Parallel and Distributed Computing
CS3006 (BCS-6C/6D)
Lecture 09

Instructor: Dr. Syed Mohammad Irteza

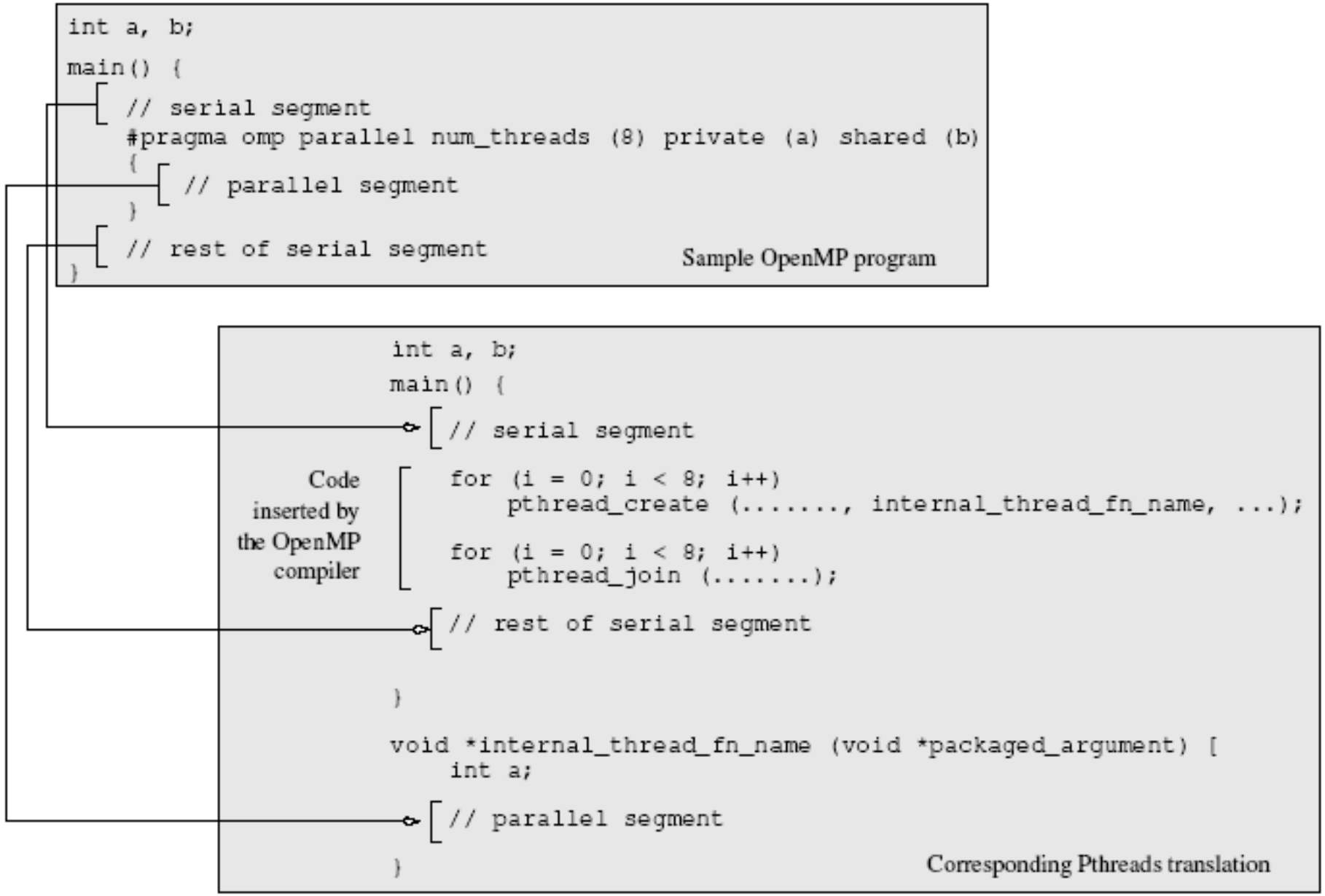
Assistant Professor, Department of Computer Science, FAST

21 February, 2023

Previous Lecture

- Decomposition Techniques
  - Speculative decomposition
  - Hybrid decomposition
- Distribution Schemes
- Block-distribution
  - Row-wise, Column-wise
  - 1D and 2D, Cyclic and Block-cyclic, Randomized
- Threads (Pthreads)
- Intro to OpenMP

Program Structure



Source: Introduction to Parallel Computing (Karypis and Co.)

First Program: hello world

```
#include <omp.h>
#include <iostream>
using namespace std;
int main()
{
 omp_set_num_threads(4);
 #pragma omp parallel
  {
    int Id = omp_get_thread_num();

    printf ("hello(%d)", Id);
    printf ("world(%d)\n", Id)
  }
}
```

Runtime function to request a certain number of threads

Runtime function returning a thread ID

```
#include <omp.h>
int numT;
int main()
{
 #pragma omp parallel num_threads(4)
   {
     int Id = omp_get_thread_num();
     numT = omp_get_num_threads();
     printf (“hello(%d)”, Id);
     printf (“world(%d)\n”, Id)
   }
}
```

Clause to request a certain number of threads

Runtime function returning the num of threads actually created

Loop work-sharing Construct

- **Sequential Code**

```
for(i = istart; i < iend;i++)  { a[i] = a[i] + b[i];}
```

- **OpenMP Parallel Region**

```
#pragma omp parallel
  {
  int id, i, Nthrds, istart, iend;
  id = omp_get_thread_num();
  Nthrds = omp_get_num_threads();
  istart = id * N / Nthrds;
  iend = (id+1) * N / Nthrds;
  for(i=istart;i<iend; i++) {a[i] = a[i] + b[i];}
  }
```

- **OpenMP parallel region and a worksharing `for` construct**

```
#pragma omp parallel
  #pragma omp for
  for(i=0; i<N;i++) {
  a[i] = a[i] + b[i];}
```

Need to add something like `num_threads(4)` to the `#pragma omp parallel`

What is OpenMP?

- OpenMP (Open Multi-Processing) is a popular shared-memory programming API
- OpenMP supports C/C++ and Fortran on a wide variety of architectures
- OpenMP is supported by popular C/C++ compilers, for e.g., LLVM/Clang, GNU GCC, Intel ICC, and IBM XLC

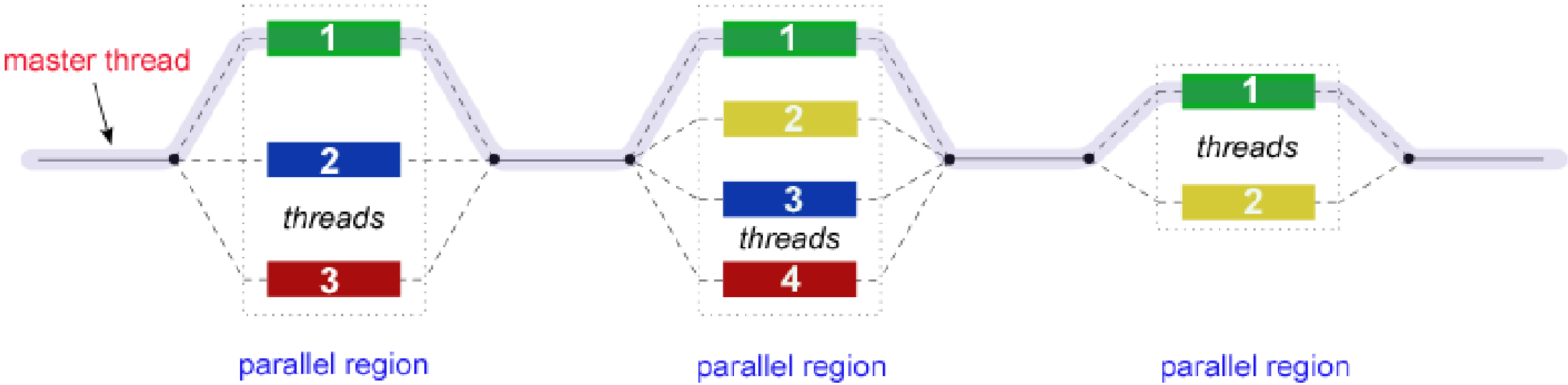
What is OpenMP?

- A directive based parallel programming model
  - OpenMP program is essentially a sequential program augmented with compiler directives to specify parallelism
  - Eases conversion of existing sequential programs

Key Concepts in OpenMP

- Parallel regions where parallel execution occurs via multiple concurrently executing threads
  - Each thread has its own program counter and executes one instruction at a time, similar to sequential program execution
- Shared and private data: shared variables are the means of communicating data between threads
- Synchronization: fundamental means of coordinating execution of concurrent threads
- Mechanism for ***automated work distribution*** across threads

Fork-Join Model of Parallel Execution



Compiling an OpenMP Program

- Linux and GNU GCC:
  - `g++ –fopenmp hello-world.cpp`
- Linux and Clang/LLVM:
  - `clang++ -fopenmp hello-world.cpp`

Basics to an OpenMP Program

- Each thread has a unique integer “id”; master thread has “id” 0, and other threads have “id” 1, 2, ...
- OpenMP runtime function `omp_get_thread_num()` returns a thread’s unique “id”
- The function `omp_get_num_threads()` returns the total number of executing threads
- The function `omp_set_num_threads(x)` asks for “x” threads to execute in the next parallel region (must be set outside region)

Numerical Integration: Pi program

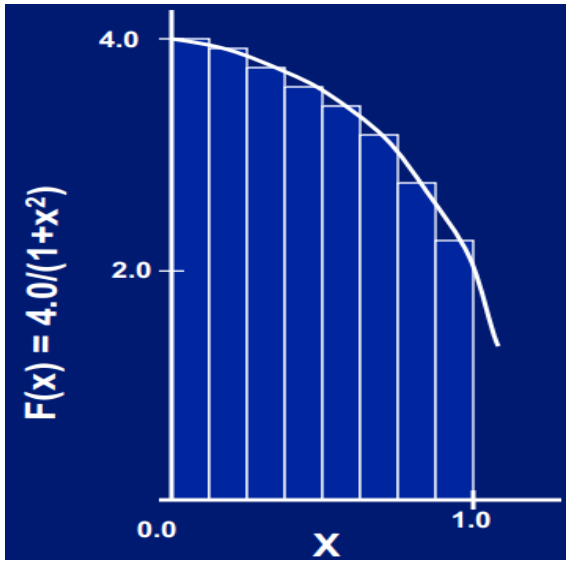
- Mathematically

$$\int_0^1 \frac{4.0}{(1+x^2)} dx = \pi$$

- Integral can be approximated as a sum of rectangles:

$$\sum_{i=0}^{N} F(x_i)\Delta x \approx \pi$$

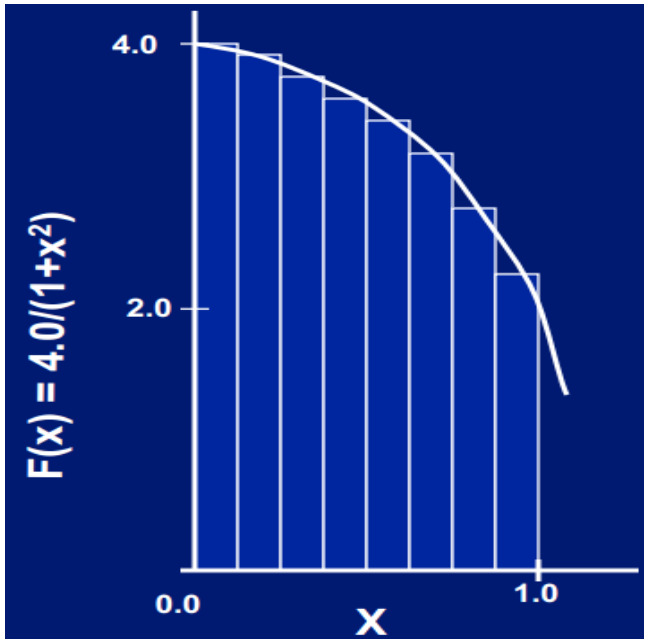
- Where each rectangle has
  width Δx and height $F(x_i)$ at
  the middle of interval i.



Source: http://openmp.org/mp-documents/omp-hands-on-SC08.pdf

Serial Pi Program

```
static long num_steps = 100000;
double step;
void main ()
{
  int i; double x, pi, sum = 0.0;
  step = 1.0/(double) num_steps;
  for (i = 0; i < num_steps; i++){
    x = (i + 0.5) * step;
    sum = sum + 4.0/(1.0 + x * x);
  }
  pi = step * sum;
}
```



Parallel Pi program

```
static long num_steps = 100000;
double step;
#define NUM_THREADS 4

int _tmain(int argc, _TCHAR* argv[]) {
  int i, nthreads;
  double pi, sum[NUM_THREADS];
  step = 1.0/(double) num_steps;
  omp_set_num_threads(NUM_THREADS);
#pragma omp parallel
  {
   int i, id, nthrds;
   double x;
   id = omp_get_thread_num();
   nthrds = omp_get_num_threads();
   if(id == 0)
      nthreads = nthrds;
    for (i=id, sum[id]=0.0; i< num_steps; i=i+nthrds){
        x = (i+0.5)*step;
        sum[id] += 4.0/(1.0+x*x);
    }
  }
  for(i=0, pi=0.0; i < nthreads; i++)
    pi += sum[i] * step;
  printf("%f\n", pi);
  return 0;
}
```

Synchronization

- Mutual exclusion: Only one thread at a time can enter critical section

```
#pragma omp critical [name]
  {
    code_block
  }
```

- [name] optional name that identifies the critical directive

Parallel Pi program using mutual exclusion

```
static long num_steps = 100000;
double step;
#define NUM_THREADS 2

int main(int argc, CHAR* argv[]) {
  double pi;
  step = 1.0/(double) num_steps;
  omp_set_num_threads(NUM_THREADS);
#pragma omp parallel
 {
   int i, id, nthrds;
   double x, sum;
   id = omp_get_thread_num();
   nthrds = omp_get_num_threads();

   for (i=id, sum[id]=0.0;i< num_steps; i=i+nthrds) {
     x = (i+0.5)*step;
     sum+= 4.0/(1.0+x*x);
   }

#pragma  omp critical
   pi += (sum * step);
 }
   printf("%f\n", pi);
}
```

Assigning Iteration to threads

- Static Scheduling
  - Splits the iteration space into equal chunks of size `chunk_size`
  - Assign them to threads in round-robin fashion
  - When no `chunk_size` is specified, the iteration space is split into as many chunks as there are threads and one chunk is assigned to each thread.

  - `#pragma omp for schedule(static, chunk_size)`

  - `#pragma omp for schedule(static)`

Assigning Iteration to threads

- Due to a number of reasons, including heterogeneous computing resources, non-uniform processor load, even equally partitioned workloads take widely varying execution times

- Dynamic Scheduling
  - Assign them (i.e., iterations) to threads when they become idle
  - Take care of the temporal imbalances resulting from static scheduling
  - If no `chunk_size` is specified, it defaults to a single iteration per chunk

  - `#pragma omp for schedule(dynamic, chunk_size)`

  - `#pragma omp for schedule(static)`

Reduction

- Sometimes there is true dependency between loop iterations which can not be removed.

```
double average=0.0, A[MAX]; int i;
for (i=0; i< MAX; i++) {
    average + = A[i];
}
average = average/MAX;
```

- We are combining values into a single accumulation variable (average)
- How to share work among threads. Such situation is called Reduction.

OpenMP reduction clause

- reduction (op : list)
- Inside a parallel work a local copy of each list variable is made
- List variable is initialized depending on the “op”

  (e.g. 0 for “+”)
- Compiler updates each local copy
- Local copies are reduced into a single value and combined with the original global value

```
double ave=0.0, A[MAX]; int i;
#pragma omp parallel for reduction (+:ave)
for (i=0; i< MAX; i++) { ave + = A[i]; }
ave = ave/MAX;
```

References

1. Kumar, V., Grama, A., Gupta, A., & Karypis, G. (1994). *Introduction to parallel computing* (Vol. 110). Redwood City, CA: Benjamin/Cummings.
2. Quinn, M. J. Parallel Programming in C with MPI and OpenMP, (2003).
3. https://www.cse.iitk.ac.in/users/swarnendu/courses/autumn2019-cs698l/OpenMP.pdf
4. https://www3.nd.edu/~zxu2/acms60212-40212/Lec-12-OpenMP.pdf