Performance Engineering of Software Systems September 30, 2021
Massachusetts Institute of Technology 6.172
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Project 2: Rendering and Simulating 3D Scenes

Last Updated: September 30, 2021

In this project you will optimize a graphical N-body gravity simulation program for multicore processors using the OpenCilk parallel programming platform. It is a good idea to fully read this handout and reread the Course Information handout before you get started!

Contents

1 Due dates

- ☐ *Team contract:* 11:59 P.M. on Friday, October 1, 2021
- ☐ *Beta submission:* 11:59 P.M. on Thursday, October 7, 2021
- ☐ *Beta write-up:* 11:59 P.M. on Friday, October 8, 2021
- ☐ *MITPOSSE meeting deadline:* 11:59 P.M. on Tuesday, October 13, 2021
- ☐ *Final submission:* 11:59 P.M. on Friday, October 15, 2021
- ☐ *Final write-up:* 11:59 P.M. on Monday, October 18, 2021

2 Getting started

Snailspeed Ltd. has been put onto the map due to its newly patented *iRotate* algorithm. Due to your role in Snailspeed's rise to prominence, you have been promoted to CCTO (Co-Chief Technology Officer). Custom engraved door plates and corner offices aren't cheap; and, unfortunately, Snailspeed didn't have enough revenue left over to hire additional engineers. Instead, Snailspeed has hired a small team of corporate management consultants from InchWorm Advisors.

InchWorm Advisors have suggested that Snailspeed pivot towards the development of multicore software in order to remain on the cutting edge. As a result of these discussions, Snailspeed is planning to launch *SnailSim*, a disruptively high-performance graphical N-body gravity simulation program designed for multicore processors.

It is up to you and your fellow CCTO to transform *SnailSim* from dream to reality. InchWorm Advisors have suggested that you look into the OpenCilk task-parallel programming platform to parallelize *SnailSim*. OpenCilk may be the key, according to Inchworm Advisors, to transforming Snailspeed Ltd. into a major player in the high-performance computing industry.

Team formation and contract

Teams will be formed by random matching and posted on Piazza. You and your teammate must write a team contract specifying how your team will operate — a set of conventions that you plan to abide by. The requirements for the team contract are the same as before. For guidance in writing your team contract, please refer to the description for Project 1. **Only one copy of the contract needs to be submitted on Gradescope. Please add both teammates to the submission.**

Getting the code

Before beginning to work on Project 2, please update your `apt` packages:

```
$ sudo apt update && sudo apt upgrade
```

The course staff will release the teams on a spreadsheet through Piazza, notifying you of your `team-name`. You can then get the project code:

```
$ git clone git@github.mit.edu:6172-Fall21/project2_<team-name>.git project2
```

You can also browse the code before that by cloning a read-only repository:

```
$ git clone git@github.mit.edu:6172-Fall21/project2.git project2
```

Pair programming

We strongly recommend that teams practice pair programming as described in the Project 1 handout. This style of programming leads to bugs being caught earlier, both programmers always remaining familiar with the code, and fewer repetitive stress injuries (RSI). Pair programming also makes it easy for you to maintain balanced commits among your team members' usernames.

3 Introduction to the codebase

In this project, you will be optimizing a 3D N-body gravity simulation with rendering. The simulation consists of a 3D virtual environment filled with colored spheres that bounce off one another according to simplified physics.

To get acquainted with the code, let's begin by compiling and running two important binaries.

3.1 Running the simulation

The simulation can be executed either with or without a graphical display. While collecting performance data, execute the program **without** the graphical display to obtain more accurate performance measurements. The execution syntax is as follows.

```
Usage: ./main [-f FILE_NAME] [-n NUM_FRAMES] [-m] [-g] [-t] [-h]
  -f fileName   Input file name                Optional, may not be used with -t flag
  -n numFrames  Number of frames to run        Optional, may not be used with -t flag
  -m            Writes ref_test files          Optional, may not be used with -t or -g flag
  -g            Runs code with graphics        Optional, may not be used with -t or -m flag
  -t            Runs performance tests         Optional, no other flags may be used
  -h            This help message
```

The input file is optional and defaults to `simulations/250.txt`. The `simulations/` directory contains several (fun!) examples of input files. Use the `-g` option to look at them. Figure 1 shows a screenshot from `simulations/250.txt`.

Here's the output of one run with the default input:

```
$ ./main
Num spheres: 250
Img size: 256x512
Num frames: 10
---- RESULTS ----
Time elapsed: 1215 ms
---- END RESULTS ----
```

Benchmark your serial code on the `awsrun` machines by using the `./main -t` command or noting

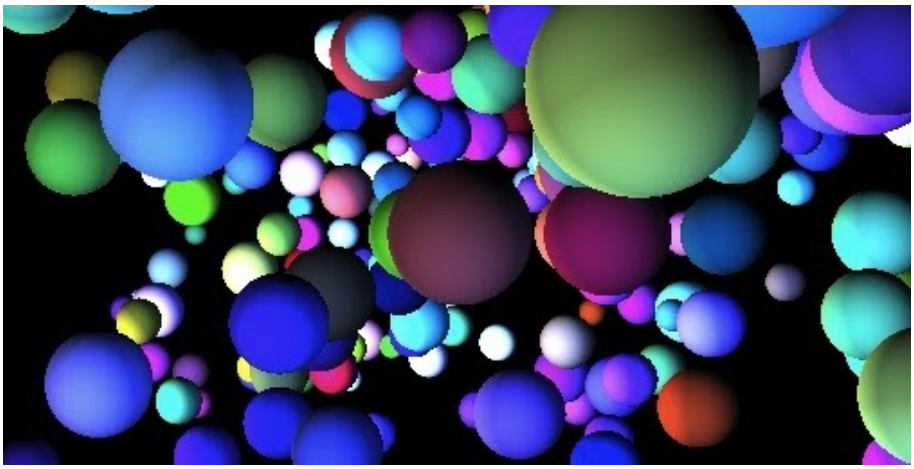


Figure 1: Screenshot from `simulations/250.txt` input produced by running `./main -g`.

the time elapsed on the execution of a certain file. The `awsrun` machines, however, don't have access to your local files. Use the `-f` flag to specify the input if you're executing on a local file.

3.2 Running the reference testing tool

To help you get started with reference testing, a method of correctness testing described in Section 4.1, we are providing a tool to check correctness by comparing implementations. This tool provides a visualization of your error and statistics about your correctness. It also separates rendering tests from simulation tests to help isolate bugs. The execution syntax is as follows.

```
Usage: ./ref_test [-r] [-s] [-g] [-h]
        -r                Run tool for render function
        -s                Run tool for simulate function
        -g                Display graphical heatmap while ref testing
        -h                This help message
```

Before you run the `ref_test` binary, however, you must run the `main` binary with the `-m` flag enabled. The `main` binary then produces a set of four files that are necessary for the reference testing tool to run. Once you have those files, you may run the `ref_test` binary with either the `-r` render flag or the `-s` simulate flag (plus the `-g` flag if you would like to view the visualization). If you specified the `-g` flag, `ref_test` pulls up a screen showing the frame-by-frame heatmap of your errors. If you see a black screen, don't worry! That means you have no errors.

After the heatmap has been displayed for each frame, or if you choose to run the tool without the `-g` flag, the `ref_test` prints out a few summary statistics about your run. We highly recommend using these statistics to test correctness. A maximum error of 0 implies correctness.

This tool is far from perfect! Don't be afraid to tweak it for your own purposes or post changes to Piazza. We appreciate all contributions (and they can help your class-contribution grade).

3.3 Modifying the files

While grading, the course staff will call only five functions: `simulate()`, `simulateOrig()`, `render()`, `renderOrig()`, and `sort()`. Thus, your grade is only affected by changes to these files: (i) `simulate.c`, (ii) `simulate.h`, (iii) `render.c`, (iv) `render.h`, and (v) `Makefile`. When you submit your code, the course staff will revert all other files to their original states. Feel free to explore the codebase, but please keep in mind that changes to files that are not in this list will be reverted for grading.

4 Optimizing the serial code

The first part of the project is to make algorithmic changes to the `render()` function to reduce the total work performed by the serial code. Currently, the rendering code uses an extremely inefficient algorithm to determine the color of a given pixel. At each time step, the algorithm iterates through all pixels, and for each pixel, it iterates through all spheres to see if that pixel should take the color of that sphere. This exhaustively iterative method is expensive, requiring $\Theta(MN)$ ray-sphere intersection tests for a size-M image and a scene containing N spheres.

Begin by implementing a new rendering algorithm that uses the mathematical concept of a projection to reduce the total amount of spheres that must be checked for each pixel. Please do **not**, at this point, complicate matters by using OpenCilk (or any other parallelization method) to parallelize your rendering algorithm. Parallelization will happen in the second part of this project, described in Section 5. Generally, when parallelizing code, it's advised to first to exploit all the serial performance enhancements you can, while preserving your options for parallelization later.

4.1 Guidelines and advice

Before you modify the implementation, please consider the following guidelines and advice:

- *Fast math:* You may **not** use the compiler flag `-ffast-math`. This flag allows the compiler to reorder certain mathematical operations, which may result in nondeterministic floating-point results. Since the course staff needs to grade the correctness of your code, nondeterminism is not okay. Although use of this flag is disallowed for your submission, feel free to play with it. (Please report on your experiments with `-ffast-math` in your write-ups.)

- *Reference testing:* You will find it useful in this project to check the correctness of your optimizations using ***reference testing***: a method of correctness testing that compares the execution of two different implementations of a function to ensure that the implementations behave identically. We have provided a tool called `ref_test` for this purpose.

  Let's say that you have modified the `render()` function in `render.c`. There are two ways to test. The first is to write unit tests. The second is to compare two versions of the function: the original implementation `renderOrig()` and your new implementation `render()`. The reference testing tool relies on this structure. By preserving the original behavior in

`renderOrig()` and `simulateOrig()` and developing new code in `render()` and `simulate()`, you will be able to use `ref_test` to perform reference testing.

- *Serial optimization:* You may be tempted to jump directly into parallelizing your code as a means to gain performance. Generally, however, the best parallel programs are those that are first highly optimized serially and then made parallel afterwards. We therefore recommend making the serial version of the program as fast as possible before parallelizing.
- *Determinacy-race freedom:* Your code must be free of determinacy races. This means you may not use parallel constructs involving locking, memory synchronization, or atomics. Stick to the `cilk_spawn`, `cilk_sync`, and `cilk_for` keywords for your parallelization.

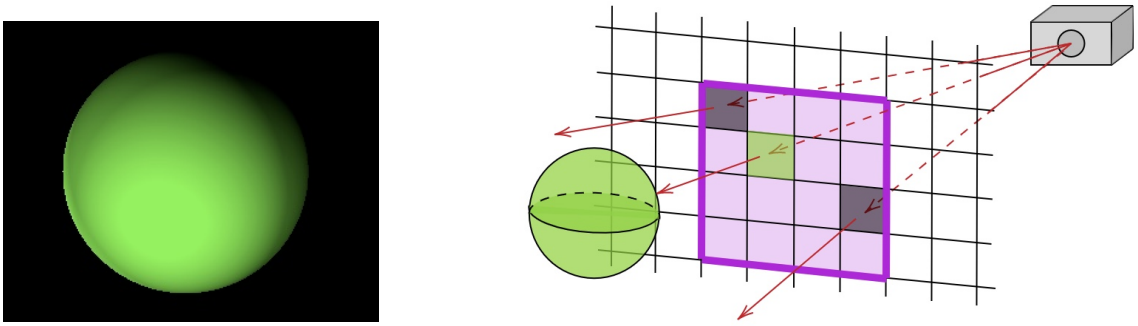
4.2 Rendering through ray tracing

To render a scene, the code uses a highly simplified version of ray tracing. Ray tracing is a rendering algorithm that mimics the behavior of the human eye in order to create realistic images. As with human vision, there are three key parameters we must set to fix the the 2D image we see when presented with a given 3D scene: the position of the eye, the plane onto which we project the image, and the size of the image. Since there are many different ways to represent these objects, let's look at the specifics as they are written in the code.

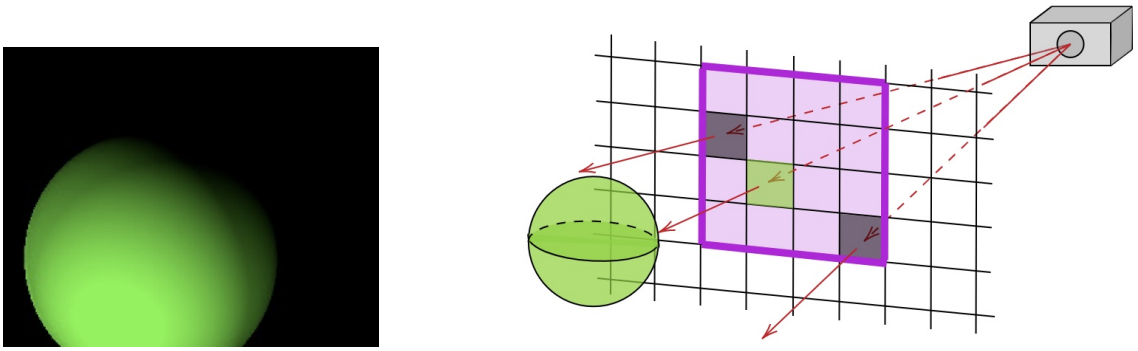
- Viewpoint e is defined by a 3D position.
- Projection plane P is defined by two 3D vectors, u and v, that lie in P. We define u and v to be orthnonormal for computational ease. Remember that the term ***orthonormal*** refers to vectors that are orthogonal to each other and of unit size. Points on P lie in 3D space, and therefore require three coordinates to fully specify their position.
- Image I, viewed from e, is then defined by a grid of size M (of height h and width w such that $M = hw$) on projection plane P. Points on the image lie in 2D space relative to the projection plane, and therefore require only two coordinates to fully specify their position.

In our case, a scene is composed of N spheres indexed from 0 to $N - 1$. Each sphere is defined by position, velocity, acceleration, radius, mass, color, and reflectivity. To see how modifying the rendering parameters changes a rendered image, let's consider a scene consisting of a single green sphere i, rendered with projection plane P, eye location e, and image size M, as illustrated in Figure 2(a). What is the impact is of changing the rendering parameters?

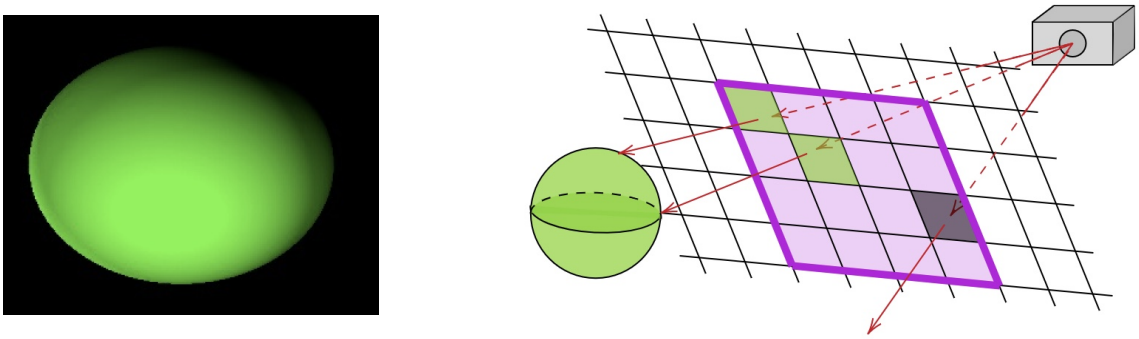
What happens, for example, if you change the position e of the eye? This parameter is fairly intuitive to understand. Imagine staring in the same direction as you walk side to side or sit down and stand up without changing the direction in which you're looking. The section of the scene you're looking at shifts as your position shifts. In Figure 2(b), observe the result of rendering sphere i when you replace e with a new position e', representing an upwards shift of the eye, while keeping P and M constant.



(a) The image (left) of a scene containing a single sphere and its corresponding ray-tracing diagram (right) showing the eye (box, top right), the projection plane (grid), and the subset of the plane that constitutes the image (shaded purple). A sample of rays from the eye to the image are shown in red.



(b) The scene from (a) with a new viewpoint. As compared to (a), the eye and the corresponding image (shaded purple) have shifted up.



(c) The scene from (a) with a new projection plane where the plane is slanted differently.

Figure 2: A comparison of the results of rendering the same scene under different parameters.

Return again to Figure 2(a), where we render the sphere with eye position e and projection plane P. What happens if you change P to P', representing a slant of the plane, while keeping e and M fixed? The resulting scene is shown in Figure 2(c). This image corresponds to keeping the position of the eye fixed, but changing the angle from which the eye looks. Since you are no longer looking at the sphere head-on, Figure 2(c) renders an ellipse instead of a circle.

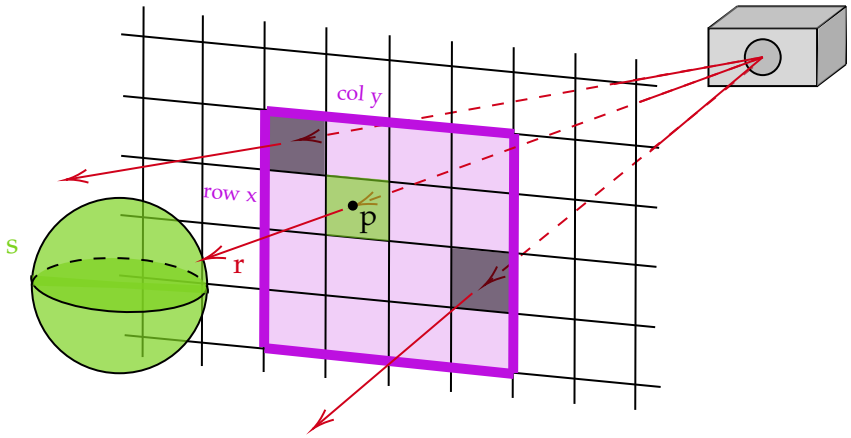


Figure 3: A visual example of the basic ray tracing algorithm showing the eye, the projection plane, the subset of the plane that constitutes the image, and a sphere. Each red ray from the eye to a pixel determines the color of that pixel from the objects in the scene that the ray intersects. An example for ray r, which intersects pixel (x, y) and corresponding 3D point p, is labeled.

Given a scene to render, you must fix the eye position, the projection plane, and the image size in order to fully specify the image. Now, what happens after you've fixed your parameters? How do you go from an infinite 3D scene to a finite 2D image? This is where the idea of ray tracing comes in. Follow along with Figure 3 to understand the procedure.

Consider a particular pixel in the 2D image you want to produce. Denote this pixel as the ordered pair (x, y) representing the pixel's x- and y-coordinates within the 2D image (labeled in purple in Figure 3). Since the image you want to produce is a subset of the projection plane, there is some known 3D point p (labeled in black in Figure 3) on that plane that corresponds to pixel (x, y). To determine the color of pixel (x, y), define a ray r (labeled in red in Figure 3) from the eye to point p. Any sphere that intersects ray r has a 2D projection that includes pixel (x, y). In other words, some part of the sphere is mapped to (x, y) when you project the sphere from 3D to 2D. Of course, with multiple spheres, because spheres closer to the eye occlude spheres farther away, you actually only use pixel (x, y) to render the sphere closest to the eye that intersects ray r.

Let's review. To determine the color of pixel (x, y), you must find point p on the projection plane, calculate ray r from the eye to point p, and find the sphere closest to the eye that intersects ray r, if such a sphere exists. If this sphere exists, pixel (x, y) adopts the color of that sphere (realistically shaded according to the Lambert diffuse). If no such sphere exists, the pixel adopts the background color (black). The image is rendered by repeating this process for each pixel, as in Figure 3. For a scene with N spheres, since we check all N spheres for intersections with r, the same ray-sphere intersection calculation is repeated N times per pixel. This strategy is inefficient.

Fortunately, this problem contains spatial locality that you can exploit. Consider some sort of projection algorithm to replace the current ray tracing algorithm. Here's the main idea: instead of iterating through the spheres for each pixel to determine the pixel's color, iterate through the spheres only once in order of increasing distance from the eye and color in the appropriate pixels as you go. Since you iterate in order of increasing distance, once a pixel is colored, you need never color it again as you continue iterating through the spheres. This way, you need only visit each sphere once and each pixel once, yielding an algorithm with runtime $\Theta(M + N)$ instead of $\Theta(MN)$ as before, where N is the number of spheres and M is the size of the image.

As you test your code, you may want to consider a few key questions for the write-up:

- What speedup did you achieve? Was this performance what you expected?
- What design choices did you make while rewriting the render function to use the idea of projections? For example, how did you determine which pixels to color for each sphere?
- Does this implementation seem parallelizable? Do you foresee any determinacy races?

Remember that the color of each pixel and the position of each sphere in the new code should be the same as in the old code. Verify your code using `ref_test` or by writing your own tests. To ensure accurate performance results, run `./main -t` on an `awsrun` machine.

4.3 Physics simulation

The function `simulate()` implements the physics of the spheres as they interact. There are two main components to the 3D physics of the simulation: gravitational forces between every pair of the N spheres and elastic collisions between spheres. This simulation aspect of the project is just as important as the rendering aspect, although we do recommend tackling simulation second.

Each sphere `i` has the following properties related to the physics of the simulation: `i.accel`, `i.vel`, `i.pos`, and `i.mass`. Acceleration, velocity, and position are updated after each time step. These calculations are handled in the functions `updateAccelerations()`, `updateVelocities()`, and `updatePositions()`, which you can find in file `simulate.c` of the starter code.

The simulation discretizes time by partitioning the time line into small intervals. A ***time step*** is a point in time connecting two adjacent intervals. At each time step, the simulation updates the acceleration, velocity, and position of all spheres based on their values at the previous time step. Let's denote the acceleration of sphere i at time t as $a_i^{(t)}$, velocity as $v_i^{(t)}$, and position as $p_i^{(t)}$. For a given time step t, let $t - \Delta t$ be the time of the previous time step.

The acceleration $a_i^{(t)}$ of sphere i at time t is provided by the Newtonian law for the forces of gravity. Let $d_{ij}^{(t)}$ be the vector difference of the positions of spheres i and j at time t, let G be the gravitational constant, and let m_j be the mass of sphere j. The net acceleration of sphere i due to the gravitational forces from the other $N - 1$ spheres at time t is then given by the formula

$$a_i^{(t)} = \sum_{\substack{j=0 \\ j \neq i}}^{N-1} \frac{G m_j}{|d_{ij}^{(t)}|^3} \cdot \overrightarrow{d_{ij}^{(t)}} \ .$$

The acceleration calculation involves $\Theta(N^2)$ work to update all spheres. There are methods in the literature, including the Barnes-Hut algorithm and the Fast Multipole Method, for reducing the work asymptotically. We do **not** recommend that you implement one of these methods. The constants in these algorithms are unlikely to make them faster than the naive $\Theta(N^2)$ for the relatively small problem instances we'll be dealing with, and they will wreak havoc on your ability to control floating-point accuracy. As further reasoning, the course staff would like you to know that none of our optimized implementations contain such algorithms or other advanced ideas such as *k-d* trees. You are free to do as you wish, but our advice is to mine the many other sources of performance before risking much or any time implementing such algorithms.

After calculating $a_i^{(t)}$, the simulation algorithm finds $v_i^{(t)}$ and $p_i^{(t)}$:

$$\begin{aligned} v_i^{(t)} &\leftarrow \Delta t \cdot a_i^{(t)} + v_i^{(t-\Delta t)} \ , \\ p_i^{(t)} &\leftarrow \Delta t \cdot v_i^{(t)} + p_i^{(t-\Delta t)} \ . \end{aligned}$$

The simulation handles collisions between spheres as follows. Suppose that the time of the current time step is t and the time of the next time step is t'. If a collision will happen between t and t' as determined by a geometric collision checker in `simulate.c`, the collision checker finds the time t'' of the first collision that occurs between times t and t'. Then, the code breaks the interval $[t, t']$ into two ***mini*** time intervals: $[t, t'']$ and $[t'', t']$. The effects of the collision are calculated after updating acceleration, velocity, and position for time t''. The code then iterates on interval $[t'', t']$, again subdividing it if a collision will occur before t'.

4.4 Floating-point woes

One particularly hairy aspect of N-body simulation and rendering is dealing with floating-point numbers. Floating-point arithmetic is not associative. In particular, there might be faster ways of computing things like velocity, but unless the same operations are performed in the same order, floating-point error can occur, causing you to fail the reference test. Thus, you should proceed with caution when modifying formulas.

The code uses double-precision floats for calculations to mitigate the effects of round-off. As you change the code, use `ref_test` with the `-g` flag to visualize the locations of floating-point error.

More subtleties arise when writing "shortcut" code. For example, you may use the fact that if the bounding cubes of two spheres do not overlap, then they cannot collide. Taking advantage of this observation can reduce the number of pairs of spheres for which you perform a collision check. Since this operation for collision detection is different than the condition used in the original code, however, it is possible, due to round-off error when computing the bounding box, for the original code to report a collision while the bounding cubes do not intersect.

4.5 Optimization ideas

Look for opportunities for serial optimization within the `render()` and `simulate()` functions and describe what you did. Here are some optimization ideas to help you get started:

- Replace the ray tracing algorithm by implementing a projection algorithm that maps 3D spheres to 2D shapes. Iterate through the spheres and color in the projection for each sphere as you go. The course staff highly recommends this as a place to start.
- A large number of calculations are repeated in each time step. For example, the rendering code recalculates the color of each sphere, even though the color never changes. Consider precomputing these calculations and storing results for reuse.
- Many calculations are repeated even within the same loop. For example, when calculating the force of gravity between spheres i and j, we effectively calculate the force of gravity between spheres j and i. Take advantage of this symmetry.
- Although the method given for testing whether two spheres collide is fairly efficient, you may wish to explore more efficient ways of testing for sphere collision.

5 Parallelization

Once you have optimized your serial execution, you can begin parallelizing with OpenCilk. Parallelization can be tricky because race conditions and nondeterminism can arise if you implement parallelism incorrectly. Careful parallelization is key to improving the performance of your code.

Profiling the serial code

Profiling your application can help determine where you should focus your time when parallelizing your code. The goal is to identify a region of code that comprises a large percentage of the total execution time but is amenable to a potentially large degree of coarse-grained parallelism. Run `awsrun perf record` and `aws-perf-report` to see the profiling statistics.

Parallelizing the application

Parallelize your code by including `cilk_spawn`, `cilk_sync`, and `cilk_for` keywords appropriately in the regions of code you have identified as worth parallelizing. If you do not see much code suitable for parallelization using the Cilk primitives, you may want take another look at both the `render.c` and `simulate.c` files.

In order to benchmark your parallel code, use:

```
$ awsrun8 ./main -t
```

The `awsrun8` command will run your code on an 8-core machine. **Warning:** If you benchmark using `awsrun` (no `8`), it will run on a single core machine, and you will get inaccurate results.

For any changes you make, verify that your code reports the same coloring of pixels and positions of spheres as before. Additionally, verify that the code is race-free by running it through the Cilksan determinacy-race detector. **Note:** Run the Cilksan binary locally on your VM.

Profiling the parallel code

You can determine the work and span of your parallel code by executing with Cilkscale. How much parallelism do you see? Vary any parameters your algorithm may take as well as any other spawn cut-offs you used. What is the maximum amount of parallelism you can achieve?

5.1 Parallel Algorithms

The serial algorithm for finding force between bodies `i`, `j` using some function `f()` looks like this:

```
for (int i = 0; i < N; i++) {
    for {int j = 0; j < N; j++) {
        if (i != j) force[i] += f(i, j);
    }
}
```

You can get an easy factor of 2 speedup by traversing only unique pairs like so:

```
for (int i = 0; i < N; i++) {
    for {int j = i+1; j < N; j++) {
        force = f(i, j);
        force[i] += force;
        force[j] -= force;
    }
}
```

One especially tricky portion of the simulation comes with parallelizing these pairwise effects. Naively, to parallelize the above code, one would just replace the outer loop with a `cilk_for`:

```
cilk_for (int i = 0; i < N; i++) {
    for {int j = i+1; j < N; j++) {
        force = f(i, j);
        force[i] += force;
        force[j] -= force;
    }
}
```

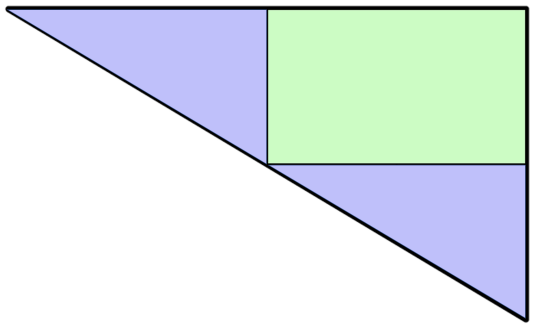


Figure 4: A figure representing the recursion of a `triangle`. The purple subtriangles can be processed in parallel, and the green rectangle can be processed either before or after. Green and purple cannot be processed at the same time, however, without creating a determinacy race.

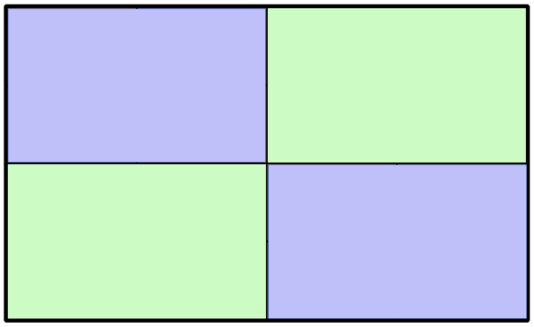


Figure 5: A figure representing the recursion of a `rectangle`. The purple subrectangles can be processed in parallel, and then the green subrectangles can be processed in parallel. However, green and purple cannot be processed at the same time without creating a determinacy race.

This, however, produces a race condition. `force[j]` may be updated over many different values of `i` at once. If reads and writes across cores occur out-of-order, we may get an incorrect result.

To properly parallelize this block of code, we use a clever recursive algorithm, whose recursive calls may be written as independent `cilk_spawn`'s.

First, we divide the triangular region described by the double loop

```
for (int i = 0; i < N; i++) {
    for {int j = i+1; j < N; j++) {
```

into two smaller triangular regions and a single rectangular region, as in Figure 4. The two triangular regions can be then run in parallel. This is because those regions update `force[i]` and `force[j]` for different values of `i` and `j`, so there are no races. The rectangle, however, races with both triangles, so it must be processed either before or after the triangles.

Fortunately, by further dividing the rectangle into four subrectangles as in Figure 5, we observe that the rectangle can also be processed in parallel. Subrectangles that are diagonal from each other can run in parallel since they update `force[i]` and `force[j]` for different values of `i`, `j`, causing no races. If all four subrectangles were to run in parallel, however, there would be a race.

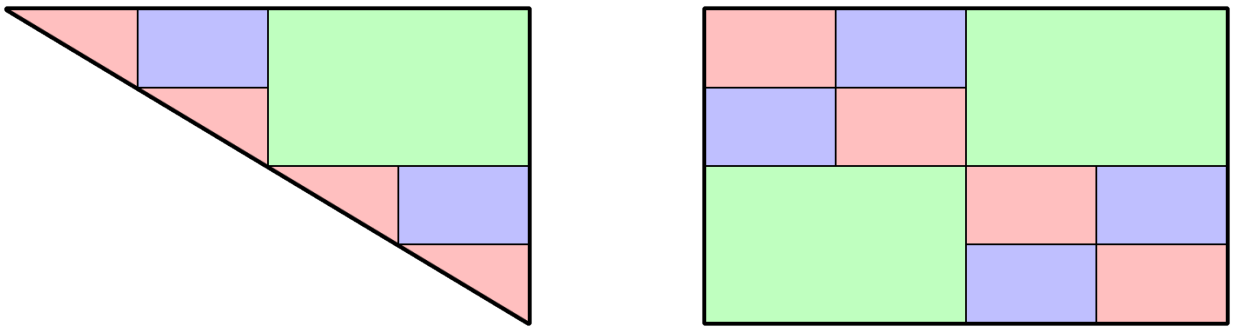


Figure 6: A figure representing the recursion of `triangle` and `rectangle` two levels down. A rectangle is recursively broken into subrectangles, and a triangle is broken into two subtriangles and a rectangle, which are then recursively subdivided. Same-colored regions may be spawned concurrently without racing.

Parallelizing render

The rendering algorithm should be sped up with parallelization as well. In the 2D projection algorithm, each pixel can be colored independently of the other pixels, making it fairly straightforward to parallelize. As you change and optimize the rendering algorithm, it will be important to ensure that this independence remains in the presence of more complex data structures.

Performance tuning

In your write-up, describe any decisions, trade-offs, and further optimizations that you made, including which parts of the code you parallelized using the divide-and-conquer algorithm explained above. While we will be grading on a machine similar to `awsrun8`, we expect your code should not rely on `CILK_NWORKERS=8` to perform correctly.

6 Evaluation

Please remember to add all new files to your repository explicitly before committing and pushing your final changes.

Evaluation measures

Your grade will be based on all of the following:

Performance (of correct code)

As with Project 1, your final performance grade will be computed by comparing the performance of your submission against a baseline to be announced. Your code will be benchmarked against inputs not made available to you. Therefore, you should keep your code general and be careful

not to over-optimize to any specific type of simulation configuration. In addition, you should keep your code as processor-oblivious as possible as a matter of portability. You can use Cilkscale to explore whether your parallel code scales well or not. As a reminder, Cilkscale runs your code serially to compare scalability so you may see the following `awsrun8` output:

```
==== Standard Error ====
Forcing CILK_NWORKERS=1.
```

For correctness, your code should:

- Match the frames of the starter code pixel-for-pixel for the entire duration of its execution.
- Contain no determinacy races.

Beta group write-up

You are required to submit on Gradescope a beta group write-up discussing the work that you performed. Please follow the same template for your project write-up as with Project 1. ***Important:*** **Please also push your write-up to your Git repository as a `.pdf` or readable `.txt` file.**

Similarly to Project 1, as part of your write-up, you must submit a log indicating how you spent your time on the project. You may choose any method that produces an easy-to-interpret log.

Addressing MITPOSSE comments

The MITPOSSE Deputies will give you feedback on `https://github.mit.edu` on your code quality. We expect you to respond thoughtfully to their comments in your final submission. We will review the MITPOSSE comments and your write-up to ensure that you are addressing them.

Final group write-up

You are required to submit on Gradescope a final group write-up, which builds on the beta group write-up and additionally discusses the work you performed since the beta release. Similarly to Project 1, in your final write-up, please include the following information:

- An overview of changes you made to your beta release for the final, their impact, and what motivated you to make those changes.
- Some comments on meeting with your MITPOSSE mentor.
- An updated project log documenting how you spent your time on the final.

Team contract

You are required to submit on Gradescope your team contract, which sets forth conventions on how you and your teammate will collaborate. Remember that you should only submit one copy

of the team contract on Gradescope and add both teammates to the submission.

Aesthetic test inputs

The staff has provided a few example input files in the `simulations` directory. A small portion of your grade is based on the quality of the new inputs you create to test and benchmark your code. These new inputs will be judged based on whether they satisfy following criteria: (i) the input has challenging performance or correctness properties; and (ii) the input is aesthetically interesting or entertaining. We will curate the most interesting inputs and show them in class.

Grade breakdown

We will grade your project submission based on the following point distribution:

	Beta	*Final*
Performance (of correct code)	36%	40%
Addressing MITPOSSE comments	—	10%
Write-up	5%	5%
Team contract	3%	—
Aesthetic test inputs	1%	—
Total	45%	55%

As with Project 1, this point distribution serves as a *guideline* and not as an exact formula. The staff will also review your Git commit logs to assess the dynamics of your team.

Before you submit

Before you submit your code, complete the checklist below.

- ☐ Run `ref_test` to verify correctness.
- ☐ Run the Cilksan race detector to confirm that you have no determinacy races.
- ☐ Run the style checker with the following command:

```
$ find . -regex '.*\.\(c\|h\)' -exec clang-format -style=file -i {} \;
```

- ☐ Ensure that you didn't modify any files that will be reverted for testing (see Section 3.3).
- ☐ Add your aesthetic test input file to the `simulations` directory.
- ☐ (*Optional*) Let us know what you think of the project on Piazza or in your status report! This is a new project this year, and we would love to hear your feedback.