Assignment 1
OpenMP Tutorial Assignment

B. Wilkinson: Modification date January 16a, 2016 **(minor clarification in green Jan 28, 2016)**

Overview

The purpose of this tutorial assignment is to become familiar with executing some simple OpenMP programs. For the most part, you will test OpenMP programs on your own computer. This will require you to have completed the "pre-assignment" installing the provided virtual machine (or a native Linux installation with the course software stack). Finally you will test a program on the UNC-Charlotte's 4-processor (16-core) **cci-grid05.uncc.edu** system. Using your own computer is much more convenient and reduces the likelihood of faulty user programs running on the UNC-C cluster affecting the whole system. Users can also easily do local editing and testing before running on the cluster.

Part 1 provides basic practice in coding, compiling, and running OpenMP programs, covering a hello world program, timing, using work sharing for, sections directives, and private variables. All the OpenMP code is given. *Part 2* asks you to parallelize matrix multiplication using the work sharing **for** directive and draw conclusions. Code for sequential matrix multiplication is given. *Part 3* asks you run the matrix multiplication program on **cci-grid05.uncc.edu**.

Compiling OpenMP programs can be done using the native gcc compiler that comes with distributions of Linux including Ubuntu.

Preliminaries

The OpenMP programs for this assignment are to be held in the directory **~/ParallelProg/OpenMP**, which is already created in the provided virtual machine with the sample programs. Cd to this directory.

Part 1 – OpenMP Tutorial (35%)

The purpose of this part is to become familiar with OpenMP constructs and programs, using your own computer.

Task 1 – "hello world" program

An OpenMP hello world program called **hello.c** is given overleaf:

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>

int main (int argc, char *argv[])  {
   int nthreads, tid;
// Fork a team of threads giving them their own copies of variables

   #pragma omp parallel private(nthreads, tid)
   {
   tid = omp_get_thread_num();                  // Obtain thread number
   printf("Hello World from thread = %d\n", tid);

   if (tid == 0) {  // Only master thread does this
      nthreads = omp_get_num_threads();
      printf("Number of threads = %d\n", nthreads);
   }
   }              // All threads join master thread and disband
   return(0);
}
```

This program has the basic **parallel** construct for defining a single parallel region for multiple threads. It also has a **private** clause for defining a variable local to each thread. *Remember that OpenMP constructs such as parallel have their opening braces on the next line and not on the same line.*

Compile the program on your own computer using the command:[1]

```
cc –fopenmp hello.c –o hello
```

Execute the program with the command:

```
./hello
```

You should get a listing showing a number of threads such as:

```
Hello World from thread = 0
Number of threads = 4
Hello World from thread = 3
Hello World from thread = 2
Hello World from thread = 1
```

The number of threads will depend upon the particular computer system, usually the number of cores available. Intel hyperthreading doubles this number. Note if you only have one thread on one core available to use, the above will show that and will prevent any speedup.

Alter the available cores to the maximum possible. In VirtualBox, this is done by first closing the VM and then going to **Machine** > **Settings** > **System** > **Processor** and altering the number of processors available to its maximum (typically half the number of physical cores). Then restart the VM.

[1] The –o option could be before the source file, i.e. cc –fopenmp –o hello hello.c.

Once you have the maximum number of cores you can use, execute the program at least four times. Explain your output. Why does the thread order change?

Alter the number of threads to 32. There are actually three ways to do this, see the class notes. Here just try adding the following function:

```
omp_set_num_threads(32);
```

before the parallel region **pragma**. Re-execute the program.

What to submit for Task 1

Your submission document should include the following:

1) Screenshot from compiling and running the hello world program on your computer and explanation of output and thread order.
2) Program listing of the hello world program with the number of threads altered
3) Screenshots of the output from running the program with 32 threads.

Task 2 – Work sharing with the for construct

This task explores the use of the **for** work-sharing construct. The following program **worksharing.c** adds two vectors together using a work-sharing approach to assign work to threads:

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
#define CHUNKSIZE 10
#define N 100

int main (int argc, char *argv[]) {
   int nthreads, tid, i, chunk;
   float a[N], b[N], c[N];
   double start, end;               // used for timing

   for (i=0; i < N; i++)
      a[i] = b[i] = i * 1.0;         // initialize arrays

   chunk = CHUNKSIZE;

   start = omp_get_wtime();   //start time measurement

   #pragma omp parallel shared(a,b,c,nthreads,chunk) private(i,tid)
   {
      tid = omp_get_thread_num();
      if (tid == 0){
         nthreads = omp_get_num_threads();
         printf("Number of threads = %d\n", nthreads);
      }
      printf("Thread %d starting...\n",tid);
      #pragma omp for schedule(dynamic,chunk)
      for (i=0; i<N; i++){
         c[i] = a[i] + b[i];
         printf("Thread %d: c[%d]= %f\n",tid,i,c[i]);
      }
   } /* end of parallel section */

   end = omp_get_wtime();     //end time measurement
   printf("Time of computation: %f seconds\n", end-start);
   return(0);
}
```

This program has an overall **parallel** region within which there is a work-sharing **for** construct. Also the time of execution is recorded by instrumenting the code with **omp_get_wtime()** in two places.

Compile and execute the program. Depending upon the scheduling of work different threads might add elements of the vector. It may be that one thread does all the work. Execute the program several times to see any different thread scheduling. In the case that multiple threads are being used, observe how they may interleave.

Experimenting with Scheduling

Alter the code from **dynamic** scheduling to **static** scheduling and repeat. What are your conclusions? Alter the code from **static** scheduling to **guided** scheduling (chunk size is irrelevant) and repeat. What are your conclusions?

What to submit for Task 2

Your submission document should include the following:

1) ~~A copy of the source program with timing added;~~ Not needed
2) Screenshot from compiling and running the program with the original dynamic scheduling;
3) Screenshots from running the program with static and with guided scheduling;
4) Your conclusions about the different scheduling approaches.

Task 3 – Work-sharing with the sections construct

This task explores the use of the **sections** construction. The program **sections.c** below adds elements of two vectors to form a third and also multiplies the elements of the arrays to produce a fourth vector.

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
#define N 50
```

```
int main (int argc, char *argv[]) {
   int i, nthreads, tid;
   float a[N], b[N], c[N], d[N];

   for (i=0; i<N; i++) {      // Some initializations, arbitrary values
      a[i] = i * 1.5;
      b[i] = i + 22.35;
      c[i] = d[i] = 0.0;
   }

   #pragma omp parallel shared(a,b,c,d,nthreads) private(i,tid)
   {
      tid = omp_get_thread_num();
      if (tid == 0)  {
         nthreads = omp_get_num_threads();
         printf("Number of threads = %d\n", nthreads);
      }
      printf("Thread %d starting...\n",tid);

      #pragma omp sections nowait
      {
         #pragma omp section
         {
            printf("Thread %d doing section 1\n",tid);
            for (i=0; i<N; i++)   {
               c[i] = a[i] + b[i];
               printf("Thread %d: c[%d]= %f\n",tid,i,c[i]);
            }
         }

         #pragma omp section
         {
            printf("Thread %d doing section 2\n",tid);
            for (i=0; i<N; i++)  {
               d[i] = a[i] * b[i];
               printf("Thread %d: d[%d]= %f\n",tid,i,d[i]);
            }
         }
      }                       // end of sections

      printf("Thread %d done.\n",tid);

   }                          // end of parallel section
   return(0);
}
```

This program has a parallel region but now with variables declared as shared among the threads as well as private variables. Also there is a sections work sharing construct. Within the sections construct, there are individual section blocks that are to be executed once by one member of the team of threads. *Remember that OpenMP constructs such as sections and section have their opening braces on the next line and not on the same line.*

Compile and execute the program and make conclusions on its execution.

What to submit for Task 3

Your submission document should include the following:

1) Screenshot from compiling and running the program
2) Your conclusions.

Task 4 – For construct with private variables

In this section we will explore private variables. Compile and execute the following code, called **privatetest.c**.

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
#define N 100000

int main(int argc, char *argv) {
      omp_set_num_threads(2);             //set number of threads here
      int i, j, x, tid;
      double start, end;                  // used for timing

      start = omp_get_wtime();            //start time measurement
      #pragma omp parallel for private(x,tid)
      for (i = 0; i < N; i++)
      for (j = 0; j < N; j++) {
            tid = omp_get_thread_num();
            x=tid;
      }
      end = omp_get_wtime();              //end time measurement
      printf("Time of parallel computation: %f seconds\n", end-start);

      return(0);
}
```

(i) Repeat with the number of threads being 1, 2, 4, and 8. Plot the execution time against number of threads. Monitor the CPU usage in the Task Manager (for a Windows system) or Activity Monitor in **Applications** > **Utilities** for a Mac. Discuss the results

(ii) Remove **x** from the private clause i.e. **private(tid)**. Compile and execute for two threads. Explain the difference in the execution time.

What to submit for Task 4

Your submission document should include the following:

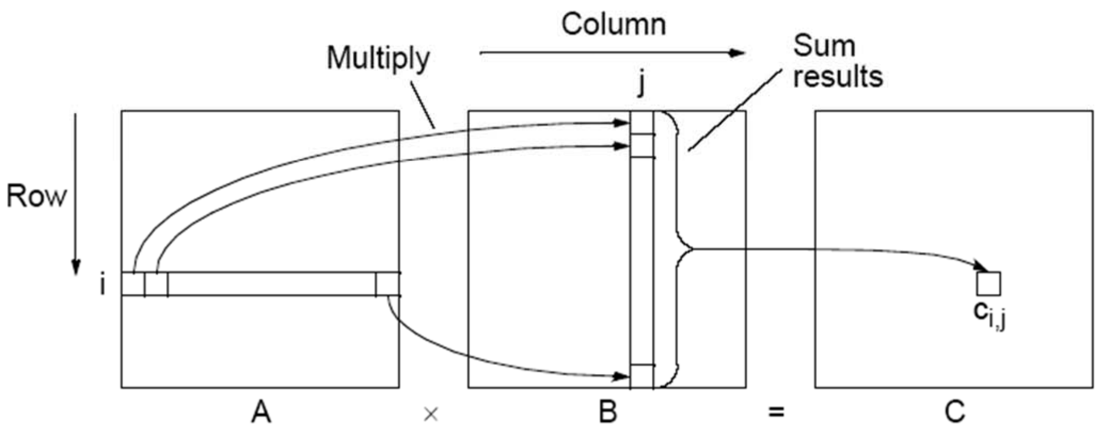
1) For (i) above, a graph of the execution time against number of threads, a screenshot of the CPU usage, and a discussion of the results.
2) For (ii) above, the execution time with and without **x** as private variable and an explanation.

Part 2 – Matrix Multiplication (50%)

Multiplication of two matrices, **A** and **B**, produces matrix **C** whose elements, $c_{i,j}$ ($0 <= i < n$, $0 <= j < m$), computed as follows:

$$c_{i,j} = \sum_{k=0}^{l-1} a_{i,k} b_{k,j}$$

where **A** is an n x l and **B** is a l x m matrix:



The sequential code to compute **A** x **B** (assumed square *N* x *N*) could simply be:

```
for (i = 0; i < N; i++)                  // for each row of A
   for (j = 0; j < N; j++) {             // for each column of B
      c[i][j] = 0;
      for (k = 0; k < N; k++)
         c[i][j] = c[i][j] + a[i][k] * b[k][j];
   }
```

It requires N^3 multiplications and N^3 additions with a sequential time complexity of $O(N^3)$. It is very easy to parallelize as each result is independent.

A skeleton of a matrix multiplication program, **matrixmult.c**, given here:

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
#define N 256

int main(int argc, char *argv) {
      omp_set_num_threads(2);//set number of threads here
      int i, j, k, x;
      double sum;
      double start, end;                  // used for timing
      double A[N][N], B[N][N], C[N][N], D[N][N];

      // set some initial values for A and B
      for (i = 0; i < N; i++) {
```

```
		for (j = 0; j < N; j++)     {
			A[i][j] = j*1;
			B[i][j] = i*j+2;
		}
	}


	// sequential matrix multiplication
	start = omp_get_wtime();      //start time measurement
	for (i = 0; i < N; i++) {
		for (j = 0; j < N; j++)   {
			sum = 0;
			for (k=0; k < N; k++) {
				sum += A[i][k]*B[k][j];
			}
			C[i][j] = sum;
		}
	}
	end = omp_get_wtime();        //end time measurement
	printf("Time of sequential computation: %f seconds\n", end-start);

	// Add OpenMP matrix multiplication here, result in array D[N][N]
	//    ...



	// check sequential and parallel versions give same answers
	int error = 0;
	for (i = 0; i < N; i++) {
		for (j = 0; j < N; j++)   {
		  if ((C[i][j] - D[i][j] > 0.001) || (D[i][j] - C[i][j] > 0.001))
				error = -1;
		}
	}
	if (error == -1) printf("ERROR, sequential and parallel versions give 
different answers\n");

	return(0);
}
```

This program includes the sequential matrix multiplication code with the result in **C[N][N]**.

The final part of the program checks that the parallel results match the sequential results to make sure the results of your parallel version are correct within rounding errors.

Task 1 Parallel Matrix Multiplication - Parallelizing the outer loop

Add an OpenMP parallel for section to perform parallel matrix multiplication, producing the result in **D[N][N]** in the place shown. Parallelize the outer **for** loop (static scheduling).

NOTE: Take extreme care to make sure that any variables that need to be private are declared as private in a private clause. Variables are private if individual threads need their own copy to modify. Note the iteration variable in the for loop being parallelized does not need to be private as that for loop is used by the OpenMP compiler, but other variables will need to be private. You will lose marks if you do not address this issue. Even if the program appears to work, it may execute slower due to memory contention.

Add statements to measure the execution time of the parallel matrix multiplication. This is done using time stamps with omp_get_wtime() as shown for the sequential code.

You will find that when you run the same program several times, the timing values can vary significantly. Therefore add a loop in the code to execute the program 10 times and display the average execution times.

The speedup will also depend upon the number of threads in the OpenMP program, set initially to two threads in the program. Collect execution times for 1 thread, 4 threads, 8 threads, and 16 threads.

Task 2 Parallelizing the middle loop

Remove the **pragma** for the outer **for** loop and add the necessary **pragma** to parallelize only the middle **for** loop in the matrix multiplication. Collect timing data with just 4 threads.[2]

Task 3 Increasing the size of the problem

The size of the ***N*** x ***N*** matrices in the program is set to 256 x 256. What happens if you increase the size to 512 x 512 and to 1024 x 1024. Why?

Add the keyword **static** in front the array declarations and try again. What happens. Why?

What to submit from for Part 2

Your submission document should include the following:

Task 1 For the outer matrix multiplication loop parallelized

a. Source program listing
b. One screenshot from compiling and running the program
c. Graphical results of the average timings with 1, 4, 8, and 16 threads.
d. Your conclusions and explanations of the results.

Task 2 For the middle for loop parallelized

a. Source program listing
b. One screenshot from compiling and running the program
c. Your conclusions and explanations of the results.

[2] Nested for loops were introduced in OpenMP version 2.5 that can parallelize both the outer and middle for loops when you place the for directive before the first for loop and use the collapse clause. gcc version 4.2 or later includes support for OpenMP 2.5. We will not try that here.

Task 3 Increasing the problem size

a. Your conclusions and explanations of the results
b. Explain the static keyword. (You are allowed to do a Google search to help!)

Part 3 Executing on cluster (15%)

For this assignment, we will briefly test the matrix multiplication program on the UNCC **cci-gridgw.uncc.edu** cluster. Specifically, we will use **cci-grid05** – four quad-core processor (16 core) shared memory system. *First carefully read the separate instructions on using this cluster.*

You cannot ssh directly into **cci-grid05**. You must log in through the gateway node **cci-gridgw.uncc.edu** first.

Log onto the UNCC cluster gateway **cci-gridgw.uncc.edu**. In your home directory, create a directory called **OpenMP** to hold all the files for this part and **cd** into this directory. Transfer the OpenMP matrix multiplication program to this directory.

We now want to execute the matrix multiplication program on **cci-grid05.** From **cci-gridgw.uncc.edu**, ssh into **cci-grid05** with the command:

```
ssh cci-grid05
```

Compile and execute the program from the **OpenMP** directory.

Record the time of executing the matrix multiplication program with the outer loop parallelized and 16 threads, and compare with that on your own computer.

What to submit for Part 3

Your submission document should include the following:

- Screenshot of sample output for the matrix multiplication program on cci-grid05
- Graph showing the executing times of cci-grid05 and your computer
- Conclusions

Assignment Report Preparation and Grading

Produce a report that shows that you successfully followed the instructions and performs all tasks by taking screenshots and include these screenshots in the document. Note it is easy to obtain screenshots in Word as now it has that option in the **Insert > Screenshot** menu.

Every task and subtask specified will be allocated a score so make sure you clearly identify each part/task you did. Make sure you include everything that is specified in the "What to include ..." section at the end of each task/part. **Include all code, not as screen shots of the listings but**

complete properly documented code listing. The programs are often too long to see in a single screenshot and also not easy to read if small. Using multiple screenshots is not option for code. Copy/paste the code into the Word document or whatever you are using to create the report.

Assignment Submission

Convert your report into a ***single pdf*** document and submit the pdf file on Moodle by the due date as described on the course home page. It is extremely important you submit only a pdf file. *It is possible to lose points if you submit in any other format (i.e. Word, OpenOffice, zip, ...).*