**Assignment 2(OpenMP Tasking) Documentation**

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Technology used:

C++, OpenMP

How to run program:

1. Compile .cpp files:

* g++ a2-sequential.cpp -o a2-sequential.exe (sequential code)
* g++ -fopenmp a2-openmp.cpp -o a2-openmp.exe (for OpenMP)

1. Run program:

* ./a2-sequential.exe
* ./a2-openmp.exe

Code Structure:

The program consists of three different C++ files: a2-helpers.hpp, a2-sequential.cpp and a2-openmp.cpp.

* a2-helpers.hpp – This is header file which contains the defined data structures of the program. It has Image data structure, gradient data structure, and some functions called interpolate\_rgb\_color, colorize and get\_2d\_kernel etc. Here, interpolate\_rgb\_color sets the image color where we need. colorize() function takes care of gradient color of the picture. And get\_2d\_kernel() function gives the kernel which one is used for image filtering.
* a2-sequential.cpp – With the help of this c plus plus file we generate our Mandelbrot set sequentially and, we print image of it and filtered it. First, a set of random gradient values adjusted for our Mandelbrot algorithm. Here we have Mandelbrot\_kernel() function which check if the given point is a member of the Mandelbrot set or not, using z = z \* z + c this formula. If the point was a member of Mandelbrot set, then we colored that point with black color otherwise used different gradient color to separate the point. In our case, we just used maximum 2048 iterations.

Another function mendelbrot() is takes as parameter an image and ratio then it takes image’s height, width, and channels then for every pixel of image it calls Mandelbrot\_kernel() function. Then Mandelbrot\_kernel() function do his job as discussed before. At the same time it do it’s job for 3 channels (r, g, b) which is last part of the nested loop.

There is another function in this file called convolution\_2d. This function is used for applying Gaussian filter into this Mandelbrot image. Note that here all works had been done in a single processor. That’s why this approach is slower.

* a2-openmp.cpp – This c plus plus file contains parallel code of Mandelbrot and Convolution part. Here inside mandelbrot() function the parallelization had been done. First, a global variable called ‘num\_of\_thread\_used’ is declared with default value 1. Then the number of threads to use for parallel execution has been set using omp\_set\_num\_threads(num\_of\_thread\_used) where num\_of\_thread\_used = 1, 2, 4, 8, 16. The performance of using different threads are given below in the Table-2. There are many versions of parallel code has been tested on ALMA but not all of then performed well. Here among them only two versions are described here. Note that, every version of the code has tested multiple times in ALMA and every time it was giving almost same results.

Mandelbrot part: Inside Mandelbrot () function there are two nested for loops. One of them has maximum iteration image height and another one has image width. This part of the code can be ideal choice for parallelization. We choose this part of code to parallel in openMP. The two different versions of Mandelbrot part parallelization described below:

* Version 1 (omp task): Our first test version was ‘omp task’ version. We tried to parallelize the code using only ‘omp task’. There is a sample structure of this version of code:

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

omp\_set\_num\_threads(num\_of\_thread\_used);

#pragma omp parallel default(none)private(i,j,pixel,c) shared(h, w, channels, ratio, image, pixels\_inside)

#pragma omp single

for (j = 0; j < h; j++)

#pragma omp task

for (i = 0; i < w; i++)

…….

#pragma omp critical

pixels\_inside++;

………

………

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

First, we set the number of threads to use for parallel execution. Then by using ‘#pagma omp parallel’ fork additional threads to carry out the work enclosed in the construct in parallel. The original thread will be denoted as master thread with thread ID 0. When the ‘#pagma omp parallel’ was used, there were also some addition clauses used. First, the default variable data scope was desabled by using default(none) clause. Then manually with the help of private() and shared() clause the variable’s data scope were defined.

‘#pragma omp single’ is single construct. With the help of single construct one thread generates only the tasks and all other threads execute the tasks as they become available. Those all generated tasks runs parallelly that’s why if we don’t use any synchronization method it will fall in data race condition. So, for synchronization we used ‘#pragma omp critical’. The critical section makes sure that which lines of code under critical section it will execute in one single thread. Critical section saved code from data racing condition, but it is also expensive sometimes. So, we have to be very careful to use critical section if we want maximum performance of our code. In out case we use critical section for just counting pixels\_inside which is a small operation that’s why the performance really doesn’t affect so much.

* Version 2 (omp parallel for): Our second and final version is ‘omp parallel for’ version. Here we tried to parallelize the code using only ‘omp parallel for’. There is a sample structure of this version of code:

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

omp\_set\_num\_threads(num\_of\_thread\_used);

#pragma omp parallel for schedule(dynamic) default(none) private(i, j, pixel, c) shared(h, w, channels, ratio, image) reduction (+:pixels\_inside) collapse(2)

for (j = 0; j < h; j++)

for (i = 0; i < w; i++)

……

pixels\_inside++;

………

………

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Here the two nested loop has been parallelized with ‘#pragma omp parallel for’. OpenMP ‘parallel for’ is work-sharing constructs that take an amount of work and distribute it over the available threads in a parallel region, created with the parallel pragma. Here one thing to note that is ‘#pragma omp parallel for’ didn’t create team of threads, it takes the team of threads that is active and divide the loop iterations over them. This means that the omp for directive needs to be inside a parallel region. In our case also the same things happened. ‘#pragma omp parallel for’ divide the for loop depends on how much threads were using (1, 2, 4, 8, 16).

After splitting the loop iteration, the work was start executing in parallel and then the split works also had been joined after all thread finished their job. Parallel for takes care of splitting total loop iterations and joining them, this the one advantage of using parallel loop for programmer.

When the ‘omp parallel for’ was used, there were also some addition clauses used. First, the default variable data scope was disabled by using default(none) clause. Then manually with the help of private() and shared() clause the variable’s data scope were defined. Those variables what needs to be updated during every iteration these were defined as private and those variables which don’t need to be updated but used inside the loop for other reason are defined as shared. For private variables the different threads make their own copy of private variables for use and at last all threads add them up.

Another important clause is we used here is reduction(). This clause was used here because when we were building mandelbrot set here we were also counting the number of pixels inside the loop. This is one kind of summation operation. The reduction() clause works really good for this kind of operation. This clause also saves the code from the data race condition.

In general, the more work split over several threads, the more efficient the parallelization will be. In the context of parallel loops, it is possible to increase the amount of work by parallelizing all levels of loops instead of just the outer one. As it was told that the 2 nested loop were parallelized here, that’s why the collapse(2) clause was used. In this case all N\*N iterations are independent but generally ‘omp parallel for’ directive will only parallelize one level so with the help of collapse(2) the 2-level parallelization had been done which is more efficient and faster. When parallelization has started different thread start work independently and these works are not always same. Some works are bigger, and some are smaller. Sometimes some threads take long time, and some threads takes less time. That’s why for final output the main worker must wait for other threads result which are not finished their work. This is time consuming which affect the parallel program performance. OpenMP has a solution for this kind of situation. There is a clause called schedule() which can take two types of parameters, one is static and another one is dynamic. OpenMP in default used static schedule. Static schedule is that kind of schedule that main worker must wait until all works ends. On the other hand, dynamic schedule is something else. It dynamically shares work. If one threads completed all his work, then that thread takes more wok from other busy threads. This way the work sharing has been done efficiently and program performs better.

Convolution part: This part looks more complicated, but it is not. There are more than 5 nested loops inside the convolution\_2d() function. But interesting thing is we don’t need to parallelize all these loops. We are interested to parallelize the large, seized loops. Here we would like to parallelize the image height loop and image width loop which are inside nsteps and channels loop. The two different versions of Convolution part parallelization described below:

* Version 1 (omp task): Our first test version was ‘omp task’ version. We tried to parallelize the code using only ‘omp task’. There is a sample structure of this version of code for convolution part:

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

for (int step = 0; step < nsteps; step++)

for (int ch = 0; ch < channels; ch++)

omp\_set\_num\_threads(num\_of\_thread\_used);

#pragma omp parallel default(none) shared(h, w, kernel, displ, ch, src, dst)

#pragma omp single

for (int i = 0; i < h; i++)

#pragma omp task

for (int j = 0; j < w; j++)

…….

………

………

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Tasking process is similar as described in the Mandelbrot part. First using default(none) clause default data scope sharing were disabled then with help of shared() clause the data scope of variables were defined. Here we didn’t need any private clause because those variables which need to be update inside loop are already private because they were declared inside pragma command. ‘#pragma omp single’ creates all the task using single threads and other threads are executing these created tasks. Parallelized loops were run independently so we didn’t need any synchronization section.

* Version 2 (omp parallel for): Our second and final version is ‘omp parallel for’ version. Here we tried to parallelize the code using only ‘omp parallel for’. There is a sample structure of this version of code of convolution part:

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

for (int step = 0; step < nsteps; step++)

for (int ch = 0; ch < channels; ch++)

omp\_set\_num\_threads(num\_of\_thread\_used);

#pragma omp parallel for default(none) shared(h, w, kernel, displ, ch, src, dst) collapse(2)

for (int i = 0; i < h; i++)

for (int j = 0; j < w; j++)

…….

………

………

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Here also like before at first the number of threads were set for parallelizing using runtime function called omp\_set\_num\_threads(num\_of\_thread\_used) where num\_of\_thread\_used = 1, 2, 4, 8, 16.

By using ‘#pragma omp parallel for’ here the image height and image width loop were parallelized. The default (none) clause was use because we want all the data scope access the closest memory location. This will increase performance of the code. After defining default(none) clause, the shared () clause was used for data scoping. As we can see form the code the loop variables and other variable which need to be updated in every iteration are all declared inside the loops. That’s why these variables are already in private data scope. So, we don’t need to define them again. So, we just need to define these variables which were pre declared outside the loop and used inside the loops as shared(). For convolution part h, w, kernel, displ, ch, src, dst etc. variables were defined as shared.

In this part we also interested to parallelize 2 loops that’s why the collapse() clause was used with parameter 2 like this collapse(2). Collapse clause parallelized height and width loop nicely. The performance is also good (see Table:2).

Tables:

Table-1 Sequential:

|  |  |  |  |
| --- | --- | --- | --- |
| Mandelbrot time (s) | Convolution time (s) | Total time (s) | Total Mandelbrot pixels |
| 20.9354 | 51.0527 | 71.9881 | 1478025 |

Table-2 Parallel OpenMP (omp parallel for):

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Threads | Mandelbrot time (s) | MT. Speedup | Convolution time (s) | CT. Speedup | Total time (s) | Total Mandelbrot pixels |
| 1 | 20.8479 | 1.0042 | 52.612 | 0.970363 | 73.4599 | 1478025 |
| 2 | 10.651 | 1.96558 | 26.5727 | 1.92125 | 37.2237 | 1478025 |
| 4 | 5.39954 | 3.87726 | 13.6441 | 3.74175 | 19.0436 | 1478025 |
| 8 | 2.97233 | 7.04344 | 7.70936 | 6.62217 | 10.6817 | 1478025 |
| 16 | 1.63255 | 12.8237 | 4.22842 | 12.0737 | 5.86097 | 1478025 |

Table-3 Parallel OpenMP (omp task):

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Threads | Mandelbrot time (s) | MT. Speedup | Convolution time (s) | CT. Speedup | Total time (s) | Total Mandelbrot pixels |
| 1 | 20.5927 | 1.01664 | 52.7829 | 0.967221 | 73.3756 | 1478025 |
| 2 | 10.4583 | 2.0018 | 26.6797 | 1.91354 | 37.138 | 1478025 |
| 4 | 5.38178 | 3.89005 | 13.6494 | 3.7403 | 19.0311 | 1478025 |
| 8 | 2.97795 | 7.03015 | 7.75953 | 6.57935 | 10.7375 | 1478025 |
| 16 | 1.79432 | 11.6676 | 4.24192 | 12.0353 | 6.03624 | 1478025 |

Speedup Graph and Description:

Fig-1: Mandelbrot speed up curve.

Fig-2: Convolution speed up curve.

Graph Description:

Two different version were tried to parallelize the code. First version was only using ‘omp task’ and another version is ‘omp parallel for’. Both version of code compiled and run in the ALMA multiple times and the result were almost same. The result data of Mandelbrot part shown in Fig-1 and convolution part shown in Fig-2. Both figures show the comparison between ‘omp parallel for’ version and the ‘omp task’ version of the code. In these both speed up curve figures, x-axis contains thread numbers and y-axis contains speedup values.

If we see Fig-1, for Mandelbrot part there are two speed up curve. One curve is ‘omp parallel for’, and another curve is ‘omp task’. From these curves is clearly seen that ‘omp parallel for’ version and ‘omp task’ version was performed almost same but for 16 threads the ‘omp parallel for’ version performed slightly better than ‘omp task’ version. For parallelizing different threads were used, they are 1, 2, 4, 8 and 16. When the threads number are increasing for parallel for versions of code, the speedup value is also increasing, which means the parallelization is working.

Similarly, For Convolution part in Fig-2 we also can see that when the threads number are increasing the speedup value of ‘omp parallel for’ version also increasing. In this part both versions of code perform almost same. There was small difference which is not visible in the curve.

Discussions:

* Performance differences between omp task and parallel for loop versions: There is almost no performance difference between these two versions. ‘omp Parallel for’ version divide the total loop iteration (depends on how much processor using for parallelization), then these division of iterations execute parallelly. This way code executes faster than sequential code which means it boost performance. Similarly, when we tried ‘omp task’ version it created multiple tasks in single threads and other threads parallelly execute these tasks. During tasking we must take care of synchronization, if gives data racing condition fee code. Here we used a critical section for synchronization. Both versions performance is almost similar but in Mandelbrot part we saw that only for 16 threads the ‘omp parallel for’ version performs slightly better. In both version for 16 threads, we got almost around 12x performance.
* Task granularity (small vs big tasks): We also tested some other version of small tasking inside the nested loops. From working experience, it has seen that yes task granularity matters. When tasks are small then the parallel execution can’t perform well because these small tasks divided into threads, but these tasks are too small and also there are a large number of tasks generated and all these tasks couldn’t finish in the same time. Then one thread has to wait for other. After all small tasing takes more time. But if we divide large work then it gives better result. For example, we parallelize for loop using ‘#pragma omp parallel for’. This omp line divide the loop into some small divisions which depends on thread number, like if we have total iteration 1024 and we use 2 threads for parallelization then chunks size will be 1024/2 = 512 iterations. The more thread we use then division size will be smaller and will start executing at the same time parallelly. The schedule clause done this job more efficiently. It helps the threads to properly use time.
* Distributed the work:

Thread 3

Thread 2

Thread 1

Thread 0

Result

Fig-3: Distribution of work in parallel for

Here we discuss about work distribution for ‘parallel for’ version. In Fig-3 there is an example of work distribution for ‘parallel for loop’ using 4 threads. The work division depends on how many threads used for parallelization. If 2 threads were used, then loop would be divided by two parts. Similarly, if 16 threads were used then loop would be divided into 16 parts. For example, suppose we want to parallelize Mandelbrot part which has multiple for loops. The outer loop has total iteration is 1536, using 4 threads. So first, we just set thread number for parallel execution. This line ‘omp\_set\_num\_threads(4)’ ensure that out code will use 4 threads. Then ‘#pragma omp parallel for’ will divide the whole loop into 4 parts. Each part of the work will take 1536/4 iterations. And then it will start executing parallelly. After execution had finished the pragma will auto gathered the parallelly executed result and will give a final output.

Fig-4: task generation in omp task

* Differences in speedup: The speedup has been measured for both version ‘parallel for’ and ‘omp task’ version. For ‘parallel for’ version using 1 thread almost give same speedup as sequential code but for 2,4,8,16 threads the scenario is different. After using one thread when the thread number is increasing the speedup also increasing. The best speedup so far, we got is ~12.85 for 16 threads in ‘parallel for’ version. When using many threads, the work divided into these threads and execute code faster which means that the more threads we use for parallel execution the more speedup we will get. But on the other hand, the speedup for ‘omp task’ version was poor, sometimes it worse than sequential version. To avoid data racing condition, we had to use critical section, but that section drops the performance of the code.
* Differences in speedup I observed with different clauses: Yes, I observed different speed up in one case with different clauses. When I try to parallelize Mandelbrot part of the code using ‘#pragma omp parallel for’ I saw some differences in speedup when using different clauses. In first try I just used ‘#pragma omp parallel for’ here by default the schedule was static in that time I got some speed up but not much, like for 16 threads I got only 5x speedup. But after adding dynamic scheduling using ‘#pragma omp parallel for schedule(dynamic)’, I got more speed up. It was around 12.8x which is great.
* Interesting findings: There are some interesting things I found during parallelization. In first try when I used omp task inside #pragma omp parallel the code was superfast but that time I realize that the output of total pixel count is incorrect. After that I try to find the reason behind it. After many research I found some issues. Here, at first time I didn’t use any critical section protection. That’s why when the threads running, they may wish to use shared variables and data race condition happened. To resolve race condition, I used a critical section inside the nested loop. After adding critical section, the code was giving correct output as I expected but unfortunately, the performance was too poor, even worse than sequential code.

After that I was trying to find another good solution. Then I tried parallel for loop version like this #pragma omp parallel for, this time also the execution speed most likely as exception but the same problem arises. The pixel counts still giving wrong result. Then with ‘parallel for’ I used reduction () clause which helps me a lot to getting correct output. Now code is faster but not too fast. After some research I found that schedule() clause. Normally omp used static schedule which can’t use time efficiently because when the parallel work is running some threads completed their works early and some threads still working that time. These ways the time-consuming increase in the code. But fortunately, omp has dynamic schedule. By using dynamic schedule this problem can be resolved. When dynamic schedule was used the threads who finished his works, take extra work from other threads, and execute code faster. By using schedule() clause I got better performance.