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| Edinburgh Napier University |
| SET10108– Concurrent and Parallel Systems (Coursework 2) |
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# Introduction

The purpose of this coursework is to solve the N-Queens problem – the problem of placing chess queens on an N x N chessboard in such a way that no two queens are a threat to another. This means that no queen can share a row, column or a diagonal space. Given the implementation provided, the task is to modify the existing serial program so that it is non-recursive and then to implement the non-recursive solution in parallel. It is important to ensure that the recursive elements are removed, as parallelisation through OpenMP and using the GPU does not play will with recursive code.

The parallelisation should be done twice; once in OpenMP and then again using the GPU using CUDA or OpenCL, and should run for N values between 4 and 10 – with the option to increase the threshold should the Laptop have the ability to handle it.

## Hardware Specs

The machine used for the creation of this program as well as running the experiments are an ASUS TUF F15 with the following specs:

* CPU – 11th Gen Intel(R) Core(TM) I5 11400H @ 2.70GHz (6 cores, 12 logical processors)
* RAM – 16GB DDR4 3200mhz
* GPU – NVIDIA GeForce RTX 3050 Ti Laptop GPU (4GB)
* OS – Windows 11 Home (Build 22000.1098)

# Serial

## Implementation

The initial serial program provided for the coursework completes the task using recursion. The code for this can be seen below:

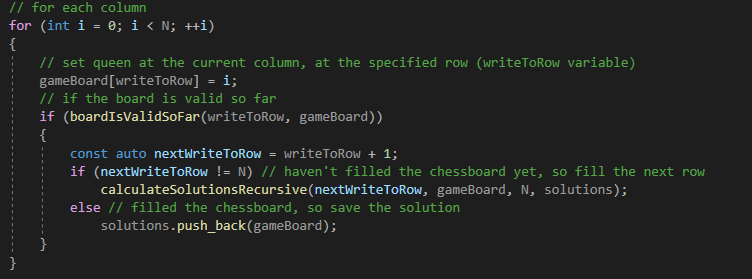


Figure 2‑1: Serial Implementation

Essentially, if the chess board is deemed valid, the function calculateSolutionsRecursive() will call upon itself continually in an attempt so solve the rest of the problem and send the solutions back to the solutions vector.

This solution is fine when done serially, however, when implemented in parallel, this won’t be the case. The reason for this is basically in the name, as recursion often relies on the results of previous recursive calls and typically means that the order of the recursive calls are important to the operation of the algorithm. For this reason, the future two sections on OpenMP and CUDA will run a different algorithm that aims to reduce or remove recursion completely.

## Serial Performance Results

This section will showcase and discuss the results specific to the running of the original recursive code provided. These results will be used as a comparison in the future sections when discussing the parallelisation of the N-Queens problem.

The performance of the serial program was measured by running it 10 times and recording how long each N-Queens problem took to solve. The table below shows these recorded times and their averages. The execution was so quick that the std::chrono couldn’t register a time at all for N = 4 through to N = 8, with a slight outlier in run 3 for N = 8. The only time properly registered was when calculating the solutions for N = 9 and N = 10. Even at that, the times were miniscule.

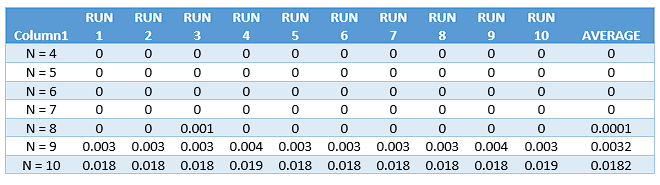


Figure 2‑2: Serial N-Queens Performance Table

The averages of these runs were then taken and the trend seems to show that the times get worse as the complexity of the problem increases, which is to be expected given the calculations that are occurring – a trend that will likely be replicated in the analysis of both parallel implementations too.

Figure 2‑3: Serial N-Queens Average Times

# Parallel – OpenMP

## Removing Recursion

As was touched upon in the Serial section – the first hurdle to overcome was changing the N-Queens solution from a recursive solution to a non-recursive solution. This was initially attempted using a backtracking algorithm. Essentially, backtracking works by trying to incrementally build the solution piece-by-piece and then going back on itself and undoing previous steps if the algorithm decides that it cannot go any further (Datta, 2022). The implementation of this can be seen in the figure below, inspiration of how to implement this was taken from Oxford College of Emory (Oxford College, n.d.)

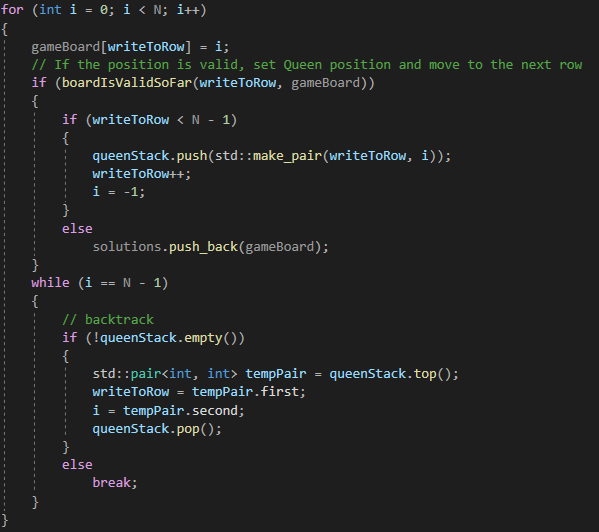
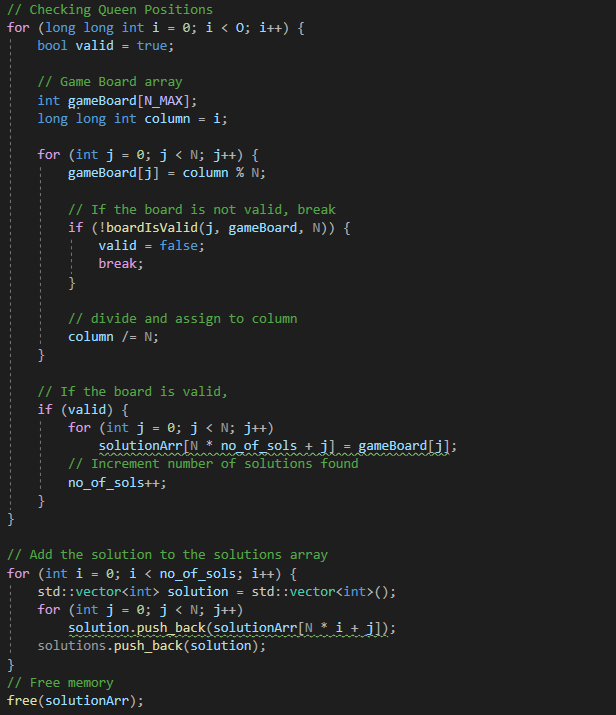


Figure 3‑1: Initial Non-Recursive Attempt

This code, however, proved to be difficult to implement in a way that would be parallelisable as it typically relies on recursion to be effective. Therefore, the decision was made to look into another iterative approach; the brute-force approach. It would be simple, and therefore likely to be rather slow, however it would be easier to parallelise using OpenMP and CUDA.

An acceptable approach to N-Queens with brute force was pieced together using techniques and examples found across the internet – these sources can be found in the references section of this paper and will be referenced in the following figure.

This brute force implementation will check the possible positioning of the all queens on the board and determine whether or not the positioning is valid. If the board is invalid, then the valid Boolean will be set to false. If the board remains valid, then the solution can be added to the solution array and the number of solutions can be incremented. A new solution vector is then created and populated with the solutions in the solution array and pushed back into the solution vector before the memory is freed up.



Initially, the game board was a vector – this came with some slowdown and as such was changed to an array. From working with OpenMP in the past, it was known that the array would likely work better across multiple threads than the vector would have anyway, so this change was made in preparation for the parallelisation.

The resources used to arrive at this solution are listed below:

* Simran (Simran, 2021)
* Stack Exchange (Stack Exchange, 2019)
* Geeks For Geeks (Geeks for Geeks, 2022)

Figure 3‑2: Final Brute Force Implementation

To accommodate the changes in the solution calculations, some changes had to be made in the boardIsValid method, however, these changes were easy to implement in comparison to researching and implementing the brute force method, especially as the brute force method was designed with the boardIsValids already functioning method in mind.

With this now in place, it came time to parallelise the new brute force solution using OpenMP.

## Method of Parallelisation

### 3.2.2. Parallel For (CalculateSolutions)

Parallisation in OpenMP was fairly straightforward given the way the brute force solution was implemented. Initially, the CalculateSolutions() method was parallelised. This was done by adding the OMP parallel for call before the main for loop, this is shown in the figure below:

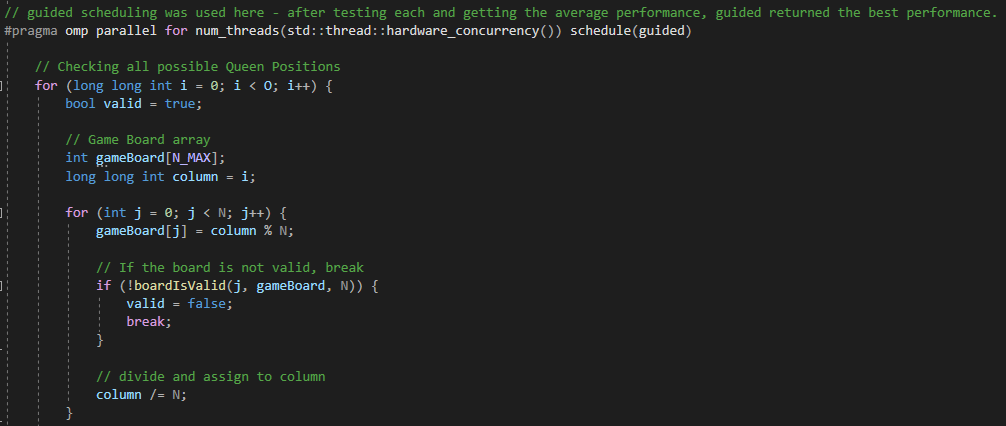


Figure 3‑3: Parallel For (calculateSolution)

The key thing to notice here is the use of the guided scheduling – after looking through recommendations of which scheduling types were best for certain scenarios (Jaka's Corner, 2016). It was determined that the OMPs Default, Guided and Static scheduling could work but it was unsure which would perform the best due to lack of experience. Therefore, the decision was made to test each of the three scheduling types to determine which once would perform the best. The findings of this will be discussed in the following section.

### 3.2.2. Scheduling Analysis

As stated before, were three scheduling types chosen to take forward for testing. There was initially a fourth which was Dynamic Scheduling. This was implemented but resulted in a slowdown rather than a speedup and was therefore axed because of this. The other three, Default, Guided and Static all performed similarly to expectations, with some providing speedup.

It is important to note that the results presented here are more limited in scope than the results presented in previous analysis. For the purpose of this test, the only numbers of interest were the performance times for the calculation of N = 9 and N = 10. This is because much like was shown in the serial program analysis, these were the only two that started to put serious load on the program whereas N = 4 through to 8 typically perform almost identically with a slight execution time increase expected each time. From N = 9 onwards, it becomes clear that the execution time is going to increase exponentially. This is shown in the figure below:

Figure 3‑4: Scheduling Performance (N=9)

Figure 3-4 shows the difference in performance between the three scheduling types when the program is asked to calculate the solutions for a 9x9 problem. The averages here show that the times are all within 0.10 of a second of eachother – so not a massive difference. Despite this, it tells us that the quickest scheduling type for this particular problem is a static scheduling type as it seems to perform better overall than guided or default. At this point, it was looking like static scheduling was going to be the best choice going forward due to the slight performance increase that it provided over the other two scheduling types.

This notion changed, however, once the results for the N = 10 runs came in, which was the highest run that the system was capable of doing due to performance issues beyond that point. The results for the N = 10 can be seen in the figure provided on the following page.

Figure 3‑5: Scheduling Performance (N=10)

Figure 3-5 shows the performance difference between the scheduling types, similar to the previous figure, but for a 10x10 problem. Instead of being split by around 0.10 of a second, the scheduling types have seconds worth of performance difference. In a turnaround from the results of Figure 3-4, Figure 3-5 indicates that guided is the quickest of the three scheduling types. When taking into consideration the difference in time saved shown in both figures, it was decided to discard the default scheduling and decided between static and guided.

Guided provided a larger boost when faced with the 9x9 problem whereas guided performed better over the 10x10 problem. It can be assumed from this that guided may perform better as the scale of the problem increases.

The key thing to note too, is the difference in time being saved. While they both provide a bonus to the speed of the program execution during different scenarios, no matter how you look at it, guided scheduling provided the solution with a larger time benefit than that of static scheduling. While static provides milliseconds worth, guided provides full seconds worth of a performance bonus – and in a system such as this where the waiting times for calculation seem to get exponentially worse with the size of the calculation, it seemed that guided would be the best scheduling choice to stick with for the final program.

### 3.2.2. Parallel For (boardIsValid)

An attempt was also made to parallelise the boardIsValid method. The implementation was once again the simple use of a parallel for – however, on this occasion, it seemed to come at a large performance cost to the system. The implementation is shown below:

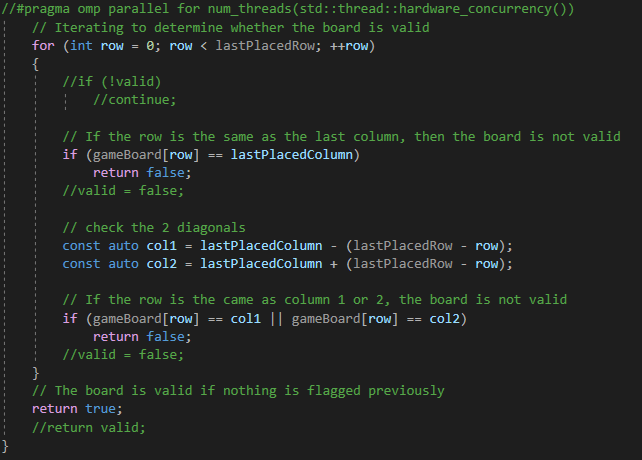


Figure 3‑6: Parallel For (boardIsValid)

Initially, the performance was in-line with what is expected from previous testing; relatively fast computation for the first 8 N values, followed by a more dramatic increase in execution time for N= 9 and 10. However, in the case of using a parallel for alongside the boardIsValid() method, the system began to struggle much more on N=8 and made testing N=9 and 10 unfeasible due to the length of time taken calculate the solutions for the final 2 N values. A comparison of N = 4 to 8 with the parallel for enabled vs disabled can be seen below and shows the difference in performance for those, given that N = 9 and 10 were impossible to test.

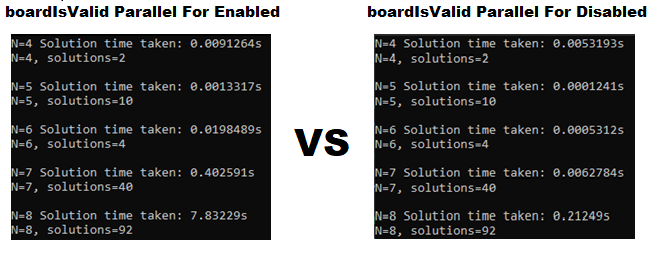


Figure 3‑7: Parallel For (boardIsValid) Enabled vs Disabled

When put into a line graph for visual comparison, the difference in performance in the complexities that could be handled become very clear:

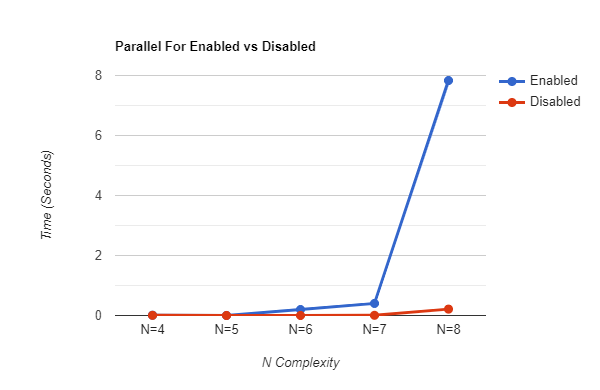


Figure 3‑8: Parallel For (boardIsValid) Comparison Graph

Evidentally, the times weren’t too far apart from eachother up to N = 7, however, when the Parallel For is enabled, the system suddenly struggles a lot more with N = 8 than it does with the Parallel For disabled. For that reason, it was decided to comment out the parallel for in the boardIsValid method and to remain with the single parallel for in the calculateSolutions method.

## OpenMP Performance Results

This section will discuss the results of the overall OpenMP performance tests. Below is a table of the results from the 10 test runs:

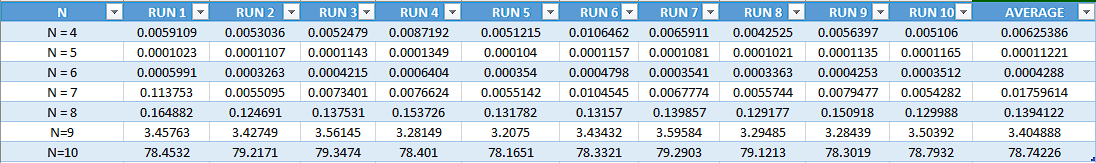


Figure 3‑9: OpenMP performance Table

Similar to the results of the Serial performance, it can be seen that the performance of the program gets worse as the complexity of the board increases – again, there is a large spike in performance loss when calculating anything above N = 9, which can be seen in the figure presented below:

Figure 3‑10: OpenMP Performance

Figure 3-10 clearly illustrates the spike mentioned previously and show how prominent the loss of performance is.

The reason for such a large time difference in this parallel solution is likely down to the nature of the N-Queens problem itself. It’s a problem that is notoriously difficult to parallelise – even when the solution is non-recursive, the problem is inherently sequential in nature. Each queen needs to be considered one at a time, and each queen must have the validity of its moves checked. This can be very intense on the CPU. When parallelised, this means that there is still a large amount of communication happening between the processes that are ensuring that no two queens can attack eachother, which when happening in parallel, is very taxing on the system.

## OpenMP vs Serial

Ideally, it would be useful to place both of the datasets of the Serial and OpenMP implementations into the same line graph and compare the times – however, the difference in times for the N = 9 and 10 is so large that it basically renders the visual elements of the Serial program uselss. As such, it is important to refer back to the two averaged individual datasets. When looking back to Figure 2:3, the upwards trajectory and the spike in time taken between N = 9 and 10 is visually apparent – this takes place over a matter of milliseconds. Comparing this to Figure 3:10, however, and we can see that while the time difference is much bigger, the trajectory is much the same. The time taken to calculate the solutions to the problems get longer when the complexity of the problem increases – starting off with a gentle increase in the time taken to calculate a solution from N = 4 to 8, but resulting in a massive spike from N = 9 to 10 as the complexity begins to rapidly increase.

The actual times, while they do not translate well over to a graph, can be seen in the table below. The tables shows a steady increase followed by a rapid upwards trend when the problem begins to reach N = 8. Again, these trends can be seen in Figures 2:3 and 3:10 for a visual representation of the steep climb.

|  |  |  |
| --- | --- | --- |
| **N** | **OpenMP** | **Serial** |
| N = 4 | 0.00625386 | 0 |
| N = 5 | 0.00011221 | 0 |
| N = 6 | 0.0004288 | 0 |
| N = 7 | 0.01759614 | 0 |
| N = 8 | 0.1394122 | 0.0001 |
| N=9 | 3.404888 | 0.0032 |
| N=10 | 78.74226 | 0.0182 |

Figure 3‑11: Performance table for Serial and OpenMP

With this in mind, it seems reasonable to assume that if the program were able to keep going with reasonable performance past N = 10, we would see a case of exponential growth in a similar upwards trend from this point on. As is has been determined that the N-Queens problem, both in serial and parallel (OpenMP) both suffer from exponential performance loss, it seems reasonable to assume that the following section on parallelising the problem in CUDA will report a similar trend. Even if the CUDA program runs faster than the Serial and OpenMP ones – expect to see the same upwards trend starting at around N = 8.

# Parallel – GPU (CUDA)

## Method of Parallelisation

## CUDA Performance Results

## CUDA vs Serial

# Parallel Performance Comparison

# Conclusions

# References

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