Comparison of Spatial Partitioning Strategies

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Abstract

Spatial partitioning is a widely used optimization strategy to efficiently optimize objects in space. It can be found in many applications, from simulating galaxies to video games. Checking collision between objects is an expensive operation that quickly becomes a bottleneck as the number of objects grow. This paper compares three different strategies, alongside a naive solution. The aim is to evaluate the use cases for the different strategies. Each strategy was implemented to fit the same interface to make it as fair of a comparison as possible. The results show how spatial hashing out performs every other method when the objects are distributed evenly while quadtrees excel with uneven object distribution.

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1 Introduction

When I was developing a small physics engine, I encountered performance issues during the collision detection phase. In this phase the program figures out which objects are close enough to be touching and overlapping. This wouldn't be an issue in a small simulation with few objects, but I was striving for something grand running in real time which made every millisecond count. Due to these constraints I had to find a way to speed things up.

On my optimization journey I encountered the concept of spatial partitioning - an elegant solution to my problem. Diving deeper I discovered the three techniques I'll be comparing in this paper, along side the naive solution. The basic theory of the technique is simply to group objects close to each other to avoid checking two objects on the opposite side of the world. This drastically decreases the number of collision checks performed each frame.

As a consequence of this constraint I had to find a way to optimize this phase. That is what sent me down the rabbit hole of spatial partitioning as an optimization to do query objects close to each other in space. During my research I found out about the three strategies I'm comparing in this paper. I'm doing this paper within the programming course.

2 Theory

2.1 Spatial Partitioning

Spatial partitioning is an optimization technique used to make programs run faster. It's often found within physics applications. The theory behind this technique is to reduce the number of times one object is checked against another. Suppose we have one hundred objects in our world. The naive way to check each one of these against the others results in a ten thousand checks. Since checks are expensive to make, we want to perform as few of them as possible.

2.2 Quadtree

A quadtree is a recursive data structure, meaning it contains pointers to each objects of the same type as itself. It's in the family of tree data structures. The data structure is comprised of nodes. Each node has four pointers to other nodes, could also be referred to as branches or leaves. This strategy works by inserting points into a leaf until the leaf reaches its capacity, then it splits into four equally large sub leaves. This subdivision pattern is shown in figure 1.

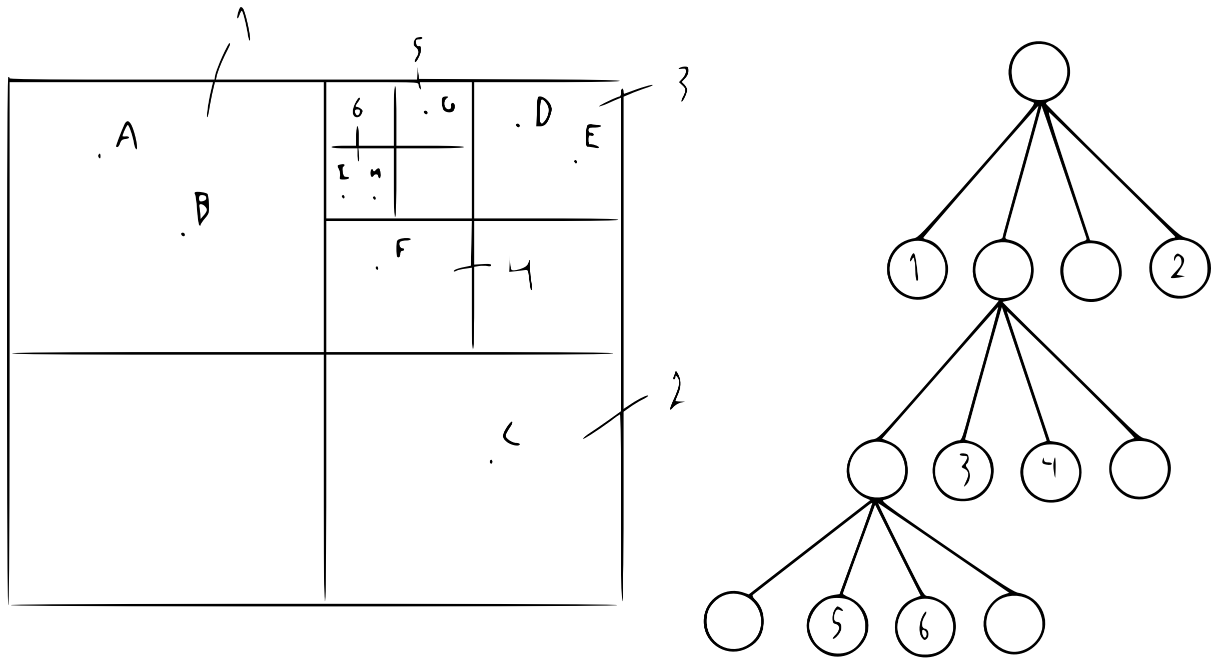


Figure 1: Visual representation of a quadtree.

2.3 The Stack and Heap

A program uses two different types of memory, the stack and the heap. When the program starts a fixed amount of bytes are allocated for the program to use, this is what is called the stack. When the program creates a variable it is allocated on the stack, which is done by incrementing the stack pointer by the size of the variable data type. Since a stack allocation is only a single instruction it is incredibly fast. The heap is much larger than the stack but slower because you have to request space within it from the operating system. Allocating is considered to be a slow operation since there's a lot of overhead introduced.

2.4 Big O notation

Big O notation is a notation system to describe the time complexity of an algorithm. If an algorithm has the time complexity of $O(n)$ then that means its time complexity grows linearly with the amount of inputs n. This could be deceiving due to a hidden constant within the expression. If $O(n)$ would be written as a function to describe the actual execution time of the algorithm then it would look like this $T(n) = C \cdot n$. A $O(n^2)$ algorithm would be considered worse than an $O(n)$ one. This assumption is, however, not always correct. If n is small enough then the $O(n^2)$ algorithm could run faster due to the constant being smaller than its $O(n)$ equivalent.

2.5 Static Grid

The static grid is built using a simple array. Indexing into the array is an $O(1)$ operation. The caveat with this approach is you're forced to know how big the area you want the to partition to be before compiling the program. Both insertion and querying only requires a simple index into the grid array which makes this approach super fast.

2.6 Spatial Hashing Grid

The spatial hashing grid is built using the same technique as a hash map. The method I used to write my spatial hashing grid was to allocate an arbitrarily sized array. When inserting into the structure I first hash the coordinate of the object, then run a modulo operation on it giving me a number within the array bounds, and then it is inserted into the cell.

3 Material and Method

3.1 Linux

Linux is the operating system used to develop the application and write this paper. The program uses a specific Linux API to acquire the current time as a UNIX time stamp. The way to do this would differ on other operating systems.

3.2 Neovim

Neovim was the editor used to edit the code. It is a modal text editor and not a full integrated development environment, or IDE as they are called. A plugin which utilizes the language server protocol was used to provide me with intellisense and to aid in development by warning me about syntax errors.

3.3 Git

Git is a version control system which helps track changes to the project. In this project it is utilized to keep a time line of the development process and make sure changes could be synced between devices. The local git repository is mirrored on GitHub making it accessible from other devices, and the source code can be read from the browser.

3.4 CMake

CMake is a buildsystem, used to generate generate the final executable from the source code. It aids in compiling and linking the program making cross compilation and dependency management trivial.

3.5 C

C was the program of choice for this project due to its low level control. Since memory is managed manually in C I could be sure the results would not be skewed by a garbage collector running in the middle of a benchmark.

3.6 SDL2

SDL2 - Simple DirectMedia Layer - is a cross-platform library supplying an easy API to create a window and render to it. This was crucial when developing since visualizing the data structures made it easier to spot errors than simply looking at the code. It also gives a nice visual representation of the program.

3.7 Python

Python is an interpreted programming language which was used for making a script to generate graphs. All the graphs used in this paper was generated from data collected from a C program, which dumped said data into a JSON file, which was then read by a Python script using the matplotlib library to generate nice looking graphs.

4 Results

This section presents the results of the benchmarking done on the three strategies - quadtrees, spatial hashing and static grids. The metrics measured was average runtime: the sum of all operations needed to run the program. Insertions: how long it took to insert all the objects into the data structure. Collision testing: total time spent checking objects against each other, which includes querying. Querying: average time spent retrieving objects from the data structure. Clearing: how long it takes to reset the data structure making it ready for rebuilding. Each metric was measured with a range of object count, labeled as 'box count' in the graphs, from ten to 2500 with an increase of ten objects between each measurement. At each stage was run 32 times and the results were averaged to give smoother graphs. Two benchmarks was run, one with an even distribution of objects and one with an uneven distribution.

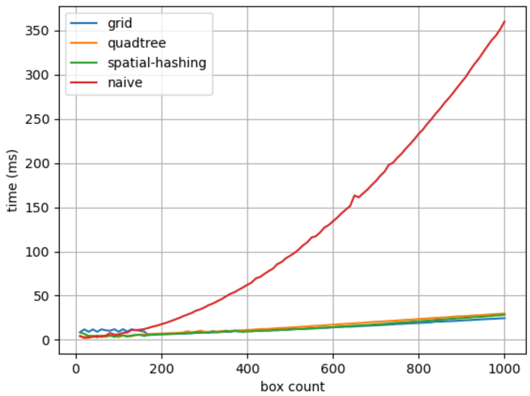


Figure 2: Runtime of naive solution and partitioning strategies.

Figure 2 shows a drastic difference in runtime between the naive solution and the optimization strategies. It is hard to evaluate which strategy performs best due to the stark difference between the naive and the optimized versions. Due to this discrepancy the naive solution will not be included in the other graphs presented. This comparison was only run with 1000 objects due to the time taken per execution.

4.1 Average Runtime

4.1.1 Evenly Distributed Objects

Figure 3 shows the average runtime for the program using the different strategies with an even object distribution. This includes all other measuring metrics. The X axis describes the amount of objects being processed. The Y axis describes how much time was spent in milliseconds executing the particular step in the program.

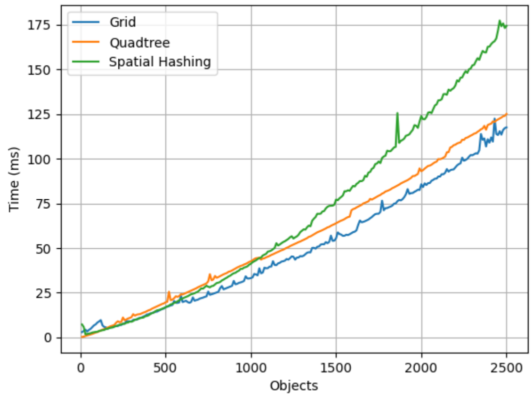


Figure 3: Average runtime of spatial partitioning strategies with evenly distributed objects.

4.1.2 Unevenly Distributed Objects

Figure 4 presents the average runtime for the program using the different strategies with an uneven object distribution. This includes all other measuring metrics. As the object count increases the spatial hashing trends towards a $O(n^2)$ runtime complexity.

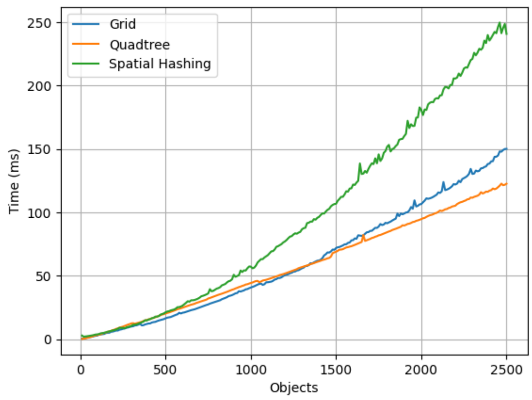


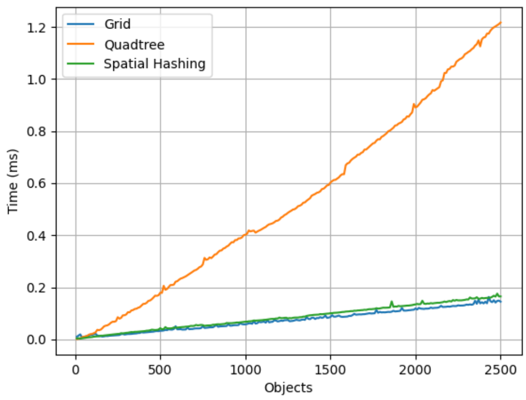
Figure 4: Average runtime of spatial partitioning strategies with unevenly distributed objects.

4.2 Insertion

4.2.1 Evenly Distributed Objects

The runtime complexity of the insertion algorithms for evenly distributed objects is shown in figure 5.

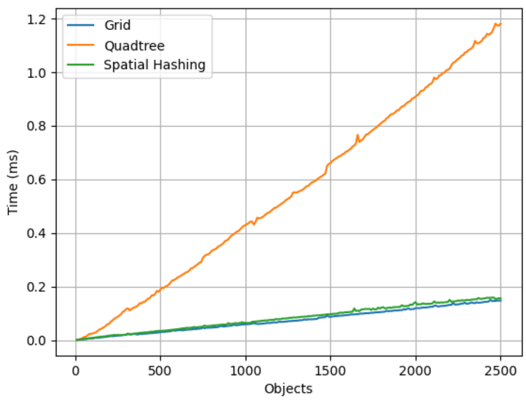
Figure 5: Average insertion time per object with evenly distributed objects.



4.2.2 Unevenly Distributed Objects

The runtime complexity of the insertion algorithms for evenly distributed objects is shown in figure 6.

Figure 6: Average insertion time per object with unevenly distributed objects.

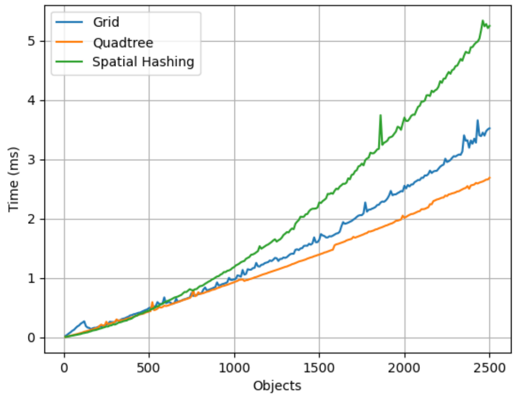


4.3 Collision

4.3.1 Evenly Distributed Objects

Figure 7 shows the total time spent checking for colliding objects per iteration with an even distribution. This time also includes the time taken for querying.

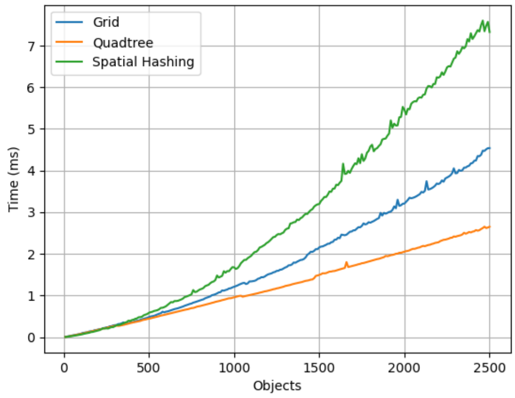
Figure 7: Average collision time for all objects with evenly distributed objects.



4.3.2 Unevenly Distributed Objects

Figure 8 shows the total time spent checking for colliding objects per iteration with an uneven distribution. This time also includes the time taken for querying.

Figure 8: Average collision time for all objects with unevenly distributed objects.

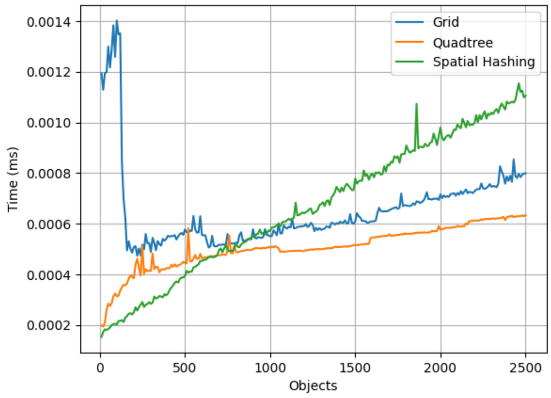


4.4 Querying

4.4.1 Evenly Distributed Objects

Figure 9 represents the average time taken to query the space per object with an even distribution.

Figure 9: Average query time per object with evenly distributed objects.



4.4.2 Unevenly Distributed Objects

Figure 10 represents the average time taken to query the space per object with an uneven distribution.

Figure 10: Average query time per object with unevenly distributed objects.