Performance Programming Coursework: Serial Optimization of a Molecular Dynamics Program

Abstract

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1. Introduction

This paper documents the serial performance optimization conducted for a molecular dynamics program written in the Fortran programming language. The program reads data from n molecules as its input and iterates a predefined amount of steps, which correspond to the progress of time in the simulation. Each step the data of the molecules (e.g. force, position in a three dimensional space, velocity) is updated. The program counts collisions between molecules and writes the data for each molecule of the simulation out after a certain interval of iterations. This interval is called a superstep. The original version of the program is not optimized for computational efficiency.

This paper describes, documents and discusses the process of optimizing the original version of the program serially. The program was optimized for the Cirrus supercomputer, a tier-2 UK national supercomputer of the engineering and physical sciences research council, which is hosted and maintained by the EPCC (EPCC, 2020a). The compilers used were Intel's Fortran compiler `ifort`, version 18.0.5 and 19.0.0 for the linux operating system (Intel, 2018, 2019c). The conducted optimizations range from choosing the appropriate compiler flags over rewriting performance critical sections of the program to hardware specific optimizations, like leveraging vectorization and cache optimizations. Since raw performance benefits are not all that is important for writing well performing and good programs, the maintainability and portability of the program are also looked at and discussed.

This paper continues in Section 2 with describing the molecular dynamics program in detail. Section 3 describes Cirrus and how the correctness of the program is tested with a regression test suite. Also the benchmark suite used for assessing the performance benefits of an optimization is outlined. Section 4 lists, describes and discusses all optimizations tested with their performance benefits. Afterwards, the results are discussed in Section 5. At least a conclusion is drawn in Section 6.

2. Molecular Dynamics Program

This section describes what the program does. The program is a simple molecular dynamics program. It reads data from n particles from a file. In the following, subscripts $1 \leq i \leq n$ refer to a particle of the simulation. The data for a particle i is its mass m_i, the viscosity

of a fluid i is part of vis_i, the position of the particle's center in a three dimensional space $\vec{p}_i$ and its velocity $\vec{v}_i$.

The program iterates a predefined amount of iterations. Each iteration represents a time step in the particle simulation. The time is updated by a constant value Δ_t. Every step the position and the velocity of each particle is updated, based on the gravitational forces operating on each particle. The gravitational forces are the forces between each particle and the gravitational force coming from a large central mass located at the origin of the Euclidean space. The particles are part of a fluid, which means the viscosity of the fluid must also be taken into account. The last external force operating on a particle is wind $\vec{w}$, which is a constant vector over the whole simulation.

The gravitational forces are computed based on Newton's law of universal gravitation. It states, that any two physical objects attract each other with a force, which is proportional to the mass of both objects and inversely proportional to the squared distance between both (Feynman, 1963). The scalar gravitational force F between two objects 1 and 2 can be mathematically described as:

$$F_{1,2} = G\frac{m_1 m_2}{||\vec{p}_1 - \vec{p}_2||_2^2}, \tag{1}$$

where G is the gravitational constant, m_i the mass of object i and $||\vec{p}_1 - \vec{p}_2||_2$ the Euclidean or L_2 distance between the centers of both objects. The vector form of the gravitational force object 2 operates on object 1, which also accounts for the direction of the force, is given by:

$$\vec{F}_{1\leftarrow 2} = -F_{1,2}\frac{\vec{p}_1 - \vec{p}_2}{||\vec{p}_1 - \vec{p}_2||_2} = -G\frac{m_1 m_2(\vec{p}_1 - \vec{p}_2)}{||\vec{p}_1 - \vec{p}_2||_2^3}. \tag{2}$$

The gravitational force, which object 1 operates on object 2 is the additive inverse of $\vec{F}_{1\leftarrow 2}$: $\vec{F}_{2\leftarrow 1} = -\vec{F}_{1\leftarrow 2}$. If particles collide, the gravitational forces between the two object are negated. The program finds collisions, by checking if the distance of two particles is smaller than a threshold $\tau_{1,2}$, which is the sum of the radii of the two particles. For the program, all particles have a radius of $\frac{1}{2}$, so the threshold for a collision is 1. Now we can define a pairwise gravitational forces function for the particles of the simulation as:

$$f_{1\leftarrow 2} := \begin{cases} \vec{F}_{1\leftarrow 2} & \text{if } ||\vec{p}_1 - \vec{p}_2||_2 \geq \tau_{1,2} \\ -\vec{F}_{1\leftarrow 2} & \text{otherwise} \end{cases}. \tag{3}$$

Other than the pairwise gravitational forces between the particles, there is the gravitational force of the central mass $\vec{F}_{1\leftarrow central}$. The central mass lies at the origin of the three dimensional space, which means its position vector $\vec{p}_{central} = 0$.

The viscosity of the fluid is another force operating on a particle. It is simply the negative of the viscosity of the fluid multiplied by the velocity vector of particle i : $-vis_i\vec{v}_i$.

Shear velocity of the fluid is not taken into account. Lastly, there is the wind force, which is simply the negated viscosity of the fluid particle i is part of multiplied by the wind vector: $-vis_i\vec{w}$. The overall force per iteration operating on particle i can now be described as:

$$\vec{F_i} = -vis_i(\vec{v_i} + \vec{w}) + \vec{F}_{i \leftarrow central} + \sum_{j \neq i}^{n} f_{i \leftarrow j}. \tag{4}$$

Based on $\vec{F_i}$ we can now update $\vec{p_i}$ and $\vec{v_i}$:

$$\vec{p_i} = \vec{p_i} + \Delta_t \vec{v_i} \tag{5}$$

$$\vec{v_i} = \vec{v_i} + \Delta_t \frac{\vec{F_i}}{m_i}. \tag{6}$$

The iterations of the program are broken down into supersteps. On completion of a superstep, the updated particles are exported to a file with the same format as the input file.

3. Setup

This section outlines the settings, under which the program was optimized for performance. Information about the used hardware is given. The way correctness of the program was tested is described. Lastly the settings and the criterion for benchmarking the computational performance are presented.

Like stated in Section 1, the program was optimized for the Cirrus supercomputer (EPCC, 2020a). Since we are running the program serially, we are not concerned with the amount of nodes or the interconnect, but will focus on a single compute node. A single compute node of Cirrus contains two 2.1 GHz, 18-core Intel Xeon E5-2695 processors (code name: Broadwell). The processor supports the AVX2 vector instruction set (Buxton, 2011). Each processor is connected to 128 Gigabyte of memory. Both processors are within a NUMA region, so 256 Gigabyte of memory are actually at ones disposal (EPCC, 2020b). The compute node offers three levels of cache:

1. 32 Kilobyte instruction and 32 Kilobyte of data cache (per core)
2. 256 Kilobyte (per core)
3. 45 Megabyte (shared)

Testing the correctness of the program is not as straight-forward as it seems at first glance. Like stated in Section 2, after each superstep, the updated particles are written out to file. Comparing the output of the optimized version of the program with the original one would be a sufficient test for correctness, if it were not for floating point rounding

errors. These accumulate and after a certain amount of time, the numbers generated by the optimized version will be too different from the original ones.

In order to avoid getting different results, just because of floating point rounding errors, the program was augmented by a special test setting. This test setting differs from the normal program, because it reads the data it has written out after a superstep back in. That way, the next superstep will work with the floating point numbers that are crippled by writing them to file. The floating point numbers are written to file text based in exponential form with 16 digits, eight digits on the right side of the decimal point (see e.g. Shene, 2020, for formatting IO in Fortran). Changing the output format to a more precise representation is not possible, because this would mean the files generated as output would not have the same format as the input file with the initial states of the particles. The test setting allows for effectively comparing the output files of both versions, because floating point rounding errors now only accumulate over a single superstep instead of the whole simulation.

Once the discrepancy between the output values of the optimized version and the original one surpasses a predefined error level, the optimization is deemed to result in an incorrect version of the program. The predefined error level was set to be 0.05. If any output file contains a `NaN` value, the program is also deemed incorrect. The regression test suite was implemented with a Python script.

The program runs five supersteps. Each superstep encompasses 100 iterations. Computation is done using double precision floats. The input file which was used for optimizing contained 4096 particles. The goal of the optimization process was to reduce the wall-clock time of the program to a minimum, while bearing in mind portability and more importantly maintainability. The program measures the time it needs for each superstep and its overall time, including the file output. In order to build the benchmark suite around the program, the timings are exported to another file when the program has finished the simulation. The program was benchmarked by running it ten times on a compute node of Cirrus and taking the average from those ten runs as the performance measurement. Running it ten times is sufficient to get a stable average, because running the program as a job on a compute node of Cirrus means exclusive hardware access to that node. Only IO performance can be influenced by other users, because Cirrus uses Lustre for its file system which is shared (EPCC, 2020b). As will be shown below, IO performance is actually negligible when it comes to performance optimization when compared to the computational effort of the simulation.

4. Optimizations

This section documents the process of performance optimization of the program. Focus lies more on the process, not the results. All the successively performed optimizations are described. Code quality in form of readability, portability and maintainability is taken into account during the whole process and the optimizations are all looked at from this

perspective. The optimization process can basically broken down into four phases: (i) rewriting the source code to Fortran 90, restructuring the source code without changing the critical section, (ii) enabling basic compiler optimizations, (iii) rewriting the program for better performance and (iv) trying out more advanced compiler optimizations on the rewritten version of the program again.

4.1 First Phase

The first phase of optimization only concerns itself with increasing the maintainability of the program. The original version of the program is written in fixed format Fortran (see e.g. Sandu, 2001, for free vs. fixed format Fortran). Readability for screen based devices was deemed more of an issue than formatting source code for punched cards, which are unfortunately not supported by Cirrus. So the first step was to reformat the source code to free format Fortran to increase maintainability.

The original version of the program is spread across four files. `control.f` contains the main program. It performs initialization of the program. This includes defining constants and reading the particles from the initial file. It contains the superstep loop and performs the output of the intermediate states of the particles to file. It also collects the timings for every superstep and the combined time for all supersteps together. The `MD.f` file contains the `evolve` subroutine. This subroutine performs the main computations for the simulation. It is called each superstep and iterates 100 times over the simulation, updating the state of the particles. The particle data is shared between the main program and the `evolve` subroutine with a `COMMON` block (see e.g. Harper and Stockman, 2020). The `COMMON` block is defined in the `coord.inc` file, which also contains the global constants G and $m_{central}$. Lastly, there is the `util.f` file containing utility subroutines and functions, e.g. `visc_force` or `wind_force`, which compute $-vis_i\vec{v}_i$ and $-vis_i\vec{w}$ respectively (see Section 2).

Modern Fortran compilers like `ifort` version 18.0.5 support all Fortran 2008 features (Intel, 2018). Fortran introduced modules in Fortran 90, which make it much easier to share data between subroutines and coupling can be much improved by using them (Moin, 2002). Because using modules increases maintainability a lot, all routines of the program are put into the main program in `control.f`, inside its `contains` block. That way the particle data can be shared with the `evolve` subroutine without a `COMMON` block. These changes greatly increased maintainability, because of the enhanced readability of the source code. Also the build process is simplified, because only a single Fortran 90 file needs to be compiled, rather than having to link `control.f` and `MD.f` with `coord.inc`.

Both, the original version and the new Fortran 90 version were modified to incorporate the test setting, where they read there intermediate outputs back in in order to compute the next superstep. In order for this setting not to interfere with the original setting used for benchmarking, Intel's Fortran preprocessor was used (Intel, 2019b). The additional reading back of the intermediate file is put into an `#ifdef` directive. This way, the original

```
ifort -g -O0  -check uninit,bounds -no-vec -fpp
-o ../bin/old_bench control.f MD.o util.o

./coord.inc(25): remark #6375: Because of COMMON, the alignment of
object is inconsistent with its type - potential performance
impact. [WIND]

      DOUBLE PRECISION wind(Ndim)
-----------------------^
```

Figure 1: Output from `ifort` when compiling the original version of the program. The constant vector $\vec{w}$ is not aligned.

version of the program used for benchmarking is not damaged by additional checks at runtime.

Another aspect to consider in favor of the new version is the fact, that the `COMMON` block is not aligned. Figure 1 shows the compiler output, when compiling the original version. The `COMMON` block has alignment issues for the wind vector $\vec{w}$, which could have an impact on the programs performance. Removing the block removes the alignment issue. So not only is the new version better maintainable, it also removes the first performance issue with the original version.

Both versions were compiled using `ifort` version 18.0.5 with the following compiler flags which influence performance: `-O0`, which disables any compiler optimization, `-no-vec`, which inhibits vectorization and `-check uninit,bounds`, which tells the compiler to add extra instructions to the program which perform explicit checking for uninitialized variables and out-of-bounds access of arrays.

Benchmarking the original version reveals that it takes on average 1270 seconds for all five supersteps to complete. A single superstep takes on average 254 seconds to complete. If one subtracts the sum of the individual timings of all five supersteps from the overall time, one gets the time spent doing the file output. The IO time lies at a quarter of a second for the original version, which is 0.02% of the overall runtime. The new Fortran 90 version of the program takes only 1110 seconds on average to complete. The average superstep time lies at 222 seconds. While the focus of the first phase of the optimization actually was about enhancing maintainability and setting the right foundation for the next phases, the performance was already increased by 12.5%.

4.2 Second Phase

The second phase was about using the more common compiler flags to enhance the performance of the Fortran 90 version. The compiler flags used in phase one not only hinder compiler optimizations with `-O0`, they even make the code perform worse by adding the

out-of-bounds access and uninitialized variables flags. Therefore the first step to better performing code was to utilize the compiler. This phase was not about finding a definitive set of flags, but only a first step to see how much the compiler can achieve using the more common compiler flags for optimization. It was more motivated by the still horrible runtime of 1110 seconds, which hinders rapid development during the third phase. Table 1 shows all the different flags tried and how they impacted performance.

The first act was to remove the unnecessary checks for out-of-bounds access of arrays and using uninitialized variables. The Fortran 90 version of the code is riddled with loops, so removing the checks for each should have quite the impact on performance. As it turned out it did. Removing the checks improved the average overall time by 33%. That means 1/3 of the time was spent checking for out-of-bounds access and the use of uninitialized variables.

The next step was to gradually increase the level of compiler optimization from `-O0` to `-O3`. The first level of optimization `-O1` enables speed optimizations that do not enlarge binary size. Optimizations done include data-flow analysis, test replacement and instruction scheduling. `-O1` is designed for large codes with many branches that are not loops (Intel, 2019f). While this description does not fit to the program at all, which has only one significant branch (code structure is discussed below) and spends most of its time in loops, `-O1` still increases the performance by 44%. Average overall time is reduced from 734 seconds to 413 seconds (see Table 1).

`-O2` is the recommended level of compiler optimization. It performs basic loop optimizations like interchanging, unrolling or scalar replacements. Furthermore inlining, intra-file ipo (interprocedural optimization), dead code elimination and many more optimizations are enabled (see Intel, 2019f). Enabling `-O2` reduced the average overall time down to 85 seconds, which is 79% better than the program compiled with `-O1` (see Table 1).

`-O3` enables more aggressive optimizations concerning loops and memory access transformations, additionally to the optimizations done using `-O2`. Optimizations include loop fusion and collapsing if statements. It is the recommended level of optimization for floating point operation heavy programs that spend a lot of time in loops (Intel, 2019f). This exactly describes the molecular dynamics program and `-O3` actually increases the performance further. The average overall time was further reduced from 85 seconds down to 62 seconds. This is an additional 27% improvement over `-O2` (see Table 1).

At this point, vectorization was still disabled with the `-no-vec` flag. Enabling vectorization on the yet unoptimized Fortran 90 program resulted in a regression of the average overall time of 33% (see Table 1). Like described above, the second phase is only about finding a set of compiler optimizations that would enable a more rapid analysis of the performance in the crucial third phase. This is the reason why the drop in performance was not analyzed further. For the unoptimized Fortran 90 version of the program somehow vectorization seems to cancel optimizations from `-O3`. The guess at this point was that the program profits more from optimizations from `-O3` (like loop unrolling) than from being vectorized.

Optimization	∅ overall time	∅ superstep time	$+/-$ %	Status
Removed checks	734s	147s	33%	Improvement
`-O1`	413s	83s	44%	Improvement
`-O2`	85s	17s	79%	Improvement
`-O3`	62s	12s	27%	Improvement
Removed `-no-vec`	82s	16s	-33%	Regression
`-Ofast`	62s	12s	0%	Invariant

Table 1: Compiler flags tried during the second phase of optimization. The $+/-$ % column displays the variation in average overall time from the best version of the program so far. For example, the best version for the removal of the extra checks was the Fortran 90 version from phase one. For `-Ofast` the best version of the code was the one compiled without the checks and with `-O3`.

Lastly other common flags for compiler optimization were considered. Two recommended options besides `-O3` are `-ipo` and `-xHOST` (User389, 2020). Neither would improve the performance of the program. `-ipo` enables interprocedural optimizations between files (Intel, 2019d). The program only consists of a single file, so `-ipo` would not improve performance. `-xHOST` forces the compiler to generate instructions from the highest instruction set supproted by the host (Intel, 2019i). The host is a frontend node of Cirrus in this case. The frontend nodes of Cirrus are the same as its compute nodes. The highest instruction set supported is AVX2 (see Section 3). `-no-vec`, which is still enabled at this point, cancels out `-xHOST`.

Lastly `-Ofast` was tested. `-Ofast` is a shorthand compiler flag, which combines `-O3` with a faster floating point model than the default one. It sets `-O3`, `-no-prec-div` and `-fp-model fast=2` (Intel, 2019g). `-no-prec-div` increases the speed of floating point divisions. The cost of this flag is a reduction in precision (Intel, 2019e). `-fp-model fast=2` works the same way. It increases the performance on the cost of less precise results of floating point operations (Intel, 2019a). Enabling `-Ofast` does not result in less accurate test results. The program's correctness is still given, even though floating point precision was lowered. `-Ofast` does not increase the performance compared to `-O3` (see Table 1).

Phase two was terminated at this point. The best compiler flags determined were `-O3` with `-no-vec`. The average overall time after phase two is 62 seconds. This is an improvement of a staggering 94% over the results after phase one (1110 seconds), simply by enabling compiler optimization and removing unnecessary checks.

4.3 Third Phase

The third phase was the most crucial phase. While the second phase already improved the performance by 94%, the quality of the program is still bad. Both in consideration of performance and more importantly maintainability. Phase three of the optimization efforts

Algorithm 1 : original computation per time step

for i=1,...,n **do**
  $\vec{F_i} := -vis_i\vec{v_i}$ {Compute viscosity force for particle i}
end for
for i=1,...,n **do**
  $\vec{F_i} := \vec{F_i} - vis_i\vec{w}$ {Compute wind force for particle i}
end for
for i=1,...,n **do**
  $r_i := ||\vec{p_i}||_2$ {r_i is used in loop below for the denominator in $\vec{F}_{i\leftarrow central}$}
end for
for i=1,...,n **do**
  $\vec{F_i} := \vec{F_i} + \vec{F}_{i\leftarrow central}$ {see Equation 2}
end for
Compute pairwise forces with Algorithm 2
for i=1,...,n **do**
  $\vec{p_i} := \vec{p_i} + \Delta_t\vec{v_i}$ {Update position vector of particle i (see Equation 5)}
end for
for i=1,...,n **do**
  $\vec{v_i} := \vec{v_i} + \Delta_t\vec{F_i}/m_i$ {Update velocity vector of particle i (see Equation 6)}
end for

Algorithm 2 : original pairwise forces computation

for i=1,...,n **do**
  for j=i+1,...,n **do**
    $\vec{p}_{i,j} := \vec{p_i} - \vec{p_j}$ {$\vec{p}_{i,j}$ is used in loop below and for the numerator in $f_{i\leftarrow j}$}
  end for
end for
for i=1,...,n **do**
  for j=i+1,...,n **do**
    $\Delta p_{i,j} := ||\vec{p}_{i,j}||_2$ {$\Delta p_{i,j}$ is used in loop below for the denominator in $f_{i\leftarrow j}$}
  end for
end for
for i=1,...,n **do**
  for j=i+1,...,n **do**
    $\vec{F_i} := \vec{F_i} + f_{i\leftarrow j}$ {see Equation 3}
    $\vec{F_j} := \vec{F_j} + f_{j\leftarrow i}$ {see Equation 3}
  end for
end for

therefore tackles this problem by rewriting the critical section of the program, which spans the computations for updating the particles at each time step.

The third phase has two main goals. The first goal is making code more readable, e.g. writing idiomatic Fortran code, array syntax instead of loops, removing unnecessary variables and computation and fusing loops by hand. This rewrite was necessary not only for increasing maintainability, but also to make the second goal easier to achieve. The second goal was about hardware and environment specific optimizations, mainly enabling vectorization. As will be shown below, idiomatic and modern Fortran code makes it easy for the compiler to auto-vectorize and only a small portion of the rewrite was actually about enforcing vectorization where the compiler could not auto-vectorize.

The common workflow for optimizing for speed normally consists of iterations, where the program is profiled, the bottleneck determined and then optimized. The workflow used here is less vigorous concerning profiling. Profiling after each change in order to identify and fix bottlenecks is not necessary, because it is well established where the bottleneck of molecular dynamics programs is: computing the pairwise forces between the particles (Chiu et al., 2011).

This assumption was validated for this program. The update operation of the simulation was split into two parts: (i) computing pairwise forces between the particles and (ii) computing the other forces and updating the position and velocity of each particle. Inlining was disabled and the program run with Intel's VTune 19 profiler (Intel, 2020). The profiler revealed that over 99% of the runtime is spend computing the pairwise forces.

Furthermore, as described above, the guiding principle for rewriting of the program was increased maintainability and elegance rather than pure speed. The codebase is not very big (approximately 250 lines of code) so not a lot of time could be wasted on rewriting parts of the code that are not part of the critical section.

The guiding tool for the environment specific optimizations was the optimization report generated by the compiler with the `-qopt-report=5` flag (Intel, 2019h). Otherwise the benchmark output and a Python script for comparing different benchmarks with each other were used to determine the impact a change to the source code had on the performance of the program. The script basically replaced using an advanced profiler like VTune after each change made to the code.

The first step rewriting the code was to remove the utility functions and subroutines and inline them by hand (see Section 4.1). This was done not in consideration of performance, but to better enable the rewriting. The utility functions were obscuring loops, making it harder to properly see loop nests which are crucial for vectorization. Looking at the optimization report revealed, that they were inlined by the compiler, so no performance difference was measured after the hand inlining.

Algorithm 1 shows the update operation per time step, as it was originally implemented. As stated above, computing $\vec{F}_i$ without the pairwise forces (Equation 4 without $\sum_{i \neq j}^{n} f_{i \leftarrow j}$) is not the critical section. Nonetheless the code is still badly written and not optimal. Algorithm 1, lines 1–12 are all needed, simply for computing Equation 4 without the

```
! This is how the old version of the program computes r
do k = 1, Nbody
  r(k) = 0.0
end do
do j = 1, Ndim
  do i = 1, Nbody
    r(i) = r(i) + pos(i,j) * pos(i,j)
  end do
end do
do k = 1, Nbody
  r(k) = sqrt(r(k))
end do

! The new version uses Fortran's array syntax to convert this
! to a 1-liner
r(:) = sqrt(sum(pos(:,:) ** 2, dim=2))
```

Figure 2: Computing r for each particle in Fortran, as done in the old version of the program and the one using array syntax.

pairwise forces. While `-O3` enables loop fusion, only the first two loops (the wind and viscosity forces) are fused together. So there are three iterations needed over n: one for the wind and viscosity forces, one for computing r and one for computing $\vec{F}_{i\leftarrow central}$. The first step was to reduce the $3n$ iterations to $2n$ iterations by fusing the viscosity, wind and central force computations all into a single loop setting $\vec{F}_i := -vis_i(\vec{v}_i + \vec{w}) + \vec{F}_{i\leftarrow central}$. Fusing the loops together by hand resulted in a regression concerning the program's performance. While the best version after phase two took on average 62 seconds overall, the version with the fused loops resulted in 64 seconds on average. This is a drop in performance of approximately 3%. The reason for this drop are reduced efficiency of the pipelines of the CPU caused by data hazards. The data hazards are caused by output dependencies (write after write) when computing $\vec{F}_i$ (see e.g. Patterson, 2014).

The next step was to beautify the computation of r (Algorithm 1, lines 7–9). Figure 2 shows the original code and the one-liner it was transformed to. Using Fortran's array syntax makes the code much more readable by being more concise and removing ten lines of code. Unfortunately, making this change results in another performance regression of about 1%.

In order to further concise the program, reduce the amount of loops and the memory footprint, r was removed from the program completely, moving the computation of $||p_i||_2$

into the actual denominator of $\vec{F}_{i \leftarrow central}$. Problematic for this operation was the memory layout of the particle vectors. All particle vectors involved (force $\vec{F}_i$, position $\vec{p}_i$ and velocity $\vec{v}_i$) are actually represented as a $n \times 3$ matrix of all particles. Fortran stores matrices column-wise. This means all particle vectors are actually strided with a separation of n and not contiguous in memory. This does not leverage locality needed for utilizing the cache for fast memory access when doing particle-wise operations, rather than dimensional-wise (outer loop over the three dimensions of the particle vectors). The current version of the program actually computes $\vec{F}_i$ dimensional-wise. r_i can only be computed particle-wise. So in order to remove r from the program the loops for computing $\vec{F}_i$ were exchanged to being particle-wise (outer loop over the particles instead of over the dimensions of each particle). While this change removes leveraging locality, removing r actually reduces the pressure on the cache. Like stated in Section 3, the whole program uses double precision floats. For $n = 4096$, this means r alone takes up 32 Kb—the whole L1 cache. The performance report reveals that the inner loop over the three dimensions of each particle is actually unrolled by the compiler. Removing r from the program resulted in a performance improvement of approximately 2%, still worse than the version of the program after phase two.

The last change made to the part of the simulation not dealing with the computation of the pairwise forces was fusing the loop computing $\vec{F}_i$ with the last two loops (Algorithm 1, lines 14–19), which were already fused. $2n$ were reduced to n iterations by fusing the two loops by hand. Again this reduction in the constant factor of n comes with the cost of locality when doing particle-wise operations instead of dimensional-wise ones. Concerning the maintainability, the whole rewrite of the program to this point saved approximately 30 lines of code and increased the readability drastically. Only a single loop is needed for computing $\vec{F}_i$ without the pairwise forces and updating $\vec{p}_i$ and $\vec{v}_i$. Fusing the two loops is invariant concerning the performance.

Next the critical section of the program—computing the pairwise forces $f_{i \leftarrow j}$—was optimized. How the original program computes the pairwise forces is shown in Algorithm 2. First two minor simplifications of the loop nest computing the pairwise forces (Algorithm 2, lines 11–16) were conducted. Two particles i and j collide, if $||\vec{p}_i - \vec{p}_j||_2 < \tau_{i,j} := radius_i + radius_j$ (see Section 2). $radius_i$ is never read from the file containing the data for each particle. Instead $\forall i : radius_i := 1/2$ is set in the routine reading the particle data from file. This way $\forall i, j : \tau_{i,j} = 1$, so we can remove $radius$ from the program (saving another 32 Kb of memory) and replace it with a single constant. The second minor change concerns an unnecessary branch. The program counts particle collisions. Whenever $||\vec{p}_i - \vec{p}_j||_2 < 1$ a counter is increased. Instead of increasing the counter in the if-statement of Equation 3, a boolean variable is set to true and another if-statement is needed for incrementing the collision counter. The second if-statement was replaced with incrementing the collision counter directly. Again the changes increased readability but the program is 5% slower than the fastest version.

The next change was the first major change of phase three where performance was significantly improved. Instead of computing $\vec{p}_{i,j}$ and $\Delta p_{i,j}$ in their own loops (Algorithm 2,

lines 1–10) for each particle and having to save the result in memory for later use in computing $f_{i\leftarrow j}$, they were reduced to two temporal variables computed in the last loop (Algorithm 2, lines 11–16). There are $n(n-1)/2$ particle pairs. This means removing the two loops results in a reduction of $n(n-1)$ iterations. The original program actually saved $\vec{p}_{i,j}$ and $\Delta p_{i,j}$ not in a matrix/array with $n(n-1)/2$ elements but in oversized containers with n^2 elements. This means the array for $\Delta p_{i,j}$ alone takes up 128 Mb of memory. The matrix which saves $\vec{p}_{i,j}$ takes up 384 Mb of memory. The fastest version took on average 62 seconds to complete the whole simulation. The new version only takes on average 42 seconds to completion, a performance improvement of 32%.

The next two changes tried to reduce the impact of the branch in Equation 3. Computing $f_{i\leftarrow j}$ was changed to a particle-wise operation (see above). This way the branch was moved up one loop in the nest and the inner loop over the dimensions was again unrolled. This resulted in a 2% performance improvement. At this point $f_{i\leftarrow j}$ and $f_{j\leftarrow i}$ were still both computed, even though $f_{j\leftarrow i} = -f_{i\leftarrow j}$. Readability is increased by using $\vec{F}_j := \vec{F}_j - f_{i\leftarrow j}$ instead of $\vec{F}_j := \vec{F}_j + f_{j\leftarrow i}$. This change has no effect on the performance.

4.4 Fourth Phase

5. Discussion

6. Conclusion

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