COSC 407
Intro to Parallel Computing

Topic 5 - Introduction to OpenMP

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Outline

Previously:

- Intro to parallel computing
  - important concepts and terminology.
- Intro to POSIX Threads

Today:

- OpenMP
  - Basics, HelloWorld
  - Distributing the work
  - Example: Summing it all up (as array)

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Roadmap

- Writing programs that use OpenMP.
- Exploiting a powerful OpenMP feature
  - Parallelize serial for loops with only small changes to the source code.
- Using other OpenMP features:
  - Task parallelism.
  - Explicit thread synchronization.
- Addresses standard problems in shared-memory programming

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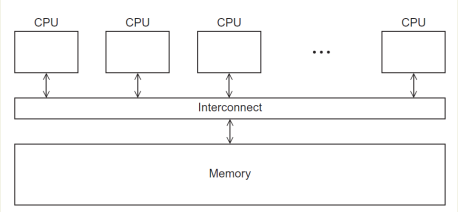
Shared Memory

- OpenMP = Open Multi-Processing
- An Application Program Interface (API) for multi-threaded, shared-memory parallel programming.
  - Designed for systems in which each thread or process can potentially have access to all available memory.
  - System is viewed as a collection of cores or CPU's, all of which have access to main memory.



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OpenMP vs Pthread

- OpenMP
  - Higher level
  - Programmer only states that a block of code is to be executed in parallel and delegates "how to" to the compiler & runtime
  - Requires compiler support (some compilers cannot compile OpenMP programs)
- Pthreads
  - Lower level
  - Requires programmer to explicitly specify behavior of each thread
  - LIbrary of functions to be linked to a C program (can use any compiler)

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Advantages of OpenMP

- Good performance and scalability
  - If you do it right
- Requires little programming effort (relatively!)
- De-facto and mature standard
- Portable program (large number of compilers)
- Allows the program to be parallelized incrementally
- Ideally suited for multicore

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Compiling and Running From the Command Line

```
gcc −g −Wall -fopenmp −o omp_hello omp_hello . c
. /omp_hello
```

compiling

running (# of threads set with OpenMP env var)

possible outputs

```
Hello from thread 0 of 4
Hello from thread 1 of 4
Hello from thread 2 of 4
Hello from thread 3 of 4
```

```
Hello from thread 1 of 4
Hello from thread 2 of 4
Hello from thread 0 of 4
Hello from thread 3 of 4
```

```
Hello from thread 3 of 4
Hello from thread 1 of 4
Hello from thread 2 of 4
Hello from thread 0 of 4
```

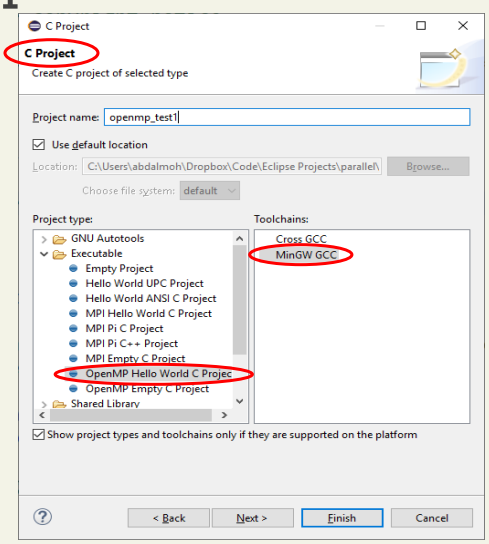

Compiling and Running with Eclipse

On Eclipse for Scientific Computing:

- Make sure your MinGW is installed and properly configured.
- Create your code:
  - Create a new “C Project” > “OpenMP Empty C Project”
  - Then create a new “Source File”
- Build your project
  - I created a shortcut for that!
- Run your project
  - Default shortcut: Ctrl+F11
  - Eclipse will take care of the flags with the command line.

- **Note that you must have the C compiler, openMP, and Eclipse installed properly (See Canvas)**

Compiling and Running with Eclipse



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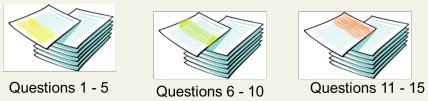
Remember!

Two ways to divide the work:

1. **Task parallelism**
   - Partition various tasks carried out solving the problem among the cores.



Questions 1 - 5 All exams | Questions 6 - 10 All exams | Questions 11 - 15 All exams

1. **Data parallelism**
   - Partition the data used in solving the problem among the cores.
   - Each core carries out **similar operations** on it's part of the data.

All tasks (questions) 1/3 of exams | All tasks (questions) 1/3 of exams | All tasks (questions) 1/3 of exams

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OpenMP API

- OpenMP specifications:
  - http://www.openmp.org/specifications
- OpenMP is based on **directives**
  - Simple syntax
  - **Risk:** you must understand exactly what the compiler will do, otherwise your program will not function as expected

OpenMP API has **three components**:

1. **Compiler directives (#)**
   - e.g., #pragma omp parallel
2. **Runtime library routines**
   - e.g., `omp_get_thread_num()`
3. **Environment variables**
   - E.g., setting an environment variable
     set OMP_NUM_THREADS=3
   - Will rarely use or refer to them (as we can set number of threads directly in code)

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OpenMP and Threads

- OpenMP implements parallelism exclusively using **threads**
- Remember Process vs Thread:
  - Threads exist within a process.
  - **Execution:**
    - Both threads and processes are **units of execution** (tasks)
  - **Memory:**
    - **Processes** will, by default, **not share memory**.
    - **Threads** of the same process will, by default, have access to the same **shared memory** (the process memory)
      - Light weight

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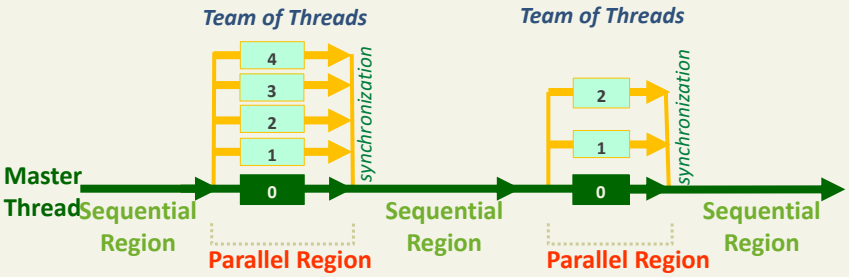
Fork - Join Model

- OpenMP uses ***Fork-Join*** model.



- *Synchronization* means that everyone must wait till everyone is finished before proceeding to the next region.
- The collection of threads executing the parallel block is called a **team**: the original thread is called the **master**, and the additional threads are called **slaves**
- Each thread takes an ***ID*** (**master always has ID 0**)

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OpenMP: pragmas

- Special preprocessor instructions that are added to a system to allow behaviors that aren't part of the basic C specification.
  - Compilers that don't support the pragmas ignore them.
    - i.e. if the compiler does not support them, the program will still yield correct behavior, but without any parallelism.
- Syntax:

```
#pragma omp directive [clause[clause]..]
```

  - **Directive**: specifies the required directive
    - *The most basic directive:* `#pragma omp parallel`
      - *The parallel construct forms a team of threads and starts parallel execution.*
  - **Clause**: information to modify the directive.
    - *e.g.:* `#pragma omp parallel num_threads(10)`
  - *Continuation: use \ in pragma*
    - *e.g.*

```
#pragma omp parallel \
                num_threads(10)
```


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OpenMP pragmas

 # pragma omp parallel

- Most basic parallel directive.
- The number of threads that run the following structured block of code is determined by the run-time system.
- There is an **implicit barrier** at the end of this directive
  - barriers are discussed later ….

 # pragma omp parallel num_threads(thread_count)

- **num_threads clause** allows the programmer to specify the number of threads that should execute the following block
- There may be system-defined limitations on the number of threads that a program can start
- The OpenMP standard doesn't guarantee that this will actually start thread_count threads
- Most current systems can start hundreds or even thousands of threads Unless we're trying to start a lot of threads, we will almost always get the desired number of threads

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Hello World
Serial Version

```
#include <stdio.h>

int main() {

     printf("Hello World!\n");

   return 0;
}
```

Output:
Hello World!

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Hello World Parallel Version

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

int main() {
   #pragma omp parallel
     printf("Hello World!\n");

   return 0;
}
```

Parallel Region.
Sent to all threads!

Output:
```
Hello World!
Hello World!
Hello World!
Hello World!
```


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Both Serial and Parallel in One Program

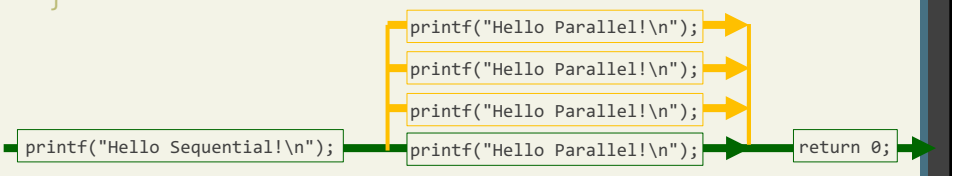
Output:
```
Hello Sequential!
Hello Parallel!
Hello Parallel!
Hello Parallel!
Hello Parallel!
```

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

int main() {
   printf("Hello Sequential!\n");

   #pragma omp parallel
     printf("Hello Parallel!\n");

   return 0;
}
```

Sequential : Only performed by master!

Parallel: SAME task sent to all threads

Sequential



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Hello World
Parallel Version (again)

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

int main() {
   #pragma omp parallel
   {
    int my_id = omp_get_thread_num();
    printf("Hello World from thread %d\n", my_id);
   }
   return 0;
}
```

Printing the thread ID

Use curly braces when having more than one statement

Possible Output:

```
Hello World from thread 2
Hello World from thread 0
Hello World from thread 1
Hello World from thread 3
```


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Hello World
Parallel Version (again), *cont'd*

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

int main() {
   #pragma omp parallel
   {
    int my_id = omp_get_thread_num();
    int tot = omp_get_num_threads();
    printf("Hello World from thread %d/%d\n", my_id, tot);
   }
   return 0;
}
```

Printing the thread ID and total num of threads

Possible Output:

```
Hello World from thread 1/4
Hello World from thread 0/4
Hello World from thread 2/4
Hello World from thread 3/4
```


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Hello World
Parallel Version (again), *cont'd*

Specifying required # of threads

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

int main() {
   #pragma omp parallel num_threads(3)
   {
    int my_id = omp_get_thread_num();
    int tot = omp_get_num_threads();
    printf("Hello World from thread %d/%d\n", my_id, tot);
   }
   return 0;
}
```

Possible Output:

```
Hello World from thread 2/3
Hello World from thread 0/3
Hello World from thread 1/3
```


Hello World
Parallel Version (again), *cont'd*

Using a function in the parallel region

```
#include <stdio.h>
#include <omp.h>
void Hello();
int main() {
   #pragma omp parallel num_threads(3)
   {
     Hello();
   }
   return 0;
}
void Hello(){
  int my_id = omp_get_thread_num();
  int count = omp_get_num_threads();
  printf("Hello World from thread %d/%d\n", my_id,count);
}
```

Possible Output:

```
Hello World from thread 2/3
Hello World from thread 0/3
Hello World from thread 1/3
```

Demo
Interleaved Execution

```
#pragma omp parallel num_threads(4)
{
   printf("T%d:A \n", omp_get_thread_num());
   printf("T%d:B \n", omp_get_thread_num());
}
printf("T%d:Done \n", omp_get_thread_num());
```

Notes:
- Output is ***interleaved***, BUT any thread has to print A first then B.
- "Done" is only printed after everyone is done (***synchronization***)

possible outputs

T0:A	T1:A	T1:A	T2:A
T0:B	T2:A	T0:A	T2:B
T1:A	T1:B	T1:B	T1:A
T1:B	T2:B	T0:B	T1:B
T2:A	T0:A	T3:A	T0:A
T2:B	T0:B	T3:B	T0:B
T3:A	T3:A	T2:A	T3:A
T3:B	T3:B	T2:B	T3:B
T0:Done	T0:Done	T0:Done	T0:Done

Distributing Tasks

- You can use Thread ID to ***assign tasks*** to different threads

```
#pragma omp parallel num_threads(4)
{  int id = omp_get_thread_num();

   printf("T%d:A\n", id);
   printf("T%d:B\n", id);

   if(id == 2)
      printf("T2:special task\n");
}
printf("End");
```

Possible output
T2:A
T1:A
T2:B
T2:special task
T1:B
T0:A
T0:B
T3:A
T3:B
End

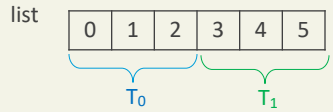
Possible output
T0:A
T2:A
T0:B
T2:B
T2:special task
T1:A
T1:B
T3:A
T3:B
End

Notes:
- Only T2 runs the special task
- No specific order for the threads, BUT the statements in the same thread are ordered

Distributing Data

- You can also use Thread ID to ***distribute data*** over different threads

```
int list[6] = {0,1,2,3,4,5};
#pragma omp parallel num_threads(2)
{
   int id = omp_get_thread_num();
   int my_a = id * 3;
   int my_b = id * 3 + 3;
   printf("T%d will process indexes %d to %d\n",id,my_a,my_b-1);
   for (int i = my_a; i < my_b; i++)
      printf("T%d:processing list[%d]\n",id,i);
}
printf("End");
return 0;
```



Possible Output 1:

```
T0 will process indexes 0 to 2
T0:processing list[0]
T0:processing list[1]
T0:processing list[2]
T1 will process indexes 3 to 5
T1:processing list[3]
T1:processing list[4]
T1:processing list[5]
End
```

Possible Output 2:

```
T0 will process indexes 0 to 2
T1 will process indexes 3 to 5
T0:processing list[0]
T1:processing list[3]
T0:processing list[1]
T1:processing list[4]
T0:processing list[2]
T1:processing list[5]
End
```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A Toy Problem

- The aim is to compute the sum of values in an array
  - While this is a straight-forward problem, it highlights the key things that need to be considered when dealing with parallelization
- One way to do this is to divide the array of values into into a series of sub-arrays
  - Find the sum of each
  - Then sum totals from sub-array

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The Serial Algorithm

```c
#include<stdio.h>

int arr[10] = { 12, 1324, 3243, 43, 44, 88, 12333, 34, 33, 4};

int main()
{

        int sum = 0;
        int size = sizeof(arr);

        //add all elements to the variable sum.
        for(int i = 0; i < size; i++)
                sum = sum + arr[i]; // same as sum += arr[i];

        //print the result
        printf("Sum of the array = %d\n",sum);

         return 0;
}
```


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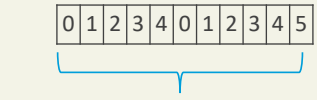
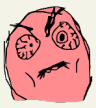
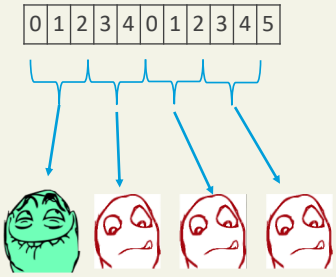
Dividing the Work!



Thread



One thread does all the work



Get some help!
divide array into n sub-arrays and compute sum

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Sum Calculation: Parallel Version

1. Two types of tasks:
   a) Computation of the sum of sub-arrays
   b) Adding the partial sums to compute total sum
2. There is no communication among the tasks in 1(a) (assuming that each thread can access the data separately) **but tasks communicates in 1(b) (bringing results back together)**
   - **Potential issues?**
3. We want to assign a single **thread to each core**
   - There could be more sub-arrays than physical cores….

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Sum Calculation: Parallel Version, cont'd

- Manually divide the work among threads
  - Use the "thread ID" and "thread count" to:
    - Compute local values for your calculations
    - Make decisions about which thread executes code
    - In this example,
      - Use "thread count" to calculate number of array slices
      - Use thread ID to determine start and end of each sub-array processed by that thread
  - Ensure no two threads perform the same calculations twice
- Use a private (local) variable to hold the local results and eventually either return them or added them to a global variable

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Serial Code

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

int *arr;
int n = 100000;                         //number of enteries in array


int serial_sum(int * arr, int size)
{
        int sum = 0;
        for (int i = 0; i < size; i++)
        {
                sum = sum + arr[i];
        }
        return sum;
}

int main()
{

        int sum = 0;
        int *arr = malloc(n * sizeof(int));
        //generate random data
        for (int i = 0; i < n; i++)
                arr[i] = rand();

        // start the timer!
        double start_time = omp_get_wtime();
        sum = serial_sum(arr, n);
        double end_time = omp_get_wtime();

        printf("Sum of the array = %d in %f ms!\n",sum, (end_time-start_time)*1000);

        free(arr);                              //housekeeping!

        return 0;
}
```

Time: 1.735000 ms
n = 1000000

To measure execution time

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Parallel Code

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

#define NUM_THREADS     8

int *arr;
int n = 100;                                    //number of enteries in array

void parallel_sum(int* arr, int*  global_sum);

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

        if (argc > 1){n = atoi(argv[1]);}       //no error checking here!!!

        int sum = 0;
        int *arr = malloc(n * sizeof(int));
        //generate random data
        for (int i = 0; i < n; i++)
        {
                arr[i] = rand();
        }

        int global_sum = 0;
        // start the timer!
        double start_time = omp_get_wtime();
#pragma omp parallel num_threads(NUM_THREADS)
        parallel_sum(arr, &global_sum);

        double end_time = omp_get_wtime();

        printf("Parallel sum of the array = %d in %f ms!\n",global_sum, (end_time-start_time)*1000);

        free(arr);                              //housekeeping!

        return 0;
}
```

Time: 0.564000 ms
n = 1000000

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Parallel Code cont.

```
void parallel_sum(int* arr, int*  global_sum)
{
        int my_id = omp_get_thread_num();       //0, 1, 2, or ...
        int my_n = n / NUM_THREADS;             //# of elements by this thread
        int start = my_id * my_n;               //first element processed
        int end = start + my_n - 1;             //last element processed
        int my_sum = 0;

#ifdef DEBUG
        printf("Thread #%d is starting at %d, ending at %d, processing %d\n",my_id, start, end, my_n);
#endif

        for(int i = start;i<=end; i++)
        {
                my_sum += arr[i];
        }

        #pragma omp critical
                *global_sum += my_sum;
}
```


What if the Compiler Doesn't Support OpenMP?

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



```
#ifdef _OPENMP
# include <omp.h>
#endif
```

```
# ifdef _OPENMP
  int my_id = omp_get_thread_num ( );
  int thread_count = omp_get_num_threads ( );
# else
  int my_id = 0;
  int thread_count = 1;
# endif
```

Conclusion/Up Next

- What we covered today (review key concepts):
  - Intro to OpenMP
    - Basics, HelloWorld
    - Distributing the work
    - Example: Summing in up
- Next:
  - Mutual Exclusion (critical, atomic, locks)
  - Variable scope (shared, private, firstprivate)
  - Reduction
  - Synchronization (barriers, nowait)

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Homework

- Please review
  - OpenMP Resources (See week three module)
  - Additional resources on Canvas
  - Run the sample code and try the challenge
    - You need to be able to run and understand how to approach a problem

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