

TITLE OF THE MASTER THESIS

by

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Abstract

This is an abstract text.

To someone

This is a dedication to my cat.

Acknowledgements

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Contents

1	Introduction	1
2	LAMMPS	3
2.1	Installation	3
2.1.1	Linux	3
2.1.2	Mac OS X with Homebrew	4
2.1.3	Windows	5
2.2	Running LAMMPS	5
2.3	Creating a custom compute	5
2.3.1	Find a similar compute	5
2.3.2	Creating the class	5
3	Setting up the system	7
3.1	Silica	7
3.1.1	Unit cell of β -cristobalite	8
3.2	Building a crystal	8
3.3	Shaping the silica	10
4	This must be sorted in designated chapters	13
4.1	Radial distribution of normal force	13
A	Source code	15
A.1	compute_group_group.h	16
A.2	compute_group_group_atom.h	17
A.3	compute_group_group_atom.cpp	18

Chapter 1

Introduction

Why is the subject of this thesis of any interest?

What is our take on the problem?

What do we hope to accomplish?

How will this be of any contribution to anything?

How is the thesis laid out?

Chapter 2

LAMMPS

LAMMPS stands for *Large-scale Atomic/Molecular Massively Parallel Simulator*. It is a classical molecular dynamics simulation code designed to run efficiently on parallel computers. Its development began in the mid 1990s at Sandia National Laboratories, with funding from the U.S. Department of Energy. It was a cooperative project between two DOE labs and three private companies. The development is still ongoing and contributions are revised thoroughly.

Today LAMMPS is an open-source code with extensive and user friendly documentation. This is one of the main reasons that we have chosen to use LAMMPS as opposed to other molecular dynamics software.

2.1 Installation

Installing LAMMPS is a fairly simple procedure if only the basic settings are needed.

2.1.1 Linux

Users with a Unix based OS may download the lammps distribution as a tarball from LAMMPS' download page¹ and then unpack it from the command line.

```
1 gunzip filename.tar.gz
2 tar xvf filename.tar
```

The user may then change directory into `/path/to/lammps/src/`, and execute the following commands in order to list available packages.

```
1 make package-status
```

Installing specific packages is accomplished as shown below.

¹<http://lammps.sandia.gov/download.html>

```
1 make yes-molecule yes-manybody yes-python yes-rigid
```

The above example installs the packages *molecule*, *manybody*, *python* and *rigid*. Next, the user can build LAMMPS using either of the lines below. Assuming the user has MPI installed line 2 makes the resulting executable compatible with parallelization in MPI.

```
1 make serial
2 make mpi
```

At this point there should be an executable in the `/path/to/lammps/src/` directory named `lmp_serial` or `lmp_mpi`, depending on the previous choice. These are now ready to run. To use it one has to point to this file from the command line at every run. It may be practical to set up a symlink as follows shown below.

```
1 sudo ln -s /path/to/lammps/src/lmp_mpi
   /usr/local/bin/lmp_mpi
```

The executable is now available as `lmp_serial` or `lmp_mpi` from anywhere.

2.1.2 Mac OS X with Homebrew

Mac users can follow the procedure described above, however they may also install even easier using *Homebrew*².

```
1 brew tap homebrew/science
2 brew install lammps           # serial version
3 brew install lammps --with-mpi # mpi support
```

Where the user obviously should choose either line 2 or line 3, depending on if the user wants MPI comparability. This will install an executable named "lammps", a python module named "lammps", and resources with standard packages. This is basically it. LAMMPS is now ready to run, however, not all packages are installed.

The location of the resources and available packages can be found using the following command.

```
1 brew info lammps
```

Specific packages are available as options, and may be installed with the following command.

```
1 brew install lammps --enable-manybody
```

In the example shown we installed the package *manybody*.

²<http://brew.sh/>

2.1.3 Windows

2.2 Running LAMMPS

2.3 Creating a custom compute

A *compute* is a LAMMPS command that defines a computation that will be performed on a group of atoms. The *computes* produce instantaneous values, using information about the atoms on the current time step.

In LAMMPS there are more than 100 computes already, and chances are they have what you're looking for. If not, one might treat the data from other computes in some way to get the desired information. However, if there are no compute command that does the desired task, it is possible to create an own custom class.

In order to compute the normal forces acting on the sphere, we have written a custom compute class. The purpose of the class was to save the forces acting on atoms in one group from atoms of another group. In this section we will try to give brief instructions on how this was done.

[MAYBE A FIGURE HERE]

2.3.1 Find a similar compute

Obviously, before writing any code we should know what we want the compute to calculate and how this should be done. Before starting off with a blank sheet in the editor, one should definitely search for similar computes in LAMMPS. This can potentially save hours of hard work!

For instance there is a compute named *group/group*³ which computes the total energy and force interaction between two groups of atoms. This is almost what we want, but we also need to know how many atoms contribute to this total force, and it should also work with the Vashishta potential. ++

Thus there are minor modifications needed, and we chose to make our compute a subclass of this one.

2.3.2 Creating the class

All computes in LAMMPS are subclasses of the class named *compute*. From this superclass they inherit a bunch of variables, functions and flags, which the user may decide to set. Functions are of course declared in the *.h*-file, while variables and flags are set in the constructor. The source code of the *group/group* compute is shown in Appendix A.1. Since we will be making a subclass of it, we change

³http://lammps.sandia.gov/doc/compute_group_group.html

the *private* property to *protected* so that we have access to all the variables and functions.

We start out by creating a header file and decide upon a name for our class. We have chosen the name *group/group/atom* since it is basically a per-atom version of already existing compute *group/group*. A complete header file is shown in Listing 2.1, and explained in detail below.

```

1  #ifndef COMPUTE_CLASS
2  ComputeStyle(group/group/atom, ComputeGroupGroupAtom)
3  #else
4
5  #ifndef LMP_COMPUTE_GROUP_GROUP_ATOM_H
6  #define LMP_COMPUTE_GROUP_GROUP_ATOM_H
7
8  #include "compute.h"
9  #include "compute_group_group.h"
10
11 namespace LAMMPS_NS {
12
13 class ComputeGroupGroupAtom : public ComputeGroupGroup {
14 public:
15     ComputeGroupGroupAtom(class LAMMPS *, int, char **);
16     ~ComputeGroupGroupAtom();
17     void compute_peratom() override;
18     int nmax;
19     double **carray;
20
21 private:
22     void pair_contribution() override;
23 };
24 }
25 #endif
26 #endif

```

Listing 2.1: Header file of our new compute: `compute_group_group_atom.h`.

`ComputeStyle` defines the command to be used in the LAMMPS input script to be `group/group/atom`, and the name to be `ComputeGroupGroupAtom`. The name will be redundant to us.

`nmax` is the number of atoms which are subject to a non zero force from atoms of another group at the current time step; it may vary.

`carray` is a two dimensional array, containing the force on atoms in one group induced by atoms of another group.

Chapter 3

Setting up the system

We wish to construct a system consisting of **two** elements made out of silica: a slab and a sphere cap. In order to do this we need to generate the spacial position coordinates (x,y,z) of every single atom. Considering that we are making a system consisting of about 10^5 atoms, this is obviously not done manually. We have chosen to use a tool named *Moltemplate*¹, which is included in the LAMMPS distribution.

The main idea is to manually enter the coordinates of only the atoms in a unit cell of the material one wish to generate, and then simply copy this unit cell wherever desired. The software will shift the coordinates of the copied unit cell by the displacement from the original image. In addition it will generate files containing data such as which atoms they share bonds with, if any, and angles between such bonds.

3.1 Silica

Silica is a chemical compound also known as Silicon dioxide, having the chemical formula SiO_2 . It has several polymorph structures, the most common being quartz, which is one of the most abundant minerals in the Earth's crust. Other polymorphs include cristobalite, tridymite, coesite and more.

For our purpose it is insignificant which one we choose. Once the material is melted, it is indifferent which configuration we started from, as long as the density is correct. In this project we will build the constituents of the system from a type of cristobalite named β -cristobalite. This is mainly because it has a simple structure and a cubical unit cell.

¹<http://www.moltemplate.org/index.html>

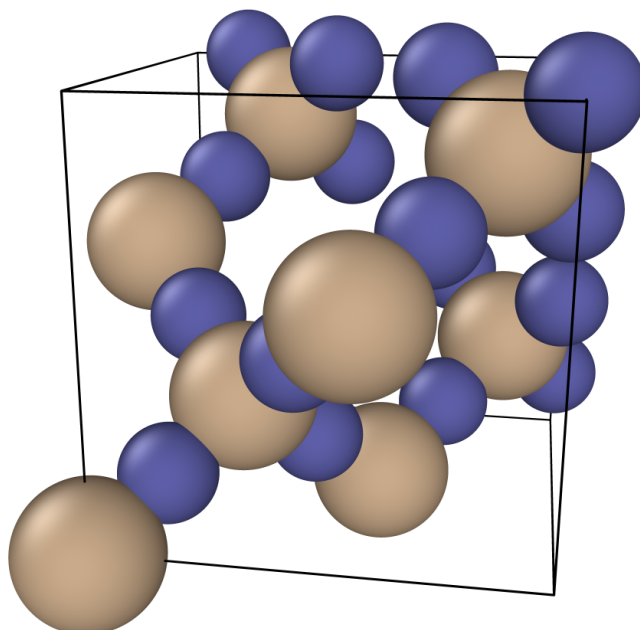


Figure 3.1: Unit cell of β -cristobalite. Tan and blue spheres represent silicon and oxygen atoms respectively.

3.1.1 Unit cell of β -cristobalite

In order to construct the unit cell of a material, one should look up the coordinates of the atoms in a crystallography database. We have used the unit cell of β -cristobalite found at *Crystallography Open Database*². At this site one can download a `.cif`-file consisting of the spatial positions of each atom, the length of the unit cell edges and angles between faces of the cell. In the case of β -cristobalite the unit cell is cubical with edges of length 7.12\AA . It contains 8 silicon atoms and 16 oxygen atoms. The density of the unit cell can easily be computed and is 2.2114 g/cm^3 .

3.2 Building a crystal

The coordinates gotten from the `.cif`-file can now be implemented into *moltemplate* together with whatever bond and angle data required by the potential. In our simulations we will use the Vashishta potential, which does not require these.

Moltemplate has its own structure and syntax. The first step to build up

²<http://www.crystallography.net/cod/1010944.html>

a larger material is, as mentioned, to create the unit cell. Data concerning the unit cell are placed in a `.lt`-file, which is readable by Moltemplate. Such a file is shown in Listing 3.1.

For a more profound understanding of the structure and syntax of these files, the reader is advised to read the moltemplate manual

```

1  # file "beta-cristobalite.lt"
2
3  beta-cristobalite {
4    write("Data Atoms") {
5      $atom:Si1    @atom:Si    0.00    0.00    0.00
6      $atom:Si2    @atom:Si    0.00    3.56    3.56
7      $atom:Si3    @atom:Si    1.78    1.78    1.78
8      $atom:Si4    @atom:Si    3.56    0.00    3.56
9      $atom:Si5    @atom:Si    1.78    5.34    5.34
10     $atom:Si6    @atom:Si    5.34    5.34    1.78
11     $atom:Si7    @atom:Si    3.56    3.56    0.00
12     $atom:Si8    @atom:Si    5.34    1.78    5.34
13     $atom:O1     @atom:O     0.89    0.89    0.89
14     $atom:O2     @atom:O     6.23    4.45    2.67
15     $atom:O3     @atom:O     2.67    2.67    0.89
16     $atom:O4     @atom:O     4.45    0.89    4.45
17     $atom:O5     @atom:O     0.89    4.45    4.45
18     $atom:O6     @atom:O     4.45    4.45    0.89
19     $atom:O7     @atom:O     2.67    6.23    4.45
20     $atom:O8     @atom:O     2.67    0.89    2.67
21     $atom:O9     @atom:O     4.45    2.67    6.23
22     $atom:O10    @atom:O     6.23    2.67    4.45
23     $atom:O11    @atom:O     2.67    4.45    6.23
24     $atom:O12    @atom:O     0.89    6.23    6.23
25     $atom:O13    @atom:O     0.89    2.67    2.67
26     $atom:O14    @atom:O     4.45    6.23    2.67
27     $atom:O15    @atom:O     6.23    6.23    0.89
28     $atom:O16    @atom:O     6.23    0.89    6.23
29   }
30
31   write_once("Data Masses") {
32     @atom:Si 28.0855
33     @atom:O  15.9994
34   }
35
36 } # end definition of beta-cristobalite molecule type

```

Listing 3.1: Typical moltemplate file containing unit cell data. The columns of the "Data Atoms" section hold, from left to right, information of atom ID, atom type, x-, y- and z-position. The "Data Masses" section stores the weight of silicon and oxygen atoms in atomic mass units.

We use the unit cell as building blocks, placing them concurrently until we

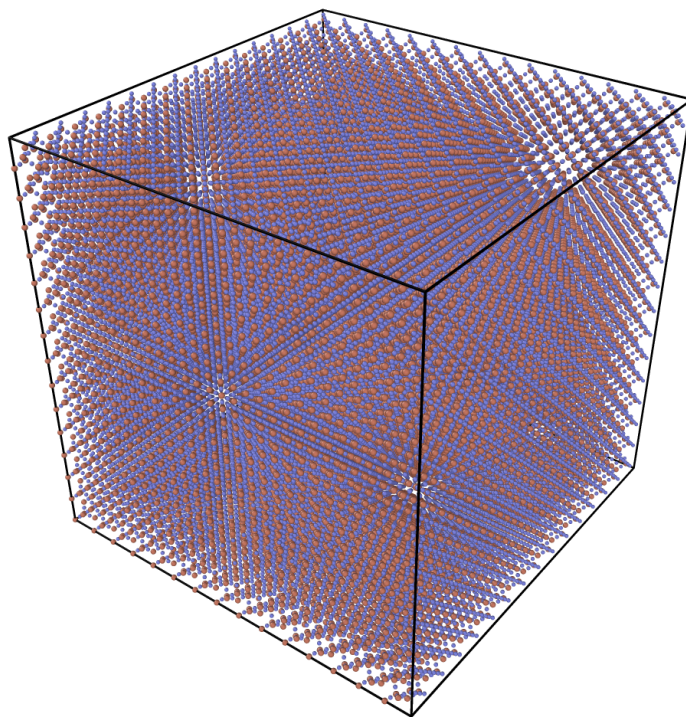


Figure 3.2: System built from $15 \times 15 \times 15$ unit cells of b-cristobalite.

have a crystal of the desired size. For our purpose, we generate a large cube of $15 \times 15 \times 15$ unit cells. This is done as follows.

3.3 Shaping the silica

The huge cube of silica can be carved however we like by defining regions from which we delete the containing atoms. In LAMMPS this is done by using the `region`, `union`, `intersect` and `delete atoms` commands. Our implementation is stated in Listing 3.2, which is very simple due to the way we are going to treat the boundary conditions.

```

1  region sphereRegion sphere 53.4 53.4 226.8 150
2  group sphereGroup region sphereRegion
3
4  region slabRegion block 0 INF 0 INF 0 35.6
5  group slabGroup region slabRegion
6
7  region bothRegion union 2 sphereRegion slabRegion side out
8  delete_atoms region bothRegion

```

Listing 3.2: Defining regions to keep or delete from a system of dimensions $106.8 \times 106.8 \times 106.8$ Å.

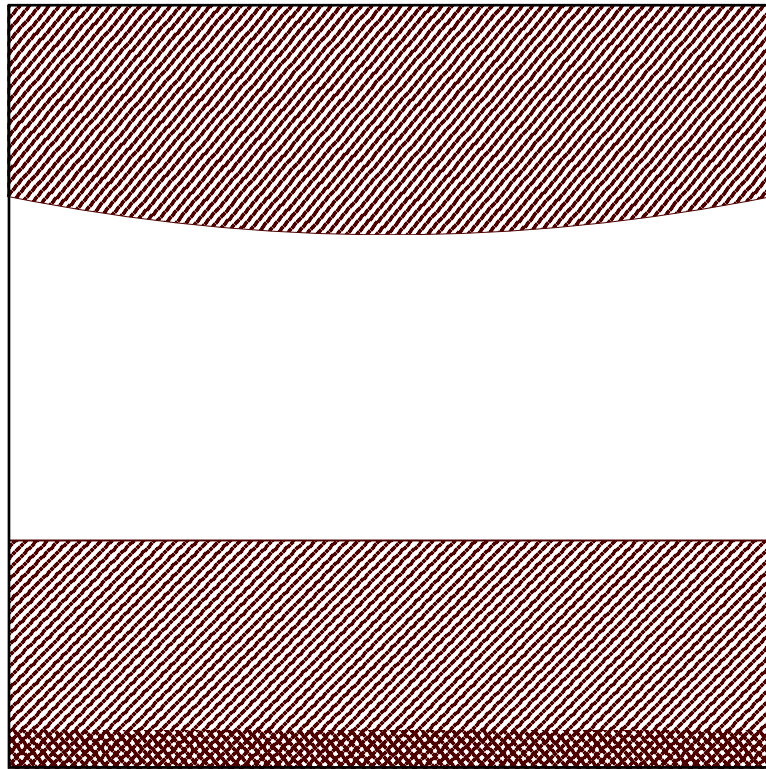


Figure 3.3: Illustrative drawing of what how the system should look. Red parallel stripes symbolize areas of silica. Red crossing stripes indicate areas of frozen silica. The boundaries are periodic in all dimensions, causing both the slab and the sphere to be connected to the frozen silica through the z-boundaries.

Chapter 4

This must be sorted in designated chapters

4.1 Radial distribution of normal force

In order to find a radial distribution of the normal force, F_N , we partition the system into a grid in the xy-plane. We then use the command

```
1  compute chunkID all chunk/atom bin/2d x 0 7.12 y 0 7.12
2  compute stressID all stress/atom NULL
3  fix fixChunkID all ave/chunk 1 1 10 chunkID
   c_stressID[3] file forcesInChunks.txt
```

to compute the stress of every chunk in the z-direction, σ_{zz} (sum of every individual atom stress in the chunk).

Line 1 establishes the grid, with bin width 7.12Å.

Line 2 creates a compute of the stress

Line 3 stores the sum of individual stresses in each chunk to the file `forcesInChunks.txt`.

This is done every 10 time steps in order to reduce correlation effects.

The data is stored from each time step can easily be averaged to produce a result as shown in figure X.

We can then find the radial distribution simply by binning this matrix in radial bins, and average the normal forces of the chunks within the bins.

Appendix A

Source code

A.1 compute_group_group.h

```

1  #ifdef COMPUTE_CLASS
2  ComputeStyle(group/group, ComputeGroupGroup)
3  #else
4
5  #ifndef LMP_COMPUTE_GROUP_GROUP_H
6  #define LMP_COMPUTE_GROUP_GROUP_H
7
8  #include "compute.h"
9
10 namespace LAMMPS_NS {
11
12 class ComputeGroupGroup : public Compute {
13 public:
14     ComputeGroupGroup(class LAMMPS *, int, char **);
15     ~ComputeGroupGroup();
16     void init();
17     void init_list(int, class NeighList *);
18     double compute_scalar();
19     void compute_vector();
20
21 protected: // private
22     char *group2;
23     int jgroup, jgroupbit, othergroupbit;
24     double **cutsq;
25     double e_self, e_correction;
26     int pairflag, kspaceflag, boundaryflag;
27     class Pair *pair;
28     class NeighList *list;
29     class KSpace *kspace;
30
31     virtual void pair_contribution();
32     void kspace_contribution();
33     void kspace_correction();
34 };
35
36 }
37
38 #endif
39 #endif

```

A.2 compute_group_group_atom.h

```
1  #ifndef COMPUTE_CLASS
2  ComputeStyle(group/group/atom,ComputeGroupGroupAtom)
3  #else
4
5  #ifndef LMP_COMPUTE_GROUP_GROUP_ATOM_H
6  #define LMP_COMPUTE_GROUP_GROUP_ATOM_H
7
8  #include "compute.h"
9  #include "compute_group_group.h"
10
11 namespace LAMMPS_NS {
12
13 class ComputeGroupGroupAtom : public ComputeGroupGroup {
14 public:
15     ComputeGroupGroupAtom(class LAMMPS *, int, char **);
16     ~ComputeGroupGroupAtom();
17     void compute_peratom() override;
18     int nmax;
19     double **carray;
20
21 private:
22     void pair_contribution() override;
23 };
24 }
25 #endif
26 #endif
```

A.3 compute_group_group_atom.cpp

```

1  #include <mpi.h>
2  #include <string.h>
3  #include "compute_group_group_atom.h"
4  #include "atom.h"
5  #include "update.h"
6  #include "force.h"
7  #include "pair.h"
8  #include "neighbor.h"
9  #include "neigh_request.h"
10 #include "neigh_list.h"
11 #include "group.h"
12 #include "kspace.h"
13 #include "error.h"
14 #include <math.h>
15 #include "comm.h"
16 #include "domain.h"
17 #include "math_const.h"
18 #include "memory.h"
19
20 #include <iostream>
21 using namespace LAMMPS_NS;
22 using namespace MathConst;
23
24 #define SMALL 0.00001
25
26 ComputeGroupGroupAtom::ComputeGroupGroupAtom(LAMMPS *lmp,
27     int narg, char **arg) :
28     ComputeGroupGroup(lmp, narg, arg),
29     carray(NULL),
30     nmax(0)
31 {
32     if (narg < 4) error->all(FLError, "Illegal compute
33         group/group command");
34
35     peratom_flag      = 1; // Indicating a peratom compute
36     size_peratom_cols = 4; // # of Columns per atom.
37     extarray          = 0; // 0/1 if global array is all
38         intensive/extensive
39     scalar_flag       = 0;
40     vector_flag       = 0;
41 }
42
43 ComputeGroupGroupAtom::~ComputeGroupGroupAtom()
44 {
45     memory->destroy(carray);
46 }

```

```

46
47 void ComputeGroupGroupAtom::compute_peratom()
48 {
49     // grow array if necessary
50     if (atom->nmax > nmax) {
51
52         memory->destroy(carray);
53         nmax = atom->nmax;
54         memory->create(carray, nmax, size_peratom_cols,
55             "group/group/atom:carray");
56         array_atom = cararray;
57     }
58
59     if (pairflag) pair_contribution();
60     if (kspaceflag) kspace_contribution(); // This doesn't
        happen though. See compute_group_group.cpp
        constructor.
61 }
62
63
64 void ComputeGroupGroupAtom::pair_contribution()
65 {
66     int i,j,ii,jj,inum,jnum,itype,jtype;
67     double xtmp,ymtp,ztmp,dex,dely,dely;
68     double rsq,eng,fpair,factor_coul,factor_lj;
69     int *ilist,*jlist,*numneigh,**firstneigh;
70
71     double **x = atom->x;
72     int *type = atom->type;
73     int *mask = atom->mask;
74     int nlocal = atom->nlocal;
75     double *special_coul = force->special_coul;
76     double *special_lj = force->special_lj;
77     int newton_pair = force->newton_pair;
78     double *columns;
79
80     // invoke half neighbor list (will copy or build if
        necessary)
81
82     neighbor->build_one(list);
83
84     inum = list->inum;
85     ilist = list->ilist;
86     numneigh = list->numneigh;
87     firstneigh = list->firstneigh;
88
89     // loop over neighbors of my atoms
90     // skip if I,J are not in 2 groups
91
92

```

```

93     for (ii = 0; ii < inum; ii++) {
94         i = ilist[ii];
95
96         // skip if atom I is not in either group
97         if (!(mask[i] & groupbit || mask[i] & jgroupbit))
98             continue;
99
100        xtmp = x[i][0];
101        ytmp = x[i][1];
102        ztmp = x[i][2];
103        itype = type[i];
104        jlist = firstneigh[i];
105        jnum = numneigh[i];
106
107        for (jj = 0; jj < jnum; jj++) {
108            j = jlist[jj];
109            factor_lj = special_lj[sbmask(j)];
110            factor_coul = special_coul[sbmask(j)];
111            j &= NEIGHMASK;
112
113            // skip if atom J is not in either group
114            if (!(mask[j] & groupbit || mask[j] &
115                jgroupbit)) continue;
116
117            int ij_flag = 0;
118            int ji_flag = 0;
119            if (mask[i] & groupbit && mask[j] & jgroupbit)
120                ij_flag = 1;
121            if (mask[j] & groupbit && mask[i] & jgroupbit)
122                ji_flag = 1;
123
124            // skip if atoms I,J are only in the same group
125            if (!ij_flag && !ji_flag) continue;
126
127            delx = xtmp - x[j][0];
128            dely = ytmp - x[j][1];
129            delz = ztmp - x[j][2];
130            rsq = delx*delx + dely*dely + delz*delz;
131            jtype = type[j];
132
133            if (rsq < cutsq[itype][jtype]) {
134                eng = pair->single(i, j, itype, jtype,
135                    rsq, factor_coul, factor_lj, fpair);
136
137                // energy only computed once so tally full
138                // amount
139                // force tally is jgroup acting on igroup
140
141                if (newton_pair || j < nlocal) {
142                    array_atom[i][0] += eng;
143                    if (ij_flag) {

```

```
138         array_atom[i][1] += delx*fpair;
139         array_atom[i][2] += dely*fpair;
140         array_atom[i][3] += delz*fpair;
141     }
142     if (ji_flag) {
143         array_atom[j][1] -= delx*fpair;
144         array_atom[j][2] -= dely*fpair;
145         array_atom[j][3] -= delz*fpair;
146     }
147
148     // energy computed twice so tally half
149     // amount
150     // only tally force if I own igroup
151     // atom
152     }
153     else {
154         array_atom[i][0] += 0.5*eng;
155         if (ij_flag) {
156             array_atom[i][1] += delx*fpair;
157             array_atom[i][2] += dely*fpair;
158             array_atom[i][3] += delz*fpair;
159         }
160     }
161 }
162 }
```


Bibliography

- [1] Bin Luan and Mark O Robbins. The breakdown of continuum models for mechanical contacts. *Nature*, 435(7044):929–932, 2005.