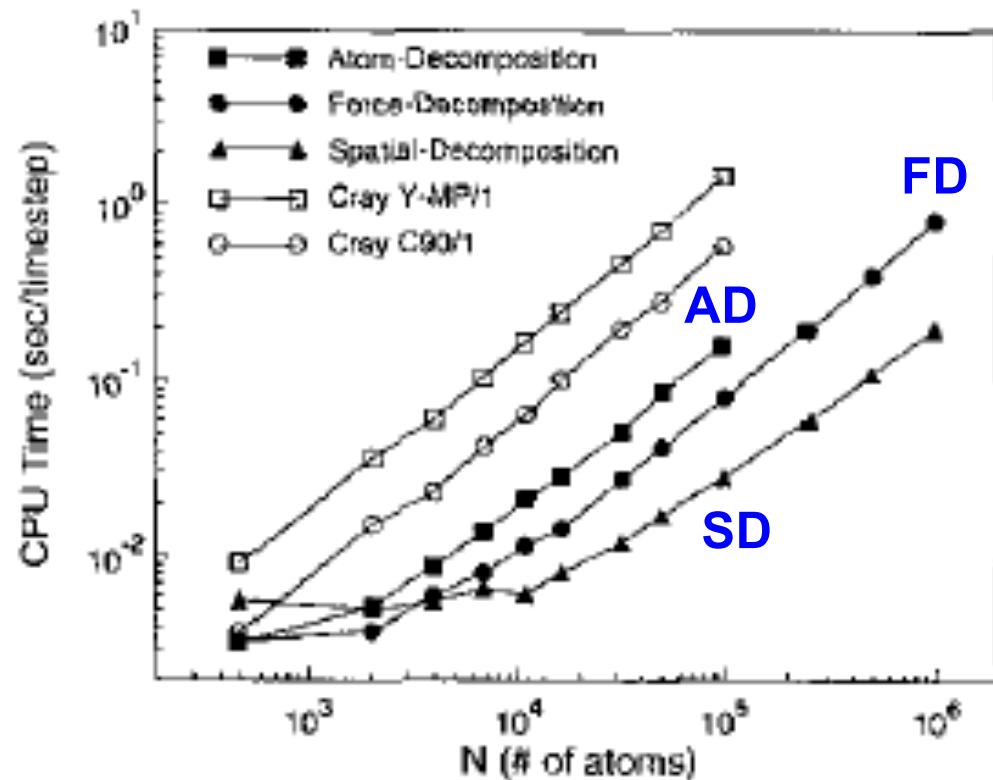
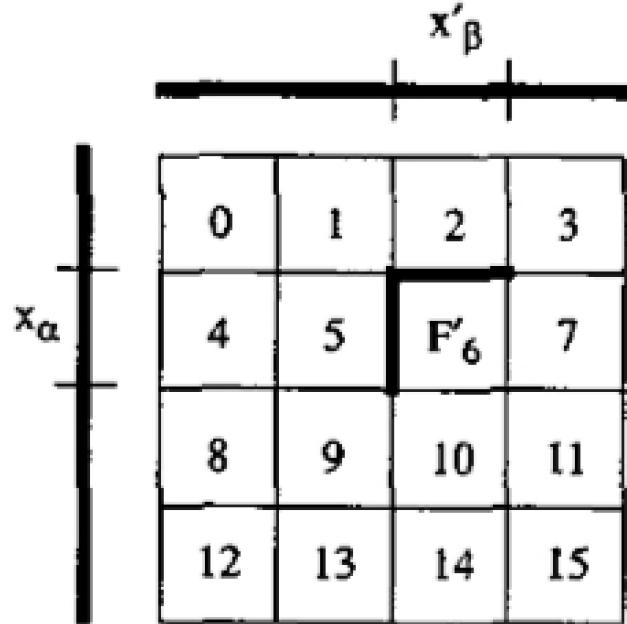


Processors	Time/step		Speedup		GFLOPS	
	Total	Per Node	MPI	Elan	MPI	Elan
1	1	28.08 s	28.08 s	1	1	0.480
128	4	248.3 ms	234.6 ms	113	119	54
256	4	135.2 ms	121.9 ms	207	230	99
512	4	65.8 ms	63.8 ms	426	440	204
510	3	65.7 ms	63.0 ms	427	445	205
1024	4	41.9 ms	36.1 ms	670	778	322
1023	3	35.1 ms	33.9 ms	799	829	383
1536	4	35.4 ms	32.9 ms	792	854	380
1536	3	26.7 ms	24.7 ms	1050	1137	504
2048	4	31.8 ms	25.9 ms	883	1083	423
1800	3	25.8 ms	22.3 ms	1087	1261	521
2250	3	19.7 ms	18.4 ms	1425	1527	684
2400	4	32.4 ms	27.2 ms	866	1032	416
2800	4	32.3 ms	32.1 ms	869	873	417
3000	4	32.5 ms	28.8 ms	862	973	414
						467

J.C. Phillips, G. Zheng, S. Kumar, & L.V. Kale,
in Proc. of IEEE/ACM SC2002

Table 1: NAMD performance on 327K atom ATPase benchmark system with multiple timestepping with PME every four steps for Charm++ based on MPI and Elan.

Force Decomposition for Parallel MD

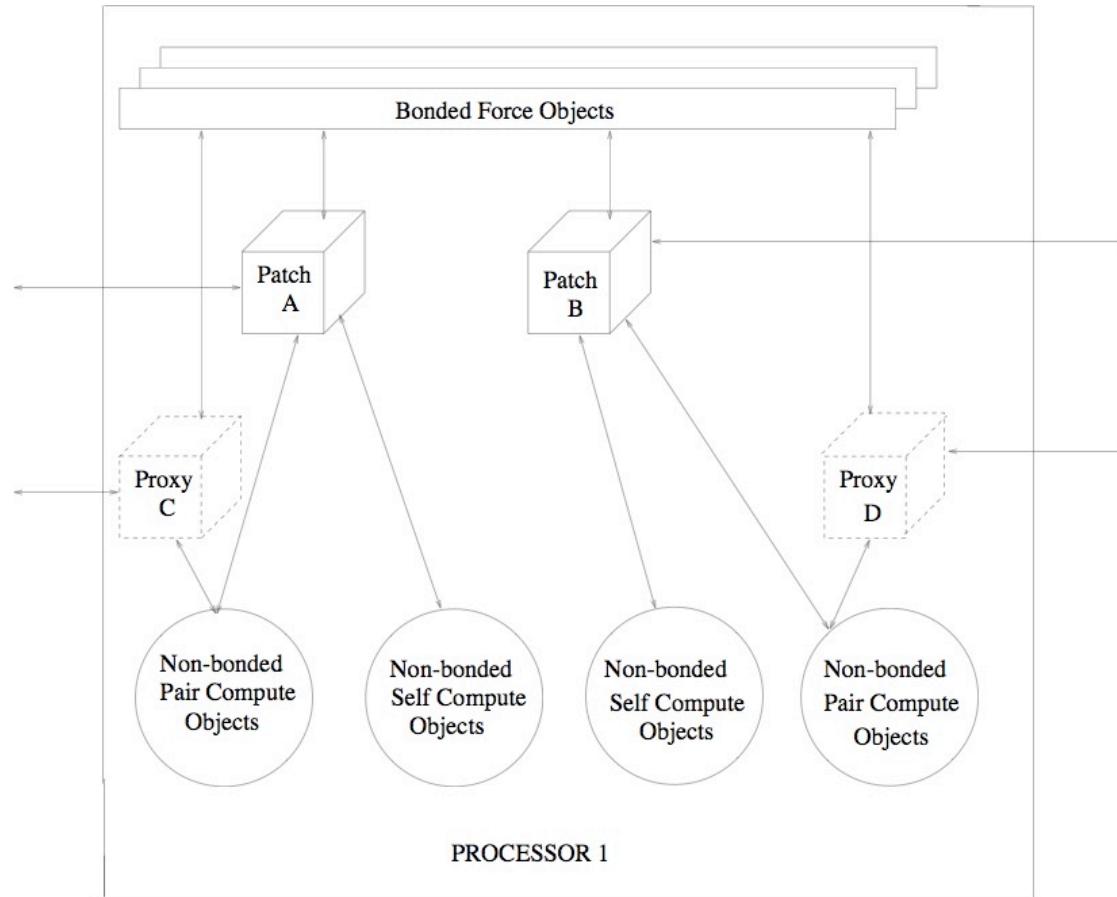


Runtime on 1,024-processor Intel Paragon

FIG. 5. The division of the permuted force matrix F' among 16 processors in the force-decomposition algorithm. Processor P_6 is assigned a sub-block F'_6 of size N/\sqrt{P} by N/\sqrt{P} . To compute its matrix elements it must know the corresponding N/\sqrt{P} -length pieces x_α and x'_β of the position vector x and permuted position vector x' .

Hybrid Spatial+Force Decomposition

- Spatial decomposition of patches (localized spatial regions & atoms within)
- Inter-patch force computation objects assigned to any processor
- Message-driven object execution



Quantum MD@Scale

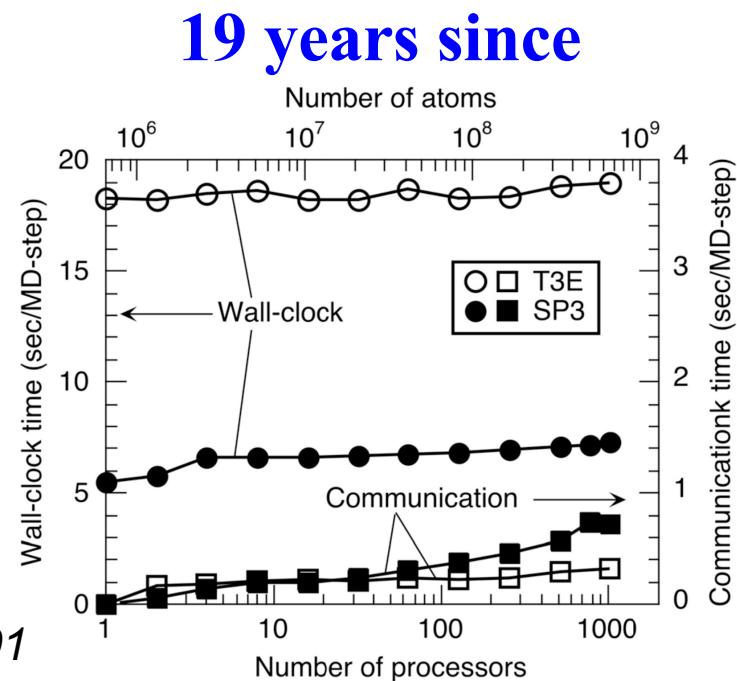
Quantum dynamics at scale: ultrafast control of emergent functional materials

S. C. Tiwari, P. Sakdhnagool, R. K. Kalia, A. Krishnamoorthy, M. Kunaseth,
A. Nakano, K. Nomura, P. Rajak, F. Shimojo, Y. Luo & P. Vashishta

Best Paper in ACM HPC Asia 2020

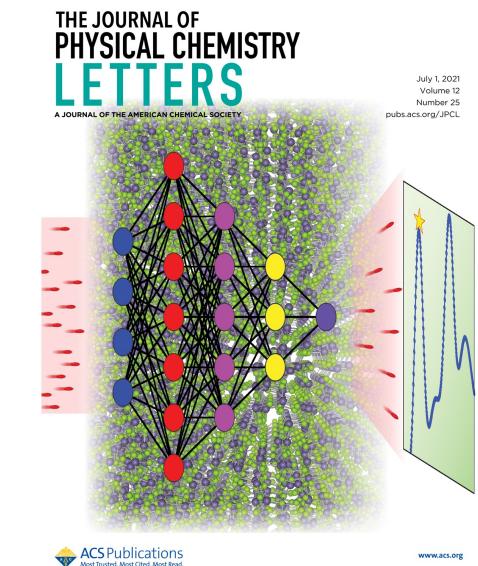
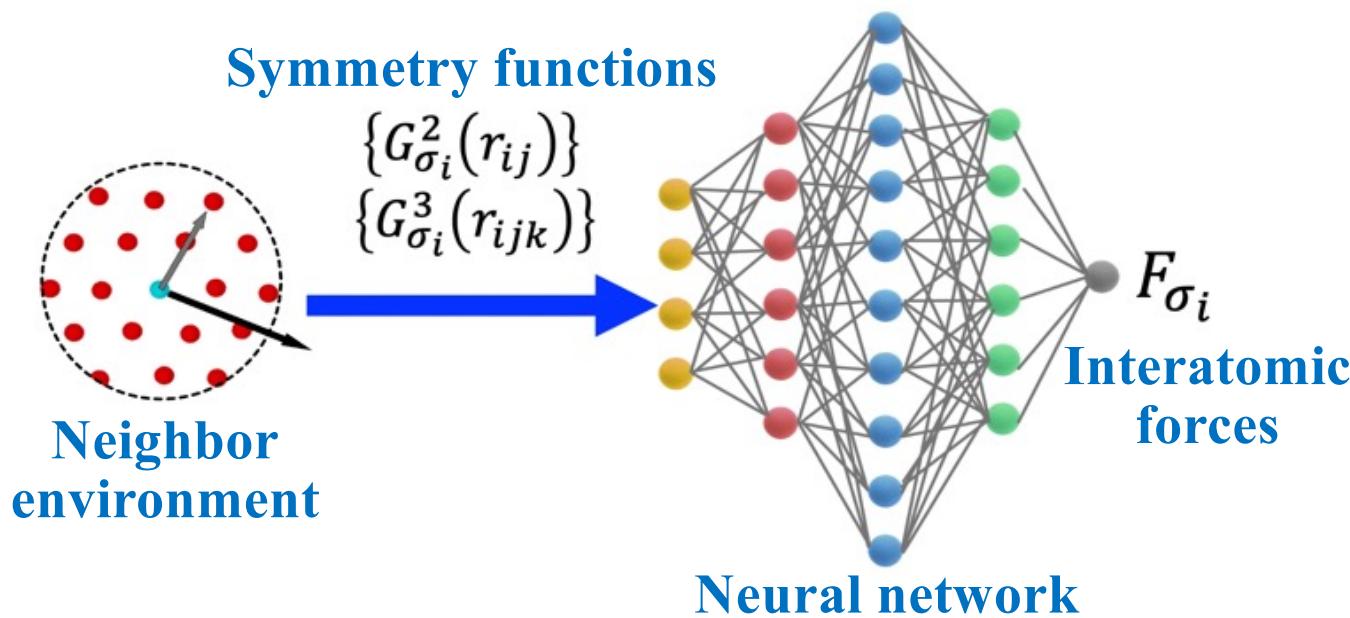


Scalable atomistic simulation algorithms
for materials research, A. Nakano *et al.*,
Best Paper, IEEE/ACM Supercomputing 2001, SC01



Neural MD@Scale

- Neural-network quantum molecular dynamics (NNQMD) could revolutionize atomistic modeling of materials, providing quantum-mechanical accuracy at a fraction of computational cost [*Phys. Rev. Lett.* **126**, 216403 ('21); *J. Phys. Chem. Lett.* **12**, 6020 ('21)]



Neural network molecular dynamics at scale & Ex-NNQMD: extreme-scale neural network quantum molecular dynamics,

P. Rajak *et al.*, IEEE IPDPS ScaDL 20 & 21

See also Pushing the limit of molecular dynamics with ab initio accuracy to 100 million atoms with machine learning

W. Jia *et al.*, ACM/IEEE Supercomputing, SC20

What We Have Learned Here

- Single program multiple data (SPMD) parallel programming for multicomputers based on message passing interface (MPI), using molecular dynamics (MD) as a prototypical example.
- Parallel computing = decomposition (who does what).
- Data locality-exposing data structure like linked-list cells leads to straightforward parallelization.
- Spatial, particle, force & hybrid decompositions.
- Scalability analysis based on analytical models.