

CPE 412/512

Fall Semester 2016

Exam 2 (Take-Home)

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**INSTRUCTIONS: CPE 512 students must work all five (5) problems. CPE 412 students should work any four (4) problems clearly indicating which problem they will omit. In addition to electronic submissions on the UAH Canvas course administration system student are required to submit a complete hardcopy of this exam by its due date at the beginning of class on Monday November 13, 2017.**

Statement of Compliance with UAH Academic Misconduct Policies

I \_Kyle Ray\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ certify that I have worked independently of others on this test and the work that I am presenting is my own. I am familiar with the UAH academic misconduct policy as outlined in the UAH student handbook and have agreed to abide by the policies that are stated in this document.

Alternative Statement

I \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ am unwilling to sign the above statement of compliance because I cheated on the problems listed below:

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1. Fully answer the following questions. Justify your answers by providing the page/section number reference from your text which supports your answer or by providing a complete citation of any external sources that you have used.

a) What OpenMP directive is used to provide mutual exclusion synchronization in sections of code? Give an example of its use and explain why it is needed.

**The critical directive is used for mutual exclusion.**

**#pragma omp critical (optional critical\_section\_name)**

**Usage:**

**// Some code**

**#pragma omp critical my\_critical\_section**

**{**

**// Critical Section Code**

**}**

b) Give the output of the following OpenMP code fragment if possible or discuss why this is not allowed. What is the effective scope of the sum variable? How could the answer be affected if the reduction clause is not used? Assume that there are 4 threads all together:

int i; double sum = 0.0;

#pragma omp parallel for reduction(+:sum)

for (i=1; i <= 4; i++)

sum = sum + i;

 cout << "The sum is " << sum << endl;

**Output: The sum is 10**

**The effective scope of the sum variable is shared. The answer will not be affected by removing the reduction clause. The reduction clause will create a private variable of sum for each thread which in turn will add the thread value of (i) to the private sum. Then at the end of the loop the reduction clause will add the private sums to the shared sum variable thus the reduction has just added another step. The for loop without the reduction clause will just add the value of (i) to the current shared value of sum, and because addition is commutative it will not matter which order this happens as we will get the same answer.**

c) For the following pthread code what is (are) the possible value(s) of num if there are no assumptions regarding the targeted system or the manner in which the pthread scheduler will operate? Justify your answer.

using namespace std;

#include <iostream>

#include <pthread.h>

#include <stdlib.h>

int num = 1;

void \*thread1(void \*dummy) {

num = num + 1;

}

void \*thread2(void \*dummy) {

num = num \* 3;

}

void \*thread3(void \*dummy) {

num = 123;

}

int main(int argc, char\* argv[]) {

pthread\_t thread1\_id, thread2\_id, thread3\_id;

pthread\_create(&thread1\_id, NULL, thread1, NULL);

pthread\_create(&thread2\_id, NULL, thread2, NULL);

pthread\_create(&thread3\_id, NULL, thread3, NULL);

cout << "num = " << num << endl;

while (1); // infinite loop

}

**First, note that num is a global variable accessible by all. From my knowledge of pthreads, when a thread is created it will automatically start executing unless told to do otherwise which is not the case here. Without making any assumptions on the targeted system or the scheduler and considering that these functions are simple operations, with this setup I can only see num = 123 in all cases. Even with a simple addition and a multiplication I feel that threads 1 and 2 will finish very soon after creation, before thread 3 is created, which will leave the assignment from thread 3 to be the last operation on the global variable num, thus leaving it with the value 123.**

d) What is the difference between the ordered directive and the critical section directives in OpenMP? Give separate examples of the use of both constructs. Which constructs might be useful to support local synchronization? Which constructs are useful for or global synchronization? Explain.

**Ordered Directive - The ordered construct will make it so the code for the structured block will execute sequentially.**

**Example.**

**#pragma omp parallel for schedule(static, 1)**

**{**

**For (int I = 0; I < n; i++)**

**{**

**// Do something here first**

**#pragma omp ordered**

**{**

**// Do these things in order**

**}**

**// Do some more stuff here**

**}**

**// Do something here first**

**}**

**Critical Directive – The critical directive will lock the structured block of code after the call to the directive until the current thread is finished, at which point it will release and allow the next thread in line to execute. This allows threads to execute code that might affect shared memory variables without entering in race conditions.**

**Example**

**// Some code**

**#pragma omp critical my\_critical\_section**

**{**

**// Critical Section Code**

**}**

**TODO: Check on the implicit barrier for both of these directives. Maybe an example of global synchronization would be the parallel directive as it has an implicit barrier to wait for everyone.**

**The ordered directive is not really used for synchronization, but to make sure that a block of statements are executed in sequential order.**

**The critical section however is a good example of local synchronization as it will block a portion of code from the rest of the threads on the team until the locking thread is finished with the task at which point the previously locking thread can move on to the next set of instructions.**

e) What is the difference between the single and master section directives in OpenMP? Give separate examples of the use of both constructs.

**Master Directive – The master directive specifies that a piece of code should be executed by the master thread.**

**Example:**

**#pragma omp parallel num\_threads(thread\_count)**

**{**

**// Do some stuff**

**#pragma omp master**

**{**

**// Allow master to do something specific**

**// Maybe output something to std out**

**}**

**}**

**Single Directive – The single directive specifies that a piece of code should be executed by a single thread, but the thread is not required to be the master thread.**

**Example:**

**#pragma omp parallel num\_threads(thread\_count)**

**{**

**// Do some stuff**

**#pragma omp single**

**{**

**// Allow a single thread to do something specific**

**// Note the thread doesn’t have to be the master thread**

**}**

**}**

f) Explain why static mapping of data blocks to processors may be bad for the Mandelbrot program that was discussed in the class lecture.

**Because of the nature of the algorithm, different regions require a different number of iterations and time to complete. If this is statically mapped / scheduled, each iteration of the loop is assigned to a thread before it executes which can introduce load imbalance, where there can be some significant idle time and wasted resources when processing this problem i.e. if a thread finishes before the others then it has nothing left to do but wait. Better solution would be to use dynamic mapping so that a thread could request more work when it is finished with its current task.**

g) What is the basic idea of a Monte Carlo simulation. Describe how this technique can be used to solve the numerical integration problem? What makes this technique so attractive for parallel processing? What are the major issues that could affect its accuracy when it is parallelized?

**The basic idea of Monte Carlo Simulation is to generate random inputs, belonging to a distribution, and evaluate the model’s/program’s risks and uncertainties.**

**In our text the author uses the Trapezoidal Rule for evaluating numerical integrals by approximating the region under a curve of a function as a trapezoid and finding the area for n trapezoids. This is a deterministic algorithm. The Monte Carlo method can also be implemented, non-deterministic algorithm, which would use number of samples in the distribution and evaluate the integral, this would be done however many times with however many samples and then the answers from the simulations would be averaged together to give the answer.**

**This technique is attractive to parallel programming because it is desired to thoroughly test a system; therefore, many test cases will need to be run which can be very time consuming. The use or parallel processing can divide the tasks up and hopefully complete the suite of simulations in a timelier manner.**

**The whole idea of the Monte Carlo Simulation is to test a model with random inputs to check risk and uncertainty. If using a pseudo random number generator, you could fall into the trap where each process/thread ends up with the same test variables and you just run the same test n times. While the results could be averaged to get a good assessment for that set of variables, there are many more combinations of tests that could have been run on the multiple processors/threads to give a better assessment of system under test.**

2. You have been provided with a sequential exhaustive search traveling salesman program that you are to parallelize using OpenMP, or pThreads. This sequential program which is named tsp\_serial.cpp, can be found on the CPE 512/412 CanvasTM site (or can be copied from /cpe412/exam2/tsp\_serial.cpp on the UAH Jetson system).

a) Examine this program and modify it so that you can measure the execution time. Using the queuing system on the Jetson system, as discussed in class, record the execution times for a 3,4,5,6,7,8,9,10,11,12, and 13 city tour. What is the time complexity of this algorithm? Develop an equation that can be used to estimate the execution time of the base sequential algorithm. Why do you think this problem is a challenging problem to solve, and inexact heuristics are utilized instead of exhaustively searching through all solutions as is done in this program?

**Time Complexity = O((n-1)!) approx. O(n!), the code is performing (n-1) permutations resulting in (n-1)! Tours.**

**TODO: Equation? Y = (6e-9)e2x**

**This problem is one of the N = NP hard problems. It is a hard problem to solve because we are looking for the shortest path in a list of (n-1) paths. The only way to know for sure that we have the shortest path is by testing every path and comparing the costs. The number of paths that have to be checked grow exponentially every time a city is added; therefore, finding a quick and correct solution to this problem is very difficult and one that many researchers and mathematicians have spent their entire careers on trying to solve.**

**There have been some newer algorithms utilizing heuristics to quickly find a path, but this is exactly what happens the algorithm will find a short path, but it might not be the shortest path in the graph.**

b) Develop a general multi-threaded version of the sequential program in either pThreads or OpenMP that will effectively divide up the amount of work that is performed. Using a single node of the Jetson queuing system, measure the execution times for an 8,9,10,11,12, and 13 city tour on a 1, 2, 3, and 4 thread implementation. For each multi-threaded implementation show the speedup, efficiency, and cost as a function of the number of cities in the tour.

**Note: See Appendix A for Source Code**

**TODO: Add the graphs for this problem**

**Table 1: TSP Run Times Serially and Multi-threaded**



**Table 2: TSP Relative Speed Up**



**Table 3: TSP Relative Efficiency**



**Figure 1: TSP Run Time Chart**

**Figure 2: TSP Relative Speed Up**

**Figure 3: TSP Relative Efficiency**

3. Expand the mm\_mult\_serial.cpp program on the CPE 512/412 CanvasTM site (or copy this program from /cpe412/exam2/mm\_mult\_serial.cpp on the UAH Jetson system) to create a hybrid multi-threaded/message passing implementation of a matrix/matrix multiplication program where the first matrix is of size lxm and the second matrix is of size mxn. Assume that the quantities being multiplied are of type float. Write the program in a general manner to allows the number of message passing processes and the number of threads per message passing process to be independently set by the user at run time. The program should be designed using the same row-wise decomposition method that was used in the two homework assignments. It should be written in a manner that will result in the total amount of computation to be divided as evenly as possible among the message-passing processes with the computation that is assigned to each message-passing processes in turn being further divided as evenly as possible between the associated threads. You are to use a combination of MPI and either OpenMP or pThreads to complete this problem. The number of threads should be a command-line parameter while the number of message-passing processes should be set by the Jetson Queuing system when you specify the number of nodes that are to be employed. The l, m, and n dimensions should also be command line parameters that can be set at run time. In other words, if the executable is named mm\_mult\_hybrid then the syntax needed to execute the code should take on the general form shown below:

srun mm\_mult\_hybrid [No. Threads per Process] [dim\_l] [dim\_m] [dim\_n])

where the number of MPI processes to be employed which is specified when the job is submitted to the Jetson queuing system.

a) Illustrate the correctness of your program for all possible combinations of thread numbers and number of MPI processes whose product is equal to 8 (i.e. 1 MPI process 8 threads per process, 2 MPI processes and 4 threads per process, 4 MPI process and 2 threads per process, and 1 MPI process and 8 threads per process) for cases where dim\_l, dim\_m, and dim\_n take on distinct values.

**See Appendix for Source Code**

**Output Serial:**

krr0010@jetson:~/jetson/Exam2/Problem3$ ./mm\_mult\_serial 4 6 3

A matrix =

48.3962 65.3245 15.0385 72.383 25.8898 46.0265

15.4881 50.6507 6.74602 71.0055 12.2209 77.5441

61.5452 31.5127 46.8515 89.4849 70.0342 57.3195

75.4144 83.5553 91.7832 7.74197 40.0845 11.1709

B matrix =

26.5416 83.9488 86.5328

51.0444 65.3442 85.2683

76.9977 49.0015 46.6826

12.2581 99.9706 40.1026

58.6347 47.2069 4.06732

37.0919 22.9082 82.6622

C matrix =

9889.42 18581 17272.7

7979.16 14392.3 15281.2

14179 23086.6 18811.4

16193.3 19210.5 19332

time=2e-06 seconds

**Output Parallel MPI = 1, NT = 8**

krr0010@jetson:~/jetson/Exam2/Problem3$ mpiexec -np 1 ./mm\_mult\_hybrid 8 4 6 3

A matrix =

48.3962 65.3245 15.0385 72.383 25.8898 46.0265

15.4881 50.6507 6.74602 71.0055 12.2209 77.5441

61.5452 31.5127 46.8515 89.4849 70.0342 57.3195

75.4144 83.5553 91.7832 7.74197 40.0845 11.1709

B matrix =

26.5416 83.9488 86.5328

51.0444 65.3442 85.2683

76.9977 49.0015 46.6826

12.2581 99.9706 40.1026

58.6347 47.2069 4.06732

37.0919 22.9082 82.6622

C matrix =

9889.42 18581 17272.7

7979.16 14392.3 15281.2

14179 23086.6 18811.4

16193.3 19210.5 19332

time = 0.0003619194 seconds

**Output Parallel MPI = 2, NT = 4**

krr0010@jetson:~/jetson/Exam2/Problem3$ mpiexec -np 2 ./mm\_mult\_hybrid 4 4 6 3

A matrix =

48.3962 65.3245 15.0385 72.383 25.8898 46.0265

15.4881 50.6507 6.74602 71.0055 12.2209 77.5441

61.5452 31.5127 46.8515 89.4849 70.0342 57.3195

75.4144 83.5553 91.7832 7.74197 40.0845 11.1709

B matrix =

26.5416 83.9488 86.5328

51.0444 65.3442 85.2683

76.9977 49.0015 46.6826

12.2581 99.9706 40.1026

58.6347 47.2069 4.06732

37.0919 22.9082 82.6622

C matrix =

9889.42 18581 17272.7

7979.16 14392.3 15281.2

14179 23086.6 18811.4

16193.3 19210.5 19332

time = 0.0049779415 seconds

**Output Parallel MPI = 4, NT = 2**

krr0010@jetson:~/jetson/Exam2/Problem3$ mpiexec -np 4 ./mm\_mult\_hybrid 2 4 6 3

A matrix =

48.3962 65.3245 15.0385 72.383 25.8898 46.0265

15.4881 50.6507 6.74602 71.0055 12.2209 77.5441

61.5452 31.5127 46.8515 89.4849 70.0342 57.3195

75.4144 83.5553 91.7832 7.74197 40.0845 11.1709

B matrix =

26.5416 83.9488 86.5328

51.0444 65.3442 85.2683

76.9977 49.0015 46.6826

12.2581 99.9706 40.1026

58.6347 47.2069 4.06732

37.0919 22.9082 82.6622

C matrix =

9889.42 18581 17272.7

7979.16 14392.3 15281.2

14179 23086.6 18811.4

16193.3 19210.5 19332

time = 0.012290955 seconds

**Output Parallel MPI = 8, NT = 1**

krr0010@jetson:~/jetson/Exam2/Problem3$ mpiexec -np 8 ./mm\_mult\_hybrid 1 4 6 3

A matrix =

48.3962 65.3245 15.0385 72.383 25.8898 46.0265

15.4881 50.6507 6.74602 71.0055 12.2209 77.5441

61.5452 31.5127 46.8515 89.4849 70.0342 57.3195

75.4144 83.5553 91.7832 7.74197 40.0845 11.1709

B matrix =

26.5416 83.9488 86.5328

51.0444 65.3442 85.2683

76.9977 49.0015 46.6826

12.2581 99.9706 40.1026

58.6347 47.2069 4.06732

37.0919 22.9082 82.6622

C matrix =

9889.42 18581 17272.7

9889.42 14392.3 15281.2

14179 23086.6 18811.4

16193.3 19210.5 19332

time = 0.069700956 seconds

b) Then perform a set of timing experiments under the same set of MPI process/thread combinations of part a (but with the output suppressed) for the cases where the dim\_l=dim\_m=dim\_n=5,000. Record the execution time associated with each multi-threaded case and compare these times with that of the original serial program. What is the relative speedup and efficiency for each case. Is there a significant difference between the various parallel implementations? If so give a possible explanation as to why the execution time was not the same for each case given that the total number of threads is the same in all cases and your code was designed to evenly distribute the workload among the threads.

**Table 4: Timing Analysis with Dim\_l = Dim\_M = Dim\_N = 5000**



**Yes, there is a significant difference between the various parallel implementations. Looking at the table above it is easy to see that the case with 8 MPI processes and 1 thread executed with the most efficiency. In the cases with more OpenMP threads than MPI processes, the threads must compete for shared resources such as cores and memory. However, we can see in the cases where the number of MPI processors is greater we achieve a higher efficiency. This is more than likely because we have evenly distributed the problem to a cluster of machines that can now each evenly distribute the workload amongst their own shared memory threads, hopefully reducing the strain on shared resources. Being curious, I went back and ran the test with the number of threads set to 1 and just varied the number of MPI processes.**

**Table 5: Timing Analysis with NT = 1**



**Comparing both tables we can see that the light weight OpenMP threads do help to reduce the overall execution time, but it doesn’t seem that, with my implementation, they are as efficient as distributing it across multiple MPI processes.**

4. Answer the following question for the code segment shown below assuming that we have a computing node that has 4 active cores that are dedicated to processing our problem and that were are utilizing OpenMP to parallelize a for-loop that initializes the upper triangle portion of a 100 ∞ 100 matrix to the values returned by the function, init\_element(x,y), which itself always executes in constant amount of time regardless of the values associated with its two arguments.

#pragma openmp parallel for schedule( ... )

for (i = 0; i < 99; i++) {

for (int j = i+1; j < 100; j++) {

a[i][j] = init\_element(i,j);

}

}

Notice that the arguments to the schedule() clause have been left undefined. Below are six example schedule clauses that could be used. Rank these clauses from slowest to fasted by closely examining the characteristics of this problem. To do this note that each iteration of the inner loop above does just one assignment and we can estimate the execution time by counting how many assignments each thread does. (Also note the total number of assignments the problem performs is exactly 4,950 assignments). For each schedule clause, estimate how long the parallelized loop will run. Explain how you arrived at your estimates.

schedule(static)

schedule(static, 10)

schedule(static, 1) **Fastest**

schedule(dynamic, 1)

schedule(dynamic, 10)

schedule(dynamic, 20) **slowest**

**Assuming init\_element always executes in a constant time (x). The parallel for will divide the first for loop based on the scheduling method used.**

**What I know about the schedule clauses:**

**The static schedule clauses perform the round robin assignment of the iterations to each thread before the loops execute; whereas, the dynamic schedule clause the iterations are assigned while the loop is executing and after a thread is finished it can request another “chunk” from the run-time system. The dynamic schedule clause does incur some extra overhead for its capability.**

**What I know about this problem:**

1. **The machine can utilize 4 cores / threads.**
2. **The call to init\_element(arg1, arg2) executes in constant time T no matter the arguments given.**
3. **Parallelization is applied to the outer loop, so the 99 iterations will be scattered amongst the cores based on the scheduling routine.**
4. **The inner loop number of iterations decreases as the outer index variable (i) increases. This will cause some iterations to take less time.**

**What I think will happen:**

1. **Schedule(static)**
   1. **In the first case (schedule(static)) the default chunk size which will be total\_iterations(99)/threat\_count(4). This means that each thread will get 25 iterations with one thread getting only 24 for this case (25, 25, 25, 24). Because the inner loop is dependent on (i) the number of inner loop iterations decrease as (i) increases and because of the default static schedule this means that the total number of assignments will be (2175, 1550, 925, 300) for each thread respectively. Note thread 1 gets the “first” 25 iterations which have the largest number of inner loop iterations. That means thread 1 will execute for approximately 2175\*T time while thread 4 will execute for 300\*T time. That means that thread 4 will be sitting idle doing nothing for a while waiting for the other threads to finish. This is load imbalanced.**
2. **Schedule(static, 10)**
   1. **In this case we are given the chunk size of 10; therefore, each thread will grab 10 iterations in a round robin fashion until no more are left thus leaving with this distribution (30, 29, 20, 20). Applying the same logic above the threads will arrive at this distribution for the total number of assignments (1635, 1335, 1090, 890). While this is still load imbalanced it is better than the first schedule clause.**
3. **Schedule(static, 1)**
   1. **In this case we are given the chunk size of 1; therefore, each thread will grab 1 iteration from the pool in a round robin fashion until no more are left thus leaving with a similar distribution as the first case (25, 25, 25, 24). Applying the same logic above the threads will arrive at this distribution for the total number of assignments (1275, 1250, 1225, 1200). This is much more balanced than the first two scheduling options.**
4. **Schedule(dynamic) / Schedule(dynamic, 10) / Schedule(dynamic, 20)**
   1. **The distribution for these clauses is left up to the run-time system and could be different every time the program is ran. It is good to note that dynamic scheduling is good for situations where the loop iterations might not execute in the same time. In this case because the number of inner loop iterations decreases as a function of the outer loop index (i), it is safe to say that if each assignment happens in a constant time T then these loops will all execute with different executions times at a delta of T. This would lead to believe that dynamic scheduling would be a good candidate for this problem.**

**Ranking:**

**Based on the above I would rank the scheduling clauses as follows:**

**Slowest: Schedule(static), most load imbalanced**

**Schedule(static, 10)**

**Schedule(dynamic) / Schedule(dynamic,10), Schedule(dynamic, 20)**

**Fastest: Schedule(static, 1)**

5. Expand upon the bounded\_buffer.cpp that is provided on Canvas (or copy this program from /cpe412/exam2/bounded\_buffer.cpp on the Jetson system) to create two separate OpenMP implementations of the producer/consumer bounded buffer-problem discussed in class that utilizes a common shared memory (between threads) and counting semaphores to ensure proper synchronization. [Note you will also need to link this program with the util.o file that is also provided on Canvas or on the Jetson system at /cpe412/exam2/util.o] One implementation should use OpenMP's standard parallel and work sharing data parallel constructs to start up the separate consumer and producer threads. The other implementation should utilize the OpenMP tasking model. Verify that both models function correctly and answer the following questions:

a) Carefully explain the characteristics of the producer and consumer bounded buffer problem? What are the major synchronization challenges that are involved.

b) Describe the function of the main, consumer, and producer module? What are the output files diary and con\_? and prod\_? reporting?

c) Execute both versions of the producer/consumer program with two producers, two consumers, number of messages of 100 and with a buffer size of 5. How many actual threads are generated when you run each version? Are they the same? How do they relate to the number of producers/consumers that are specified at run time?

d) How is it possible for the buffer size to be smaller than the number of data that is to be passed between producer and consumer? Explain how this is actually implemented in the program.

e) Experiment with different size buffers, messages, and consumer processes and producer processes. From the diary file and other files can you determine if the semaphore releasing strategy is fair? Explain your answer.

**TODO: Try to finish this problem and hope for some credit.**