

# Chen GU Assignment 4 CPSC 424

## Building and running information

### Development environment

#### Module loaded

Currently Loaded Modulefiles:

- 1) Base/yale\_hpc
- 2) Langs/Intel/15
- 3) MPI/OpenMPI/1.8.6-intel15
- 4) Tools/TotalView/8.14.1-8

#### env command

```
MKLR00T=/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/mkl
MANPATH=/home/apps/fas/Tools/TotalView/toolworks/totalview.8.14.1-8/man:/usr/local/cluster/hpc/MPI/OpenMPI/1.8.6-intel15/share/man:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/man/en_US:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/debugger/gdb/intel64/share/man:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/debugger/gdb/intel64_mic/share/man:/usr/share/man:/opt/moab/share/man:
GDB_HOST=/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/debugger/gdb/intel64_mic/bin/gdb-ia-mic
HOSTNAME=compute-32-14.local
PBS_VERSION=TORQUE-4.2.9
IPPR00T=/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/ipp
INTEL_LICENSE_FILE=/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/licenses:/opt/intel/licenses:/home/apps/fas/Licenses/intel_site.lic
TERM=xterm-256color
SHELL=/bin/bash
HISTSIZE=1000
GDBSERVER_MIC=/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/debugger/gdb/target/mic/bin/gdbserver
PBS_JOBNAME=STDIN
```

```
LIBRARY_PATH=/usr/local/cluster/hpc/MPI/OpenMPI/1.8.6-intel15/lib:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/ipp/./compiler/lib/intel64:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/ipp/lib/intel64:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/mkl/lib/intel64:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/tbb/lib/intel64/gcc4.4
PERL5LIB=/opt/rocks/lib/perl5
FPATH=/usr/local/cluster/hpc/MPI/OpenMPI/1.8.6-intel15/include:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/mkl/include
PBS_ENVIRONMENT=PBS_INTERACTIVE
QTDIR=/usr/lib64/qt-3.3
QTINC=/usr/lib64/qt-3.3/include
MIC_LD_LIBRARY_PATH=/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/mpirt/lib/mic:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/ipp/lib/mic:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/compiler/lib/mic:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/mkl/lib/mic:/opt/intel/mic/coi/device-linux-release/lib:/opt/intel/mic/myo/lib:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/tbb/lib/mic
PBS_O_WORKDIR=/lustre/home/client/fas/cpsc424/cg736
ANT_HOME=/opt/rocks
LC_ALL=en_US
PBS_TASKNUM=1
USER=cg736
LD_LIBRARY_PATH=/usr/local/cluster/hpc/MPI/OpenMPI/1.8.6-intel15/lib:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/mpirt/lib/intel64:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/ipp/./compiler/lib/intel64:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/ipp/lib/intel64:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/ipp/tools/intel64/perfsys:/opt/intel/mic/coi/host-linux-release/lib:/opt/intel/mic/myo/lib:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/compiler/lib/intel64:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/mkl/lib/intel64:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/tbb/lib/intel64/gcc4.4:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/debugger/ipt/intel64/lib
PBS_O_HOME=/home/fas/cpsc424/cg736
MIC_LIBRARY_PATH=/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/compiler/lib/mic:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/mpirt/lib/mic:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/tbb/lib/mic
ROCKS_ROOT=/opt/rocks
CPATH=/usr/local/cluster/hpc/MPI/OpenMPI/1.8.6-intel15/include:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/ipp/include:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/mkl/include:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/tbb/include
PBS_WALLTIME=1800
PBS_GUPFILE=/var/spool/torque/aux//5436955.rocks.omega.hpc.yale.internalgpu
```

PBS\_MOMPORT=15003  
PBS\_O\_QUEUE=cpsc424  
YHPC\_COMPILER=Intel  
OMPI\_MCA\_orte\_precondition\_transports=f20cd2d28f432704-15e3f8c3bb8e89d6  
NLSPATH=/home/apps/fas/Langs/Intel/2015\_update2/composer\_xe\_2015.2.164/compiler/lib/intel64/locale/%l\_%t/%N:/home/apps/fas/Langs/Intel/2015\_update2/composer\_xe\_2015.2.164/ipp/lib/intel64/locale/%l\_%t/%N:/home/apps/fas/Langs/Intel/2015\_update2/composer\_xe\_2015.2.164/mkl/lib/intel64/locale/%l\_%t/%N:/home/apps/fas/Langs/Intel/2015\_update2/composer\_xe\_2015.2.164/debugger/gdb/intel64\_mic/share/locale/%l\_%t/%N:/home/apps/fas/Langs/Intel/2015\_update2/composer\_xe\_2015.2.164/debugger/gdb/intel64/share/locale/%l\_%t/%N  
MAIL=/var/spool/mail/cg736  
PBS\_O\_LOGNAME=cg736  
PATH=/home/apps/fas/Tools/TotalView/toolworks/totalview.8.14.1-8/bin:/home/apps/fas/Tools/TotalView/toolworks/memoryscape.3.6.1-8/bin:/home/apps/fas/Tools/TotalView:/usr/local/cluster/hpc/MPI/OpenMPI/1.8.6-intel15/bin:/home/apps/fas/Langs/Intel/2015\_update2/composer\_xe\_2015.2.164/bin/intel64:/home/apps/fas/Langs/Intel/2015\_update2/composer\_xe\_2015.2.164/mpirt/bin/intel64:/home/apps/fas/Langs/Intel/2015\_update2/composer\_xe\_2015.2.164/debugger/gdb/intel64\_mic/bin:/home/apps/fas/Langs/Intel/2015\_update2/composer\_xe\_2015.2.164/debugger/gdb/intel64/bin:/home/apps/fas/Modules:/usr/lib64/qt-3.3/bin:/opt/rocks/bin:/usr/bin:/usr/local/sbin:/usr/sbin:/sbin:/usr/java/latest/bin:/opt/rocks/bin:/opt/rocks/sbin:/home/apps/bin:/home/fas/cpsc424/cg736/bin  
YHPC\_COMPILER\_MINOR=164  
PBS\_O\_LANG=en\_US.iso885915  
PBS\_JOBID=B00CD7EA66C9A03486F801149B353642  
TBBROOT=/home/apps/fas/Langs/Intel/2015\_update2/composer\_xe\_2015.2.164/tbb  
C\_INCLUDE\_PATH=/usr/local/cluster/hpc/MPI/OpenMPI/1.8.6-intel15/include  
F90=ifort  
PWD=/home/fas/cpsc424/cg736  
\_LMFILES\_=/home/apps/fas/Modules/Base/yale\_hpc:/home/apps/fas/Modules/Langs/Intel/15:/home/apps/fas/Modules/MPI/OpenMPI/1.8.6-intel15:/home/apps/fas/Modules/Tools/TotalView/8.14.1-8  
YHPC\_COMPILER\_MAJOR=2  
JAVA\_HOME=/usr/java/latest  
GDB\_CROSS=/home/apps/fas/Langs/Intel/2015\_update2/composer\_xe\_2015.2.164/debugger/gdb/intel64\_mic/bin/gdb-mic  
DOMAIN=omega  
PBS\_NODENUM=0  
LANG=C  
MODULEPATH=/home/apps/fas/Modules  
MOABHOMEDIR=/opt/rocks  
YHPC\_COMPILER\_RELEASE=2015  
LOADED\_MODULES=Base/yale\_hpc:Langs/Intel/15:MPI/OpenMPI/1.8.6-intel15:Tools/TotalView/8.14.1-8  
KDEDIRS=/usr  
PBS\_NUM\_NODES=1  
F77=ifort



```
PBS_0_SHELL=/bin/bash
LM_LICENSE_FILE=/home/apps/fas/Tools/TotalView/license.dat
PBS_JOBID=5436955.rocks.omega.hpc.yale.internal
MPM_LAUNCHER=/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/debugger/mpm/bin/start_mpm.sh
CXX=icpc
SSH_ASKPASS=/usr/libexec/openssh/gnome-ssh-askpass
HISTCONTROL=ignoredups
INTEL_PYTHONHOME=/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/debugger/python/intel64/
SHLVL=1
HOME=/home/fas/cpsc424/cg736
PBS_0_HOST=compute-33-1.local
FC=ifort
PBS_VNODENUM=0
LOGNAME=cg736
QTLIB=/usr/lib64/qt-3.3/lib
CVS_RSH=ssh
PBS_QUEUE=cpsc424
MODULESHOME=/usr/share/Modules
LESSOPEN=||/usr/bin/lesspipe.sh %s
PBS_MICFILE=/var/spool/torque/aux//5436955.rocks.omega.hpc.yale.internalmic
PBS_0_MAIL=/var/spool/mail/cg736
arch=intel64
INFOPATH=/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/debugger/gdb/intel64/share/info:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/debugger/gdb/intel64_mic/share/info/
CC=icc
PBS_NP=8
PBS_NUM_PPN=1
PBS_0_SERVER=rocks.omega.hpc.yale.internal
INCLUDE=/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/mkl/include
MPI_PATH=/usr/local/cluster/hpc/MPI/OpenMPI/1.8.6-intel15
G_BROKEN_FILENAMES=1
PBS_NODEFILE=/var/spool/torque/aux//5436955.rocks.omega.hpc.yale.internal
PBS_0_PATH=/home/apps/fas/Tools/TotalView/toolworks/totalview.8.14.1-8/bin:/home/apps/fas/Tools/TotalView/toolworks/memoryscape.3.6.1-8/bin:/home/apps/fas/Tools/TotalView:/usr/local/cluster/hpc/MPI/OpenMPI/1.8.6-intel15/bin:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/bin/intel64:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/mpirt/bin/intel64:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/debugger/gdb/intel64_mic/bin:/home/apps/fas/Langs/Intel/2015_update2/composer_xe_2015.2.164/debugger/gdb/intel64/bin:/home/apps/fas/Modules:/usr/lib64/qt-3.3/bin:/opt/moab/bin:/usr/local/bin:/bin:/usr/bin:/usr/local/sbin:/usr/sbin:/sbin:/usr/java/latest/bin:/opt/rocks/bin:/opt/rocks/sbin:/home/apps/bin:/home/fas/cpsc424/cg736/bin
BASH_FUNC_module()=() { eval ` /usr/bin/modulecmd bash $*`
```

```
}  
_=/bin/env
```

## How to run the code

I wrote a bash script that can build and run the code automatically. To do so, simply type

```
qsub build_run.sh
```

## Output

### Output for task1

#### Performance

The following table shows the wall clock timing for actual data sets (in seconds).

actualdata1	actualdata2	actualdata3	actualdata4
3.819550	16.144769	68.937818	264.022366

### Output for actualdata1

Initial Conditions (time = 0.0)

Center of Mass: (2.153875e-08, 1.148863e-09, 4.334575e-09)  
Average Velocity: (-1.560600e-08, -6.291000e-09, 2.288737e-10)

Conditions after timestep 128 (time = 4.000000)

Center of Mass: (-4.088525e-08, -2.401514e-08, 5.250070e-09)  
Average Velocity: (-1.560600e-08, -6.291000e-09, 2.288737e-10)

Conditions after timestep 256 (time = 8.000000)

Center of Mass: (-1.033092e-07, -4.917914e-08, 6.165565e-09)  
Average Velocity: (-1.560600e-08, -6.291000e-09, 2.288737e-10)

Conditions after timestep 384 (time = 12.000000)

Center of Mass:  $(-1.657332e-07, -7.434314e-08, 7.081059e-09)$   
Average Velocity:  $(-1.560600e-08, -6.291000e-09, 2.288737e-10)$

Conditions after timestep 512 (time = 16.000000)

Center of Mass:  $(-2.281572e-07, -9.950714e-08, 7.996555e-09)$   
Average Velocity:  $(-1.560600e-08, -6.291000e-09, 2.288737e-10)$

Conditions after timestep 640 (time = 20.000000)

Center of Mass:  $(-2.905812e-07, -1.246711e-07, 8.912050e-09)$   
Average Velocity:  $(-1.560600e-08, -6.291000e-09, 2.288737e-10)$

Conditions after timestep 768 (time = 24.000000)

Center of Mass:  $(-3.530052e-07, -1.498351e-07, 9.827544e-09)$   
Average Velocity:  $(-1.560600e-08, -6.291000e-09, 2.288737e-10)$

Conditions after timestep 896 (time = 28.000000)

Center of Mass:  $(-4.154292e-07, -1.749991e-07, 1.074304e-08)$   
Average Velocity:  $(-1.560600e-08, -6.291000e-09, 2.288737e-10)$

Conditions after timestep 1024 (time = 32.000000)

Center of Mass:  $(-4.778533e-07, -2.001631e-07, 1.165854e-08)$   
Average Velocity:  $(-1.560600e-08, -6.291000e-09, 2.288737e-10)$

Time for 1024 timesteps with 800 bodies: 3.819550 seconds

## Output for actualdata2

Initial Conditions (time = 0.0)

Center of Mass:  $(-4.128124e-09, -1.835931e-10, -1.653466e-08)$   
Average Velocity:  $(-6.789229e-10, -3.510628e-09, 2.741372e-09)$

Conditions after timestep 128 (time = 4.000000)



Center of Mass:  $(-6.843818e-09, -1.422610e-08, -5.569169e-09)$   
Average Velocity:  $(-6.789225e-10, -3.510627e-09, 2.741372e-09)$

Conditions after timestep 256 (time = 8.000000)

Center of Mass:  $(-9.559511e-09, -2.826861e-08, 5.396319e-09)$   
Average Velocity:  $(-6.789230e-10, -3.510628e-09, 2.741372e-09)$

Conditions after timestep 384 (time = 12.000000)

Center of Mass:  $(-1.227520e-08, -4.231112e-08, 1.636181e-08)$   
Average Velocity:  $(-6.789231e-10, -3.510628e-09, 2.741372e-09)$

Conditions after timestep 512 (time = 16.000000)

Center of Mass:  $(-1.499090e-08, -5.635363e-08, 2.732729e-08)$   
Average Velocity:  $(-6.789231e-10, -3.510628e-09, 2.741372e-09)$

Conditions after timestep 640 (time = 20.000000)

Center of Mass:  $(-1.770659e-08, -7.039614e-08, 3.829278e-08)$   
Average Velocity:  $(-6.789232e-10, -3.510627e-09, 2.741372e-09)$

Conditions after timestep 768 (time = 24.000000)

Center of Mass:  $(-2.042228e-08, -8.443865e-08, 4.925827e-08)$   
Average Velocity:  $(-6.789231e-10, -3.510627e-09, 2.741372e-09)$

Conditions after timestep 896 (time = 28.000000)

Center of Mass:  $(-2.313798e-08, -9.848116e-08, 6.022375e-08)$   
Average Velocity:  $(-6.789232e-10, -3.510627e-09, 2.741372e-09)$

Conditions after timestep 1024 (time = 32.000000)

Center of Mass:  $(-2.585367e-08, -1.125237e-07, 7.118924e-08)$   
Average Velocity:  $(-6.789231e-10, -3.510628e-09, 2.741372e-09)$

Time for 1024 timesteps with 1600 bodies: 16.144769 seconds

## Output for actualdata3

Initial Conditions (time = 0.0)

Center of Mass: (2.738440e-09, -8.980691e-09, -3.708599e-09)

Average Velocity: (3.605630e-10, 1.931760e-08, 3.645550e-09)

Conditions after timestep 128 (time = 4.000000)

Center of Mass: (4.180686e-09, 6.828971e-08, 1.087360e-08)

Average Velocity: (3.605628e-10, 1.931760e-08, 3.645550e-09)

Conditions after timestep 256 (time = 8.000000)

Center of Mass: (5.622935e-09, 1.455601e-07, 2.545580e-08)

Average Velocity: (3.605623e-10, 1.931760e-08, 3.645550e-09)

Conditions after timestep 384 (time = 12.000000)

Center of Mass: (7.065183e-09, 2.228305e-07, 4.003800e-08)

Average Velocity: (3.605622e-10, 1.931760e-08, 3.645550e-09)

Conditions after timestep 512 (time = 16.000000)

Center of Mass: (8.507430e-09, 3.001009e-07, 5.462021e-08)

Average Velocity: (3.605623e-10, 1.931760e-08, 3.645550e-09)

Conditions after timestep 640 (time = 20.000000)

Center of Mass: (9.949683e-09, 3.773713e-07, 6.920241e-08)

Average Velocity: (3.605621e-10, 1.931760e-08, 3.645550e-09)

Conditions after timestep 768 (time = 24.000000)

Center of Mass: (1.139193e-08, 4.546417e-07, 8.378461e-08)

Average Velocity: (3.605622e-10, 1.931760e-08, 3.645550e-09)

Conditions after timestep 896 (time = 28.000000)

Center of Mass: (1.283418e-08, 5.319121e-07, 9.836681e-08)

Average Velocity: (3.605621e-10, 1.931760e-08, 3.645550e-09)



Conditions after timestep 1024 (time = 32.000000)

Center of Mass: (1.427643e-08, 6.091825e-07, 1.129490e-07)

Average Velocity: (3.605623e-10, 1.931760e-08, 3.645550e-09)

Time for 1024 timesteps with 3200 bodies: 68.937818 seconds

## Output for actualdata4

Initial Conditions (time = 0.0)

Center of Mass: (-2.018758e-08, 1.012155e-08, -3.957608e-09)

Average Velocity: (-5.540198e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 128 (time = 4.000000)

Center of Mass: (-4.234837e-08, 2.443709e-08, 2.578647e-08)

Average Velocity: (-5.540198e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 256 (time = 8.000000)

Center of Mass: (-6.450916e-08, 3.875264e-08, 5.553055e-08)

Average Velocity: (-5.540197e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 384 (time = 12.000000)

Center of Mass: (-8.666995e-08, 5.306819e-08, 8.527463e-08)

Average Velocity: (-5.540197e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 512 (time = 16.000000)

Center of Mass: (-1.088307e-07, 6.738374e-08, 1.150187e-07)

Average Velocity: (-5.540197e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 640 (time = 20.000000)

Center of Mass: (-1.309915e-07, 8.169929e-08, 1.447628e-07)

Average Velocity: (-5.540197e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 768 (time = 24.000000)

Center of Mass: (-1.531523e-07, 9.601484e-08, 1.745069e-07)

Average Velocity: (-5.540197e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 896 (time = 28.000000)

Center of Mass: (-1.753131e-07, 1.103304e-07, 2.042509e-07)

Average Velocity: (-5.540198e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 1024 (time = 32.000000)

Center of Mass: (-1.974739e-07, 1.246459e-07, 2.339950e-07)

Average Velocity: (-5.540197e-09, 3.578887e-09, 7.436020e-09)

Time for 1024 timesteps with 6400 bodies: 264.022366 seconds

## Output for task2

### Performance

The following table shows the wall clock timing for actual data sets (in seconds).

actualdata1	actualdata2	actualdata3	actualdata4
1.425180	5.505876	21.939878	79.868258

### Output for actualdata1

Initial Conditions (time = 0.0)

#boides each octant has: (93, 98, 112, 104, 85, 107, 105, 96)

Center of Mass: (2.153875e-08, 1.148862e-09, 4.334575e-09)

Average Velocity: (-1.560600e-08, -6.291000e-09, 2.288737e-10)

Conditions after timestep 128 (time = 4)

#boides each octant has: (107, 84, 101, 109, 108, 94, 83, 114)

Center of Mass: (-4.088525e-08, -2.401514e-08, 5.250070e-09)

Average Velocities: (-1.560600e-08, -6.291000e-09, 2.288738e-10)

Conditions after timestep 256 (time = 8)

#boides each octant has: (72, 124, 135, 64, 51, 142, 149, 63)  
Center of Mass: (-1.033092e-07, -4.917914e-08, 6.165565e-09)  
Average Velocities: (-1.560600e-08, -6.291000e-09, 2.288738e-10)

Conditions after timestep 384 (time = 12)

#boides each octant has: (45, 135, 150, 52, 42, 158, 170, 48)  
Center of Mass: (-1.657333e-07, -7.434314e-08, 7.081060e-09)  
Average Velocities: (-1.560600e-08, -6.291000e-09, 2.288738e-10)

Conditions after timestep 512 (time = 16)

#boides each octant has: (36, 137, 154, 38, 37, 176, 181, 41)  
Center of Mass: (-2.281573e-07, -9.950714e-08, 7.996555e-09)  
Average Velocities: (-1.560600e-08, -6.291000e-09, 2.288738e-10)

Conditions after timestep 640 (time = 20)

#boides each octant has: (38, 144, 152, 33, 29, 173, 192, 39)  
Center of Mass: (-2.905813e-07, -1.246711e-07, 8.912050e-09)  
Average Velocities: (-1.560600e-08, -6.291000e-09, 2.288738e-10)

Conditions after timestep 768 (time = 24)

#boides each octant has: (32, 150, 171, 26, 23, 179, 186, 33)  
Center of Mass: (-3.530053e-07, -1.498351e-07, 9.827545e-09)  
Average Velocities: (-1.560600e-08, -6.291000e-09, 2.288738e-10)

Conditions after timestep 896 (time = 28)

#boides each octant has: (31, 151, 148, 23, 22, 186, 212, 27)  
Center of Mass: (-4.154293e-07, -1.749991e-07, 1.074304e-08)  
Average Velocities: (-1.560600e-08, -6.291000e-09, 2.288738e-10)

Conditions after timestep 1024 (time = 32)

#boides each octant has: (29, 140, 167, 23, 24, 199, 193, 25)  
Center of Mass: (-4.778533e-07, -2.001631e-07, 1.165853e-08)  
Average Velocities: (-1.560600e-08, -6.291000e-09, 2.288738e-10)

Time for 1024 timesteps with 800 bodies: 1.425180 seconds



## Output for actualdata2

Initial Conditions (time = 0.0)

#boides each octant has: (194, 203, 188, 188, 234, 213, 188, 192)  
Center of Mass: (-4.128125e-09, -1.835931e-10, -1.653466e-08)  
Average Velocity: (-6.789231e-10, -3.510627e-09, 2.741372e-09)

Conditions after timestep 128 (time = 4)

#boides each octant has: (238, 223, 161, 164, 197, 220, 206, 191)  
Center of Mass: (-6.843818e-09, -1.422610e-08, -5.569169e-09)  
Average Velocities: (-6.789231e-10, -3.510628e-09, 2.741372e-09)

Conditions after timestep 256 (time = 8)

#boides each octant has: (109, 306, 268, 113, 114, 276, 300, 114)  
Center of Mass: (-9.559510e-09, -2.826861e-08, 5.396319e-09)  
Average Velocities: (-6.789231e-10, -3.510627e-09, 2.741372e-09)

Conditions after timestep 384 (time = 12)

#boides each octant has: (90, 332, 291, 73, 73, 295, 343, 103)  
Center of Mass: (-1.227520e-08, -4.231112e-08, 1.636181e-08)  
Average Velocities: (-6.789232e-10, -3.510627e-09, 2.741372e-09)

Conditions after timestep 512 (time = 16)

#boides each octant has: (64, 337, 301, 71, 62, 315, 372, 78)  
Center of Mass: (-1.499090e-08, -5.635363e-08, 2.732729e-08)  
Average Velocities: (-6.789232e-10, -3.510628e-09, 2.741372e-09)

Conditions after timestep 640 (time = 20)

#boides each octant has: (54, 339, 315, 65, 52, 327, 374, 74)  
Center of Mass: (-1.770659e-08, -7.039614e-08, 3.829278e-08)  
Average Velocities: (-6.789232e-10, -3.510627e-09, 2.741372e-09)

Conditions after timestep 768 (time = 24)

```
#boides each octant has: (61, 339, 322, 66, 42, 335, 367, 68)
Center of Mass:      (-2.042228e-08, -8.443865e-08, 4.925827e-08)
Average Velocities: (-6.789232e-10, -3.510627e-09, 2.741372e-09)
```

Conditions after timestep 896 (time = 28)

```
#boides each octant has: (56, 335, 337, 70, 52, 323, 356, 71)
Center of Mass:      (-2.313797e-08, -9.848116e-08, 6.022376e-08)
Average Velocities: (-6.789232e-10, -3.510627e-09, 2.741372e-09)
```

Conditions after timestep 1024 (time = 32)

```
#boides each octant has: (73, 300, 330, 92, 75, 303, 341, 86)
Center of Mass:      (-2.585366e-08, -1.125237e-07, 7.118924e-08)
Average Velocities: (-6.789231e-10, -3.510627e-09, 2.741372e-09)
```

Time for 1024 timesteps with 1600 bodies: 5.505876 seconds

### Output for actualdata3

Initial Conditions (time = 0.0)

```
#boides each octant has: (432, 416, 368, 395, 439, 410, 355, 385)
Center of Mass:      (2.738438e-09, -8.980691e-09, -3.708599e-09)
Average Velocity: (3.605623e-10, 1.931760e-08, 3.645550e-09)
```

Conditions after timestep 128 (time = 4)

```
#boides each octant has: (422, 436, 397, 408, 398, 397, 364, 378)
Center of Mass:      (4.180687e-09, 6.828971e-08, 1.087360e-08)
Average Velocities: (3.605622e-10, 1.931760e-08, 3.645550e-09)
```

Conditions after timestep 256 (time = 8)

```
#boides each octant has: (180, 605, 620, 215, 194, 580, 617, 189)
Center of Mass:      (5.622936e-09, 1.455601e-07, 2.545580e-08)
Average Velocities: (3.605623e-10, 1.931760e-08, 3.645550e-09)
```

Conditions after timestep 384 (time = 12)

```
#boides each octant has: (149, 676, 635, 145, 165, 595, 691, 144)
```

Center of Mass: (7.065185e-09, 2.228305e-07, 4.003800e-08)  
Average Velocities: (3.605622e-10, 1.931760e-08, 3.645550e-09)

Conditions after timestep 512 (time = 16)

#boides each octant has: (113, 696, 684, 107, 125, 637, 722, 116)  
Center of Mass: (8.507434e-09, 3.001009e-07, 5.462021e-08)  
Average Velocities: (3.605623e-10, 1.931760e-08, 3.645550e-09)

Conditions after timestep 640 (time = 20)

#boides each octant has: (90, 742, 704, 91, 101, 617, 757, 98)  
Center of Mass: (9.949683e-09, 3.773713e-07, 6.920241e-08)  
Average Velocities: (3.605622e-10, 1.931760e-08, 3.645550e-09)

Conditions after timestep 768 (time = 24)

#boides each octant has: (82, 757, 694, 92, 100, 602, 785, 88)  
Center of Mass: (1.139193e-08, 4.546417e-07, 8.378461e-08)  
Average Velocities: (3.605622e-10, 1.931760e-08, 3.645550e-09)

Conditions after timestep 896 (time = 28)

#boides each octant has: (117, 713, 685, 120, 127, 592, 746, 100)  
Center of Mass: (1.283418e-08, 5.319121e-07, 9.836681e-08)  
Average Velocities: (3.605622e-10, 1.931760e-08, 3.645550e-09)

Conditions after timestep 1024 (time = 32)

#boides each octant has: (184, 622, 650, 181, 182, 537, 698, 146)  
Center of Mass: (1.427643e-08, 6.091825e-07, 1.129490e-07)  
Average Velocities: (3.605622e-10, 1.931760e-08, 3.645550e-09)

Time for 1024 timesteps with 3200 bodies: 21.939878 seconds

## Output for actualdata4

Initial Conditions (time = 0.0)

#boides each octant has: (828, 790, 769, 814, 802, 808, 809, 780)  
Center of Mass: (-2.018758e-08, 1.012155e-08, -3.957608e-09)



Average Velocity: (-5.540198e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 128 (time = 4)

#boides each octant has: (834, 889, 802, 754, 775, 775, 763, 808)  
Center of Mass: (-4.234837e-08, 2.443709e-08, 2.578647e-08)  
Average Velocities: (-5.540197e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 256 (time = 8)

#boides each octant has: (400, 1219, 1220, 398, 400, 1169, 1169, 425)  
Center of Mass: (-6.450916e-08, 3.875264e-08, 5.553055e-08)  
Average Velocities: (-5.540197e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 384 (time = 12)

#boides each octant has: (295, 1301, 1300, 275, 275, 1339, 1306, 309)  
Center of Mass: (-8.666995e-08, 5.306819e-08, 8.527463e-08)  
Average Velocities: (-5.540197e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 512 (time = 16)

#boides each octant has: (222, 1342, 1355, 210, 188, 1444, 1393, 246)  
Center of Mass: (-1.088307e-07, 6.738374e-08, 1.150187e-07)  
Average Velocities: (-5.540198e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 640 (time = 20)

#boides each octant has: (195, 1364, 1337, 175, 158, 1512, 1465, 194)  
Center of Mass: (-1.309915e-07, 8.169929e-08, 1.447628e-07)  
Average Velocities: (-5.540198e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 768 (time = 24)

#boides each octant has: (172, 1385, 1299, 164, 158, 1526, 1520, 176)  
Center of Mass: (-1.531523e-07, 9.601483e-08, 1.745069e-07)  
Average Velocities: (-5.540197e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 896 (time = 28)

#boides each octant has: (184, 1410, 1273, 164, 152, 1511, 1519, 187)  
Center of Mass: (-1.753131e-07, 1.103304e-07, 2.042509e-07)

Average Velocities: (-5.540197e-09, 3.578887e-09, 7.436020e-09)

Conditions after timestep 1024 (time = 32)

#bodies each octant has: (196, 1397, 1265, 182, 171, 1504, 1490, 195)

Center of Mass: (-1.974739e-07, 1.246459e-07, 2.339950e-07)

Average Velocities: (-5.540197e-09, 3.578887e-09, 7.436020e-09)

Time for 1024 timesteps with 6400 bodies: 79.868258 seconds

## Discussion

### Performance

The following table shows the comparison between serial program and parallel program. It is clear that when the dataset is large, the performance of parallel program is much better than serial one.

program\dataset	actualdata1	actualdata2	actualdata3	actualdata4
serial	3.819550	16.144769	68.937818	264.022366
parallel	1.425180	5.505876	21.939878	79.868258

Using the table above, we can construct speedup table.

actualdata1	actualdata2	actualdata3	actualdata4
2.68	2.93	3.14	3.31

We can see with the scale of problem increases, the speedup increases steadily. When dataset is small, much effort is spent on communication rather than computation, the benefit of parallel computing is not obvious. When the scale of problem increase, communication time is small compared with computation time.

### Load Balance

The load balance is quite good at the beginning because bodies scatters quite evenly in the universe. For example, we can take a look at the initial conditions of actualdata4. We can see process0 has 828 bodies, 1 has 790, 2 has 769... every octant has almost the same number of bodies.

Initial Conditions for actualdata4 (time = 0.0)

```
#boides each octant has: (828, 790, 769, 814, 802, 808, 809, 780)
Center of Mass: (-2.018758e-08, 1.012155e-08, -3.957608e-09)
Average Velocity: (-5.540198e-09, 3.578887e-09, 7.436020e-09)
```

But the load balance degrades when time goes on. At the last times step of actualdata4, we can see that octant1 only has 196 bodies, while octant 5 has 1504 bodies. My guess is that some large mass bodies will drag other light bodies towards them, which result in a situation that large body is surrounded by many small bodies. This situation will lead to many bodies residing in one octant, while some other octants only have a few bodies because they doesn't have large bodies to drag other bodies.

Conditions after timestep 1024 for dataset4 (time = 32)

```
#boides each octant has: (196, 1397, 1265, 182, 171, 1504, 1490, 195)
Center of Mass: (-1.974739e-07, 1.246459e-07, 2.339950e-07)
Average Velocities: (-5.540197e-09, 3.578887e-09, 7.436020e-09)
```

Time for 1024 timesteps with 6400 bodies: 79.868258 seconds