LAB 3

Introduction

In this laboratory we are going to discuss about the implementation of "divide and conquer" strategy using OpenMP parallelization. Fist of all, we will take a look to dependence graph and the potential performance of the algorithm with different number of cores.

At second chapter, we will discuss about implementation and the performance of leaf, tree and cut-off. Using paraver and plots of elapsed time and speed up.

At last, we are going to modify the implementation of tree method in order to get a task dependence based parallelization strategy. Then we are going to compare the performance.

Task decomposition analysis for Mergesort

Divide and conquer

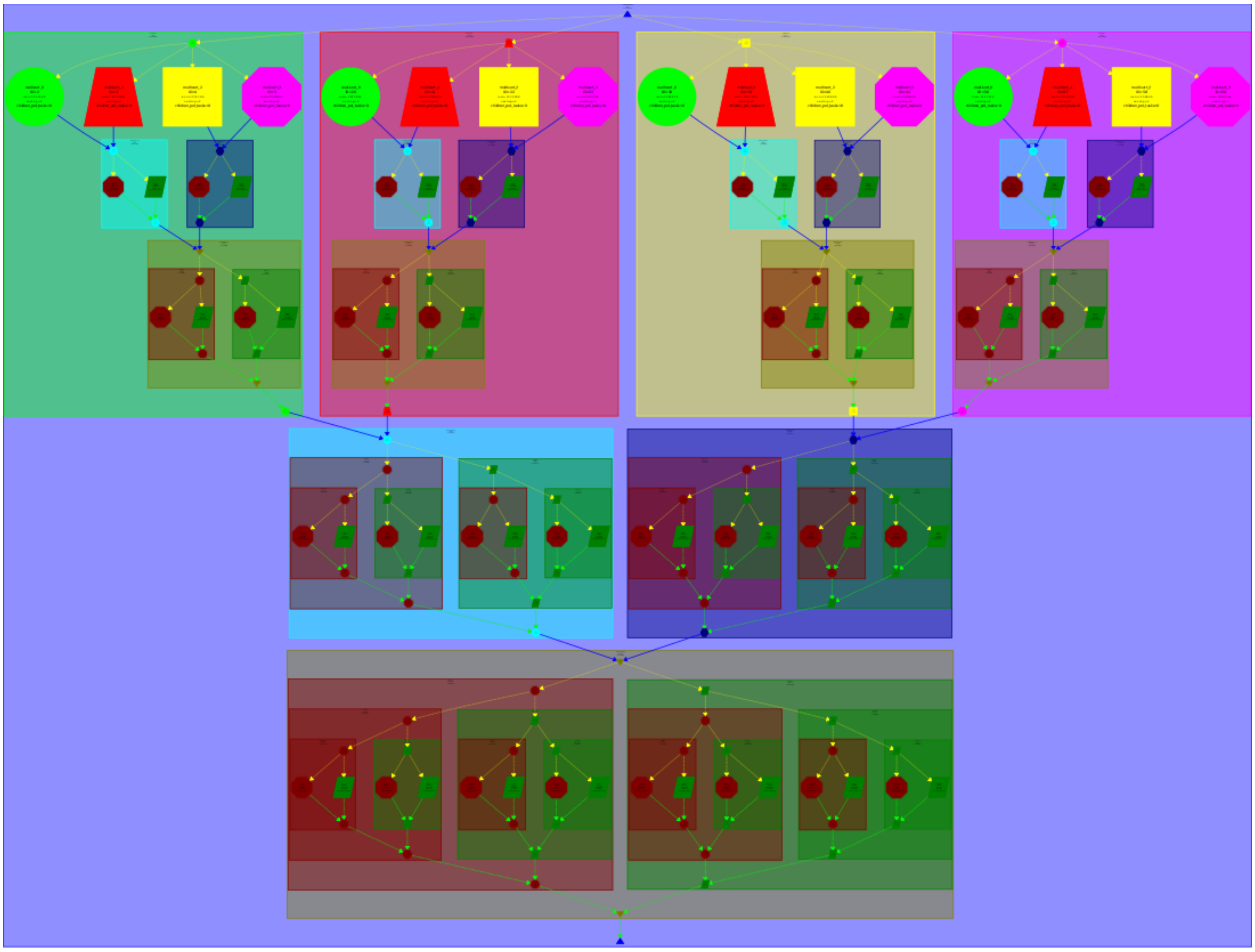
Task decomposition analysis with Tareador

```
void merge(long n, T left[n], T right[n], T result[n*2], long start, long
length) {
        if (length < MIN_MERGE_SIZE*2L) {
                // Base case
                basicmerge(n, left, right, result, start, length);
        } else {
                // Recursive decomposition
                tareador_start_task("merge 0");
                merge(n, left, right, result, start, length/2);
                tareador_end_task("merge 0");
                tareador_start_task("merge 1");
                merge(n, left, right, result, start + length/2, length/2);
                tareador_end_task("merge 1");
        }
}

void multisort(long n, T data[n], T tmp[n]) {

                if (n >= MIN_SORT_SIZE*4L) {
                                // Recursive decomposition
                                tareador_start_task("multisort 0");
                                multisort(n/4L, &data[0], &tmp[0]);
                   tareador_end_task("multisort 0");
                                tareador_start_task("multisort 1");
                                multisort(n/4L, &data[n/4L], &tmp[n/4L]);
                                tareador_end_task("multisort 1");
                                tareador_start_task("multisort 2");
                                multisort(n/4L, &data[n/2L], &tmp[n/2L]);
                                tareador_end_task("multisort 2");
                                tareador_start_task("multiosrt 3");
                                multisort(n/4L, &data[3L*n/4L],
&tmp[3L*n/4L]);
                                
                                tareador_end_task("multisort 3");

                                tareador_start_task("merge_multi 0");
                                merge(n/4L, &data[0], &data[n/4L], &tmp[0],
0, n/2L);
                                
                                tareador_end_task("merge_multi 0");
                                tareador_start_task("merge_multi 1");
                                merge(n/4L, &data[n/2L], &data[3L*n/4L],
&tmp[n/2L], 0, n/2L);
                                tareador_end_task("merge_multi 1");
                                tareador_start_task("merge_multi 2");
                                merge(n/2L, &tmp[0], &tmp[n/2L], &data[0],
0, n);
```

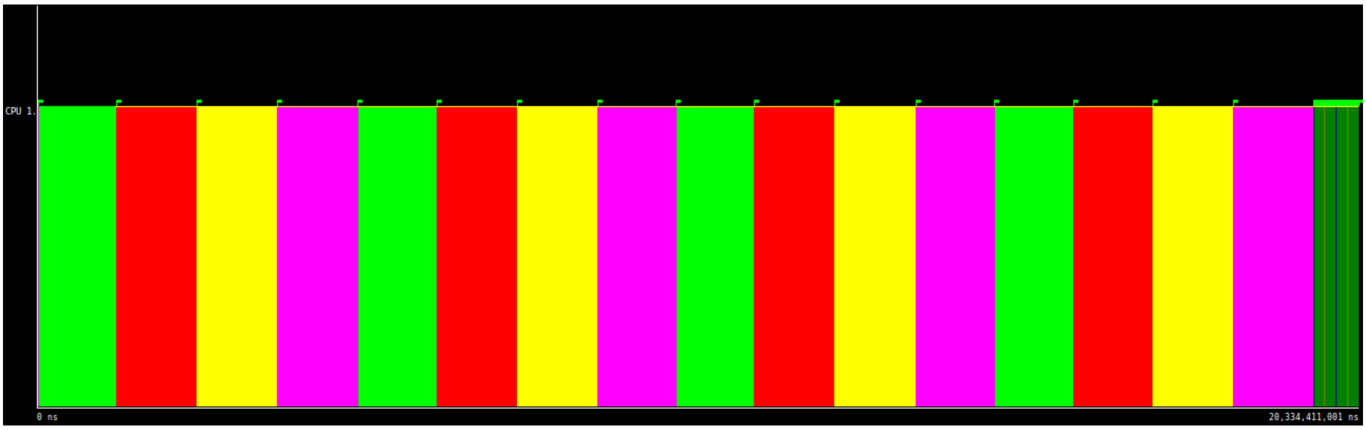
```
                                                tareador_end_task("merge_multi 2");
                } else {
                        // Base case
                        basicsort(n, data);
                }
        }
```

multisort-tareador.c

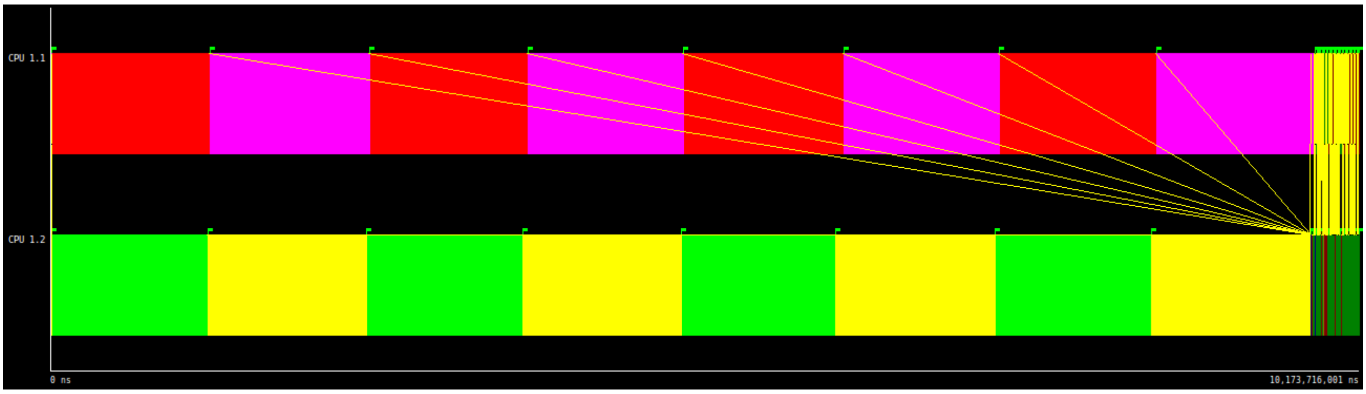
That peace of code give us the following dependcence graph:



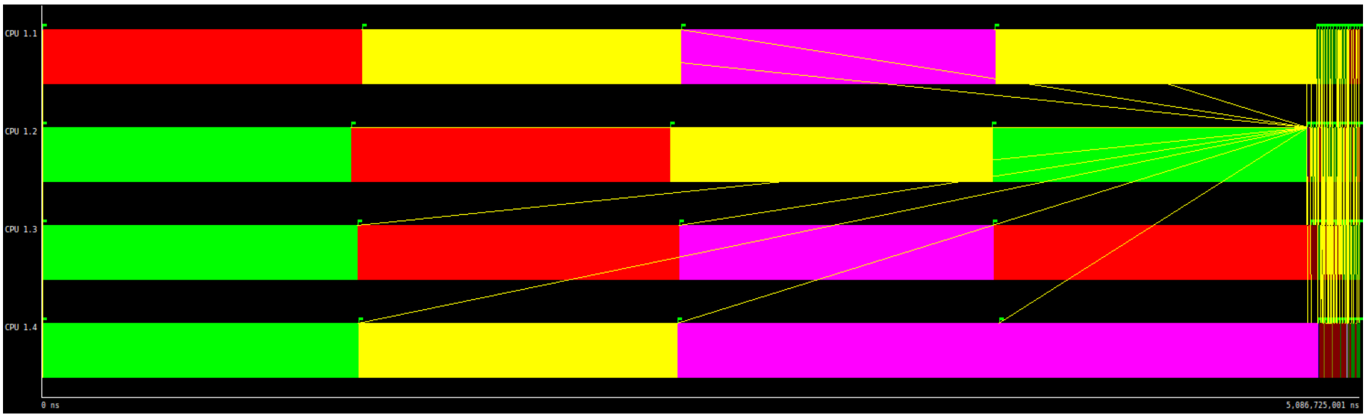
We have added a tareador task in each of the recursive tasks, to fully visualize the possible parallelization of the code.



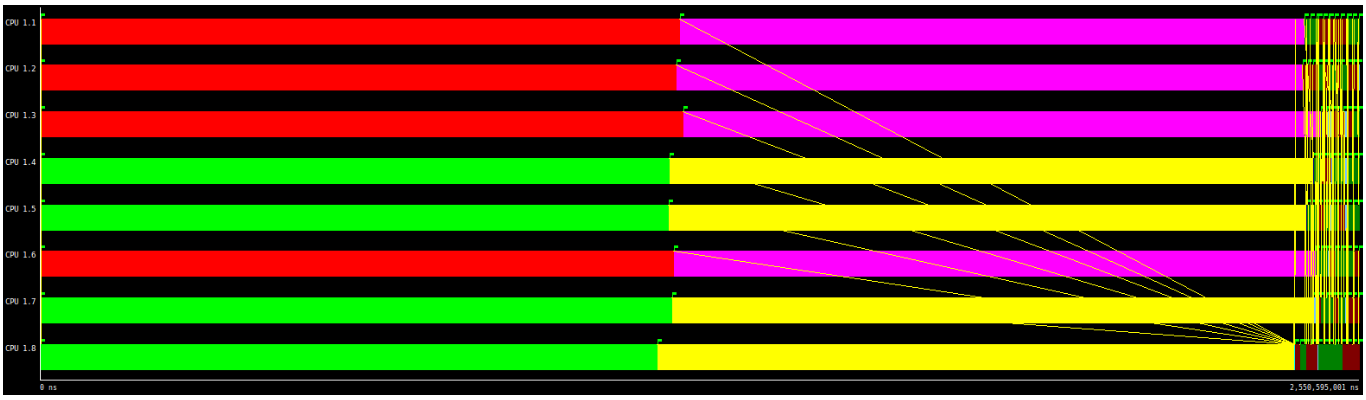
Trace of multisort-tareador using 1 core



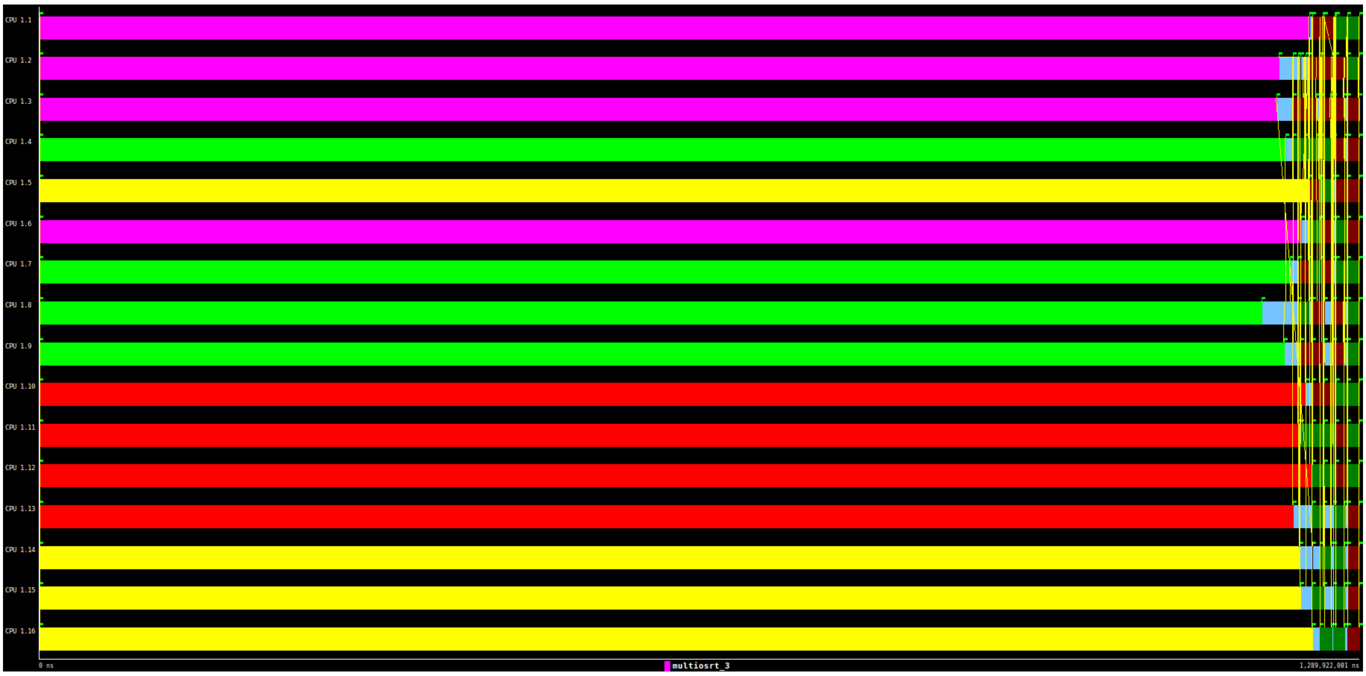
Trace of multisort-tareador using 2 core



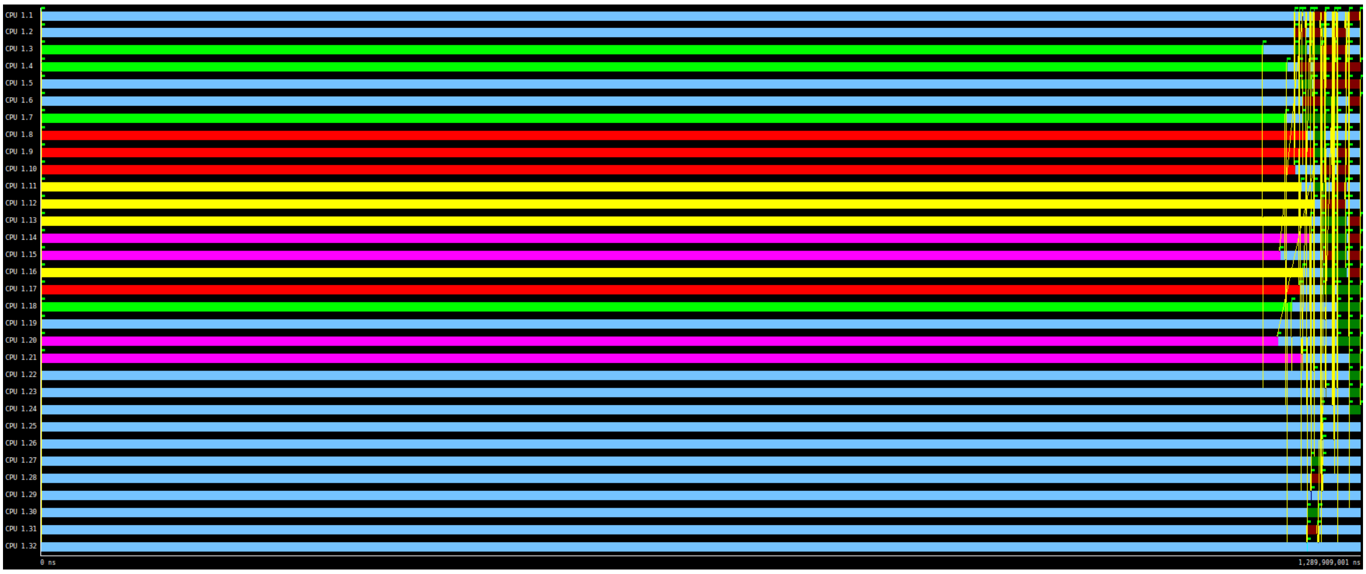
Trace of multisort-tareador using 4 core



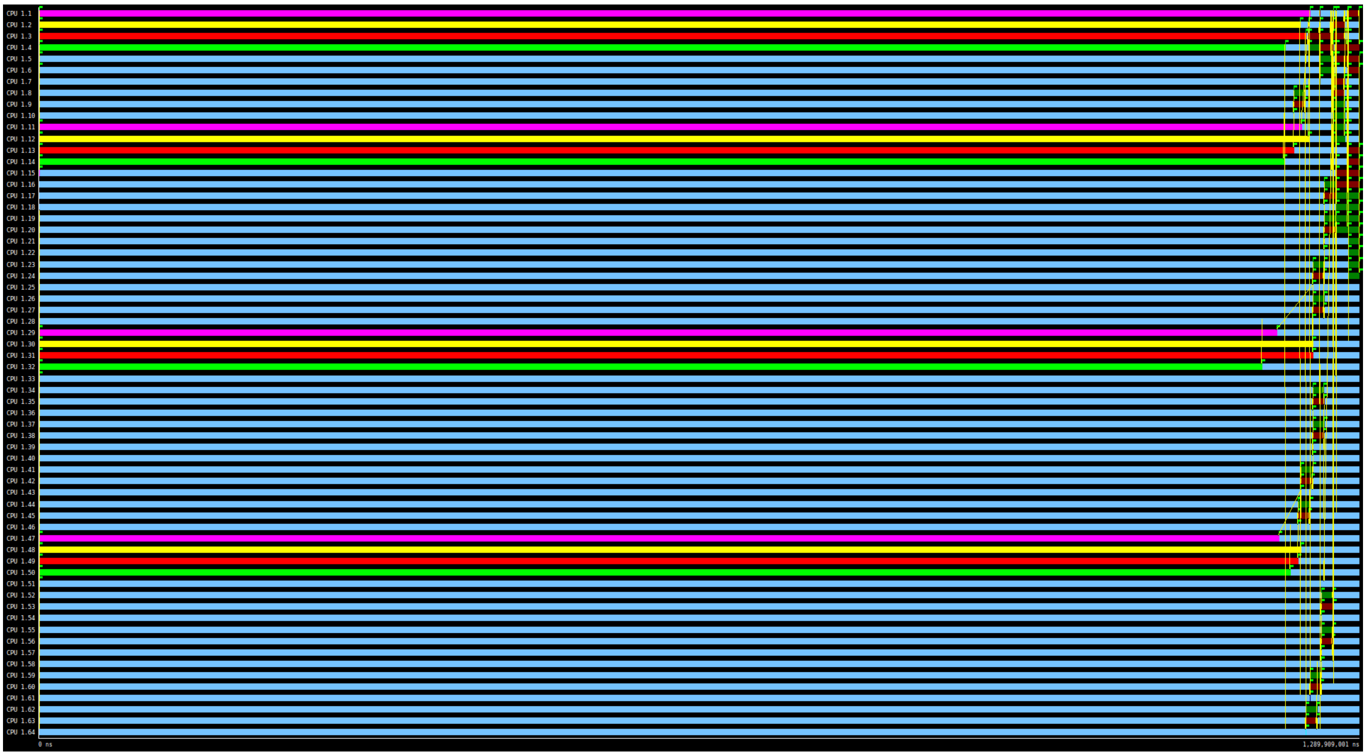
Trace of multisort-tareador using 8 core



Trace of multisort-tareador using 16 core



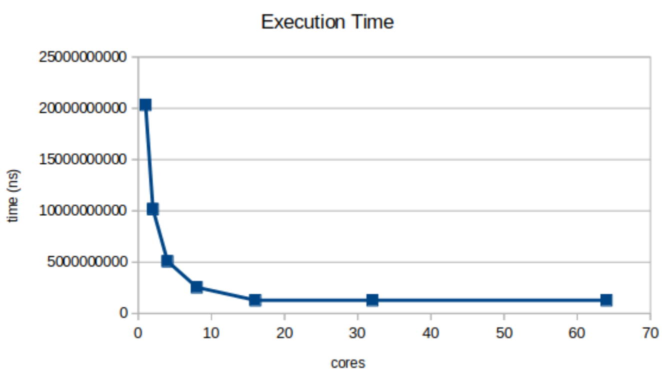
Trace of multisort-tareador using 32 core

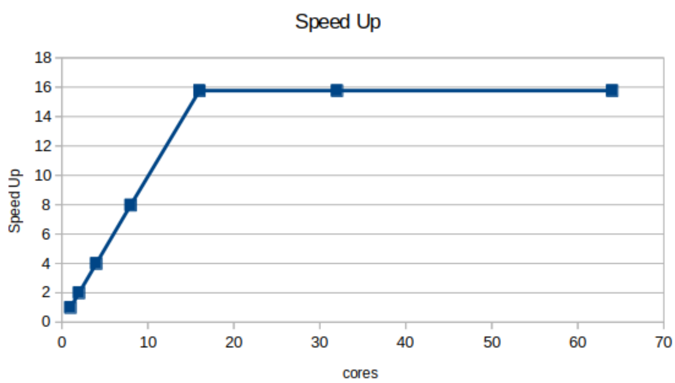


Trace of multisort-tareador using 64 core

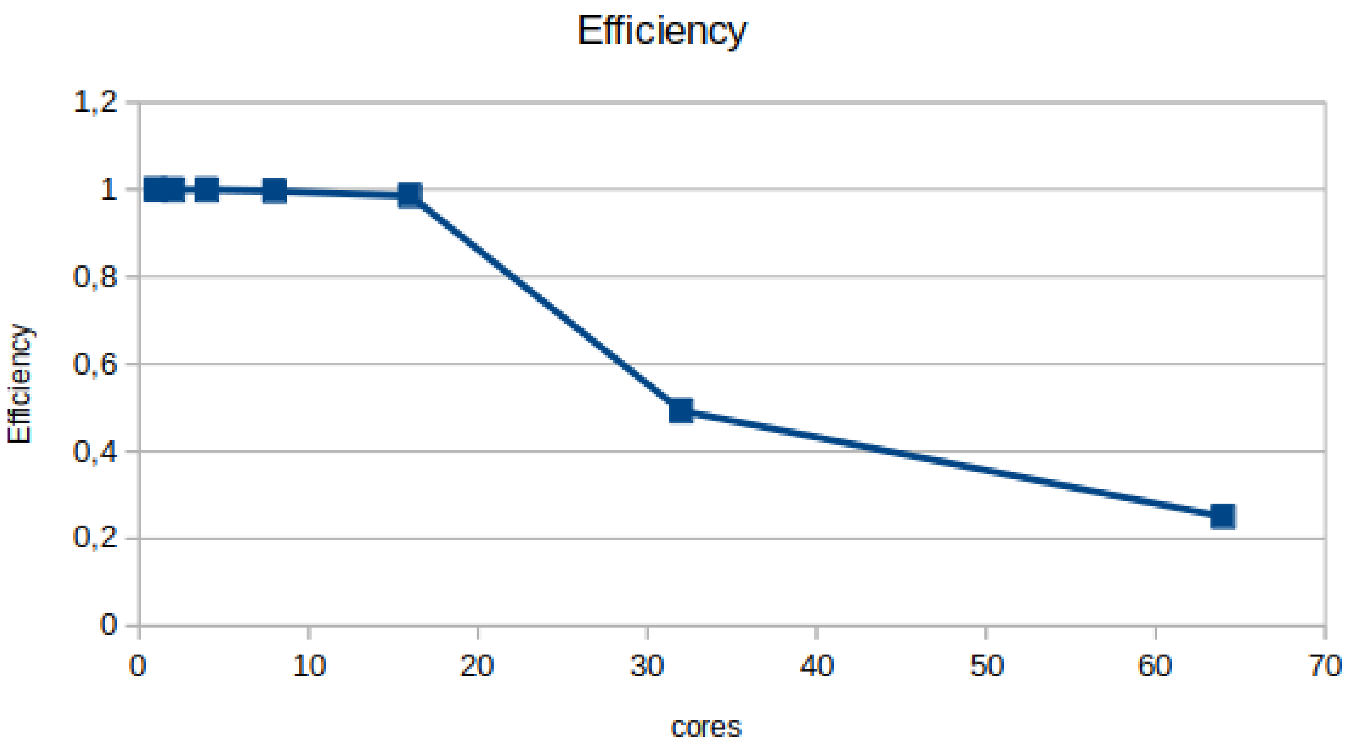
NUM CPUs	time (ns)	SPEED UP	EFFICIENCY
1	20334411001	1	0.999360066616823
2	10173716001	1.99872013323365	0.99938619627572
4	5086725001	3.99754478510288	0.99938619627572
8	2550595001	7.97241858979085	0.996552323723856
16	1289922001	15.7640624667507	0.985253904171916
32	1289909001	15.7642213406029	0.492631916893841
64	1289909001	15.7642213406029	0.246315958446921

The following pots represents number of cores vs. plot of time, speed up and efficiency, respectively.





Number of cores vs. execution time plot and number of cores vs. speed up plot.



Number of cores vs. efficiency plot.

The multisort program will parallise ideally until 16 cores, when , the dependence between the multisort marge calls, as seen in the tareador capture of the tasks, doesn't allow for more. The efficiency drops going further than 16 threads (i.e fig: efficiency plot and 32,64 captures) Proving that adding more CPUs is pointless.

Shared-memory parallelization with OpenMP tasks

Task cut–off mechanism

First of all, we are going to implement two versions of multisort algorithm. One using a tree strategy and another using a leaf strategy.

Tree strategy code:

```
void merge(long n, T left[n], T right[n], T result[n*2], long start, long
length) {
    if (length < MIN_MERGE_SIZE*2L) {
        // Base case
        basicmerge(n, left, right, result, start, length);
    } else {
        // Recursive decomposition
        #pragma omp taskgroup
        {
            #pragma omp task
            merge(n, left, right, result, start, length/2);
            #pragma omp task
            merge(n, left, right, result, start + length/2, length/2);
        }
    }
}

void multisort(long n, T data[n], T tmp[n]) {
    if (n >= MIN_SORT_SIZE*4L)
    {
        #pragma omp taskgroup
        {
            #pragma omp task
            multisort(n/4L, &data[0], &tmp[0]);
            #pragma omp task
            multisort(n/4L, &data[n/4L], &tmp[n/4L]);
            #pragma omp task
            multisort(n/4L, &data[n/2L], &tmp[n/2L]);
            #pragma omp task
            multisort(n/4L, &data[3L*n/4L], &tmp[3L*n/4L]);
        }
        #pragma omp taskgroup
        {
            #pragma omp task
            merge(n/4L, &data[0], &data[n/4L], &tmp[0], 0, n/2L);
            #pragma omp task
            merge(n/4L, &data[n/2L], &data[3L*n/4L], &tmp[n/2L], 0, n/2L);
            //#pragma omp taskwait
        }
        #pragma omp task
        merge(n/2L, &tmp[0], &tmp[n/2L], &data[0], 0, n);
        }
```

```
    else
    {
                basicsort(n, data);
        }
}
```

multisort-omp-tree.c

	multisort	merge
THREAD 1.1.1	266	3,098
THREAD 1.1.2	259	2,956
THREAD 1.1.3	329	1,990
THREAD 1.1.4	280	2,782
THREAD 1.1.5	329	2,028
THREAD 1.1.6	294	1,812
THREAD 1.1.7	301	1,872
THREAD 1.1.8	329	1,896
Total	2,387	18,434
Average	298.38	2,304.25
Maximum	329	3,098
Minimum	259	1,812
StDev	26.87	506.70
Avg/Max	0.91	0.74

Paraver capture of number of tasks created using tree strategy

Leaf strategy code:

```
void multisort(long n, T data[n], T tmp[n]) {
        if (n >= MIN_SORT_SIZE*4L) {
                // Recursive decomposition
                multisort(n/4L, &data[0], &tmp[0]);
                multisort(n/4L, &data[n/4L], &tmp[n/4L]);
                multisort(n/4L, &data[n/2L], &tmp[n/2L]);
                multisort(n/4L, &data[3L*n/4L], &tmp[3L*n/4L]);

                merge(n/4L, &data[0], &data[n/4L], &tmp[0], 0, n/2L);
                merge(n/4L, &data[n/2L], &data[3L*n/4L], &tmp[n/2L], 0,
n/2L);

                merge(n/2L, &tmp[0], &tmp[n/2L], &data[0], 0, n);
        }
    else {
                // Base case
                #pragma omp taskgroup
                {
                        #pragma omp task
                        basicsort(n, data);
                }
                //#pragma omp taskwait
        }
}
```

multisort-omp-leaf.c

	multisort
THREAD 1.1.1	136
THREAD 1.1.2	102
THREAD 1.1.3	100
THREAD 1.1.4	167
THREAD 1.1.5	147
THREAD 1.1.6	104
THREAD 1.1.7	158
THREAD 1.1.8	110
Total	1,024
Average	128
Maximum	167
Minimum	100
StDev	25.51
Avg/Max	0.77

Paraver capture of number of tasks created using leaf strategy

For the cut-off strategy we need to marge tree and leaf methods. Until a specified number of created tasks, the program will be creating tasks like the tree strategy, recursively. Then, when the limit is reached, the program is going to create sequentially one task for each leaf of the recursion.

Cut-off strategy code:

```
void merge(long n, T left[n], T right[n], T result[n*2], long start, long
length) {
        if (length < MIN_MERGE_SIZE*2L) {
                // Base case
                basicmerge(n, left, right, result, start, length);
        } else {
                if(NUM_TASKS < CUTOFF){
                                        #pragma omp taskgroup
                                        {
                                                NUM_TASKS++;
                                                #pragma omp task
                                                merge(n, left, right,
result, start, length/2);
                                                NUM_TASKS++;
                                                #pragma omp task
                                                merge(n, left, right,
result, start + length/2, length/2);
                                        }
                                        NUM_TASKS -= 2;
                                }
                                else{
                                        merge(n, left, right, result,
```

```
start, length/2);
                                        merge(n, left, right, result, start
+ length/2, length/2);
                                }
        }
}

void multisort(long n, T data[n], T tmp[n]) {
        if (n >= MIN_SORT_SIZE*4L) {
                 // Recursive decomposition
                if(NUM_TASKS < CUTOFF){
                                        #pragma omp taskgroup
                                        {
                                                NUM_TASKS++;
                                                #pragma omp task
                                                multisort(n/4L, &data[0],
&tmp[0]);
                                                NUM_TASKS++;
                                                #pragma omp task
                                                multisort(n/4L,
&data[n/4L], &tmp[n/4L]);
                                                NUM_TASKS++;
                                                #pragma omp task
                                                multisort(n/4L,
&data[n/2L], &tmp[n/2L]);
                                                NUM_TASKS++;
                                                #pragma omp task
                                                multisort(n/4L,
&data[3L*n/4L], &tmp[3L*n/4L]);
                                        }
                                        NUM_TASKS -= 4;
                                        #pragma omp taskgroup
                                        {
                                                NUM_TASKS++;
                                                #pragma omp task
                                                merge(n/4L, &data[0],
&data[n/4L], &tmp[0], 0, n/2L);
                                                NUM_TASKS++;
                                                #pragma omp task
                                                merge(n/4L, &data[n/2L],
&data[3L*n/4L], &tmp[n/2L], 0, n/2L);
                                                //#pragma omp taskwait
                                        }
                                        NUM_TASKS -= 2;

                                        NUM_TASKS++;
                                        #pragma omp task
                                        merge(n/2L, &tmp[0], &tmp[n/2L],
&data[0], 0, n);
                                }
                                else{
                                        // Recursive decomposition
                                        multisort(n/4L, &data[0], &tmp[0]);
                                        multisort(n/4L, &data[n/4L],
```

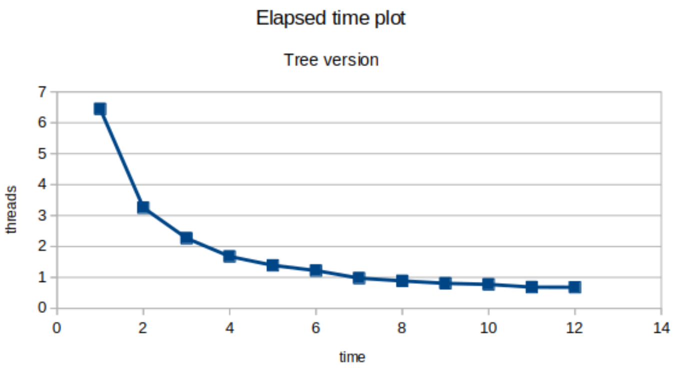
```
&tmp[n/4L]);
                                        multisort(n/4L, &data[n/2L],
&tmp[n/2L]);
                                        multisort(n/4L, &data[3L*n/4L],
&tmp[3L*n/4L]);

                                        merge(n/4L, &data[0], &data[n/4L],
&tmp[0], 0, n/2L);
                                        merge(n/4L, &data[n/2L],
&data[3L*n/4L], &tmp[n/2L], 0, n/2L);

                                        merge(n/2L, &tmp[0], &tmp[n/2L],
&data[0], 0, n);
                                }
        } else {
                if(NUM_TASKS >= CUTOFF){
                        #pragma omp task
                        basicsort(n, data);
                        #pragma omp taskwait
                }
                else{
                        basicsort(n, data);
                }
        }
}
```

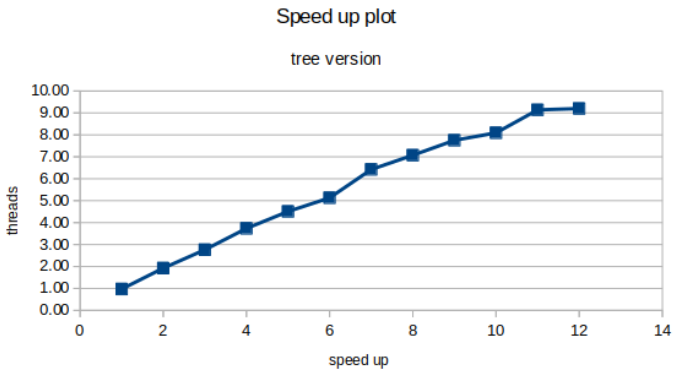
multisort-omp-cutoff.c

	multisort	merge
THREAD 1.1.1	263	-
THREAD 1.1.2	256	-
THREAD 1.1.3	256	2
THREAD 1.1.4	256	2
THREAD 1.1.5	-	-
THREAD 1.1.6	-	-
THREAD 1.1.7	-	-
THREAD 1.1.8	-	2
Total	1,031	6
Average	257.75	2
Maximum	263	2
Minimum	256	2
StDev	3.03	0
Avg/Max	0.98	1

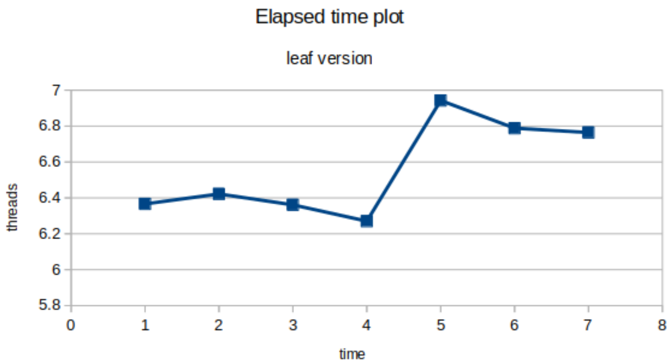
Paraver capture of number of tasks created using cut-off strategy

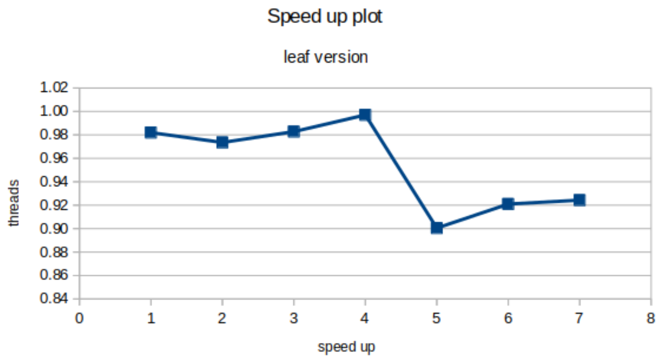
Down bellow we are going to study the strong scalability of the three different versions of the multisort algorithm using cores vs time/speed up plots.



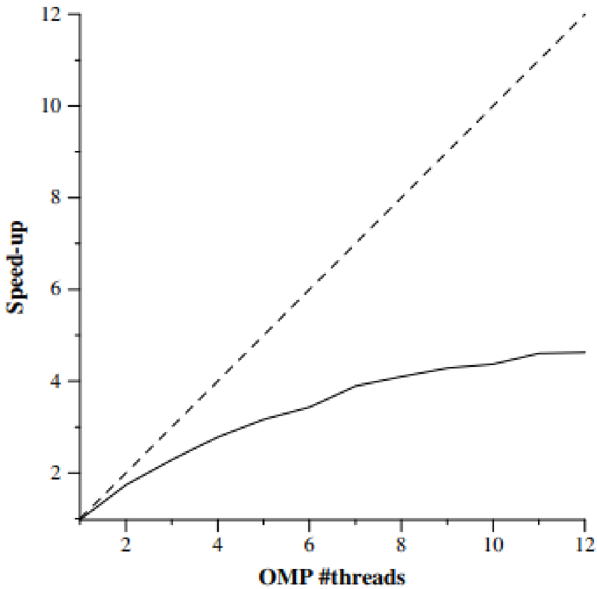


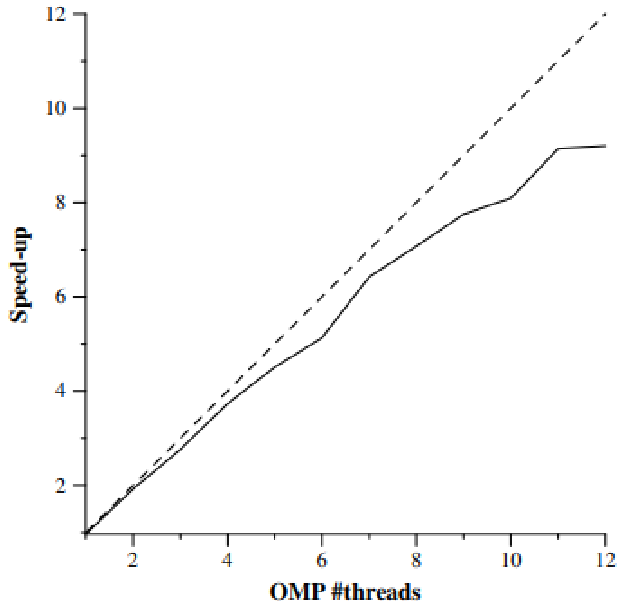
Elapsed time plot and speed up plot for tree version of multisort algorithm





Elapsed time plot and speed up plot for leaf version of multisort algorithm





PostScript plots generated by submit-cutoff.sh

We can observe that the speed up at first plot (using the execution time of the whole program) reach a limit on 10 cores, as equal as the second plot (only using the time of multisort function). Nevertheless the scalability ratio is better in the second plot, because there is where the parallelization is implemented.

Using OpenMP task dependencies

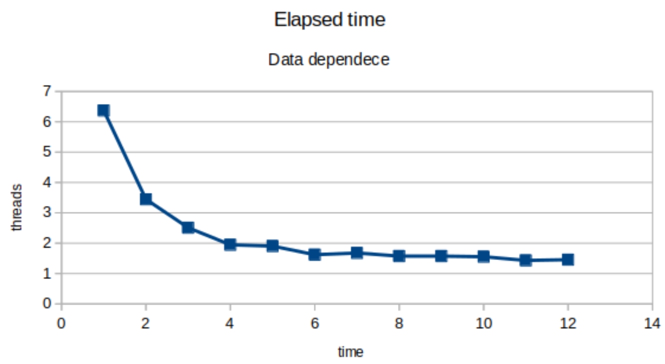
At last we are going to implement, based in tree strategy, a task dependence model.

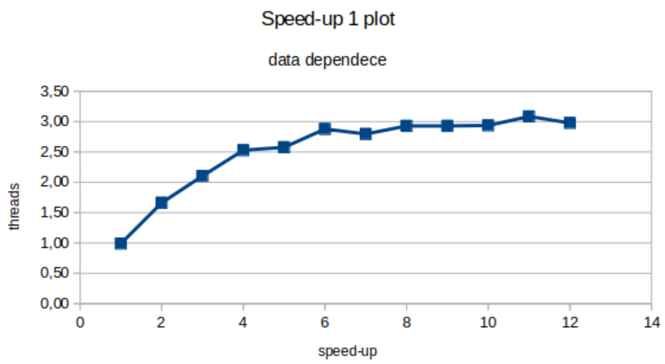
```
void merge(long n, T left[n], T right[n], T result[n*2], long start, long
length) {
   if (length < MIN_MERGE_SIZE*2L) {
      // Base case
      basicmerge(n, left, right, result, start, length);
   } else {
      // Recursive decomposition
      #pragma omp task depend(in:left,right) depend(out:result)
      merge(n, left, right, result, start, length/2);
      #pragma omp task depend(in:left,right) depend(out:result)
      merge(n, left, right, result, start + length/2, length/2);

      #pragma omp taskwait
   }
}

void multisort(long n, T data[n], T tmp[n]) {
        if (n >= MIN_SORT_SIZE*4L) {
                        // Recursive decomposition
                        #pragma omp task depend(out:data[0])
                        multisort(n/4L, &data[0], &tmp[0]);
                        #pragma omp task depend(out:data[n/4L])
                        multisort(n/4L, &data[n/4L], &tmp[n/4L]);
                        #pragma omp task depend(out:data[n/2L])
                        multisort(n/4L, &data[n/2L], &tmp[n/2L]);
                        #pragma omp task depend(out:data[3L*n/4L])
                        multisort(n/4L, &data[3L*n/4L], &tmp[3L*n/4L]);

                        #pragma omp task depend(in: data[0], data[n/4L])
depend(out: tmp[0])
                        merge(n/4L, &data[0], &data[n/4L], &tmp[0], 0,
n/2L);
                        #pragma omp task depend(in: data[n/2L],
data[3L*n/4L]) depend(out: tmp[n/2L])
                        merge(n/4L, &data[n/2L], &data[3L*n/4L],
&tmp[n/2L], 0, n/2L);

                        #pragma omp task depend(in: tmp[0],tmp[n/2L])
                        merge(n/2L, &tmp[0], &tmp[n/2L], &data[0], 0, n);

                        #pragma omp taskwait
        } else {
                // Base case
                basicsort(n, data);
        }
}
```

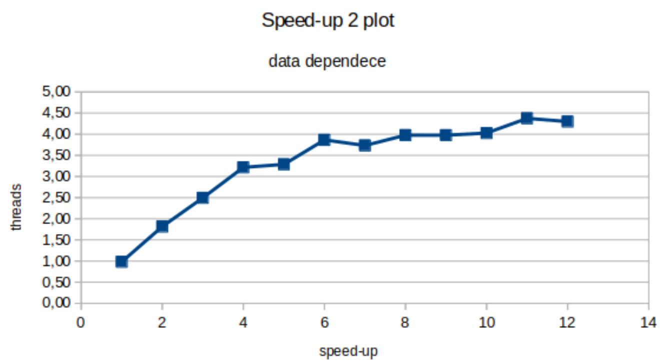
multisort-omp-depencences.c

In marge function, every marge call depends of left and write as an "in" dependence and result as "out". This is caused by basic marge because it has to read from right to left and write to result.

In multisort function, multisort recursive calls needs to write on a data array, then it has a "out" dependence in data array. Every marge call depends of a block of the data array and it needs to write in tmp array at same position than data array.



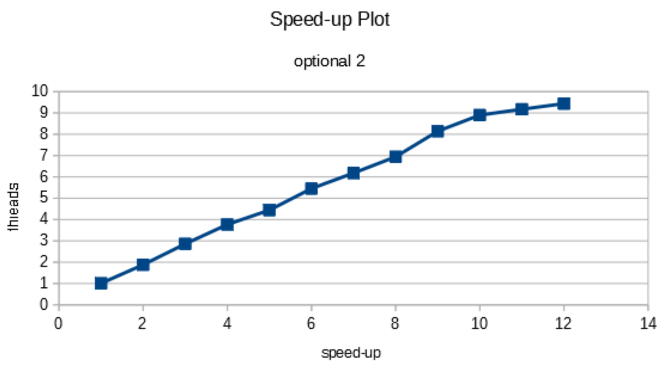


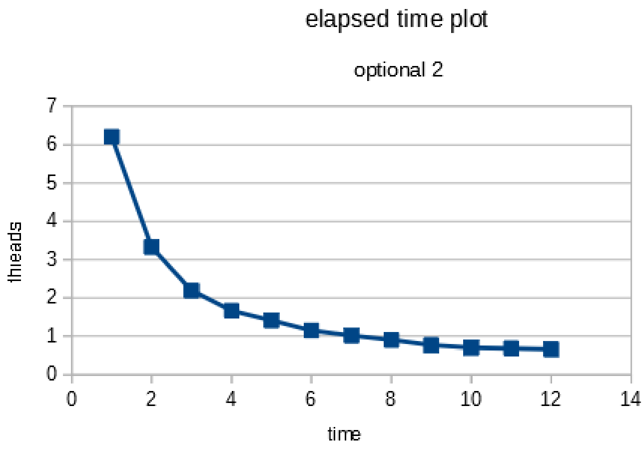


With a quick look at the plots we can see that executing the program with more than 4 cores the speed-up starts to normalize. We also can observe that the speed-up in the sp2 plot, which takes the speed-up of the parallel part of the program, it's around 1 to 1.5 times greater than the speed-up of the whole program (speed-up 1 plot).

Optional 2 - Parallelization of initialize and clear

In this optional we expanded the tree versions adding paralelitzation in the initialization of the tmp and data vectors. We choose to not implement any specific schedule to the for, because they didn't improve over the default version.





We got an overall better time than the basic tree version, even if it's not very noticeable, it's worth the implementation if done correctly. For example, scheduling with static and n=1, pushes the initialize time up to 2s.

```
static void initialize(long length, T data[length]) {
   long i;
   #pragma omp parallel for private(i)
   for (i = 0; i < length; i++) {
      if (i==0) {
         data[i] = rand();
      } else {
         data[i] = ((data[i-1]+1) * i * 104723L) % N;
      }
   }
}

static void clear(long length, T data[length]) {
   long i;
      #pragma omp parallel for private(i)
   for (i = 0; i < length; i++) {
      data[i] = 0;
   }
}
```

multisort-omp-optional2.c

Conclusions

In this assignment, we explored different ways to parallelism a recursive portion of a program. Tree, leaf or cut-off. With our results we concluded that, due to the nature of the code, a tree strategy will aport better results as seen in the time and speed up versions. Where while the gain of the first method is great, the leaf version doesn't improve at all, in fact, it decreases.

Further exploring the tree version, we implemented a data dependence parallelization, avoiding as many task synchronizations as we could. However, we didn't manage to improve over the previous version . This may be because some redundant dependencies.