CSCI596 Assignment 4—Hybrid MPI+OpenMP Parallel Molecular Dynamics

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CSCI-596 assignment4

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**1. source code of hmd.c：**

/\*----------------------------------------------------------------------

Program pmd.c performs parallel molecular-dynamics for Lennard-Jones

systems using the Message Passing Interface (MPI) standard.

----------------------------------------------------------------------\*/

#include "hmd.h"

/\*--------------------------------------------------------------------\*/

int main(int argc, char \*\*argv) {

/\*--------------------------------------------------------------------\*/

double cpu1;

MPI\_Init(&argc,&argv); /\* Initialize the MPI environment \*/

MPI\_Comm\_rank(MPI\_COMM\_WORLD, &sid); /\* My processor ID \*/

/\* Vector index of this processor \*/

vid[0] = sid/(vproc[1]\*vproc[2]);

vid[1] = (sid/vproc[2])%vproc[1];

vid[2] = sid%vproc[2];

omp\_set\_num\_threads(nthrd);

init\_params();

set\_topology();

init\_conf();

atom\_copy();

compute\_accel(); /\* Computes initial accelerations \*/

cpu1 = MPI\_Wtime();

for (stepCount=1; stepCount<=StepLimit; stepCount++) {

single\_step();

if (stepCount%StepAvg == 0) eval\_props();

}

cpu = MPI\_Wtime() - cpu1;

if (sid == 0) printf("CPU & COMT = %le %le\n",cpu,comt);

MPI\_Finalize(); /\* Clean up the MPI environment \*/

return 0;

}

/\*--------------------------------------------------------------------\*/

void init\_params() {

/\*----------------------------------------------------------------------

Initializes parameters.

----------------------------------------------------------------------\*/

int a;

double rr,ri2,ri6,r1;

FILE \*fp;

/\* Read control parameters \*/

fp = fopen("pmd.in","r");

fscanf(fp,"%d%d%d",&InitUcell[0],&InitUcell[1],&InitUcell[2]);

fscanf(fp,"%le",&Density);

fscanf(fp,"%le",&InitTemp);

fscanf(fp,"%le",&DeltaT);

fscanf(fp,"%d",&StepLimit);

fscanf(fp,"%d",&StepAvg);

fclose(fp);

/\* Compute basic parameters \*/

DeltaTH = 0.5\*DeltaT;

for (a=0; a<3; a++) al[a] = InitUcell[a]/pow(Density/4.0,1.0/3.0);

if (sid == 0) printf("al = %e %e %e\n",al[0],al[1],al[2]);

/\* Compute the # of cells for linked cell lists \*/

for (a=0; a<3; a++) {

lc[a] = al[a]/RCUT;

/\* Size of cell block that each thread is assigned \*/

thbk[a] = lc[a]/vthrd[a];

/\* # of cells = integer multiple of the # of threads \*/

lc[a] = thbk[a]\*vthrd[a]; /\* Adjust # of cells/MPI process \*/

rc[a] = al[a]/lc[a];

}

if (sid == 0) {

printf("lc = %d %d %d\n",lc[0],lc[1],lc[2]);

printf("rc = %e %e %e\n",rc[0],rc[1],rc[2]);

}

/\* Constants for potential truncation \*/

rr = RCUT\*RCUT; ri2 = 1.0/rr; ri6 = ri2\*ri2\*ri2; r1=sqrt(rr);

Uc = 4.0\*ri6\*(ri6 - 1.0);

Duc = -48.0\*ri6\*(ri6 - 0.5)/r1;

}

/\*--------------------------------------------------------------------\*/

void set\_topology() {

/\*----------------------------------------------------------------------

Defines a logical network topology. Prepares a neighbor-node ID table,

nn, & a shift-vector table, sv, for internode message passing. Also

prepares the node parity table, myparity.

----------------------------------------------------------------------\*/

/\* Integer vectors to specify the six neighbor nodes \*/

int iv[6][3] = {

{-1,0,0}, {1,0,0}, {0,-1,0}, {0,1,0}, {0,0,-1}, {0,0,1}

};

int ku,a,k1[3];

/\* Set up neighbor tables, nn & sv \*/

for (ku=0; ku<6; ku++) {

/\* Vector index of neighbor ku \*/

for (a=0; a<3; a++)

k1[a] = (vid[a]+iv[ku][a]+vproc[a])%vproc[a];

/\* Scalar neighbor ID, nn \*/

nn[ku] = k1[0]\*vproc[1]\*vproc[2]+k1[1]\*vproc[2]+k1[2];

/\* Shift vector, sv \*/

for (a=0; a<3; a++) sv[ku][a] = al[a]\*iv[ku][a];

}

/\* Set up the node parity table, myparity \*/

for (a=0; a<3; a++) {

if (vproc[a] == 1)

myparity[a] = 2;

else if (vid[a]%2 == 0)

myparity[a] = 0;

else

myparity[a] = 1;

}

}

/\*--------------------------------------------------------------------\*/

void init\_conf() {

/\*----------------------------------------------------------------------

r are initialized to face-centered cubic (fcc) lattice positions.

rv are initialized with a random velocity corresponding to Temperature.

----------------------------------------------------------------------\*/

double c[3],gap[3],e[3],vSum[3],gvSum[3],vMag;

int j,a,nX,nY,nZ;

double seed;

/\* FCC atoms in the original unit cell \*/

double origAtom[4][3] = {{0.0, 0.0, 0.0}, {0.0, 0.5, 0.5},

{0.5, 0.0, 0.5}, {0.5, 0.5, 0.0}};

/\* Set up a face-centered cubic (fcc) lattice \*/

for (a=0; a<3; a++) gap[a] = al[a]/InitUcell[a];

n = 0;

for (nZ=0; nZ<InitUcell[2]; nZ++) {

c[2] = nZ\*gap[2];

for (nY=0; nY<InitUcell[1]; nY++) {

c[1] = nY\*gap[1];

for (nX=0; nX<InitUcell[0]; nX++) {

c[0] = nX\*gap[0];

for (j=0; j<4; j++) {

for (a=0; a<3; a++)

r[n][a] = c[a] + gap[a]\*origAtom[j][a];

++n;

}

}

}

}

/\* Total # of atoms summed over processors \*/

MPI\_Allreduce(&n,&nglob,1,MPI\_INT,MPI\_SUM,MPI\_COMM\_WORLD);

if (sid == 0) printf("nglob = %d\n",nglob);

/\* Generate random velocities \*/

seed = 13597.0+sid;

vMag = sqrt(3\*InitTemp);

for(a=0; a<3; a++) vSum[a] = 0.0;

for(j=0; j<n; j++) {

RandVec3(e,&seed);

for (a=0; a<3; a++) {

rv[j][a] = vMag\*e[a];

vSum[a] = vSum[a] + rv[j][a];

}

}

MPI\_Allreduce(vSum,gvSum,3,MPI\_DOUBLE,MPI\_SUM,MPI\_COMM\_WORLD);

/\* Make the total momentum zero \*/

for (a=0; a<3; a++) gvSum[a] /= nglob;

for (j=0; j<n; j++)

for(a=0; a<3; a++) rv[j][a] -= gvSum[a];

}

/\*--------------------------------------------------------------------\*/

void single\_step() {

/\*----------------------------------------------------------------------

r & rv are propagated by DeltaT using the velocity-Verlet scheme.

----------------------------------------------------------------------\*/

int i,a;

half\_kick(); /\* First half kick to obtain v(t+Dt/2) \*/

for (i=0; i<n; i++) /\* Update atomic coordinates to r(t+Dt) \*/

for (a=0; a<3; a++) r[i][a] = r[i][a] + DeltaT\*rv[i][a];

atom\_move();

atom\_copy();

compute\_accel(); /\* Computes new accelerations, a(t+Dt) \*/

half\_kick(); /\* Second half kick to obtain v(t+Dt) \*/

}

/\*--------------------------------------------------------------------\*/

void half\_kick() {

/\*----------------------------------------------------------------------

Accelerates atomic velocities, rv, by half the time step.

----------------------------------------------------------------------\*/

int i,a;

for (i=0; i<n; i++)

for (a=0; a<3; a++) rv[i][a] = rv[i][a]+DeltaTH\*ra[i][a];

}

/\*--------------------------------------------------------------------\*/

void atom\_copy() {

/\*----------------------------------------------------------------------

Exchanges boundary-atom coordinates among neighbor nodes: Makes

boundary-atom list, LSB, then sends & receives boundary atoms.

----------------------------------------------------------------------\*/

int kd,kdd,i,ku,inode,nsd,nrc,a;

int nbnew = 0; /\* # of "received" boundary atoms \*/

double com1;

/\* Main loop over x, y & z directions starts--------------------------\*/

for (kd=0; kd<3; kd++) {

/\* Make a boundary-atom list, LSB---------------------------------\*/

/\* Reset the # of to-be-copied atoms for lower&higher directions \*/

for (kdd=0; kdd<2; kdd++) lsb[2\*kd+kdd][0] = 0;

/\* Scan all the residents & copies to identify boundary atoms \*/

for (i=0; i<n+nbnew; i++) {

for (kdd=0; kdd<2; kdd++) {

ku = 2\*kd+kdd; /\* Neighbor ID \*/

/\* Add an atom to the boundary-atom list, LSB, for neighbor ku

according to bit-condition function, bbd \*/

if (bbd(r[i],ku)) lsb[ku][++(lsb[ku][0])] = i;

}

}

/\* Message passing------------------------------------------------\*/

com1=MPI\_Wtime(); /\* To calculate the communication time \*/

/\* Loop over the lower & higher directions \*/

for (kdd=0; kdd<2; kdd++) {

inode = nn[ku=2\*kd+kdd]; /\* Neighbor node ID \*/

/\* Send & receive the # of boundary atoms-----------------------\*/

nsd = lsb[ku][0]; /\* # of atoms to be sent \*/

/\* Even node: send & recv \*/

if (myparity[kd] == 0) {

MPI\_Send(&nsd,1,MPI\_INT,inode,10,MPI\_COMM\_WORLD);

MPI\_Recv(&nrc,1,MPI\_INT,MPI\_ANY\_SOURCE,10,

MPI\_COMM\_WORLD,&status);

}

/\* Odd node: recv & send \*/

else if (myparity[kd] == 1) {

MPI\_Recv(&nrc,1,MPI\_INT,MPI\_ANY\_SOURCE,10,

MPI\_COMM\_WORLD,&status);

MPI\_Send(&nsd,1,MPI\_INT,inode,10,MPI\_COMM\_WORLD);

}

/\* Single layer: Exchange information with myself \*/

else

nrc = nsd;

/\* Now nrc is the # of atoms to be received \*/

/\* Send & receive information on boundary atoms-----------------\*/

/\* Message buffering \*/

for (i=1; i<=nsd; i++)

for (a=0; a<3; a++) /\* Shift the coordinate origin \*/

dbuf[3\*(i-1)+a] = r[lsb[ku][i]][a]-sv[ku][a];

/\* Even node: send & recv \*/

if (myparity[kd] == 0) {

MPI\_Send(dbuf,3\*nsd,MPI\_DOUBLE,inode,20,MPI\_COMM\_WORLD);

MPI\_Recv(dbufr,3\*nrc,MPI\_DOUBLE,MPI\_ANY\_SOURCE,20,

MPI\_COMM\_WORLD,&status);

}

/\* Odd node: recv & send \*/

else if (myparity[kd] == 1) {

MPI\_Recv(dbufr,3\*nrc,MPI\_DOUBLE,MPI\_ANY\_SOURCE,20,

MPI\_COMM\_WORLD,&status);

MPI\_Send(dbuf,3\*nsd,MPI\_DOUBLE,inode,20,MPI\_COMM\_WORLD);

}

/\* Single layer: Exchange information with myself \*/

else

for (i=0; i<3\*nrc; i++) dbufr[i] = dbuf[i];

/\* Message storing \*/

for (i=0; i<nrc; i++)

for (a=0; a<3; a++) r[n+nbnew+i][a] = dbufr[3\*i+a];

/\* Increment the # of received boundary atoms \*/

nbnew = nbnew+nrc;

/\* Internode synchronization \*/

MPI\_Barrier(MPI\_COMM\_WORLD);

} /\* Endfor lower & higher directions, kdd \*/

comt += MPI\_Wtime()-com1; /\* Update communication time, COMT \*/

} /\* Endfor x, y & z directions, kd \*/

/\* Main loop over x, y & z directions ends--------------------------\*/

/\* Update the # of received boundary atoms \*/

nb = nbnew;

}

/\*--------------------------------------------------------------------\*/

void compute\_accel() {

/\*----------------------------------------------------------------------

Given atomic coordinates, r[0:n+nb-1][], for the extended (i.e.,

resident & copied) system, computes the acceleration, ra[0:n-1][], for

the residents.

----------------------------------------------------------------------\*/

int i,j,a,lc2[3],lcyz2,lcxyz2,mc[3],c,mc1[3],c1;

//int bintra;

double rrCut,lpe;

double lpe\_td[nthrd]

/\* Reset the potential & forces \*/

lpe = 0.0;

for( i=0; i<nthrd; i ++) lpe\_td[i]= 0.0;

for (i=0; i<n; i++) for (a=0; a<3; a++) ra[i][a] = 0.0;

/\* Make a linked-cell list, lscl------------------------------------\*/

for (a=0; a<3; a++) lc2[a] = lc[a]+2;

lcyz2 = lc2[1]\*lc2[2];

lcxyz2 = lc2[0]\*lcyz2;

/\* Reset the headers, head \*/

for (c=0; c<lcxyz2; c++) head[c] = EMPTY;

/\* Scan atoms to construct headers, head, & linked lists, lscl \*/

for (i=0; i<n+nb; i++) {

for (a=0; a<3; a++) mc[a] = (r[i][a]+rc[a])/rc[a];

/\* Translate the vector cell index, mc, to a scalar cell index \*/

c = mc[0]\*lcyz2+mc[1]\*lc2[2]+mc[2];

/\* Link to the previous occupant (or EMPTY if you're the 1st) \*/

lscl[i] = head[c];

/\* The last one goes to the header \*/

head[c] = i;

} /\* Endfor atom i \*/

/\* Calculate pair interaction---------------------------------------\*/

rrCut = RCUT\*RCUT;

#pragma omp parallel private(a,mc,c,mc1,c1,i,j)

{

double dr[3],rr,ri2,ri6,r1,fcVal,f,vVal;

int std,vtd[3],mofst[3];

std = omp\_get\_thread\_num();

vtd[0] = std/(vthrd[1]\*vthrd[2]);

vtd[1] = (std/vthrd[2])%vthrd[1];

vtd[2] = std%vthrd[2];

for (a=0; a<3; a++)

mofst[a] = vtd[a]\*thbk[a];

/\* Scan inner cells \*/

//for (mc[0]=1; mc[0]<=lc[0]; (mc[0])++)

//for (mc[1]=1; mc[1]<=lc[1]; (mc[1])++)

//for (mc[2]=1; mc[2]<=lc[2]; (mc[2])++) {

for (mc[0]=mofst[0]+1; mc[0]<=mofst[0]+thbk[0]; (mc[0])++)

for (mc[1]=mofst[1]+1; mc[1]<=mofst[1]+thbk[1]; (mc[1])++)

for (mc[2]=mofst[2]+1; mc[2]<=mofst[2]+thbk[2]; (mc[2])++){

/\* Calculate a scalar cell index \*/

c = mc[0]\*lcyz2+mc[1]\*lc2[2]+mc[2];

/\* Skip this cell if empty \*/

if (head[c] == EMPTY) continue;

/\* Scan the neighbor cells (including itself) of cell c \*/

for (mc1[0]=mc[0]-1; mc1[0]<=mc[0]+1; (mc1[0])++)

for (mc1[1]=mc[1]-1; mc1[1]<=mc[1]+1; (mc1[1])++)

for (mc1[2]=mc[2]-1; mc1[2]<=mc[2]+1; (mc1[2])++) {

/\* Calculate the scalar cell index of the neighbor cell \*/

c1 = mc1[0]\*lcyz2+mc1[1]\*lc2[2]+mc1[2];

/\* Skip this neighbor cell if empty \*/

if (head[c1] == EMPTY) continue;

/\* Scan atom i in cell c \*/

i = head[c];

while (i != EMPTY) {

/\* Scan atom j in cell c1 \*/

j = head[c1];

while (j != EMPTY) {

/\* No calculation with itself \*/

if (j != i) {

/\* Logical flag: intra(true)- or inter(false)-pair atom \*/

//bintra = (j < n);

/\* Pair vector dr = r[i] - r[j] \*/

for (rr=0.0, a=0; a<3; a++) {

dr[a] = r[i][a]-r[j][a];

rr += dr[a]\*dr[a];

}

/\* Calculate potential & forces for intranode pairs (i < j)

& all the internode pairs if rij < RCUT; note that for

any copied atom, i < j \*/

// if (i<j && rr<rrCut) {

if(rr<rrCut){

ri2 = 1.0/rr; ri6 = ri2\*ri2\*ri2; r1 = sqrt(rr);

fcVal = 48.0\*ri2\*ri6\*(ri6-0.5) + Duc/r1;

vVal = 4.0\*ri6\*(ri6-1.0) - Uc - Duc\*(r1-RCUT);

// if (bintra) lpe += vVal; else lpe += 0.5\*vVal;

lpe\_td[std] += 0.5\*vVal;

for (a=0; a<3; a++) {

f = fcVal\*dr[a];

ra[i][a] += f;

// if (bintra) ra[j][a] -= f;

}

}

} /\* Endif not self \*/

j = lscl[j];

} /\* Endwhile j not empty \*/

i = lscl[i];

} /\* Endwhile i not empty \*/

} /\* Endfor neighbor cells, c1 \*/

} /\* Endfor central cell, c \*/

}//end parallel section

// thread reduction

for(i=0;i<nthrd;i++) lpe += lpe\_td[i];

/\* Global potential energy \*/

MPI\_Allreduce(&lpe,&potEnergy,1,MPI\_DOUBLE,MPI\_SUM,MPI\_COMM\_WORLD);

}

/\*--------------------------------------------------------------------\*/

void eval\_props() {

/\*----------------------------------------------------------------------

Evaluates physical properties: kinetic, potential & total energies.

----------------------------------------------------------------------\*/

double vv,lke;

int i,a;

/\* Total kinetic energy \*/

for (lke=0.0, i=0; i<n; i++) {

for (vv=0.0, a=0; a<3; a++) vv += rv[i][a]\*rv[i][a];

lke += vv;

}

lke \*= 0.5;

MPI\_Allreduce(&lke,&kinEnergy,1,MPI\_DOUBLE,MPI\_SUM,MPI\_COMM\_WORLD);

/\* Energy paer atom \*/

kinEnergy /= nglob;

potEnergy /= nglob;

totEnergy = kinEnergy + potEnergy;

temperature = kinEnergy\*2.0/3.0;

/\* Print the computed properties \*/

if (sid == 0) printf("%9.6f %9.6f %9.6f %9.6f\n",

stepCount\*DeltaT,temperature,potEnergy,totEnergy);

}

/\*--------------------------------------------------------------------\*/

void atom\_move() {

/\*----------------------------------------------------------------------

Sends moved-out atoms to neighbor nodes and receives moved-in atoms

from neighbor nodes. Called with n, r[0:n-1] & rv[0:n-1], atom\_move

returns a new n' together with r[0:n'-1] & rv[0:n'-1].

----------------------------------------------------------------------\*/

/\* Local variables------------------------------------------------------

mvque[6][NBMAX]: mvque[ku][0] is the # of to-be-moved atoms to neighbor

ku; MVQUE[ku][k>0] is the atom ID, used in r, of the k-th atom to be

moved.

----------------------------------------------------------------------\*/

int mvque[6][NBMAX];

int newim = 0; /\* # of new immigrants \*/

int ku,kd,i,kdd,kul,kuh,inode,ipt,a,nsd,nrc;

double com1;

/\* Reset the # of to-be-moved atoms, MVQUE[][0] \*/

for (ku=0; ku<6; ku++) mvque[ku][0] = 0;

/\* Main loop over x, y & z directions starts------------------------\*/

for (kd=0; kd<3; kd++) {

/\* Make a moved-atom list, mvque----------------------------------\*/

/\* Scan all the residents & immigrants to list moved-out atoms \*/

for (i=0; i<n+newim; i++) {

kul = 2\*kd ; /\* Neighbor ID \*/

kuh = 2\*kd+1;

/\* Register a to-be-copied atom in mvque[kul|kuh][] \*/

if (r[i][0] > MOVED\_OUT) { /\* Don't scan moved-out atoms \*/

/\* Move to the lower direction \*/

if (bmv(r[i],kul)) mvque[kul][++(mvque[kul][0])] = i;

/\* Move to the higher direction \*/

else if (bmv(r[i],kuh)) mvque[kuh][++(mvque[kuh][0])] = i;

}

}

/\* Message passing with neighbor nodes----------------------------\*/

com1 = MPI\_Wtime();

/\* Loop over the lower & higher directions------------------------\*/

for (kdd=0; kdd<2; kdd++) {

inode = nn[ku=2\*kd+kdd]; /\* Neighbor node ID \*/

/\* Send atom-number information---------------------------------\*/

nsd = mvque[ku][0]; /\* # of atoms to-be-sent \*/

/\* Even node: send & recv \*/

if (myparity[kd] == 0) {

MPI\_Send(&nsd,1,MPI\_INT,inode,110,MPI\_COMM\_WORLD);

MPI\_Recv(&nrc,1,MPI\_INT,MPI\_ANY\_SOURCE,110,

MPI\_COMM\_WORLD,&status);

}

/\* Odd node: recv & send \*/

else if (myparity[kd] == 1) {

MPI\_Recv(&nrc,1,MPI\_INT,MPI\_ANY\_SOURCE,110,

MPI\_COMM\_WORLD,&status);

MPI\_Send(&nsd,1,MPI\_INT,inode,110,MPI\_COMM\_WORLD);

}

/\* Single layer: Exchange information with myself \*/

else

nrc = nsd;

/\* Now nrc is the # of atoms to be received \*/

/\* Send & receive information on boundary atoms-----------------\*/

/\* Message buffering \*/

for (i=1; i<=nsd; i++)

for (a=0; a<3; a++) {

/\* Shift the coordinate origin \*/

dbuf[6\*(i-1) +a] = r [mvque[ku][i]][a]-sv[ku][a];

dbuf[6\*(i-1)+3+a] = rv[mvque[ku][i]][a];

r[mvque[ku][i]][0] = MOVED\_OUT; /\* Mark the moved-out atom \*/

}

/\* Even node: send & recv, if not empty \*/

if (myparity[kd] == 0) {

MPI\_Send(dbuf,6\*nsd,MPI\_DOUBLE,inode,120,MPI\_COMM\_WORLD);

MPI\_Recv(dbufr,6\*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,6\*nrc,MPI\_DOUBLE,MPI\_ANY\_SOURCE,120,

MPI\_COMM\_WORLD,&status);

MPI\_Send(dbuf,6\*nsd,MPI\_DOUBLE,inode,120,MPI\_COMM\_WORLD);

}

/\* Single layer: Exchange information with myself \*/

else

for (i=0; i<6\*nrc; i++) dbufr[i] = dbuf[i];

/\* Message storing \*/

for (i=0; i<nrc; i++)

for (a=0; a<3; a++) {

r [n+newim+i][a] = dbufr[6\*i +a];

rv[n+newim+i][a] = dbufr[6\*i+3+a];

}

/\* Increment the # of new immigrants \*/

newim = newim+nrc;

/\* Internode synchronization \*/

MPI\_Barrier(MPI\_COMM\_WORLD);

} /\* Endfor lower & higher directions, kdd \*/

comt=comt+MPI\_Wtime()-com1;

} /\* Endfor x, y & z directions, kd \*/

/\* Main loop over x, y & z directions ends--------------------------\*/

/\* Compress resident arrays including new immigrants \*/

ipt = 0;

for (i=0; i<n+newim; i++) {

if (r[i][0] > MOVED\_OUT) {

for (a=0; a<3; a++) {

r [ipt][a] = r [i][a];

rv[ipt][a] = rv[i][a];

}

++ipt;

}

}

/\* Update the compressed # of resident atoms \*/

n = ipt;

}

/\*----------------------------------------------------------------------

Bit condition functions:

1. bbd(ri,ku) is .true. if coordinate ri[3] is in the boundary to

neighbor ku.

2. bmv(ri,ku) is .true. if an atom with coordinate ri[3] has moved out

to neighbor ku.

----------------------------------------------------------------------\*/

int bbd(double\* ri, int ku) {

int kd,kdd;

kd = ku/2; /\* x(0)|y(1)|z(2) direction \*/

kdd = ku%2; /\* Lower(0)|higher(1) direction \*/

if (kdd == 0)

return ri[kd] < RCUT;

else

return al[kd]-RCUT < ri[kd];

}

int bmv(double\* ri, int ku) {

int kd,kdd;

kd = ku/2; /\* x(0)|y(1)|z(2) direction \*/

kdd = ku%2; /\* Lower(0)|higher(1) direction \*/

if (kdd == 0)

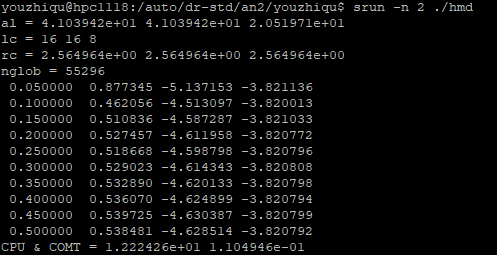
return ri[kd] < 0.0;

else

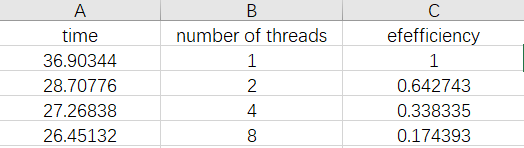
return al[kd] < ri[kd];

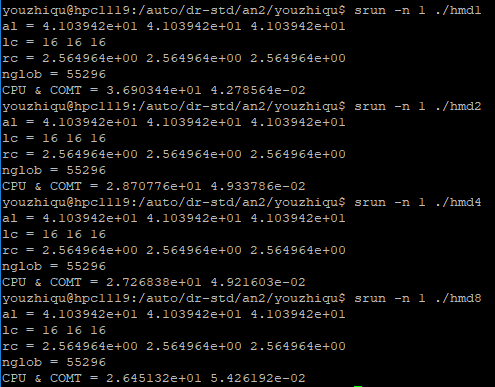
}

**2. output:**

****

**3. the strong-scaling parallel efficiency**



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